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Neo-Tethys geodynamics and mantle convection: from extension to compression in Africa and a conceptual model for obduction¹

Laurent Jolivet, Claudio Faccenna, Philippe Agard, Dominique Frizon de Lamotte, Armel Menant, Pietro Sternai, and François Guillocheau

Abstract: Since the Mesozoic, Africa has been under extension with shorter periods of compression associated with obduction of ophiolites on its northern margin. Less frequent than “normal” subduction, obduction is a first order process that remains enigmatic. The closure of the Neo-Tethys Ocean, by the Upper Cretaceous, is characterized by a major obduction event, from the Mediterranean region to the Himalayas, best represented around the Arabian Plate, from Cyprus to Oman. These ophiolites were all emplaced in a short time window in the Late Cretaceous, from ~100 to 75 Ma, on the northern margin of Africa, in a context of compression over large parts of Africa and Europe, across the convergence zone. The scale of this process requires an explanation at the scale of several thousands of kilometres along strike, thus probably involving a large part of the convecting mantle. We suggest that alternating extension and compression in Africa could be explained by switching convection regimes. The extensional situation would correspond to steady-state whole-mantle convection, Africa being carried northward by a large-scale conveyor belt, while compression and obduction would occur when the African slab penetrates the upper–lower mantle transition zone and the African plate accelerates due to increasing plume activity, until full penetration of the Tethys slab in the lower mantle across the 660 km transition zone during a 25 Myr long period. The long-term geological archives on which such scenarios are founded can provide independent time constraints for testing numerical models of mantle convection and slab–plume interactions.

Résumé : Depuis le Mésozoïque, l’Afrique a été en extension avec de courtes périodes de compression associées à l’obduction d’ophiolites sur sa marge nord. Moins fréquente que la subduction, l’obduction est néanmoins un phénomène de premier ordre qui reste énigmatique. La fermeture de la Neo-Téthys au Crétacé supérieur est caractérisée par un épisode majeur d’obduction, depuis la Méditerranée jusqu’à l’Himalaya, en particulier sur la marge de l’Arabie, de Chypre à l’Oman. Ces ophiolites furent toutes mises en place dans un court laps de temps pendant le Crétacé supérieur, de 100 à 75 Ma, dans un contexte de compression enregistré en de larges portions de l’Afrique et de l’Europe, au travers de la zone de convergence. L’échelle de ce processus requiert une explication à l’échelle de plusieurs milliers de kilomètres et donc impliquant vraisemblablement l’ensemble du manteau convectif. Nous suggérons que l’alternance de périodes extensives et compressives en Afrique résulte de changements du régime convectif. Les périodes extensives correspondraient à la convection impliquant tout le manteau, l’Afrique étant portée par une grande cellule de type tapis-roulant, tandis que la compression et l’obduction se produiraient quand le panneau plongeant africain pénètre la transition entre le manteau supérieur et le manteau inférieur et quand la plaque Afrique accélère en conséquence d’une plus grande activité du panache, jusqu’à pénétration complète, durant une période d’environ 25 Myr. Les archives géologiques sur lesquelles ce type de scénarios est fondé peuvent fournir des contraintes temporelles indépendantes pour tester les modèles numériques de convection mantellique et les interactions panache–panneau plongeant.

Introduction

One of the characteristics of mountains formed during closure of the Neo-Tethys Ocean is the existence of large ophiolitic nappes, remnants of oceanic lithosphere (Gass 1968; Coleman

1977, 1981; Dewey 1976). Some of these ophiolites were deeply subducted, metamorphosed, and exhumed to the surface like most of the Alpine ophiolites (Oberhänsli et al. 2004; Lardeaux et al. 2006; Angiboust et al. 2009), whereas other ophiolites were simply thrust over the continental margin, despite an a priori

higher density, escaping metamorphism (like the Semail ophiolite in Oman or the Lycian ophiolite in Turkey (Coleman 1981; Okay 1989; Ricou 1971; Şengör and Yılmaz 1981) or again the Newfoundland ophiolites (Kidd et al. 1978; Dewey and Casey 2013)) through a process called obduction. One of the best-documented examples is the Late Cretaceous obduction of the Tethys ocean floor. Two episodes of obduction of oceanic nappes on the northern continental margin of Apulia and Africa are recognized, one in the Late Jurassic – Early Cretaceous in the Dinarides (Dercourt et al. 1986; Schmid et al. 2008) and one in the Late Cretaceous, from Greece to Oman (Ricou 1971; Coleman 1981; Okay and Tüysüz 1999) for which Şengör and Stock (2014) recently coined the name Ayyubid Orogen.

The Neo-Tethys realm is characterized by a second feature: the microcontinent Apulian (or Adria) that separated from Africa sometime in the Jurassic (Ricou 1994; Barrier and Vrielynck 2008; Frizon de Lamotte et al. 2011) and drifted away to collide with Eurasia, forming the Mediterranean belts from the Late Cretaceous onward. At a later stage, Arabia was detached from Africa from the Late Eocene (Jolivet and Faccenna 2000; Bellahsen et al. 2003; McQuarrie et al. 2003). This process of rifting of continental blocks away from the northern margin of Africa also occurred much earlier in the Permian when the Cimmerian blocks rifted away from Africa (Matte 2001) or even earlier in the Devonian when the Paleotethys Ocean formed at the expense of the Rheic Ocean (Stampfli and Borel 2002). Earlier, identical processes were active several times along the Palaeozoic when Avalonia, Armorica, and Hun terranes rifted away from Gondwana (Matte 2001; Stampfli and Borel 2002). We are thus searching for a conceptual model that could explain the following two main features: (i) obduction and (ii) fragmentation of the northern part of the southern continent and northward travel of the rifted blocks, at the scale of several thousands of kilometres. We herein present a model based on an extensive compilation of geological observations on the obduction process itself and on the large-scale geological evolution of Africa and surrounding mid-ocean ridges.

Obduction of the Neo-Tethys ophiolites

High-pressure and low-temperature (HP–LT) metamorphic conditions recorded in the tectonic units found below ophiolites do not differ from those retrieved in Alpine-type mountain belts and show that obduction results from subduction of the former continental margin below the oceanic lithosphere (Goffé et al. 1988; Searle et al. 1994, 2004; Yamato et al. 2007). Small units made of metamorphic units of oceanic origin, the so-called metamorphic sole, sandwiched between the ophiolite and the subducted margin, sign the first stages of obduction. These metamorphic soles are characterized instead by high-temperature and low-pressure (HT–LP) metamorphic conditions and are systematically older than the HP–LT metamorphic rocks of the subducted continental margin (Hacker 1991; Hacker et al. 1996; Agard et al. 2007).

In Oman or western Turkey, the radiometric ages of magmatic rocks from the obducted ophiolite or the biostratigraphic ages of supra-ophiolite pelagic sediments, such as radiolarites, show that the ophiolite was very young (<~5 Myr) at the time of obduction (Nicolas 1989; Rioux et al. 2013; Çelik et al. 2006), implying the formation of an oceanic basin along the southern Neo-Tethys margin a few million years before obduction. Two types of models are debated for the Late Cretaceous obduction (Rioux et al. 2013): either subduction initiation along or near a mid-ocean ridge (Nicolas 1989) or formation of intra-oceanic subduction and later oceanic accretion in the upper plate as a result of mantle upwelling (Pearce et al. 1981; Rioux et al. 2013; MacLeod et al. 2013). Whether this young basin was formed as a back-arc basin above a north-dipping subduction, as a prelude to obduction, or along a new mid-ocean ridge is beyond the scope of this paper, but the two models have drastically different consequences. In the latter

case, this new subduction would result from the same compressional episode as obduction, but there is then only a short time from the formation of the first intra-oceanic thrust, the formation of a back-arc basin to its obduction. In the former case, the cause for the formation of this new ridge remains enigmatic, but it could be part of the generalized extension that predates compression. In this particular case, the age of the ophiolite should be older than the beginning of compression (i.e., provided by metamorphic sole ages). By contrast, the ophiolite in Armenia was much older at the time of obduction, and published models suggest the existence of an intra-oceanic subduction and a long-lived intra-oceanic back-arc domain where the ophiolite would have been rejuvenated before it was obducted (Rolland et al. 2009; Hässig et al. 2013, 2016).

These different models, obduction starting at the mid-oceanic ridge or as an intra-oceanic subduction associated with back-arc extension (supra-subduction zone ophiolites), provide good explanations for the evolution of metamorphic rocks found below the ophiolites, the HT–LP sole or the HP–LT blueschists and eclogites in the subducted margin (Searle et al. 2004; Yamato et al. 2007), but not for the subduction initiation precluding to obduction.

What is then the cause of the initial thrusting leading to obduction? This question has been approached by two different models: (i) acceleration of convergence, as a result of regional-scale plate reorganization (Agard et al. 2006), that makes subduction more difficult below Eurasia and induces transmission of compression within the subducting plate that buckles and finally breaks (Agard et al. 2007); or (ii) enhanced compression by increasing mantle plume activity (Vaughan and Scarrow 2003). Open questions include the cause of plate acceleration inducing compression and the cause for the asymmetry of the resulting subduction, always northward (i.e., south-directed obduction) in the case of the Neo-Tethys.

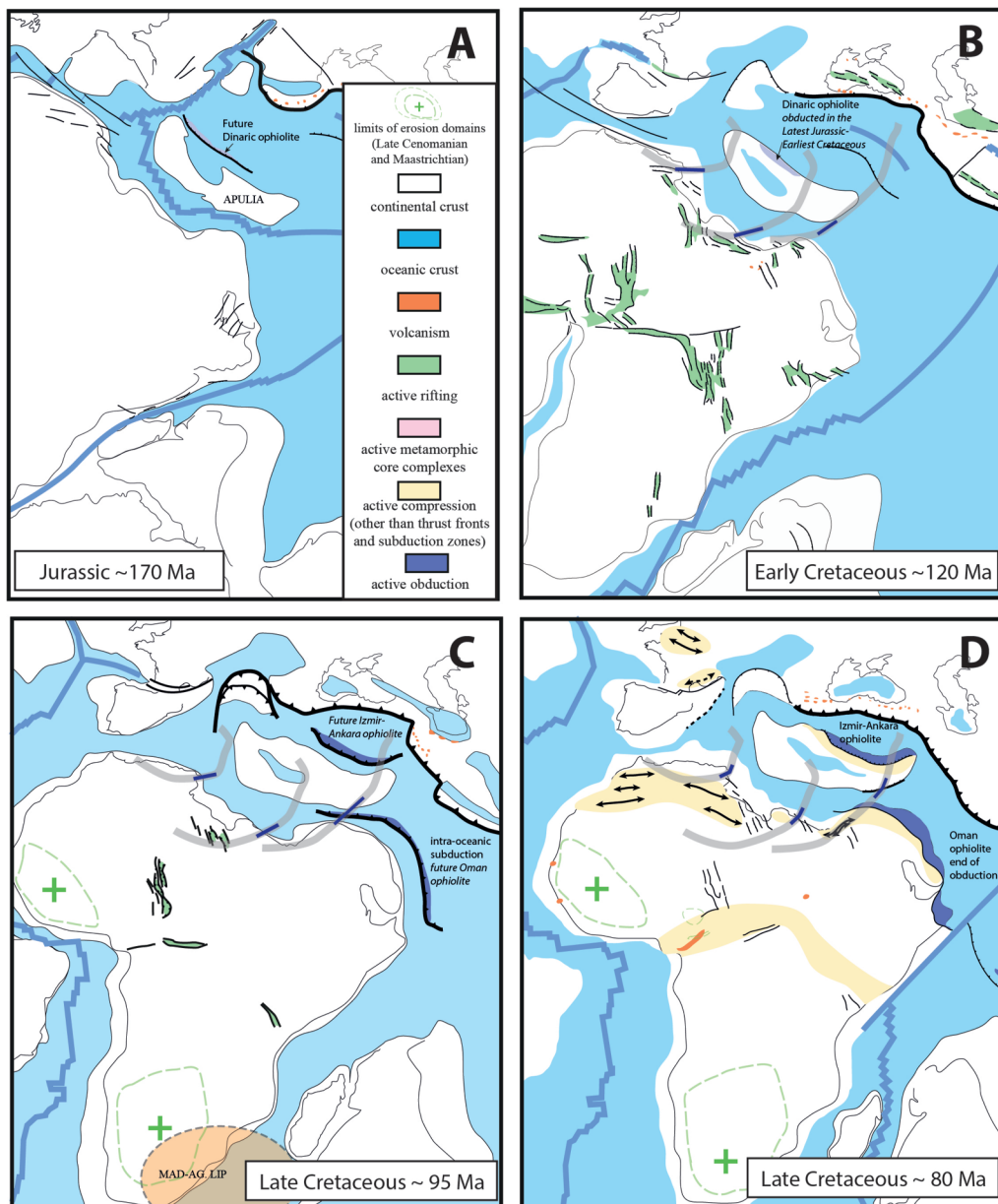
Tectonic history of Africa and the Neo-Tethys Ocean

A series of reconstructions (Fig. 1) and a compilation of geological events (Fig. 2) show the succession of events in the Neo-Tethys Ocean and Africa since the Jurassic. In the Middle Jurassic (~170 Ma, Fig. 1A), the Neo-Tethys, widely opened in the east, subducts below the southern margin of Eurasia (Agard et al. 2011 and references therein), making its connection with the Atlantic through the Alpine Tethys (Dercourt et al. 1986; Ricou 1994). In the meantime, a second-order rifted basin develops within Africa (Frizon de Lamotte et al. 2011) and the rifted Apulian s.l. continent migrates northward with respect to Africa, forming the eastern Mediterranean Basin (Ricou 1994). The Western Indian Ocean starts to open by rifting between India and Africa during the same period (see a recent review in Frizon de Lamotte et al. 2015). At the end of the Jurassic, the Dinaric ophiolites are emplaced on the northern margin of the Apulian block, as a result of the onset of intra-oceanic subduction dated by metamorphic soles at 175–160 Ma (Agard et al. 2007).

In the Early Cretaceous (~120 Ma, Fig. 1B), the African Plate is entirely under tension and numerous rifts develop within Africa and Arabia (Guiraud et al. 2005; Frizon de Lamotte et al. 2015), while the South Atlantic Ocean opens. Back-arc basins develop above the northern subduction zone, forming oceanic crust now flooring the Black Sea and the Caspian Sea and small back-arc domains in Central Iran (Hippolyte et al. 2010; Nikishin et al. 1998, 2015a, 2015b; Agard et al. 2011). Since the Jurassic, an intra-oceanic subduction induces back-arc spreading, forming the ophiolite that will be obducted later on the northern margin of Apulia in Armenia (Hässig et al. 2013, 2016).

After a significant plate reorganization and increase of the Africa–Eurasia convergence velocity at ~118 Ma (Agard et al. 2007), continuing extension on the northern margin of Gondwana and

Fig. 1. Reconstructions of Africa and the Tethys Ocean from the Late Jurassic to the Present. Plate kinematics is based upon [Barrier and Vrielynck \(2008\)](#), [Jolivet et al. \(2003\)](#), and [Menant et al. \(2016\)](#). Thick grey lines represent the motion paths of three points of Africa across the reconstructions. The detailed paths with the successive points are shown on [Fig. 1H](#) (Present stage) with ages in million years (Ma). Thick blue lines along the paths represent the average direction of motion at the time of reconstruction. Further explanation in text. [Colour online.]

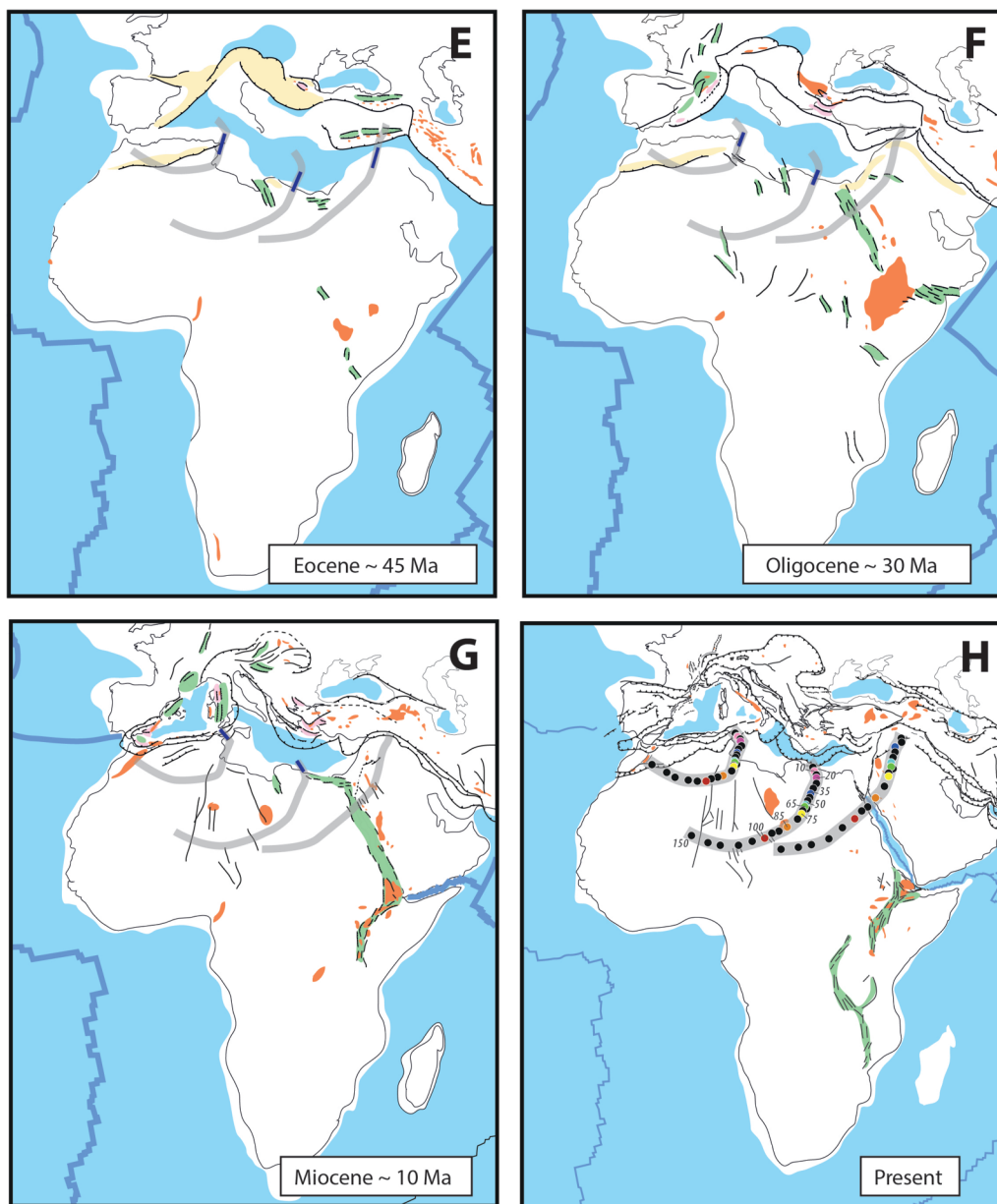


on the active southern margin of Eurasia from 120 to 95 Ma, compression is recorded in Africa and Europe in the Late Cretaceous (Figs. 1C and 1D) (Bosworth et al. 1999; Guiraud et al. 2005). It is preceded by a short event at about 110 Ma characterized by the reactivation of north-south-trending structures (the so-called Austrian phase) mainly observed in western Africa and independent from the Africa-Eurasia convergence. Except for this short earlier event, including the whole obduction process, the compressional episode lasted from ~100 to ~75 Ma. This first compressional event is coeval with the initiation of the intra-oceanic subduction leading to obduction and forming the large ophiolitic nappes observed nowadays (Fig. 1C). The age of this initiation is best constrained by the ages of metamorphic soles that all cluster around 100–95 Ma. Compression then progressively propagates over a large part of Africa with basement undulations and compressional reactivation of the previously formed rifts at about

85 Ma, i.e., the so-called Santonian event (Benkhelil et al. 1988; Benkhelil 1989; Genik 1993; Bosworth et al. 1999; Guiraud et al. 2005; Bevan and Moustafa 2012; Arsenikos et al. 2013) (Fig. 1D). This Santonian event is not present everywhere but is well characterized in the northern part of Africa and Arabia and also along the east-west segment of the Sub-Sahara Rift System. It has apparently not been recorded everywhere and some regions such as the Sirt Basin or the Muglad Rift in Sudan have not been reactivated (McHargue et al. 1992; Wennekers et al. 1996), but it is nevertheless widely distributed all over the northern half of Africa.

Special attention should be paid to the Sirt Basin. This basin developed from the Early Cretaceous to the Present on top of a highly pre-structured and faulted Panafrican basement with a Proterozoic metamorphic basement and a Paleozoic to Early Cenozoic cover (Wennekers et al. 1996; Abadi et al. 2008). Thick accumulations of sediments developed in the Cretaceous with the

Fig. 1 (concluded).



irregular deposition of the lower Cretaceous, followed by a period of major syn-rift subsidence during the Cenomanian and Turonian and then by the transgressive deposition of the Late Cretaceous up to the end of the Cretaceous. So, in Sirt, the Late Cretaceous contractional event is only underlined by a decrease of the subsidence rate (Frizon de Lamotte et al. 2011). An additional observation may explain why the Late Cretaceous inversion is not obvious in the Sirt Basin. The main depot-centres of the Sirt Basin strike northwest-southeast, almost perpendicular to the compressional fold axes in the nearby Cyrenaica (Arsenikos et al. 2013). The development of these basins in the Jurassic and Cretaceous was highly influenced by the pre-existing faults and basins with that same strike (Wennekers et al. 1996). The compression recorded in Cyrenaica was not properly oriented to reactivate the Sirt Basin normal faults.

Compression is also recorded during the same period across western Europe, from the Pyrenees where compression starts in the Santonian (~85 Ma, Vergés et al. 2002; Jammes et al. 2010) and southeastern France, all the way to the Paris Basin and the North

Sea (Guillocheau et al. 2000), ending up with slow subduction initiation in the western Mediterranean (the future Apennines subduction zone). During the same period, between 95 and 85 Ma, blueschists forming in the subduction zone are exhumed to shallow depth along the southern margin of Eurasia along thousands of kilometres (Agard et al. 2006, 2007; Monié and Agard 2009).

After a period of relative quiescence between 65 and 45 Ma (Rosenbaum et al. 2002), the Middle – Late Eocene shows renewed compression (Fig. 1E) in the Atlas Mountains, Cyrenaica, Syrian Arch, and all the way to the Zagros (Arsenikos et al. 2013; Frizon de Lamotte et al. 2011) and north of the young west Mediterranean subduction zone in the Iberian Range and the Pyrenees (Vergés et al. 2002). This new compressional period preceded the Oligocene uplift of large parts of Africa (Burke et al. 2003; Burke and Gunnell 2008) amounting to 200–300 m in North Africa, coeval with the early formation of the North African volcanic province (Liégeois et al. 2005; Wilson 1993; Wilson and Guiraud 1992). Volcanism is recorded earlier in the Central Sahara, as early as 34 Ma (Ait-Hamou 2006). The uplift is, for instance recorded during the

Fig. 2. Compilation of indicators of mantle convection activity and tectonic and metamorphic events related with the Late Cretaceous compression and obduction event. Green shadings represent the periods of faster Africa–Eurasia convergence, faster spreading in the South Atlantic, and compressional period in Africa in the Late Cretaceous. Labels 1–6: Spreading rates after [Conrad and Lithgow-Bertelloni \(2007\)](#) and [Colli et al. \(2014\)](#). 1: West Indian Ridge. 2: South Atlantic Ridge. 2b: South Atlantic full spreading rate. 3: West Pacific. 4: East Pacific. 5: Global average with Farallon. 6: Global average with Farallon. Most of the average value originates in the Pacific ridges, especially the peak around 120–110 Ma. Although velocities are much lower, the South Atlantic ridge shows an increased velocity between 120 and 70 Ma. Labels 7–8: Global figure of formation of oceanic crust and sea level variations. The Pacific peak of accretion in the Pacific reflects on the global production rates and the first order high in the sea level is coeval with this globally high production rates in the Cretaceous. 7: Sea-level after [Müller et al. \(2008a, 2008b\)](#). 8: Global oceanic flux (ridges and plateaus) after [Cogné and Humler \(2006\)](#). Label 9: LIPS after [Gaina et al. \(2013\)](#). Abbreviations: Mad. Agh, Madagascar-Agulhas; SWI, Southwest Indian; SEA, Southeast Atlantic. Labels 10–13: African plate velocity. All models of the Africa–Eurasia convergence show an increase between 120 and 70 Ma that is coeval with the higher velocity along the South Atlantic Ridge. Absolute velocity models show different figures and the peak of velocity is either between 110 and 100 Ma or around 80–70 Ma. 10: Africa–Eurasia convergence velocity at the longitude of the west Mediterranean after [Rosenbaum et al. \(2002\)](#). 11: Africa absolute velocity ([Dobrovine et al. 2012](#); [Gaina et al. 2013](#)) based on moving hot spots and a true polar wander model before 124 Ma. 12: Africa RMS velocity, hybrid moving hotspots, and true polar wander corrected reference frame ([Zahirovic et al. 2015](#)). 13: Africa–Eurasia convergence velocity at the longitude of Oman ([Agard et al. 2007](#)). 14–15: India plate velocity. The velocity peak is recorded after the peak for Africa, around 60 Ma. 14: India absolute velocity ([van Hinsbergen et al. 2011](#)). 15: India–Asia convergence ([van Hinsbergen et al. 2011](#)). Label 16: Sediments accumulation rates on South African margins ([Guillocheau et al. 2012](#)). The peak centered on 80 Ma comes after a period of increasing sediment discharge and a period of uplift and erosion of South Africa. Label 17: Subsidence of northern Africa ([Guiraud et al. 2005](#)). Label 18: Timing of subduction, exhumation, and back-arc extension in the western Mediterranean ([Jolivet et al. 2003](#)). Label 19: Timing of subduction, exhumation, and back-arc extension in the western Mediterranean ([Jolivet and Brun 2010](#); [Jolivet et al. 2003](#)). Label 20: Folding in the Paris Basin ([Guillocheau et al. 2000](#)). Label 21: Timing of subduction and obduction in Oman ([Agard et al. 2007](#); [Hacker et al. 1996](#); [Nicolas 1989](#); [Rioux et al. 2013](#)). Label 22: Timing of subduction and obduction in Turkey ([Çelik et al. 2011](#); [Pourteau et al. 2013](#)). Label 23: Timing of subduction and obduction in Armenia ([Hässig et al. 2013, 2016](#); [Rolland et al. 2009](#)). Label 24: Timing of subduction and obduction in the Zagros Internal Zones ([Agard et al. 2006, 2005, 2011](#)). Label 25: Timing of subduction and obduction in the Sabzevar Zone in Iran ([Rossetti et al. 2014, 2010](#)). Label 26: Timing of subduction and obduction in Sistan (Iran) ([Angiboust et al. 2013](#); [Monié and Agard 2009](#)). Label 27: Tectonic timing in the Black Sea region ([Hippolyte et al. 2010](#); [Nikishin et al. 2015a, 2015b](#)). Label 28: Tectonometamorphic timing in the Himalayas ([Guillot and Replumaz 2013](#)). [Colour online.]

Early Oligocene in the Niger Delta ([Petters 1983](#)), associated with a major regression but its exact age is poorly constrained. Otherwise, the upper plate of the convergence zone to the east records extensional deformation during this period.

A major change in subduction dynamics then occurs around 30–35 Ma ([Fig. 1F](#)), and back-arc basins start to form in the Mediterranean ([Jolivet and Faccenna 2000](#)). Meanwhile, rifting starts along the future Gulf of Aden and Red Sea, coeval with the Afar plume-related traps, and most of the sub-Saharan rifts are reactivated. The Miocene and Present stages ([Figs. 1G and 1H](#)) are the continuation of the same situation with separation of Arabia from Africa, and opening of Mediterranean back-arc basins.

These reconstructions show that, during 140 Ma, Africa has been mostly under extension and the subduction zone north of it has been forming back-arc basins, except during two periods: (i) an ~25 Myr long period (100–75 Ma) of compression associated with obduction, propagating away from the obduction zone within Africa and Europe in the Late Cretaceous and culminating in the Santonian and, after a period of quiescence, from 65 to 45 Ma; and (ii) compression resuming at 45 Ma and persisting until ~35 Ma, mostly in the west, before extension was again the predominant regime in Africa and Arabia, except within the Arabia–Eurasia collision zone ([Agard et al. 2011](#); [Mouthereau et al. 2012](#)). The intervening extensional periods were associated with plate fragmentation and the formation of Apulia and Arabia. The compressional periods thus seem accidental interruptions in a continuous process of extension and fragmentation of Africa during its motion toward Eurasia. During the Mesozoic this succession of extension and compression and obduction thus occurred at least twice: (i) rifting of Adria and Apulia away from Africa around 180–170 Ma, followed by the Dinaric obduction between 170 and 150 Ma; and (ii) distributed extension in Africa in the Early Cretaceous followed by compression and obduction in the Late Cretaceous. The separation of Arabia from Africa from the Late Eocene onwards seems the repetition of the same process, but very little oceanic lithosphere is left and collision occurs coevally ([Jolivet and Faccenna 2000](#)).

One important additional observation is that the newly created subduction zones leading to obduction dipped everywhere toward the north, with the same orientation as the already existing subduction zones beneath Eurasia, resulting in a totally asymmetrical situation where the continental lithosphere subducted northward below oceanic lithosphere, while the classical view would be that the oceanic lithosphere sinks below the continental lithosphere, whatever the polarity of subduction.

Africa from mantle plumes to subduction

During this evolution, several mantle plume events and associated large igneous provinces (LIPS) are recognized ([Fig. 3](#)), from the Central Atlantic Magmatic Province (CAMP) at 200 Ma ([Marzoli et al. 1999](#)), the Karoo event some 183–182 Ma ago ([Riley et al. 2004](#); [Svensen et al. 2012](#)), the Etendeka LIPS between 135 and 130 Ma ([Turner et al. 1994](#); [Dodd et al. 2015](#)), the Madagascar–Agulhas LIPS around 100 Ma within a greater southeast African LIP ([Gohl et al. 2011](#)), and finally the Afar volcanism ~45 to 30 Ma ago ([Hofmann et al. 1997](#); [Ershov and Nikishin 2004](#)) further north and the subsequent northward migration of intraplate volcanism across the western Arabian plate and eastern Anatolia ([Courtillet et al. 1999](#); [Faccenna et al. 2013b](#); [Gaina et al. 2013](#)). The Madagascar–Agulhas LIP, in particular, has been present offshore South Africa from ~140 to 95 Ma ([Gohl et al. 2011](#)). These successive volcanic events sign the presence of a long-lasting mantle upwelling underneath South Africa during a long period, also responsible for the evolution of dynamic topography in eastern Africa ([Burke 1996](#); [Burke et al. 2008](#); [Moucha and Forte 2011](#); [Torsvik et al. 2014](#)). This conclusion is further corroborated by the occurrence of kimberlites from ~200 to ~50 Ma with a younging from east to west ([Jelsma et al. 2009, 2004](#); [Torsvik et al. 2010](#)) suggesting that South Africa has slowly overridden the plume, before the latter migrated northward ([Braun et al. 2014](#)). The plume influence is also suggested by erosion and uplift of the Southern African Plateau in the Late Cretaceous ([Fig. 2](#), label 16; [MacGregor 2010](#); [Guillocheau et al. 2012](#); [Colli et al. 2014](#)). Similar uplift and erosion is also recorded in West Africa ([Leprêtre et al. 2014](#)). [Frizon de Lamotte](#)

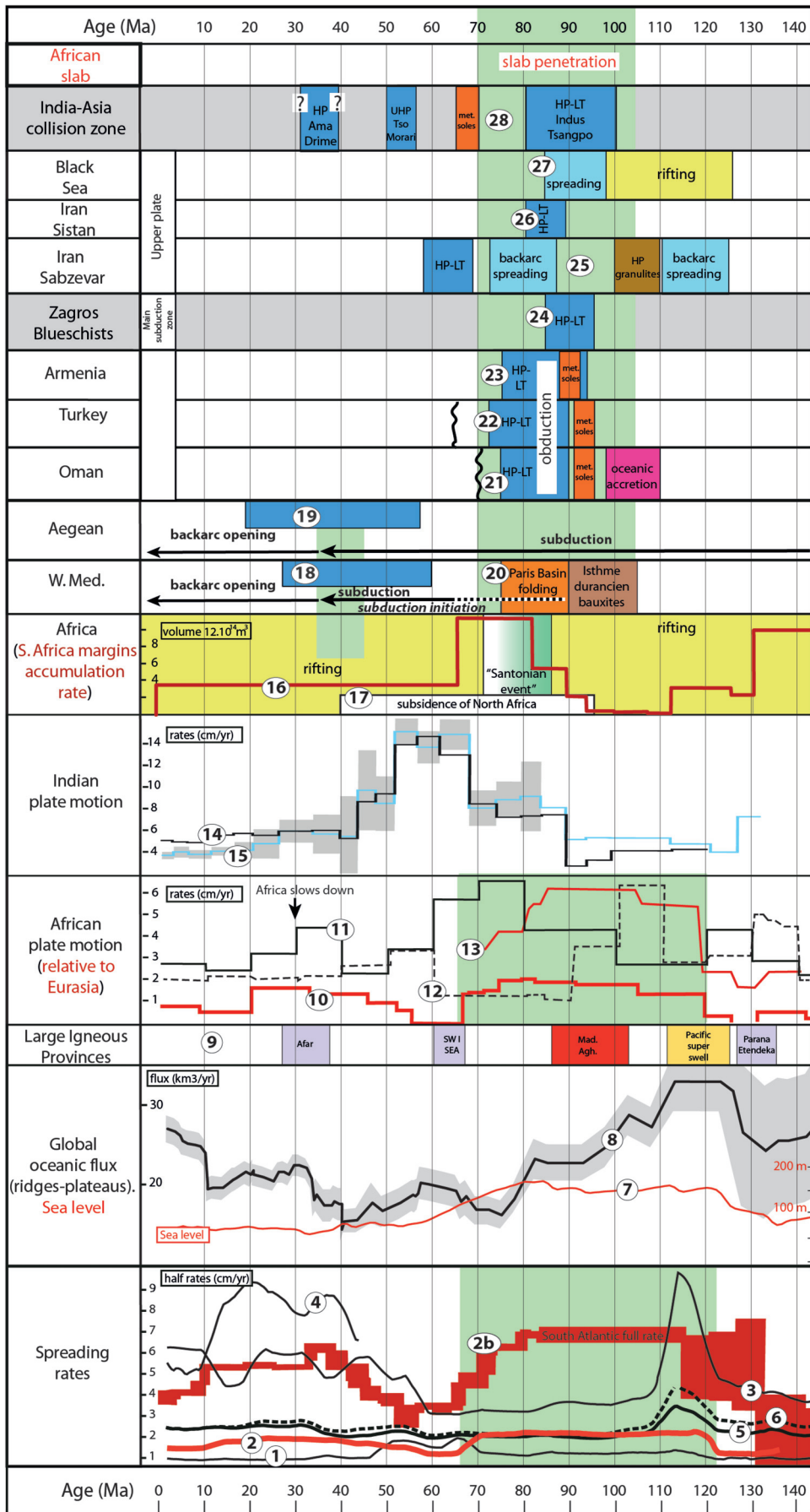
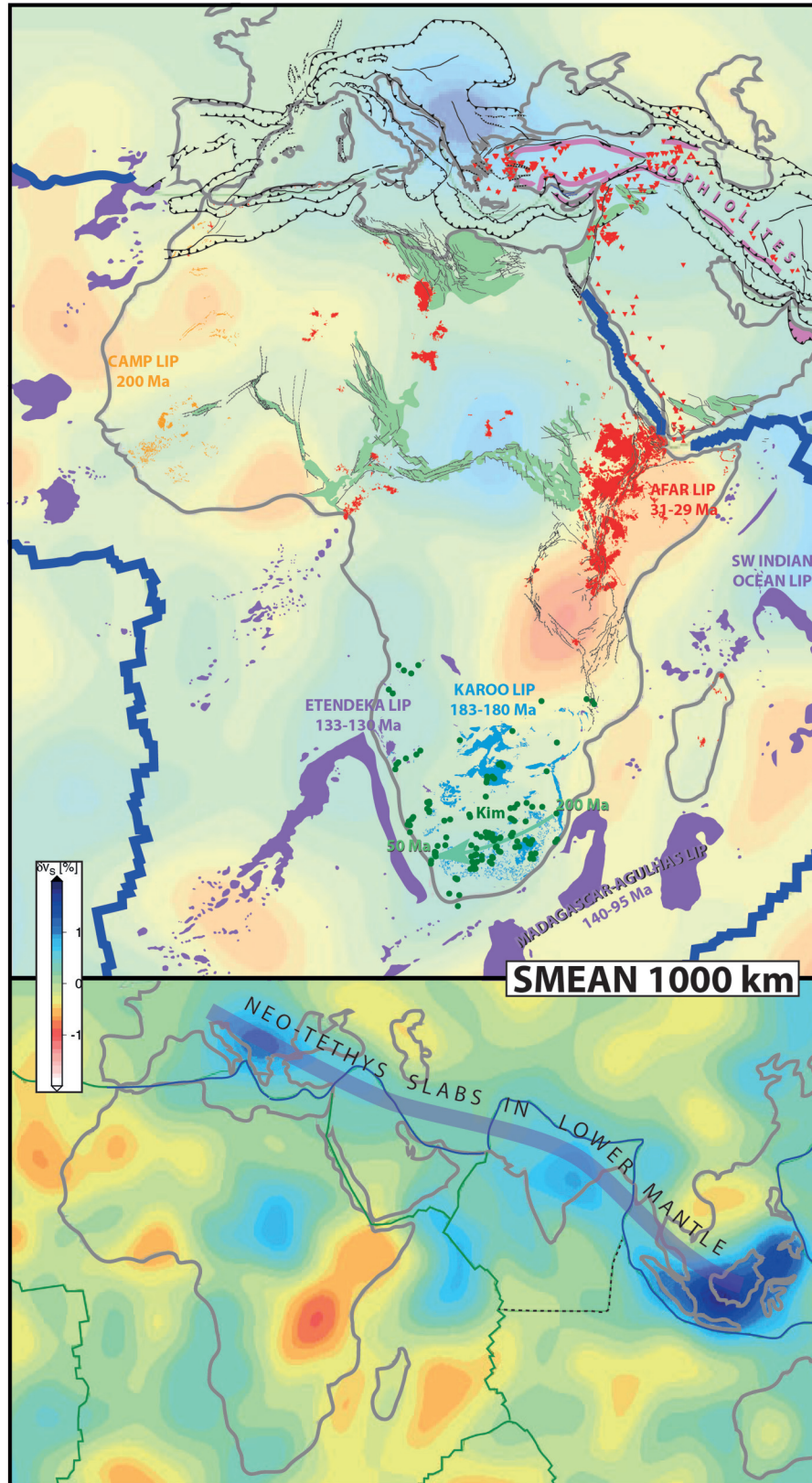


Fig. 3. Tectonic and volcanic features of Africa and the Mediterranean and lower mantle seismic velocity anomalies (1000 km, SMEAN model (Becker and Boschi 2002)). Upper panel: Tectonic map of Africa after Milesi et al. (2010) and the Mediterranean region showing the main Cretaceous Rifts (in light green), and the main volcanic provinces (Afar in red, Southwest Indian Ocean, Madagascar–Agulhas, Etendeka, and CAMP in violet, Karoo in blue). Dark green dots are the main kimberlites (Jelsma et al. 2004, 2009). Lower panel: SMEAN tomographic model and the outline of the Neo-Tethys slab in the lower mantle after Faccenna et al. (2013a). [Colour online.]



et al. (2015) have recently discussed the different styles of rifting that led to the fragmentation of Gondwana, emphasizing the difference between “passive” rifting episodes (the rift is localized by inherited structures) and “active” ones (the rift is localized by the plume that weakens the lithosphere) temporally related to evidence of plume activity. This new understanding derives from modelling by Burov and Gerya (2014) showing that a plume cannot trigger a rifting without external extensional forces as it was previously supposed by Şengör and Burke (1978). The Karoo LIPS (Fig. 3) at 183 Ma is associated with an episode of rifting leading to the opening of the West Indian Ocean. Similarly, the Early Cretaceous rifting episode can be seen as a consequence of the Paran -Etendeka LIPS.

From the Late Cenomanian until the Eocene, the northern part of Africa was under sea water and subsiding with a decrease at the Paleocene–Eocene boundary (Guiraud et al. 2005; Swezey 2009). Africa thus shows in the Late Cretaceous and early Cenozoic subsidence of the northern regions in the vicinity of the subduction and uplift in the south above mantle plumes. Convergence is accommodated by several subduction zones, one along the southern margin of Eurasia and two others where continental lithosphere underthrusts oceanic lithosphere, which all show the same asymmetry with the southern plate underthrusting the northern one.

A horizontal tomographic section (Becker and Boschi 2002) (Fig. 3) in the lower mantle (1000 km) distinctly shows the plume now sitting below eastern Africa at this depth. It also shows cold material further north, interpreted as remnants of the Neo-Tethys slab in the lower mantle (Ricard et al. 1993; Lithgow-Bertelloni and Silver 1998; Ritsema et al. 1999; Van der Voo et al. 1999; Steinberger 2000; Burke and Torsvik 2004; McNamara and Zhong 2005; Hafkenscheid et al. 2006; Garnero and McNamara 2008; van der Meer et al. 2010; Faccenna et al. 2013a) from the eastern Mediterranean region to India and Indonesia, signing the place where the slab has penetrated the upper–lower mantle transition zone. The timing of full penetration across the transition zone can be loosely bracketed by matching reconstructions and tomographic images (backward reconstructions of the slabs seen on tomographic models) between 70 and 45 Ma with probable significant error bars (Faccenna et al. 2013a; Replumaz et al. 2013).

The Eocene compression has more limited effects compared to the Late Cretaceous one, and these are mostly restricted to the western end of the convergence system with, however, the reactivation of earlier extensional structures in the east (Arsenikov et al. 2013). Nevertheless, the effects of compression are felt over a large domain from the Atlas Mountains to the Pyrenees (Frizon de Lamotte et al. 2000; Verg s et al. 2002; Mouthereau et al. 2014). This compression ended at ~35 Ma, when the subduction regime changed and back-arc extension started (Jolivet and Faccenna 2000).

Plate velocities

The two successive periods of compression (100–75 Ma and 45–35 Ma) correspond to faster convergence between Africa and Eurasia (Fig. 2, label 10). They are separated during the Paleocene by a period of very slow convergence (Fig. 2, label 10; Rosenbaum et al. 2002). The progressive build-up of Late Cretaceous compression is also coeval with an increase of the Africa absolute velocity (Fig. 2, label 11; Gaina et al. 2013), as well as a maximum of sea level at global scale (Fig. 2, label 7; M ller et al. 2008a, 2008b). It is also contemporaneous with higher velocities of spreading in the South Atlantic (Fig. 2, label 2b). The absolute motion of Africa gradually increased from the time of emplacement of the Paran -Etendeka LIP in the southern Atlantic to the emplacement of the Madagascar–Aghulas LIP in the Indian Ocean (Fig. 2, label 11; Gaina et al. 2013). After this period, the absolute motion of Africa slowed down before a new peak before 30 Ma and a new decrease after-

ward. The peak of convergence velocity predates the peak of absolute velocity (Fig. 2, labels 10, 11, 13). Faster African plate motion is associated with a period of increased spreading rate between 120 and 70 Ma in the southern Atlantic (Fig. 2, labels 2, 2b; Cogn  and Humler 2006; Conrad and Lithgow-Bertelloni 2007; Colli et al. 2014), although the global peak of oceanic crust production is recorded earlier at 120 Ma coeval with the Pacific superplume (Fig. 2, label 3; Larson 1991; Conrad and Lithgow-Bertelloni 2007). Subduction initiation in the Tethys Ocean in the Late Cretaceous, as shown by the age of metamorphic soles beneath ophiolites (Fig. 2, labels 21, 22, 23), temporally coincides with the period of increasing absolute velocity and the peak of convergence velocity (see green-shaded periods in Fig. 2). Similarly, the peak of Indian Plate velocity (Fig. 2, labels 14, 15) coincides with the age of metamorphic sole below ophiolites obducted onto the northern and western margins of India and the age of the southwest Indian plume at the very end of the Cretaceous (Gnos et al. 1997).

Discussion

In a recent paper, Şeng r and Stock (2014) have analyzed the Late Cretaceous compressional episode along the northern margin of Africa and proposed the name of Ayyubid Orogen. In their interpretation, the eastern part of this orogen, equivalent to the Croissan Ophiolitique P ri-Arabe of Ricou (1971), results from the obduction of the Tethys oceanic floor, while the western part results from an aborted obduction. They have analyzed the kinematic changes in the motion of Africa and conclude that the Ayyubid Orogen started to form before the kink in the motion path of Africa at 84 Ma (see also Figs. 1C and 1D), which implies that some other cause should be investigated. This also shows that the state of stress in the subducting plate is not simply related to the direction of convergence between Africa and Eurasia. They further propose that one has to invoke the plates that were lost during the convergence process, but they do not put forward an explanation for the change in stress regime that finally led to the observed obduction. The data compiled here illustrate that obduction is a large-scale tectonic process completed within a short time frame. One may then speculate that it is related to a large geodynamic cause, involving changes in subduction dynamics, increase plume activity, and plate velocity increase and not only to local plate motion re-orientation. Vaughan and Scarrow (2003) proposed for instance that obduction can be linked to superplume events producing compression over the entire subduction system. The period of compression in the Late Cretaceous, including obduction, is indeed coeval with faster convergence, increasing absolute motion of Africa and interaction with superplumes. Recent studies have shown the importance of mantle plumes in governing the mantle flow beneath Africa and supporting its topography (Forte et al. 2010; Glišovi  et al. 2012; Moucha and Forte 2011; Glišovi  and Forte 2014). Large-scale mantle plumes emanating from large low-shear velocity provinces in the lower mantle, one below South Africa and one below the Pacific (Behn et al. 2004; Torsvik et al. 2006; Burke 2011; Bower et al. 2013), are thought to be stable over tens or hundreds of millions of years (Glišovi  et al. 2012; Bower et al. 2013), suggesting a rather stable pattern of convection in the mantle. Strain pattern in the mantle below Africa, deduced from SKS seismic anisotropy, is furthermore compatible with northward mantle flow related to the African superplume (Bagley and Nyblade 2013; Hansen et al. 2012). Similarly, the northward motion of Arabia, after its separation from Africa some 30 Ma ago, and the migration of hotspot-related volcanism toward the collision zone are also compatible with a northward asthenospheric flow dragging Africa and Arabia (Faccenna et al. 2013b). Plume drag and push efficiency is attested by the fact that the motion of Arabia did not stop after collision, although there is no longer any significant slab to power its northward motion (McQuarrie et al. 2003; Alvarez 2010; Faccenna et al. 2013b).

Recent analogue experiments (Agard et al. 2014; Edwards et al. 2015) suggest that subducting a continental margin below a denser oceanic lithosphere is feasible once subduction has initiated, which remains the main problem. In a set of models comparable to the Tethyan system, Agard et al. (2014) show that the jamming of the northern subduction can lead to subduction initiation further south, leading to obduction on the African margin, reemphasizing the model proposed by Agard et al. (2007) in which faster plate velocity renders subduction more difficult, putting the system in compression and inducing the formation of a new subduction zone.

Elaborating on the ideas suggested by Vaughan and Searrow (2003), we now discuss a new plausible scenario coupling the evolution of the Tethyan subduction with a superplume below South Africa (Fig. 4) that should take into account three main large-scale observations: (i) the repeated detachment of continental pieces from Africa in the north; (ii) the contemporaneity of faster Africa motion, plume activity in the south, and compression and obduction; and (iii) the systematic southward polarity of obduction (northward subduction).

Step 1 (Fig. 4A): Assuming a continuous northward asthenospheric flow, which the superplume is part of, since the Jurassic, we first propose that extension and fragmentation of Africa (in the middle Jurassic and “middle” Cretaceous) result from this flow and the shear, or the push, it imposes to the base of the lithosphere (Bott 1993; Ziegler 1992; Stoddard and Abbott 1996). Africa was thus driven both by this drag and push and by slab pull in the subduction zone below Eurasia through a convective conveyor belt. We speculate that as long as the continuity of the conveyor belt existed, plume push resulted in extension episodes and sometimes in the stripping of microcontinents in the north of Africa. This hypothesis offers the advantage of explaining the repetition of the same process above a continuous northward mantle flow from the Paleozoic to the present, if Africa has been all along under the influence of mantle flow largely controlled by a long-lasting plume. Before plate acceleration and compression, the slab was not restricted to the upper mantle and partly retreated southward, leading to back-arc rifting in the upper Eurasian plate (Black Sea; South Caspian; Nain-Baft, Sabzevar, and possibly Sistan in central Iran).

Step 2 (Fig. 4B): Obduction. Interactions of mantle flow and cratonic lithospheric keels has long been discussed (Stoddard and Abbott 1996), and it has been recently suggested that continental cratonic keels may lead to plate acceleration when a plume arrives (Zahirovic et al. 2015). The detailed interactions between a plume and a continent above are not known but some recent investigations by Koptev et al. (2015) have confirmed the early work of Stoddard and Abbott (1996) and the importance of the push of the plume of the irregularities of the base of the lithosphere to move continents. Following up on this suggestion, we propose that the push due to the African superplume forced the (African) slab beneath Eurasia into the upper mantle at a faster rate. Slab penetration in the lower mantle could have produced a surge of compression within the subducting plate, leading to the formation of a new subduction zone close to the North African margin (Figs. 4B). Stresses would then build up until the whole system is in compression, leading to the so-called Santonian event. The Late Cretaceous compression is associated with an uplift of South Africa when it passes above the plume, while North Africa is instead subsiding and subducting below the obducting Tethys oceanic lithosphere. A mechanical link between slab penetration and the progressive reorientation of the Africa–Eurasia convergence around 84 Ma should be studied.

Step 3 (Fig. 4C): These compressional stresses would then be relaxed once the penetration beneath Eurasia is complete in the lower mantle and the conveyor belt is restored, that is some 70 Ma ago, when the Neo-Tethys obduction process stopped. The 25 Myr of compression would then be the time needed from plate accel-

eration to full slab penetration into the lower mantle. The same process may have happened again further east at the very end of the Cretaceous with the obduction of ophiolites on top of the northern and western margins of India. It may also have happened earlier at the end of the Jurassic to form the Dinaric ophiolite.

The boundary conditions of the model would then be radically different before and during the compressional episode. Before compression the plume in the south pushes on a plate that is free to move northward on its northern boundary and the system is driven by slab pull that is more efficient than plume push. During compression the more active plume induces a stronger push in the south while the slab is penetrating the upper-lower mantle discontinuity in the north, thus inducing compression in the whole northern half of the African plate.

This scenario can furthermore create the asymmetrical boundary conditions explaining the polarity of the newly created subductions and the underthrusting of old and dense continental mantle below younger and lighter oceanic mantle. We show in Fig. 5 a possible evolution at the start of obduction, shortly after a young oceanic domain had formed (hence before compression started). The mantle flow dragging, or pushing, Africa northward imposes a general shear sense such that the newly created subduction is dipping north, leading to the underthrusting of the African margin and continental domain, supported by an old and cold lithospheric mantle, below the young and hot oceanic domain newly formed.

Step 4 (Fig. 4D): In the eastern part of the system the conveyor belt is active between the slab penetrating deep in the mantle in the north and the plume pushing the African plate toward the north. The situation is quite similar to the Jurassic stage with this time extension active in the future Gulf of Aden and Red Sea and the separation of Arabia from Africa. Back-arc extension is active in the Mediterranean. In the west, compression resumed in the Eocene in Africa and the most significant compressional tectonics is restricted to the western half of the system, especially in the Atlas system, with also some inversion of extensional features farther east from Cyrenaica to the Palmyrides. This new compressional period is coeval with the building of the Hellenides–Taurides accretionary wedge at the expense of the Pindos Ocean and then the northern margin of Apulia. In the westernmost Mediterranean, compression is active from the Atlas to the Pyrenees and the question of stress propagation from Africa to Eurasia must be discussed. If collision was already going on in the future Gibraltar Arc (Jolivet and Faccenna 2000; Jolivet et al. 2003), compressional stresses were transmitted across the collision zone within the lithosphere from the Atlas to the Pyrenees. If one assumes instead that collision was not yet effective and that some narrow oceanic domain was still present between Africa and Iberia (Vergés and Sabat 1999; Frizon de Lamotte et al. 2000), the compressional stress regime before 35 Ma may be due to the progressive formation of the subduction zone since the Late Cretaceous, very slow in the first period and then becoming mature enough for arc volcanism to develop and slab pull to be active and accommodate slab retreat after 35–30 Ma. The slight velocity increase of the absolute motion of Africa seen in some kinematic models between 40 and 30 Ma may also suggest that coupling with the Afar plume when it impacted the base of the African lithosphere has accelerated the displacement of Africa before the effective collision in the Caucasus–Zagros region that slowed it drastically.

An alternative scenario was recently discussed by Jagoutz et al. (2015) to explain the velocity increase of the India–Asia convergence in the Latest Cretaceous, involving a double subduction north of India. The southernmost of these two subduction zones in the west is equivalent to the obduction zone in our model. So the geometry is similar in the two models, and Jagoutz et al. (2015) argue through numerical modelling that this double subduction

Fig. 4. Scenario linking the Late Cretaceous obduction of the Tethyan ophiolites on Apulia and Africa to convection. (A) ~170 Ma. An established conveyor belt with plume push and slab pull below Africa drags continental blocks northward away from the main African plate, forming the Apulia microcontinent. The whole system is under extension, rifts develop far within the African plate (Late Jurassic – Early Cretaceous). (B) ~90 Ma. The slab has detached below Eurasia and the African plate is driven by plume push and less slab pull. The plume beneath South Africa is more active and accelerates the northward drift of Africa and pushes the African slab faster in the mantle thus rendering subduction more difficult and putting the whole system under compression. Compression during penetration of the slab in the lower mantle induces shortening within Africa and Eurasia and initiates a new subduction along the northern margin of Africa, leading to obduction of the oceanic crust onto the continental margin (100–90 Ma). At maximum compression shortening propagates far inside Africa reactivating all the Cretaceous rifts (Santonian event, 85 Ma). (C) ~70 Ma. Slab avalanches in the lower mantle and a progressive relaxation of compressional stresses ensues. (D) ~30 Ma. After full penetration, the conveyor belt is functional again. The slab is deep into the lower mantle like below the Aegean and retreats. Back-arc extension in the upper plate is observed. Extension is active above the northward moving plume leading to the separation of Arabia from the main body of the African plate. [Colour online.]

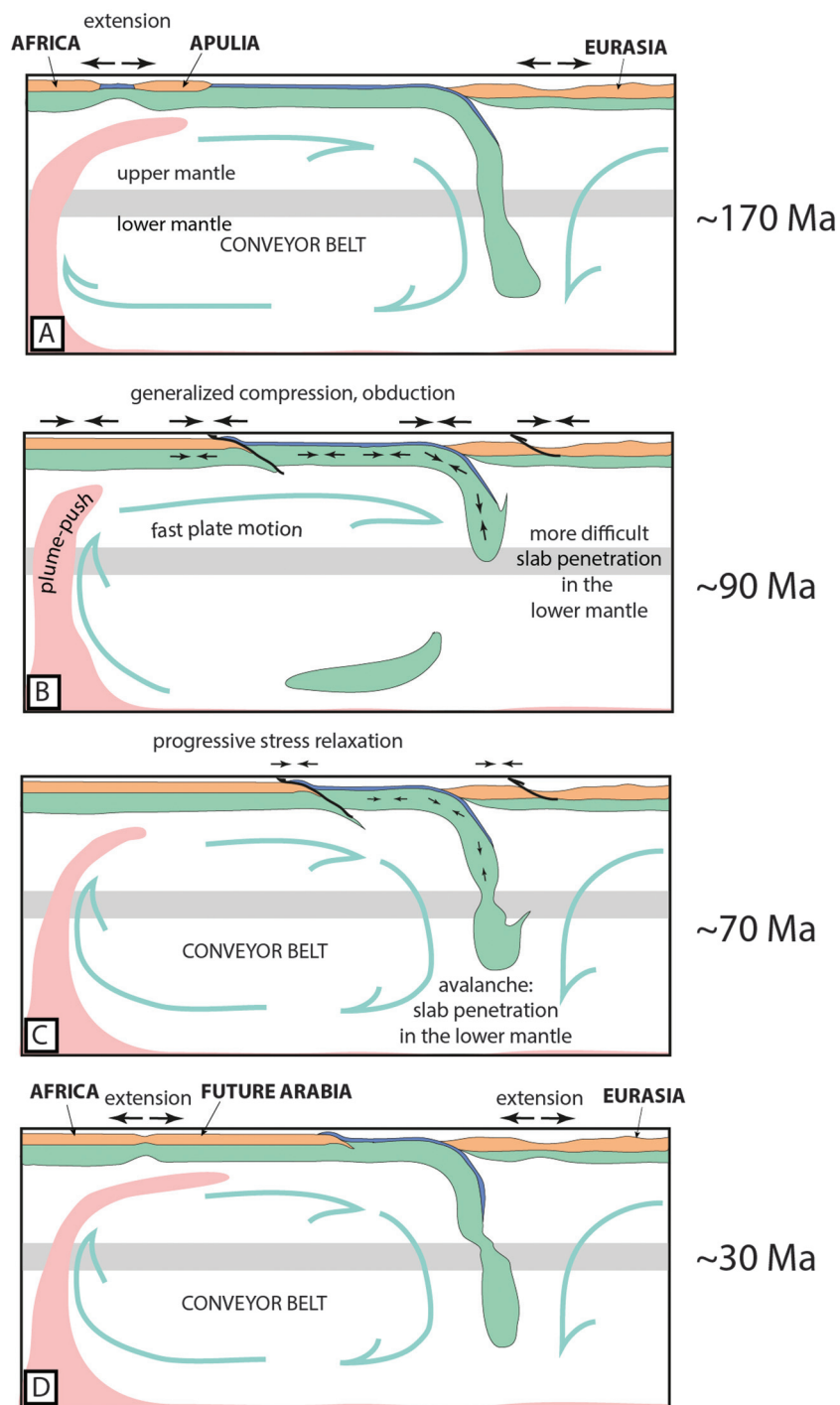
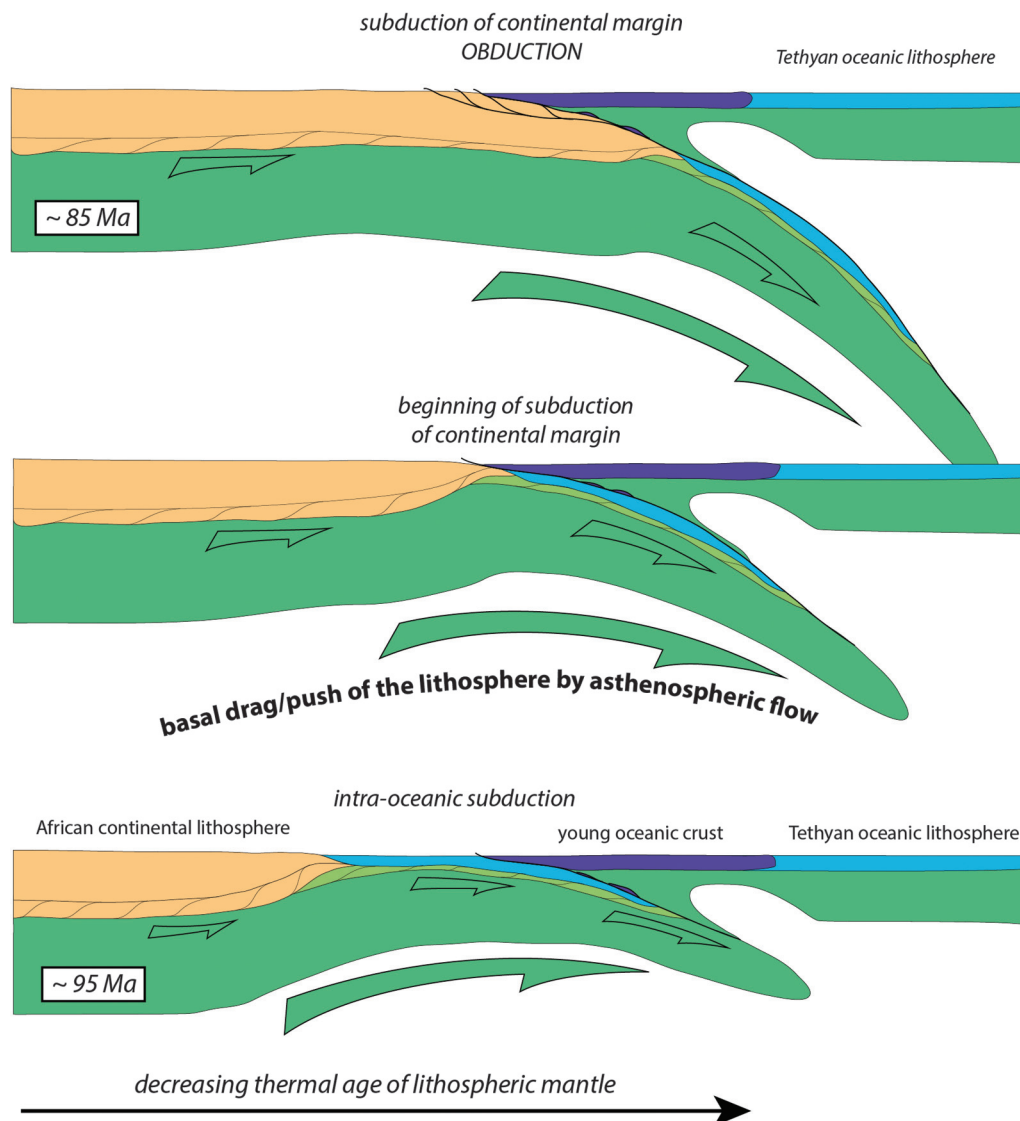


Fig. 5. A scenario of obduction driven by basal drag. Northward movement of the asthenospheric mantle with respect to Africa favours the subduction of the subcontinental lithospheric mantle below the young and light oceanic one. [Colour online.]



is likely to have accelerated convergence, but they do not address the question of the initiation of this subduction zone, which is the topic of the present paper, nor do they explain the observed polarity of subduction.

Conclusion

Our scenario aims at integrating large-scale tectonic processes within a progressive evolution of the convergence zone between Africa and Eurasia. Because the scale of plate fragmentation and subsequent obduction is so large, we look for processes involving the whole mantle. We stress that the Late Cretaceous compression cannot have been a consequence of continental collision since the Neo-Tethys Ocean was still widely open when it happened. We propose that the alternation of periods of extension and compression (including obduction) in Africa and the Neo-Tethys realm result from changes in the dynamics of convection underneath, combined with regional-scale reorganizations. The long-term geological record suggests that the normal extensional situation corresponds to steady-state whole-mantle convection, Africa being carried northward by a large-scale conveyor belt, through plume push in the south and slab pull in the north, while the Late Cretaceous compression and obduction would result from plate acceleration due to increasing plume

push below South Africa and difficult penetration before slab avanching in the lower mantle, until full penetration of the Tethyan slab across the transition zone and reestablishment of the conveyor belt. This would have produced a strong compression at plate boundaries and, as a consequence, would have activated a new plate boundary at the location of previous crustal weakness (Agard et al. 2014). The asymmetry of the northward mantle flow may explain the polarity of initiation of a northward subduction, leading to obduction with oceanic crust emplaced on top of the subducting continental margins of Africa and Apulia through basal drag or push. Although the scale of the obduction at the Jurassic–Cretaceous boundary in the Dinarides cannot compare with the Late Cretaceous one, a similar scenario could be envisaged. The later Eocene compression would be the consequence of either subduction initiation in the western Mediterranean or plate collision. As superplumes and subduction zones, which govern mantle convection, are long-lived features, testing models of mantle convection requires using sequences of events on long durations that only the geological record is able to provide. Such scenarios can be useful to modellers as they may provide time constants (~20 Myr) for the establishment and destruction of whole-mantle convection cells or slab penetration in the lower mantle.

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References

- Abadi, A.M., van Wees, J.D., van Dijk, P.M., and Cloetingh, S.A.P.L. 2008. Tectonics and subsidence evolution of the Sirt Basin, Libya. *AAPG Bulletin*, **92**: 993–1027. doi:10.1306/03310806070.
- Agard, P., Omrani, J., Jolivet, L., and Mouthereau, F. 2005. Convergence history across Zagros (Iran): constraints from collisional and earlier deformation. *International Journal of Earth Sciences*, **94**: 401–419. doi:10.1007/s00531-005-0481-4.
- Agard, P., Monié, P., Gerber, W., Omrani, J., Molinaro, M., Labrousse, L., et al. 2006. Transient, synobduction exhumation of Zagros blueschists inferred from P-T-t and kinematic constraints: implications for Neotethyan wedge dynamics. *Journal of Geophysical Research: Solid Earth*, **111**: doi:10.1029/2005JB004103.
- Agard, P., Jolivet, L., Vrielynck, B., Monié, P., and Burov, E. 2007. Plate acceleration: the obduction trigger? *Earth and Planetary Science Letters*, **258**: 428–441. doi:10.1016/j.epsl.2007.04.002.
- Agard, P., Omrani, J., Jolivet, L., Whitechurch, H., Vrielynck, B., Spakman, W., et al. 2011. Zagros orogeny: a subduction-dominated process. *Geological Magazine*. doi:10.1017/S001675681100046X.
- Agard, P., Zuo, X., Fucicello, F., Bellahsen, N., Faccenna, C., and Savva, D. 2014. Obduction: Why, how and where. Clues from analog models. *Earth and Planetary Science Letters*, **393**: 132–145. doi:10.1016/j.epsl.2014.02.021.
- Ait-Hamou, F. 2006. Le volcanisme cénozoïque à l'échelle du bombardement de l'Ahaggar (Sahara Central algérien): synthèse géochronologique et répartition spatio-temporelle. Quelques implications en relation avec l'histoire eo-alpine de la plaque Africaine. *Mem. Serv. Géologique Nation*, **13**: 155–167.
- Alvarez, W. 2010. Protracted continental collisions argue for continental plates driven by basal traction. *Earth and Planetary Science Letters*, **296**: 434–442. doi:10.1016/j.epsl.2010.05.030.
- Angiboust, S., Agard, P., Jolivet, L., and Beyssac, O. 2009. The Zermatt-Saas ophiolite: the largest (60-km wide) and deepest (c. 70–80 km) continuous slice of oceanic lithosphere detached from a subduction zone? *Terra Nova*, **21**: 171–180. doi:10.1111/j.1365-3121.2009.00870.x.
- Angiboust, S., Agard, P., De Hoog, J.C.M., Omrani, J., and Plunder, A. 2013. Insights on deep, accretionary subduction processes from the Sistan ophiolitic “mélange” (eastern Iran). *Lithos*, **156–159**: 139–158. doi:10.1016/j.lithos.2012.11.007.
- Arsenikos, S., Frizon de Lamotte, D., Chamot-Rooke, N., Mohn, G., Bonneau, M.C., and Blanpied, C. 2013. Mechanism and timing of tectonic inversion in Cyrenaica (Libya): integration in the geodynamics of the East Mediterranean. *Tectonophysics*, **608**: 319–329. doi:10.1016/j.tecto.2013.09.025.
- Bagley, B., and Nyblade, A.A. 2013. Seismic anisotropy in eastern Africa, mantle flow, and the African superplume. *Geophysical Research Letters*, **40**: 1500–1505. doi:10.1002/grl.50315.
- Barrier, E., and Vrielynck, B. 2008. Paleotectonic maps of the Middle East. Atlas of 14 Maps, Paris.
- Becker, T.W., and Boschi, L. 2002. A comparison of tomographic and geodynamic mantle models. *Geochemistry, Geophysics, Geosystems*, **3**. doi:10.1029/2001GC000168.
- Behn, M.D., Conrad, C.P., and Silver, P.G. 2004. Detection of upper mantle flow associated with the African superplume. *Earth and Planetary Science Letters*, **224**: 259–274. doi:10.1016/j.epsl.2004.05.026.
- Bellahsen, N., Faccenna, C., Fucicello, F., Daniel, J.M., and Jolivet, L. 2003. Why did Arabia separate from Africa? Insights from 3-D laboratory experiments. *Earth and Planetary Science Letters*, **216**: 365381. doi:10.1016/S0012-821X(03)00516-8.
- Benkheilil, J. 1989. The origin and evolution of the Cretaceous Benue Trough (Nigeria). *Journal of African Earth Sciences (and the Middle East)*, **8**: 251–282. doi:10.1016/S0899-5362(89)80028-4.
- Benkheilil, J., Dainelli, P., Ponsard, J.F., Popoff, M., and Saugy, L. 1988. The Benue Trough: wrench-fault related basin on the border of the equatorial Atlantic. In *Triassic–Jurassic rifting. Continental breakup and the origin of the Atlantic Ocean and passive margins*. Part A. Edited by W. Manspeizer. Elsevier, Amsterdam, pp. 787–819.
- Bevan, T.G., and Moustafa, A.R. 2012. Inverted rift-basins of Northern Egypt. In *Regional geology and tectonics: Phanerozoic rift systems and sedimentary basins*. Edited by D.G. Roberts, and A.W. Bally. Elsevier, Amsterdam, pp. 483–507.
- Bosworth, W., Guiraud, R., and Kessler, L.G. 1999. Late Cretaceous (ca. 84 Ma) compressive deformation of the stable platform of northeast Africa (Egypt): far-field stress effects of the “Santonian event” and origin of the Syrian arc deformation belt. *Geology*, **27**: 633–636. doi:10.1130/0091-7613(1999)027%3C0633:LCCMD%3E2.3.CO;2.
- Bott, M.H.P. 1993. Modelling the plate-driving mechanism. *Journal of the Geological Society*, **150**: 941–951. doi:10.1144/gsjgs.150.5.0941.
- Bower, D.J., Gurnis, M., and Seton, M. 2013. Lower mantle structure from paleogeographically constrained dynamic Earth models. *Geochemistry, Geophysics, Geosystems*, **14**: 44–63. doi:10.1029/2012GC004267.
- Braun, J., Guillocheau, F., Robin, C., Baby, G., and Jelsma, H. 2014. Rapid erosion of the Southern African Plateau as it climbs over a mantle superswell. *Journal of Geophysical Research: Solid Earth*, **119**: 6093–6112. doi:10.1002/2014JB010998.
- Burke, K. 1996. The African Plate. *South African Journal of Geology*, **99**: 341–409.
- Burke, K. 2011. Plate tectonics, the Wilson cycle, and mantle plumes: geodynamics from the top. *Annual Review of Earth and Planetary Sciences*, **39**: 1–29. doi:10.1146/annurev-earth-040809-152521.
- Burke, K., and Gunnell, Y. 2008. The African erosion surface: a continental-scale synthesis of geomorphology, tectonics and environmental changes over the past 180 million years. *Memoirs of the Geological Society of America*, **201**, 66 p.
- Burke, K., and Torsvik, T.H. 2004. Derivation of Large Igneous Provinces of the past 200 million years from long-term heterogeneities in the deep mantle. *Earth and Planetary Science Letters*, **227**: 531–538. doi:10.1016/j.epsl.2004.09.015.
- Burke, K., MacGregor, D.S., and Cameron, N.R. 2003. Africa's Petroleum systems: four tectonic Aces in the past 600 million years. In *Petroleum Geology of Africa: New Themes and Developing Technologies*. Edited by T.J. Arthur, D.S. MacGregor, and N.R. Cameron. The Geological Society of London, pp. 21–60.
- Burke, K., Steinberger, B., Torsvik, T.H., and Smethurst, M.A. 2008. Plume Generation Zones at the margins of Large Low Shear Velocity Provinces on the core–mantle boundary. *Earth and Planetary Science Letters*, **265**: 49–60. doi:10.1016/j.epsl.2007.09.042.
- Burov, E., and Gerya, T. 2014. Asymmetric three-dimensional topography over mantle plumes. *Nature*, **513**: 85–89. doi:10.1038/nature13703. PMID:25186903.
- Çelik, Ö.F., Delaloye, M., and Feraud, G. 2006. Precise ⁴⁰Ar–³⁹Ar ages from the metamorphic sole rocks of the Tauride Belt ophiolites, southern Turkey: implications for the rapid cooling history. *Geological Magazine*, **143**: 213–227. doi:10.1017/S0016756805001524.
- Çelik, Ö.F., Marzoli, A., Marschik, R., Chiaradia, M., Neubauer, F., and Öz, I. 2011. Early–Middle Jurassic intra-oceanic subduction in the İzmir-Ankara-Erzincan Ocean, Northern Turkey. *Tectonophysics*, **509**: 120–134. doi:10.1016/j.tecto.2011.06.007.
- Cogné, J.P., and Humler, E. 2006. Trends and rhythms in global seafloor generation rate. *Geochemistry, Geophysics, Geosystems*, **7**: Q03011. doi:10.1029/2005GC001148.
- Coleman, R.G. 1977. Ophiolites. Springer Verlag, Berlin.
- Coleman, R.G. 1981. Tectonic setting for ophiolite obduction in Oman. *Journal of Geophysical Research*, **86**: 2497–2508. doi:10.1029/JB086iB04p02497.
- Colli, L., Stotz, I., Bunge, H.P., Smethurst, M., Clark, S., Iaffaldano, G., et al. 2014. Rapid South Atlantic spreading changes and coeval vertical motion in surrounding continents: evidence for temporal changes of pressure-driven upper mantle flow. *Tectonics*, **32**: 1304–1321. doi:10.1002/2014TC003612.
- Conrad, C.P., and Lithgow-Bertelloni, C. 2007. Faster seafloor spreading and lithosphere production during the mid-Cenozoic. *Geology*, **35**: 29–32. doi:10.1130/G22759A.1.
- Courtilot, V., Jaupart, C., Manighetti, I., Tapponnier, P., and Besse, J. 1999. On causal links between flood basalts and continental breakup. *Earth and Planetary Science Letters*, **166**: 177–195. doi:10.1016/S0012-821X(98)00282-9.
- Dercourt, J., Zonenshain, L.P., Ricou, L.E., Kuzmin, V.G., Le Pichon, X., Knipper, A.L., et al. 1986. Geological evolution of the Tethys belt from the Atlantic to the Pamir since the Lias. *Tectonophysics*, **123**: 241–315. doi:10.1016/0040-1951(86)90199-X.
- Dewey, J.F. 1976. Ophiolite obduction. *Tectonophysics*, **31**: 93–120. doi:10.1016/0040-1951(76)90169-4.
- Dewey, J.F., and Casey, J.F. 2013. The sole of an ophiolite: the Ordovician Bay of Islands Complex, Newfoundland. *Journal of the Geological Society*, **170**: 715–722. doi:10.1144/jgs2013-017.
- Dodd, S.C., Mac Niocaill, C., and Muxworthy, A.R. 2015. Long duration (>4 Ma) and steady-state volcanic activity in the early Cretaceous Paraná–Etendeka Large Igneous Province: new palaeomagnetic data from Namibia. *Earth and Planetary Science Letters*, **414**: 16–29. doi:10.1016/j.epsl.2015.01.009.
- Doubrovine, P., Steinberger, B., and Torsvik, T.H. 2012. Absolute plate motions in a reference frame defined by moving hotspots in the Pacific, Atlantic and Indian oceans. *Journal of Geophysical Research: Solid Earth*, **117**: B09101. doi:10.1029/2011JB009072.
- Edwards, S.J., Schellart, W.P., and Duarte, J.C. 2015. Geodynamic models of continental subduction and obduction of overriding plate forearc oceanic lithosphere on top of continental crust. *Tectonics*, **34**: 1494–1515. doi:10.1002/2015TC003884.
- Ershov, A.V., and Nikishin, A.M. 2004. Recent geodynamics of the Caucasus–Arabia–East Africa Region. *Geotectonics*, **38**: 123–136.
- Faccenna, C., Becker, T.W., Conrad, C.P., and Husson, L. 2013a. Mountain building and mantle dynamics. *Tectonics*, **32**: 80–93. doi:10.1029/2012TC003176.
- Faccenna, C., Becker, T.W., Jolivet, L., and Keskin, M. 2013b. Mantle convection in the Middle East: reconciling Afar upwelling, Arabia indentation and Aegean trench rollback. *Earth and Planetary Science Letters*, **375**: 254–269. doi:10.1016/j.epsl.2013.05.043.
- Forté, A.M., Quéré, S., Moucha, R., Simmons, N.A., Grand, S.P., Mitrovica, J.X., and Rowley, D.B. 2010. Joint seismic–geodynamic–mineral physical model-

- ling of African geodynamics: a reconciliation of deep-mantle convection with surface geophysical constraints. *Earth and Planetary Science Letters*, **295**: 329–341. doi:10.1016/j.epsl.2010.03.017.
- Frizon de Lamotte, D., Saint Bezar, B., Bracène, R., and Mercier, E. 2000. The two main steps of the Atlas building and geodynamics of the western Mediterranean. *Tectonics*, **19**: 740–761. doi:10.1029/2000TC900003.
- Frizon de Lamotte, D., Raulin, C., Mouchot, N., Wrobel-Daveau, J.C., Blanpied, C., and Ringenbach, J.C. 2011. The southernmost margin of the Tethys realm during the Mesozoic and Cenozoic: initial geometry and timing of the inversion processes. *Tectonics*, **30**: TC3002. doi:10.1029/2010TC002691.
- Frizon de Lamotte, D., Fourdan, B., Leleu, S., Leparmentier, F., and de Clarens, P. 2015. Style of rifting and the stages of Pangea breakup. *Tectonics*, **34**: 1009–1029. doi:10.1002/2014TC003760.
- Gaina, C., Torsvik, T.H., van Hinsbergen, D.J.J., Medvedev, S., Werner, S.C., and Labails, C. 2013. The African Plate: a history of oceanic crust accretion and subduction since the Jurassic. *Tectonophysics*, **604**: 4–25. doi:10.1016/j.tecto.2013.05.037.
- Garnero, E.J., and McNamara, A.K. 2008. Structure and dynamics of Earth's lower mantle. *Science*, **320**: 626–628. doi:10.1126/science.1148028. PMID:18451293.
- Gass, I.G. 1968. Is the Troodos Massif of Cyprus a fragment of Mesozoic ocean floor? *Nature*, **220**: 39–42. doi:10.1038/220039a0.
- Genik, G.J. 1993. Petroleum geology of Cretaceous–Tertiary rift basins in Niger, Chad, and Central African Republic. *AAPG Bulletin*, **77**: 1405–1434.
- Glišović, P., and Forte, A.M. 2014. Reconstructing the Cenozoic evolution of the mantle: implications for mantle plume dynamics under the Pacific and Indian plates. *Earth and Planetary Science Letters*, **390**: 146–156. doi:10.1016/j.epsl.2014.01.010.
- Glišović, P., Forte, A.M., and Moucha, R. 2012. Time-dependent convection models of mantle thermal structure constrained by seismic tomography and geodynamics: implications for mantle plume dynamics and CMB heat flux. *Geophysical Journal International*, **190**: 785–815. doi:10.1111/j.1365-246X.2012.05549.x.
- Gnos, E., Immenhauser, A., and Peters, T. 1997. Late Cretaceous/early Tertiary convergence between the Indian and Arabian plates recorded in ophiolites and related sediments. *Tectonophysics*, **271**: 1–19. doi:10.1016/S0040-1951(96)00249-1.
- Goffé, B., Michard, A., Kienast, J.R., and Le Mer, O. 1988. A case of obduction-related high-pressure, low-temperature metamorphism in upper crustal nappes, Arabian continental margin, Oman: P–T paths and kinematic interpretation. *Tectonophysics*, **151**: 363–386. doi:10.1016/0040-1951(88)90253-3.
- Gohl, K., Uenzelmann-Neben, G., and Grobys, N. 2011. Growth and dispersal of a southeast African large igneous province. *South African Journal of Geology*, **114**: 379–386. doi:10.2113/gssajg.114.3-4.379.
- Guillocheau, F., Robin, C., Allemand, P., Bourquin, S., Brault, N., Dromart, G., et al. 2000. Meso-cenozoic geodynamic evolution of the Paris Basin: 3D stratigraphic constraints. *Geodynamica Acta*, **13**: 189–246. doi:10.1080/09853111.2000.11105372.
- Guillocheau, F., Rouby, D., Robin, C., Helm, C., Rolland, N., Le Carlier de Veslud, C., and Braunz, J. 2012. Quantification and causes of the terrigenous sediment budget at the scale of a continental margin: a new method applied to the Namibia–South Africa margin. *Basin Research*, **24**: 3–30. doi:10.1111/j.1365-2117.2011.00511.x.
- Guillot, S., and Replumaz, A. 2013. Importance of continental subductions for the growth of the Tibetan plateau. *Bulletin Societe géologique de France*, **184**: 199–223. doi:10.2113/gssgfbull.184.3.199.
- Guiraud, R., Bosworth, W., Thierry, J., and Delplanque, A. 2005. Phanerozoic geological evolution of Northern and Central Africa: an overview. *Journal of African Earth Sciences*, **43**: 83–143. doi:10.1016/j.jafrearsci.2005.07.017.
- Hacker, B.R. 1991. The role of deformation in the formation of metamorphic gradients: ridge subduction beneath the Oman ophiolite. *Tectonics*, **10**: 455–473. doi:10.1029/90TC02779.
- Hacker, B.R., Mosenfelder, J.L., and Gnos, E. 1996. Rapid emplacement of the Oman ophiolite: thermal and geochronologic constraints. *Tectonics*, **15**: 1230–1247. doi:10.1029/96TC01973.
- Hafkenscheid, E., Wortel, M.J.R., and Spakman, W. 2006. Subduction history of the Tethyan region derived from seismic tomography and tectonic reconstructions. *Journal of Geophysical Research*, **111**. doi:10.1029/2005JB003791.
- Hansen, S.E., Nyblade, A.A., and Benoit, M.H. 2012. Mantle structure beneath Africa and Arabia from adaptively parameterized P-wave tomography: implications for the origin of Cenozoic Afro–Arabian tectonism. *Earth and Planetary Science Letters*, **319–320**: 23–34. doi:10.1016/j.epsl.2011.12.023.
- Hässig, M., Rolland, Y., Sosson, M., Galoyan, G., Müller, C., Avagyan, A., and Sahakyan, L. 2013. New structural and petrological data on the Amasia ophiolites (NW Sevan–Akera suture zone, Lesser Caucasus): insights for a large-scale obduction in Armenia and NE Turkey. *Tectonophysics*, **588**: 135–153. doi:10.1016/j.tecto.2012.12.003.
- Hässig, M., Rolland, Y., Duret, T., and Sosson, M. 2016. Obduction triggered by regional heating during plate reorganization. *Terra Nova*, **28**: 76–82. doi:10.1111/ter.12193.
- Hippolyte, J.C., Müller, C., Kaymakci, N., and Sangu, E. 2010. Dating of the Black Sea Basin: new nannoplankton ages from its inverted margin in the Central Pontides (Turkey). *In* *Sedimentary Basin Tectonics from the Black Sea and Caucasus to the Arabian Platform*. Edited by M. Sosson, N. Kaymakci, R. Stephenson, F. Bergerat, and V. Starostenko. Geological Society, London, Special Publications, **340**: 113–136. doi:10.1144/SP340.7.
- Hofmann, C., Courtillot, V., Feraud, G., Rochette, P., Yirgu, G., Ketefo, E., and Pik, R. 1997. Timing of the Ethiopian flood basalt event and implications for plume birth and global change. *Nature*, **389**: 838–841. doi:10.1038/39853.
- Jagoutz, O., Royden, L., Holt, A.F., and Becker, T.W. 2015. Anomalously fast convergence of India and Eurasia caused by double subduction. *Nature Geoscience*, **8**: 475–479. doi:10.1038/NNGEO2418.
- Jammes, S., Tiberi, C., and Manatschal, G. 2010. 3D architecture of a complex transcurrent rift system: the example of the Bay of Biscay–Western Pyrenees. *Tectonophysics*, **489**: 210–226. doi:10.1016/j.tecto.2010.04.023.
- Jelsma, H.A., de Wit, M.J., Thiart, C., Dirks, P.H.G.M., Viola, G., Basson, I.J., and Ankar, E. 2004. Preferential distribution along transcontinental corridors of kimberlites and related rocks of Southern Africa. *South African Journal of Geology*, **107**: 301–324. doi:10.2113/107.1-2.301.
- Jelsma, H., Barnett, W., Richards, S., and Lister, G. 2009. Tectonic setting of kimberlites. *Lithos*, **112**: 155–165. doi:10.1016/j.lithos.2009.06.030.
- Jolivet, L., and Brun, J.P. 2010. Cenozoic geodynamic evolution of the Aegean. *International Journal of Earth Sciences*, **99**: 109–138. doi:10.1007/s00531-008-0366-4.
- Jolivet, L., and Faccenna, C. 2000. Mediterranean extension and the Africa–Eurasia collision. *Tectonics*, **19**: 1095–1106. doi:10.1029/2000TC900018.
- Jolivet, L., Faccenna, C., Goffé, B., Burrov, E., and Agard, P. 2003. Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean orogens. *American Journal of Science*, **303**: 353–409. doi:10.2475/ajs.303.5.353.
- Kidd, W.S.F., Dewey, J.F., and Bird, J.M. 1978. The Mings Bight Ophiolite Complex, Newfoundland: Appalachian oceanic crust and mantle. *Canadian Journal of Earth Sciences*, **15**: 781–804. doi:10.1139/e78-084.
- Koptev, A., Calais, E., Burrov, E., Leroy, S., and Gerya, T. 2015. Dual continental rift systems generated by plume–lithosphere interaction. *Nature Geoscience*, **8**: 388–392. doi:10.1038/ngeo2401.
- Lardeaux, J.M., Schwartz, S., Tricart, P., Paul, A., Guillot, S., Béthoux, N., and Masson, F. 2006. A crustal-scale cross-section of the south-western Alps combining geophysical and geological imagery. *Terra Nova*, **18**: 412–422. doi:10.1111/j.1365-3121.2006.00706.x.
- Larson, R.L. 1991. Latest pulse of Earth: evidence for a mid-Cretaceous superplume. *Geology*, **19**: 547–550. doi:10.1130/0091-7613(1991)019<0547:LPOEEF>2.3.CO;2.
- Leprêtre, R., Barbarand, J., Missenard, Y., Leparmentier, F., and Frizon de Lamotte, D. 2014. Vertical movements along the northern border of the West African Craton: the Reguibat Shield and adjacent basins. *Geological Magazine*, **151**: 885–898. doi:10.1017/S0016756813000939.
- Liégeois, J.P., Benhallou, A., Azzouni-Sekkal, A., Yahiaoui, R., and Bonin, B. 2005. The Hoggar swell and volcanism: reactivation of the Precambrian Tuareg shield during Alpine convergence and West African Cenozoic volcanism. *In* *Plates, plumes, and paradigms*. Edited by G.R. Foulger, J.H. Natland, D.C. Presnall, and D.L. Anderson. Geological Society of America, Boulder, Colorado, pp. 379–400.
- Lithgow-Bertelloni, C., and Silver, P.G. 1998. Dynamic topography, plate driving forces and the African superswell. *Nature*, **395**: 269–272. doi:10.1038/26212.
- Macgregor, D. 2010. Understanding African and Brazilian margin climate, topography and drainage systems, implications for predicting deepwater reservoirs and source rock burial history. Search and Discovery Article #90100.
- Macleod, C.J., Lissenberg, C.J., and Bibby, L.E. 2013. “Moist MORB” axial magmatism in the Oman ophiolite: the evidence against a mid-ocean ridge origin. *Geology*, **41**: 459–462. doi:10.1130/G33904.1.
- Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, M.G., and De, Min, A. 1999. Extensive 200-million-year-old continental flood basalts of the central Atlantic magmatic province. *Science*, **284**: 616–618. doi:10.1126/science.284.5414.616. PMID:10213679.
- Matte, P. 2001. The Variscan collage and orogeny (480±290 Ma) and the tectonic definition of the Armorica microplate: a review. *Terra Nova*, **13**: 122–128. doi:10.1046/j.1365-3121.2001.00327.x.
- McHargue, T.R., Heidrick, T.L., and Livingston, J.E. 1992. Tectonostratigraphic development of the Interior Sudan Rifts, Central Africa. *Tectonophysics*, **213**: 187–202. doi:10.1016/0040-1951(92)90258-8.
- McNamara, A.K., and Zhong, S. 2005. Thermochemical structures beneath Africa and the Pacific Ocean. *Nature*, **437**: 1136–1139. doi:10.1038/nature04066. PMID:16237440.
- McQuarrie, N., Stock, J.M., Verdel, C., and Wernicke, B.P. 2003. Cenozoic evolution of Neotethys and implications for the causes of plate motions. *Geophysical Research Letters*, **30**: 3620. doi:10.1029/2003GL017992.
- Menant, A., Jolivet, L., and Vrielynck, B. 2016. From crustal to mantle dynamics, insight from kinematic reconstructions and magmatic evolution of the eastern Mediterranean region since the late Cretaceous. *Tectonophysics*. In press.
- Milesi, J.P., Frizon de Lamotte, D., de Kock, G., and Toteu, F. 2010. Tectonic map of Africa, 1:10 000 000 scale. CCGM-CGMW, Paris.
- Monié, P., and Agard, P. 2009. Coeval blueschist exhumation along thousands of kilometers: implications for subduction channel processes. *Geochimistry, Geophysics, Geosystems*, **10**: Q07002. doi:10.1029/2009GC002428.

- Moucha, R., and Forte, A.M. 2011. Changes in African topography driven by mantle convection. *Nature Geoscience*, **4**: 707–712. doi:10.1038/ngeo1235.
- Mouthereau, F., Lacombe, O., and Vergés, J. 2012. Building the Zagros collisional orogen: timing, strain distribution and the dynamics of Arabia/Eurasia plate convergence. *Tectonophysics*, **532–535**: 27–60. doi:10.1016/j.tecto.2012.01.022.
- Mouthereau, F., Filleaudeau, P.Y., Vacherat, A., Pik, R., Lacombe, O., Fellin, M.G., et al. 2014. Placing limits to shortening evolution in the Pyrenees: role of margin architecture and implications for the Iberia/Europe convergence. *Tectonics*, **33**: 2283–2314. doi:10.1002/2014TC003663.
- Müller, R.D., Sdrölias, M., Gaina, C., and Roest, W.R. 2008a. Age, spreading rates, and spreading asymmetry of the world's ocean crust. *Geochemistry, Geophysics, Geosystems*, **9**: Q04006. doi:10.1029/2007GC001743.
- Müller, R.D., Sdrölias, M., Gaina, C., Steinberger, B., and Heine, C. 2008b. Long-term sea-level fluctuations driven by ocean basin dynamics. *Science*, **319**: 1357–1362. doi:10.1126/science.1151540. PMID:18323446.
- Nicolas, A. 1989. Structures of ophiolites and dynamic of oceanic lithosphere. Kluwer Academic Publishing, Dordrecht.
- Nishikin, A.M., Cloething, S., Brunet, M.F., Stephenson, R.A., Bolotov, S.N., and Ershov, A.V. 1998. Scythian platform, Caucasus and Black Sea region: Mesozoic–Cenozoic tectonic history and dynamics. In *Peri-Tethys Memoir 3: stratigraphy and evolution of Teri-Tethyan platforms*. Edited by S. Crasquin-Soleau, and E. Barrier. Paris, pp. 163–176.
- Nikishin, A.M., Okay, A., Tüysüz, O., Demire, A., Amelin, N., and Petrov, E. 2015a. The Black Sea basins structure and history: new model based on new deep penetration regional seismic data. Part 1: Basins structure and fill. *Marine and Petroleum Geology*, **59**: 638–655. doi:10.1016/j.marpetgeo.2014.08.017.
- Nikishin, A.M., Okay, A., Tüysüz, O., Demire, A., Wannier, H., Amelin, N., and Petrov, E. 2015b. The Black Sea basins structure and history: new model based on new deep penetration regional seismic data. Part 2: Tectonic history and paleogeography. *Marine and Petroleum Geology*, **59**: 656–670. doi:10.1016/j.marpetgeo.2014.08.018.
- Oberhänsli, R., Bousquet, R., Engi, M., Goffé, B., Gosso, G., Handy, M., et al. 2004. Metamorphic structure of the Alps. Edited by the Commission for the Geological Map of the World. Miit. österr. geol. Ges. 149.
- Okay, A.I. 1989. Geology of the Menderes Massif and the Lycian Nappes south of Denizli, western Taurides. *Mineral Research and Exploration Bulletin*, **109**: 37–51.
- Okay, A., and Tüysüz, O. 1999. Tethyan sutures of northern Turkey. In *The Mediterranean basins: Tertiary extension within the alpine orogen*. Edited by B. Durand, L. Jolivet, F. Horvath, and M. Séranne. Geological Society, London, Special Publications, **156**: 475–515. doi:10.1144/GSL.SP.1999.156.01.22.
- Pearce, J.A., Alabaster, T., Shelton, A.W., and Searle, M.P. 1981. The Oman ophiolite as a Cretaceous arc-basin complex: evidence and implications. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **300**: 299–317. doi:10.1098/rsta.1981.0066.
- Petters, S.W. 1983. Gulf of Guinea planktonic foraminiferal biochronology and geological history of the South Atlantic. *The Journal of Foraminiferal Research*, **13**: 32–59. doi:10.2113/jsjfr.13.1.32.
- Pourteau, A., Sudo, M., Candan, O., Lanari, P., Vidal, O., and Oberhänsli, R. 2013. Neotethys closure history of Anatolia: insights from ⁴⁰Ar–³⁹Ar geochronology and P–T estimation in high-pressure metasedimentary rocks. *Journal of Metamorphic Geology*, **31**: 585–606. doi:10.1111/jmg.12034.
- Replumaz, A., Guillot, S., Villaseñor, A., and Negro, A.M. 2013. Amount of Asian lithospheric mantle subducted during the India/Asia collision. *Gondwana Research*, **24**: 936–945. doi:10.1016/j.gr.2012.07.019.
- Ricard, Y., Richards, M.A., Lithgow-Bertelloni, C., and LeStunff, Y. 1993. A Geodynamic model of mantle density heterogeneity. *Journal of Geophysical Research*, **98**: 21895–21909. doi:10.1029/93JB02216.
- Ricou, L.E. 1971. Le croissant ophiolitique péri-arabe, une ceinture de nappes mise en place au crétacé supérieur. *Revue de géographie physique et de géologie dynamique*, **13**: 327–350.
- Ricou, L.E. 1994. Tethys reconstructed: plates, continental fragments and their boundaries since 260 Ma from Central America to south-eastern Asia. *Geodinamica Acta*, **7**: 169–218. doi:10.1080/09853111.1994.11105266.
- Riley, T.R., Millar, I.L., Watkeys, M.K., Curtis, M.L., Leat, P.T., Klausen, M.B., and Fanning, C.M. 2004. U–Pb zircon (SHRIMP) ages for the Lebombo rhyolites, South Africa: refining the duration of Karoo volcanism. *Journal of the Geological Society*, **161**: 547–550. doi:10.1144/0016-764903-181.
- Rioux, M., Bowring, S., Kelemen, P., Gordon, S., Miller, R., and Dudás, F. 2013. Tectonic development of the Samail ophiolite: high-precision U–Pb zircon geochronology and Sm–Nd isotopic constraints on crustal growth and emplacement. *Journal of Geophysical Research*, **118**: 1–17. doi:10.1002/jgrb.50139.
- Ritsema, H.J., van Heijst, J.H., and Woodhouse, J.H. 1999. Complex shear wave velocity structure beneath Africa and Iceland. *Science*, **286**: 1925–1928. doi:10.1126/science.286.5446.1925.
- Rolland, Y., Billo, S., Corsini, M., Sossou, M., and Galoyan, G. 2009. Blueschists of the Amassia–Stepanavan Suture Zone (Armenia): linking Tethys subduction history from E-Turkey to W-Iran. *International Journal of Earth Sciences*, **98**: 533–550. doi:10.1007/s00531-007-0286-8.
- Rosenbaum, G., Lister, G.S., and Duboz, C. 2002. Relative motions of Africa, Iberia and Europe during Alpine orogeny. *Tectonophysics*, **359**: 117–129. doi:10.1016/S0040-1951(02)00442-0.
- Rossetti, F., Nasrabad, M., Vignaroli, G., Theye, T., Gerdes, A., Razavi, M.H., and Vaziri, H.M. 2010. Early Cretaceous migmatitic mafic granulites from the Sabzevar range (NE Iran): implications for the closure of the Mesozoic peri-Tethyan oceans in central Iran. *Terra Nova*, **22**: 26–34. doi:10.1111/j.1365-3121.2009.00912.x.
- Rossetti, F., Nasrabad, M., Theye, T., Gerdes, A., Monié, P., Lucci, F., and Vignaroli, G. 2014. Adakite differentiation and emplacement in a subduction channel: the late Paleocene Sabzevar magmatism (NE Iran). *Geological Society of America Bulletin*, **126**: 317–343. doi:10.1130/B30913.1.
- Schmid, S.M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., et al. 2008. The Alpine–Carpathian–Dinaric orogenic system: correlation and evolution of tectonic units. *Swiss Journal of Geosciences*, **101**: 139–183. doi:10.1007/s00015-008-1247-3.
- Searle, M.P., Waters, D.J., Martin, H.N., and Rex, D.C. 1994. Structure and metamorphism of blueschist-eclogite facies rocks from the northeastern Oman Mountains. *Journal of the Geological Society*, **151**: 555–576. doi:10.1144/gsjgs.151.3.0555.
- Searle, M.P., Warren, C.J., Waters, D.J., and Parrish, R.R. 2004. Structural evolution, metamorphism and restoration of the Arabian continental margin, Saih Hatat region, Oman mountains. *Journal of Structural Geology*, **26**: 451–473. doi:10.1016/j.jsg.2003.08.005.
- Şengör, A.M.C., and Burke, K. 1978. Relative timing of rifting and volcanism on Earth and its tectonic implications. *Geophysical Research Letters*, **5**: 419–421. doi:10.1029/GL1005i1006p00419.
- Şengör, A.M.C., and Stock, J. 2014. The Ayyubid Orogen: an ophiolite obduction-driven orogen in the late Cretaceous of the Neo-Tethyan south margin. *Geoscience Canada*, **41**: 225–254. doi:10.12789/geocanj.2014.41.042.
- Şengör, A.M.C., and Yilmaz, Y. 1981. Tethyan evolution of Turkey: a plate tectonic approach. *Tectonophysics*, **75**: 181–241. doi:10.1016/0040-1951(81)90275-4.
- Stampfli, G.M., and Borel, G.D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters*, **196**: 17–33. doi:10.1016/S0012-821X(01)00588-X.
- Steinberger, B. 2000. Slabs in the lower mantle—results of dynamic modeling compared with tomographic images and the geoid. *Physics of the Earth and Planetary Interiors*, **118**: 241–257. doi:10.1016/S0031-9201(99)00172-7.
- Stoddard, P.R., and Abbott, D. 1996. Influence of the tectosphere upon plate motion. *Journal of Geophysical Research*, **101**: 5425–5433. doi:10.1029/95JB03540.
- Svensen, H., Corfu, F., Polteau, S., Hammer, O., and Planke, S. 2012. Rapid magma emplacement in the Karoo Large Igneous Province. *Earth and Planetary Science Letters*, **325–326**: 1–9. doi:10.1016/j.epsl.2012.01.015.
- Swezey, C.S. 2009. Cenozoic stratigraphy of the Sahara, Northern Africa. *Journal of African Earth Sciences*, **53**: 89–121. doi:10.1016/j.jafrearsci.2008.08.001.
- Torsvik, T.H., Smethurst, M.A., Burke, K., and Steinberger, B. 2006. Large Igneous Provinces generated from the margins of the Large Low-Velocity Provinces in the deep mantle. *Geophysical Journal International*, **167**: 1447–1460. doi:10.1111/j.1365-246X.2006.03158.x.
- Torsvik, T.H., Burke, K., Steinberger, B., Webb, S.J., and Ashwal, L.D. 2010. Diamonds sampled by plumes from the core–mantle boundary. *Nature*, **466**: 352–355. doi:10.1038/nature09216.
- Torsvik, T.H., van der Voo, R., Doubrovine, P.V., Burke, K., Steinberger, B., Ashwal, L.D., et al. 2014. Deep mantle structure as a reference frame for movements in and on the Earth. *PNAS* **111**: 8735–8740. doi:10.1073/pnas.1318135111.
- Turner, S., Regelous, M., Kelley, S., Hawkesworth, C., and Mantovani, M. 1994. Magmatism and continental break-up in the South Atlantic: high precision ⁴⁰Ar–³⁹Ar geochronology. *Earth and Planetary Science Letters*, **121**: 333–348. doi:10.1016/0012-821X(94)90076-0.
- Van der Voo, R., Spakman, W., and Bijwaard, H. 1999. Tethyan subducted slabs under India. *Earth and Planetary Science Letters*, **171**: 7–20. doi:10.1016/S0012-821X(99)00131-4.
- van der Meer, D.G., Spakman, W., van Hinsbergen, D.J.J., Amaru, M.L., and Torsvik, T.H. 2010. Towards absolute plate motions constrained by lower-mantle slab remnants. *Nature Geoscience*, **3**: 36–40. doi:10.1038/ngeo708.
- van Hinsbergen, D.J.J., Steinberger, B., Doubrovine, P.V., and Gassmüller, R. 2011. Acceleration and deceleration of India–Asia convergence since the Cretaceous: roles of mantle plumes and continental collision. *Journal of Geophysical Research*, **116**: B06101. doi:10.1029/2010JB008051.
- Vaughan, A.P.M., and Scarrow, J.H. 2003. Ophiolite obduction pulses as a proxy indicator of superplume events? *Earth and Planetary Science Letters*, **213**: 407–416. doi:10.1016/S0012-821X(03)00330-3.
- Vergés, J., and Sabat, F. 1999. Constraints on the western Mediterranean kinematic evolution along a 1000 km transect, from Iberia to Africa. In *The Mediterranean basins: Tertiary extension within the Alpine orogen*. Edited by B. Durand, L. Jolivet, F. Horvath, and M. Séranne. Geological Society, London, pp. 63–80.
- Vergés, J., Fernandez, M., and Martinez, A. 2002. The Pyrenean orogen: pre-, syn-, and post-collisional evolution. In *Reconstruction of the evolution of the Alpine–Himalayan orogeny*. Edited by G. Rosenbaum and G.S. Lister. pp. 57–76.

- Wennekers, J.H.N., Wallace, F.K., and Abugares, Y.I. 1996. The geology and hydrocarbons of the Sirt Basin: a synopsis. In *The geology of Sirt Basin*. Edited by M.J. Salem, A.J. Mouzughy, and O.S. Hammuda. Elsevier, Amsterdam, pp. 3–55.
- Wilson, M. 1993. Magmatism and the geodynamics of basin formation. *Sedimentary Geology*, **86**: 5–29. doi:10.1016/0037-0738(93)90131-N.
- Wilson, M., and Guiraud, R. 1992. Magmatism and rifting in Western and Central Africa, from Late Jurassic to Recent times. *Tectonophysics*, **213**: 203–225. doi:10.1016/0040-1951(92)90259-9.
- Yamato, P., Agard, P., Goffé, B., De Andrade, V., Vidal, O., and Jolivet, L. 2007. New, high-precision P-T estimates for Oman blueschists: implications for obduction, nappe stacking and exhumation processes. *Journal of Metamorphic Geology*, **25**: 657–682. doi:10.1111/j.1525-1314.2007.00722.x.
- Zahirovic, S., Müller, R.D., Seton, M., and Flament, N. 2015. Tectonic speed limits from plate kinematic reconstructions. *Earth and Planetary Science, Letters*, **418**: 40–52. doi:10.1016/j.epsl.2015.02.037.
- Ziegler, P.A. 1992. Plate tectonics, plate moving mechanisms and rifting. *Tectonophysics*, **215**: 9–34. doi:10.1016/0040-1951(92)90072-E.