Back-arc underplating provided crustal accretion affecting topographic and sedimentation in the Adria microplate

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Magmatic underplating in crustal formation and evolution is often related to plate tectonics and dynamics. Despite underplating is very common in extensional settings where it is associated to crustal breakup, this process is also responsible of large-scale flood basalt volcanic districts. Conversely, in compressional settings the role of underplated volumes is less obvious and the effects on crustal accretion in the back-arc area are still questioned. Traditionally, the distinctive features of magmatic underplating are high P- and S-wave velocity, high density and high Vp/Vs of the intruded volume when compared to surrounding crust. More in general, the products and crustal structures derived from underplating processes may range in a wide spectra, mostly depending on the geodynamic setting. Supported by evidences of deep crustal sources for the observed magnetic anomalies in Central Italy and by outcropping gabbros in the Croatian archipelago, we model the observed gravity and magnetic anomalies in the Central Adriatic Sea and surroundings. We find that the major magnetic anomalies in the area are related to wide underplated Permian gabbros and propose that the underplated volumes represent the first stage of the back-arc Adria continental breakup in Permian. During the Palaeotethys-Adria collision, underplating controlled topography and palaeogeographic domains resulting in the observed asymmetrical sedimentary evolution since Triassic across the Adria microplate. Finally, we propose that the Palaeotethys-Adria boundary in Permian was similar to the actual Pacific-Okhotsk plate boundary.

The Adria plate today extends along the Adriatic Sea from the Po plain to the Apulian promontory and is surrounded by the Alpine, Dinaric and Apenninic orogens to the north, east and west, respectively (Figure 1a). There are evidences suggesting that the Adria plate may be fragmented in two microplates, the Adria *sensu stricto* (s.str.) to the north and the Apulia s.str. to the south (Oldow et al., 2002; D'Agostino et al., 2008; Handy et al., 2019) but if this division has developed in recent times or if it was inherited from older epochs is unclear. Mesozoic and Cenozoic evolution of the Adria plate is related to a wider geodynamic setting involving the African and the Eurasian Plates whose relative motions allowed for the observed counterclockwise rotation of the plate since Cretaceous (Bennett et al., 2008; Faccenna et al., 2014). In Permian times this area was located in the northernmost pivot of the Palaeotethys, in a region supposed to have undergone wide continental extension related to the opening of the Palaeotethys ocean and, during late Permian and Trias, of the Neotethys to the west (Moix et al., 2008; Stampfli and Hochard, 2009; Stampfli et al., 2013). To date however, evidences of the ancient Adria s.str. oceanic crust are missing across the entire plate from the Dinarides to the Apennines (Sun et al., 2019; van Unen et al., 2019).

Despite the actual tight setting, locations of the boundaries between the Adria plate and the surrounding plates are still matter of debate (Anderson and Jackson, 1987; Stampfli and Hochard, 2009; Stein and Sella, 2005), while several evidences (Herak, 1986; Moretti and Royden, 1988; Doglioni et al., 1994; Tari, 2002; Bennett et al., 2008; Korbar, 2009; Faccenna et al., 2014; Mancinelli et al., 2018; Sun et al., 2019) suggest that Adria is subducting both beneath the Dinaric and the Apenninic belts. The Central Adriatic Sea is geographically surrounded by Permian and Triassic volcanism that is outcropping or has been drilled by explorative boreholes. These events are distinguished in two major episodes, on one side there are evidences of scattered Neotethys-related volcanism between Late Permian and Middle Triassic in the Po Plain, Northern Adriatic, Istria Peninsula, Dinarides and Apulian Peninsula (Buser, 1987; Tari, 2002; Velić et al, 2002; Pamic and Balen, 2005; Bernoulli, 2007; Cassinis et al., 2008; Gaetani, 2010; Scisciani and Esestime, 2017), while in Southern Alps there are evidences of wide intrusive and effusive bodies related to the subduction of Palaeotethys ocean beneath Eurasia in Permian (Cassinis et al., 2012). Moreover, a Permian underplating event was associated to post-Hercynian outcrops across the European Alps (Schuster and Stüwe, 2008).

Some clues about the early history of the Adria plate are preserved in the Croatian archipelago where gabbroic intrusions are found on the Jabuka and Brusnik islets (Balogh et al., 1994; Juracic et al., 2004; Pamic and Balen, 2005; Palinkaš et al., 2010). Targeted by several datings during the years, the estimated age of these gabbroic intrusions has ranged between 200 and 273 ± 1.1 My with latter dating (Palinkaš et al., 2010) supporting the older age together with later reworking of the gabbros of Jabuka at 77 ± 2.4 My.

Two main questions arise from these outcrops in the Croatian archipelago: are these evidences representative of some larger-scale event? And how do these gabbroic intrusions survived in this complex geodynamic scenario?

Several authors attempted in the last years to answer these questions through several efforts focused on the analysis and modeling of the Adriatic Magnetic Anomaly (AMA, Figure 1b-d). The AMA represents the most prominent feature within the Adria plate due to the paucity of seismicity with respect to the neighboring chains (Faccenna et al., 2014; Sun et al., 2019) and its moderate average crustal thickness (~30 km – Nicolich, 2001; Sumanovac, 2010; Tassis et al., 2013). The first evidence of a ~100 km-wide and ~400 km-long AMA was provided by the aeromagnetic map of Italy (Chiappini et al., 2000; Caratori Tontini et al., 2004). Later, the dataset was extended towards the Croatian onshore by Giori et al. (2007) producing a larger coverage but still incomplete map over the AMA that was used to support a regional-scale source rather than local smaller sources (Mancinelli et al., 2015). These findings, despite based on incomplete data coverage, were later validated by inverse modeling over a full-coverage map (Milano and Fedi, 2016).

At full data coverage, the AMA extends over 200 km in the SW-NE direction and 400 km in the NW-SE direction along the Adriatic Sea with maximum anomaly values of ~370 nT (Milano and Fedi, 2016). When observed at regularly-spaced color intervals the AMA shows two main peaks (Figure 1c) and a straight NW-SE boundary along the Croatian onshore-offshore transition with a negative anomaly area still trending NW-SE in the Croatian and Bosnia and Herzegovina onshore. Conversely, the southwestern boundary is arcuate with a trend ranging N-S to W-E from north to south of the boundary. In the southwestern Central Adriatic the magnetic anomaly is alternatively mapped by positive and negative spots while more towards southwest, on the Italian shoreline and onshore areas, three main highs (A, B and C) are found (Figure 1c). The AMA results with clear and sharp northern and eastern boundaries while the western and southern boundaries are less obvious and possibly blurred with surrounding anomalies. The AMA locates the only clearly observable signal at satellite altitude over Southern Europe (Milano et al., 2019) and thus it certainly represents a deep and regional-scale phenomena that is related to the geodynamic evolution of the Adria plate and whose source cannot be limited to the outcropping gabbroic intrusions. To date however, the geodynamic context that led to the emplacement of the causative source of the AMA was never investigated. Similarly, eventual relations between the AMA and the A-C surrounding positive anomalies were never investigated despite some authors (Minelli et al., 2018; Mancinelli et al., 2019) suggested that the B anomaly is related to high magnetic susceptibility (~0.05 SI units) sources at the base of the crust.

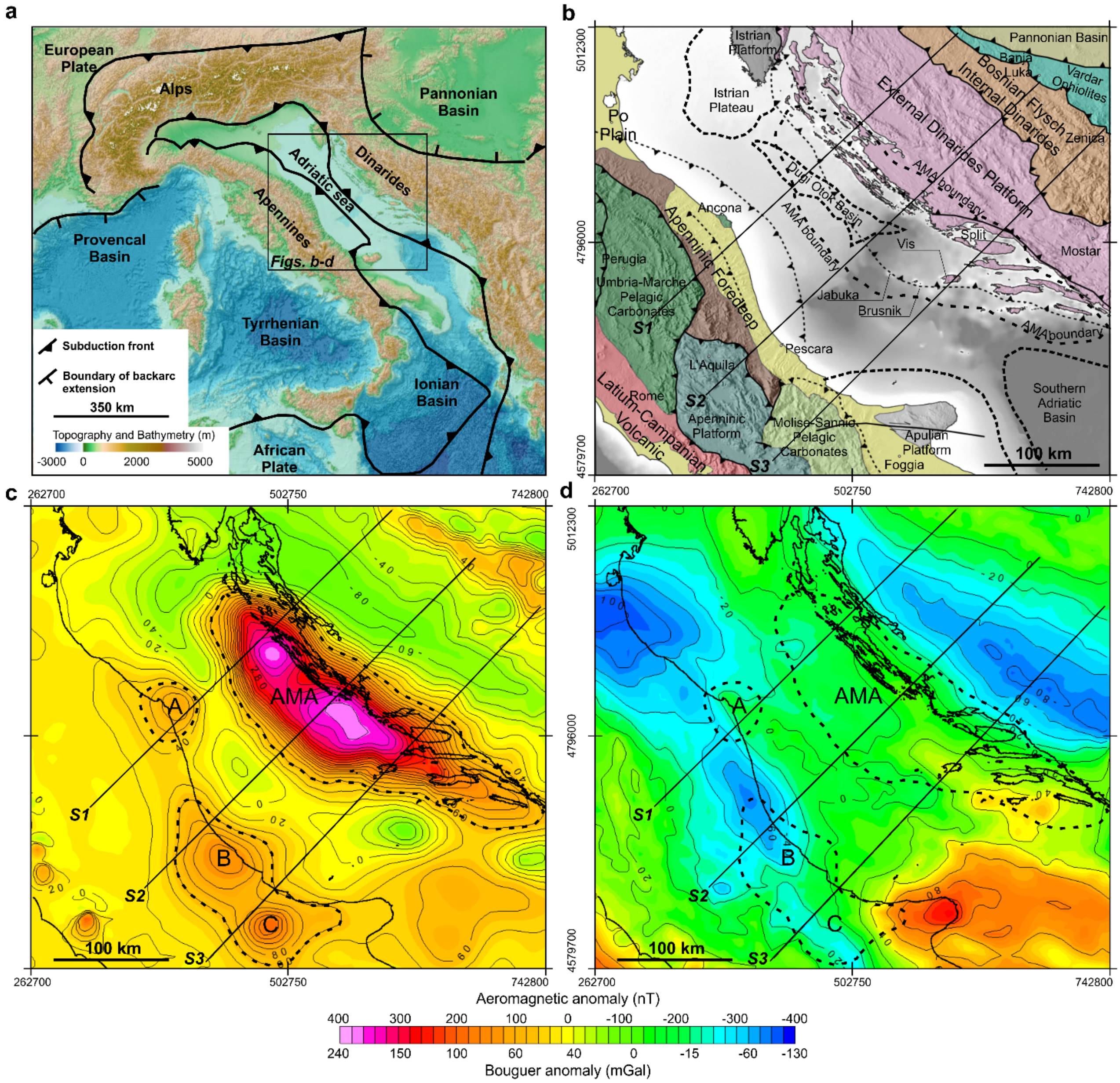

Figure 1 Geodynamic, geological and geophysical characters of the Central Adriatic Sea and surroundings. **a**, Actual geodynamic settings of the Central Mediterranean Sea and location of the study area. **b,** Simplified geological sketch map over the Central Adriatic Sea, Apennines and Dinarides (CNR – PFG, 1991; van Unen et al., 2019). **c,** Aeromagnetic anomaly at 2500 m height showing the AMA and A-C positive anomalies after Caratori Tontini et al. (2004) and Milano and Fedi (2016). AMA peaks are centered at 486000 E, 4873000 N and 557000 E, 4812000 N. Anomaly A is centered at 395000 E, 4825000 N (~85 nT) few km offshore the Ancona promontory; anomaly B is centered at 442000 E, 4681000 N (~130 nT) and anomaly C is centered at 483000 E, 4617000 N on the Abruzzo-Molise onshore. These three highs in the Apenninic foreland domain are relatively closer to the AMA from south to north with maximum and minimum distances along the SW-NE direction of ~200 and 100 km. **d,** Bouguer anomaly over the modeled area (reduction density of 2670 kg m^{-3}) after Tassis et al. (2013) and data over Italy and surroundings (CNR – PFG, 1991). When compared with the Bouguer gravity map over the area, the AMA northeastern boundary clearly relates to the boundary of the NW-SE Bouguer gravity minimum mapped over Dinarides, while all the other AMA boundaries do not match with gravity highs or lows. Black continuous lines in b-d locate the modeled sections (S1-S3). Coordinates in this and following figures are in UTM33N WGS84.

Available deep seismic data across the area are limited to the CROsta Profonda (CROP) profiles (Scrocca et al., 2003) that across the Adriatic Sea generally show poor data quality below 7 s two-way-time (TWT) with an exception given by CROP M17C crossing the area NNW-SSE (Figure S1). Several other commercial seismic profiles were acquired for hydrocarbon prospection but these were always limited in depth to 6 or 7 s TWT. Similarly, tens of boreholes were drilled in the Central Adriatic Sea for exploration purposes but these never reached the pre-Permian sedimentary sequences across the entire Central Adriatic Sea (Scisciani and Esestime, 2017).

To address the open questions about the AMA and provide a plausible geodynamic interpretation of the causative source, we forward model the observed aeromagnetic anomaly and Bouguer gravity along three SW-NE trending ~400 km-long sections extending from the onshore Central Italy through the Adriatic Sea, onshore Croatia and Bosnia and Herzegovina (S1-S3 in Figures 1 and 2).

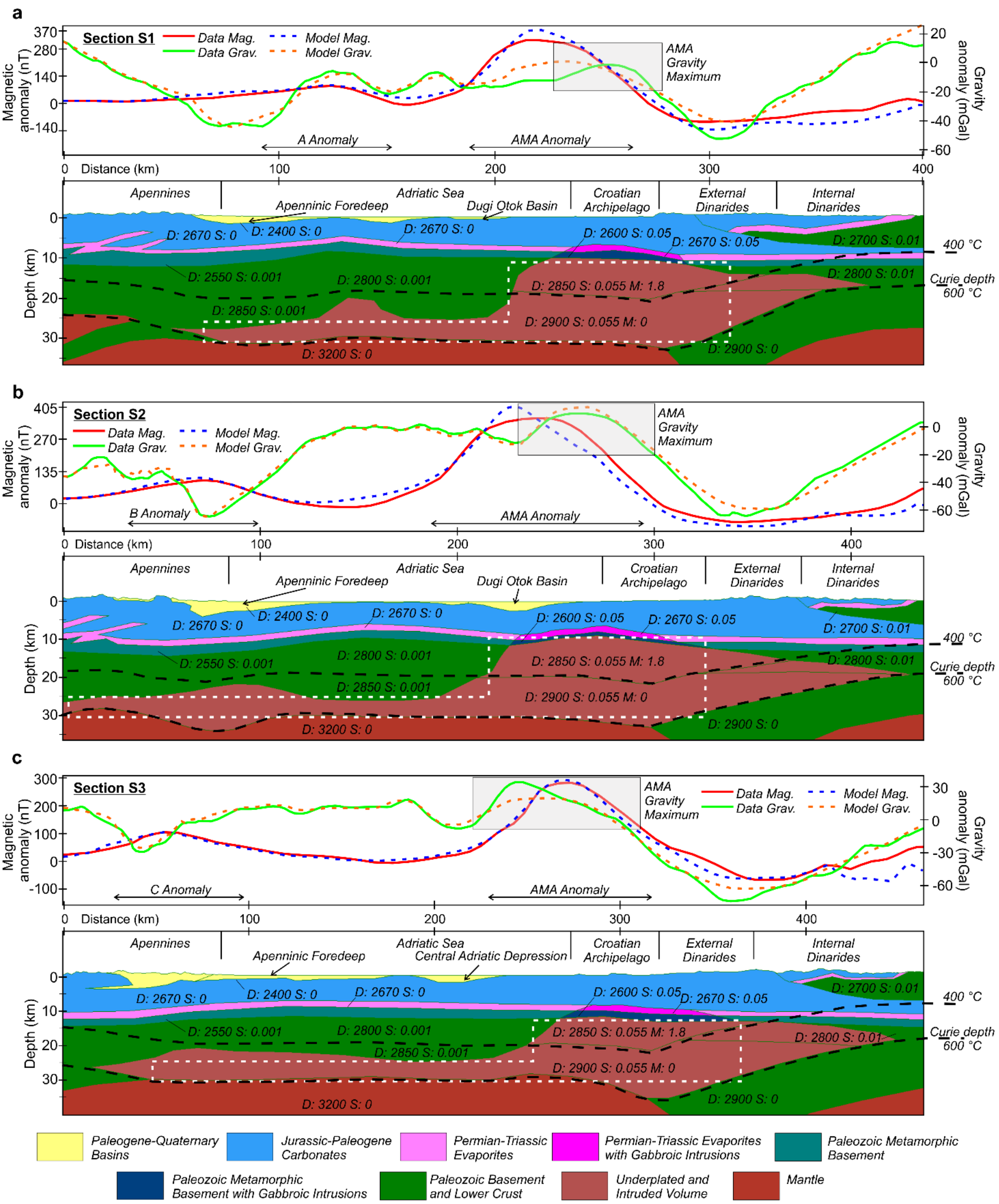

Figure 2. Forward modeling of the S1-S3 sections. a, Magnetic and gravity anomalies forward modeling across section S1. **b,** Magnetic and gravity anomalies forward modeling across section S2. **c,** Magnetic and gravity anomalies forward modeling across section S3. Modeled density (D) and magnetic susceptibility (S) values are indicated for each body. Remanent magnetization (M) is assigned only to high susceptibility volumes above the 400 °C isotherm (see methods section). Areas bounded by white dashed lines locate are those considered for estimation of the volume of the magnetic sources (see methods section). Vertical-to-horizontal scale ratio across the modeled sections is 0.5. Reference starting values for the Moho depth across the modeled area are from literature (Scarascia et al., 1998; Sumanovac, 2010; Tassis et al., 2013).

The modeled sources extend upwards from the Moho discontinuity through the crust with higher density and magnetic susceptibility (≥0.05 SI units) than the surrounding volumes. The modeled susceptibility values are comparable to those related to deep sources in Central Apennines (Minelli et al., 2018; Mancinelli et al., 2019). Minimum thicknesses of the sources are observed toward model ends, both NE and SW, and beneath the Central Adriatic Sea. However, lateral continuity is never interrupted along all the three models. The shape of the magnetic sources results coherently from the modeled sections in the form of an asymmetric crustal batholith whose basal layer widens southwards (Figure 2a-c). The thickness of the source increases northeastwards to maximum values of ~20 km along sections S1 and S2 beneath the Croatian archipelago, while its lateral extent ranges between 250 and 400 km from north to south. Beneath the Dinaric belt, the modeled AMA source base is at ~20 km depth due to shallower Curie isotherm (see methods section) but we can speculate that also the volumes constituting the crustal root of the Dinarides may have undergone the same processes because the modeled density values fit the AMA source density. The AMA source is laterally asymmetric also considering its upper bound because in the Dinaric domain the top of the source propagates to depths significantly shallower than in the Adriatic domain (Figure 2). Given the evidences of significant volume transfer from Adria to Dinarides during their Eocene-to-present collision (Bennett et al., 2008), we speculate that this asymmetry is representative of tectonic reworking of the AMA source during the Adria-Eurasia collision.

In the upper crust, the AMA source propagates with gabbroic intrusions through the basement and the sedimentary cover reaching a minimum depth of 9 km within the Triassic evaporites NE of the Dugi Otok depression along section 2 (Figure 2b). This suggests that the Triassic evaporites postdated the AMA source, whose emplacement probably occurred before mid-late Permian age. Thus, our modeling supports the latter dating of the gabbroic intrusions on Jabuka and Brusnik islets (Palinkaš et al., 2010) rather than previous estimates proposing younger ages. The gabbros outcropping in these islands were later exhumed by compressional and transpressional tectonics (Tari, 2002) related to the Dinaric chain emplacement.

The observed magnetic anomalies over the Central Adriatic Sea and surroundings are thus prevalently related to deep sources with small contributions from low susceptibility lower crust and basement. Given the spatial distribution at the base of the crust and the magnetic susceptibility of the modeled bodies, these sources are interpreted as massive underplated and intruded gabbros beneath the Adria s.str. microplate. This view is also supported by the Bouguer gravity anomaly because local maximums of the observed gravity are found over the AMA in all the modeled sections (Figure 2a-c) suggesting that the cooling of the underplated and intruded material has increased also the density of the lower crust. If our interpretation is correct, the modeling provides an estimate of the longitudinal extent of the underplated material that may range up to ~400 km. Furthermore, the modeled sections suggest that given its volume and extent, the underplated material represents an episode of massive and large-scale magmatic activity of Permian affinity rather than Triassic (Cassinis et al., 2012).

A conservative estimate of the volume of the modeled high-susceptibility sources (see methods section) provides a value of ~0.5×10^6 km^3. This volume encompasses both the underplated and intruded material and accounts also for the small portions of the upper crustal volumes hosting the shallow magmatic intrusions within the basement and early Triassic succession.

Considering the volume of the batholith and intruded gabbros as resulting from the modeling and its transparency as shown in deep seismic profiles imaging in the area (figure S1), we can speculate that after the underplated and intruded material was supplied, it undergone a long-lasting cooling and solidification period (Thybo and Artemieva, 2013). This implies that in the Adria s.str. area the continental breakup never evolved to oceanic spreading with new crust formation but it aborted soon after the first underplating phase, following an evolution similar to that proposed for the Permian igneous and metamorphic rocks in the European Alps by Schuster and Stüwe (2008). This supposed interruption of the breakup evolution is supported by the lacking of volcanic evidences from outcrops and boreholes in the entire Central Adriatic Sea because short timings (< 0.1 Ma) are required between underplating and the following magmatism (Petford et al., 2000; Thybo and Artemieva, 2013). However, we suggest that some consequences of the aborted rift in the Central Adriatic Sea are still evident.

In figure 3 we compare the top of the underplated and intruded volumes against the distribution of known long-lasting carbonate platforms and Permo-Triassic structural highs in Central Adriatic and surroundings. These regions locate palaeogeographical scenarios that never evolved to slope or basin domains during Jurassic or Cretaceous times (Dinaric platform) or made their transition during Triassic or Jurassic, with significant delay when compared to surrounding depositional sequences. Among the latter, we include the Ancona and Villadegna highs where stratigraphic evidences (Cazzola and Soudet, 1993; Scisciani and Esestime, 2017) suggest that palaeogeographical domains during Triassic and early Jurassic were tectonically controlled. In these areas, the uplifted regions allowed for longer-living shallow water environments while these were surrounded by deeper conditions such as the Emma and the East Gran Sasso basins located east and west of the Villadegna area, respectively (Scisciani and Esestime, 2017). In the case of anomaly C such evidences are buried beneath ~12 km of overlying Apulian platform and Southern Apennines foredeep deposits (Butler et al., 2004) that cover the westward-subducting Adria crust and prevents any detection of eventual Permian uplift of Adriatic affinity.

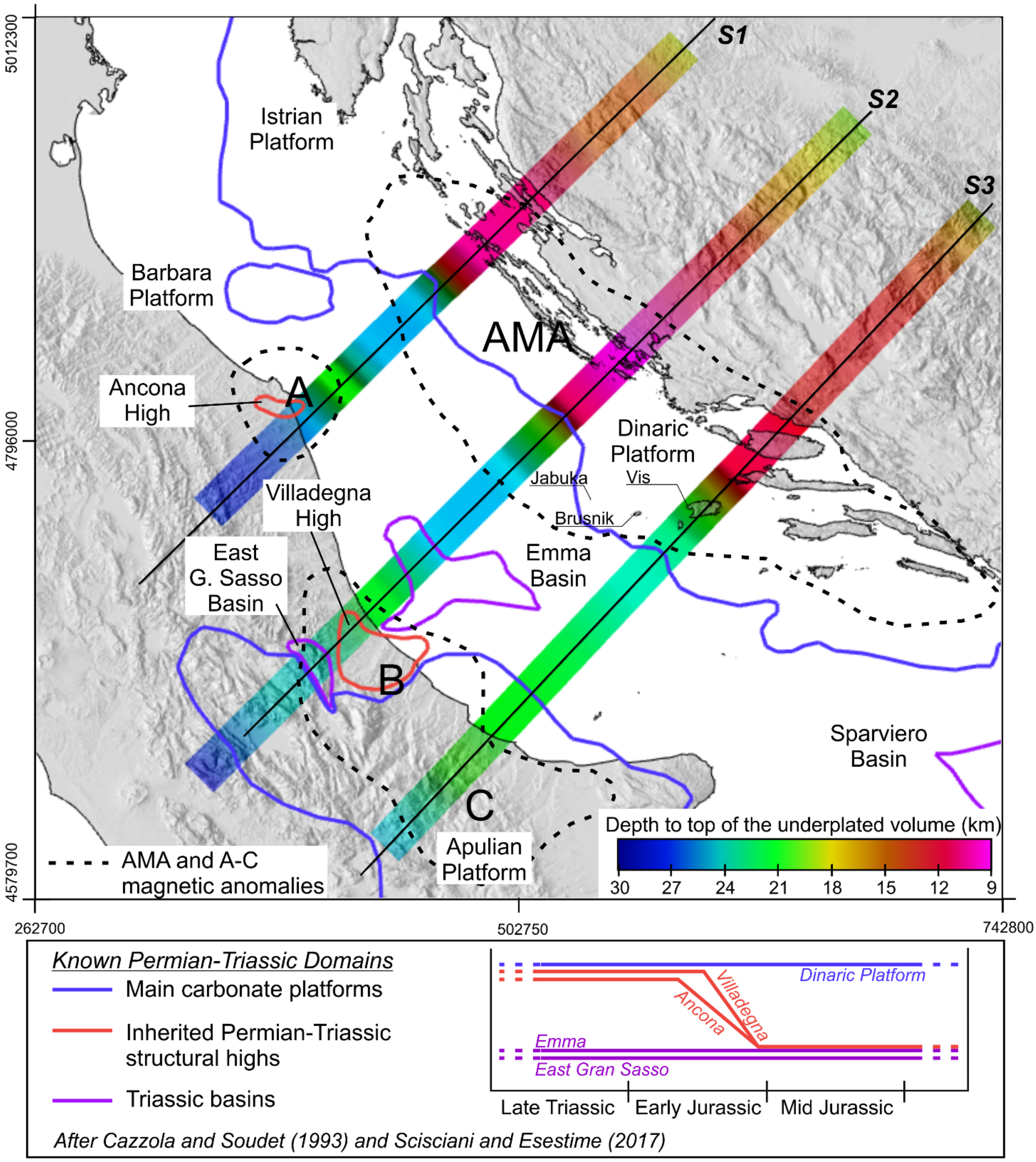

Figure 3. Comparison between the modeled underplated volume and known Adria Permian-Triassic domains. The spatial trend of the top of the underplated volume (color-coded bands) is compared against the boundaries of the mapped magnetic anomalies (dashed black lines) and the spatial distribution of the known palaeogeographical domains in late Permian-early Triassic (color-coded lines). The drowning timing of the inherited structural highs is also provided in the lower plot and compared to surrounding basins and Dinaric platform. The north-eastern areas where shallower magnetic sources are found along modeled sections S1 and S2, matches the boundary of the long-living Dinaric carbonate platform. The south-western areas below the A-C anomalies correspond to inherited structural highs from Permian uplifted regions (A and B) and to a region of Adriatic affinity beneath the Apulian platform and Southern Apennines foredeep (C).

The fitting between the modeled deep crustal magnetic source and these regions is surprising and intriguing. Considering the spatial distribution of such domains and the marked asymmetry across Central Adriatic given by the thick and continuous Dinaric platform (Scisciani and Esestime, 2017) compared to the scattered structural highs and basins in the Western Adriatic area, we speculate that the causes for such evidences are related to regional-scale phenomena affecting the tectonic setting of the upper crust. Furthermore, we suggest that the observed heterogeneity in the palaeogeographical Permian domains is a direct consequence of the underplated and intruded material that over-compensated the rift-related crustal thinning resulting in uplifted regions of crust corresponding to major underplated volumes (figure 4a-b).

The basement that was exhumed because of the underplating was eroded during Permian allowing the intruded gabbros in the basement to further shallow. Possibly, thanks to later tectonic reworking and uplift, these small and shallower volumes are those outcropping in the Croatian archipelago. After an evaporitic sedimentation phase in Lower Triassic, whose products show heterogeneous thickness and distribution across the area (figure 4c; Scisciani and Esestime, 2017), carbonate platforms lasted longer in the uplifted regions and were preserved since Cretaceous with respect to the surrounding regions where marginal and basin conditions rapidly developed since late Triassic (figure 4c-d). Such heterogeneous scenario implies that the flexural strength of the crust was very low or null, a view that is compatible with the continental breakup phase and the related crustal thermal regime.

In figure 4e we propose an interpretative view of the Palaeotethys-Adria s.str. boundary in Permian suggesting that this collisional margin was similar to the actual Pacific-Okhotsk plate boundary where underplating contributes to crustal accretion beneath and behind the Kuril arc (Nakanishi et al., 2009; Thybo and Artemieva, 2013). In this scenario, the minimum distance between the AMA anomaly and the Permian Palaeotethys subduction front was ~150 km (figure 4e). This spatial reference is compatible with the proposed collisional scheme and with the regional palaeogeographic Permian scenario (Stampfli et al., 2013). Moreover, this interpretation is further supported by the depth (~160 km) reached by the subducted Adria slab beneath Dinarides during their Eocene-to-present collision (Bennett et al., 2008).

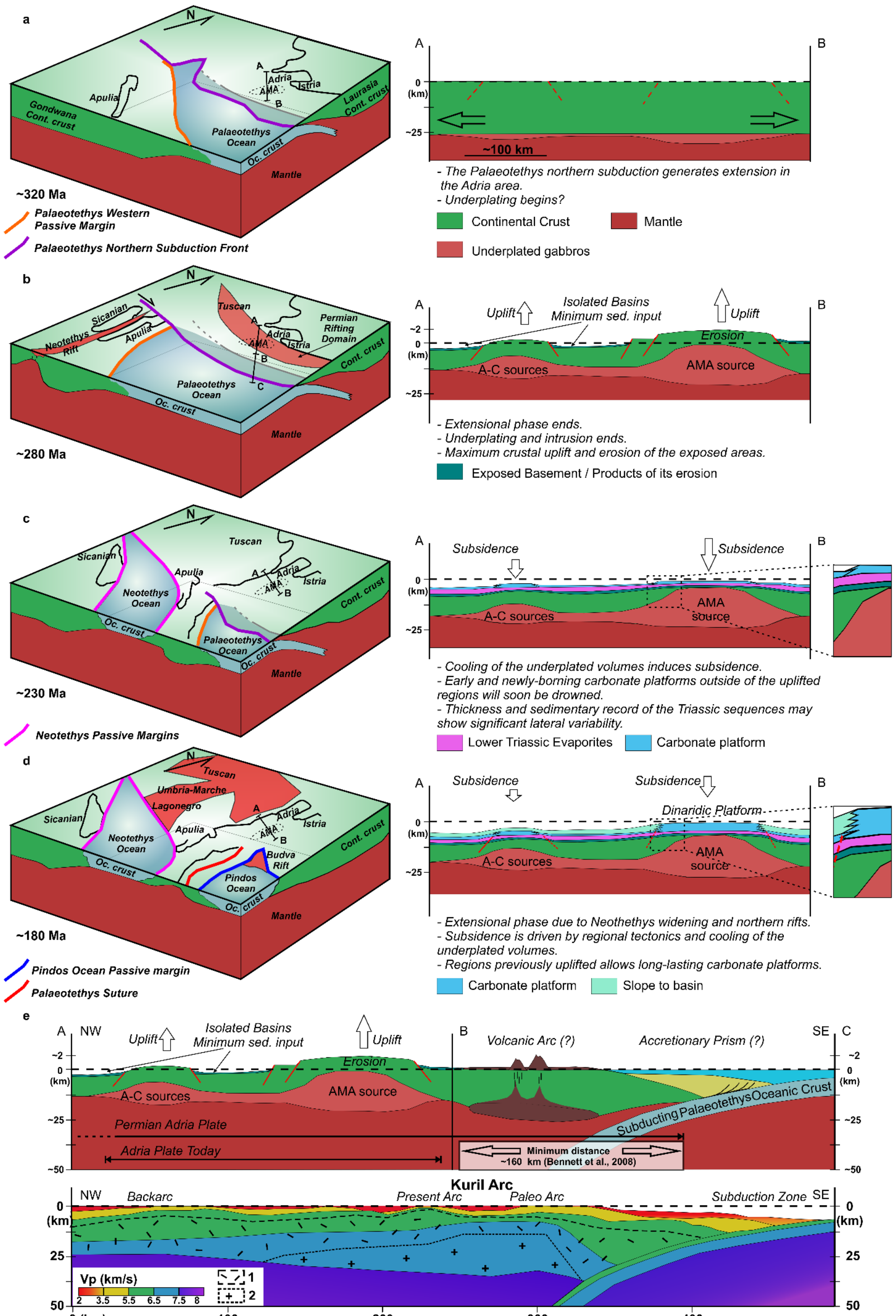
a
N
Apulia
Adria
AMA
Istria
A
B
Gondwana Cont. crust
Laurasia Cont. crust
Palaeotethys Ocean
Oc. crust
Mantle
~320 Ma
Palaeotethys Western Passive Margin
Palaeotethys Northern Subduction Front
A
B
0 (km)
~25
~100 km
- The Palaeotethys northern subduction generates extension in the Adria area.
- Underplating begins?
Continental Crust
Mantle
Underplated gabbros
b
Sicanian
Neotethys Rift
Apulia
Tuscan
Adria
AMA
Istria
Permian Rifting Domain
Cont. crust
Palaeotethys Ocean
Oc. crust
Mantle
~280 Ma
Uplift
Isolated Basins Minimum sed. input
Uplift
Erosion
A-C sources
AMA source
~2
0 (km)
~25
- Extensional phase ends.
- Underplating and intrusion ends.
- Maximum crustal uplift and erosion of the exposed areas.
Exposed Basement / Products of its erosion
c
Sicanian
Tuscan
Apulia
Adria
AMA
Istria
Neotethys Ocean
Oc. crust
Palaeotethys Ocean
Cont. crust
Mantle
~230 Ma
Neotethys Passive Margins
Subsidence
Subsidence
AMA source
A-C sources
- Cooling of the underplated volumes induces subsidence.
- Early and newly-borning carbonate platforms outside of the uplifted regions will soon be drowned.
- Thickness and sedimentary record of the Triassic sequences may show significant lateral variability.
Lower Triassic Evaporites
Carbonate platform
d
Tuscan
Umbria-Marche
Lagonegro
Sicanian
Apulia
Adria
AMA
Istria
Neotethys Ocean
Budva Rift
Pindos Ocean
Oc. crust
Cont. crust
Mantle
~180 Ma
Pindos Ocean Passive margin
Palaeotethys Suture
Subsidence
Subsidence
Dinaridic Platform
A-C sources
AMA source
- Extensional phase due to Neothethys widening and northern rifts.
- Subsidence is driven by regional tectonics and cooling of the underplated volumes.
- Regions previously uplifted allows long-lasting carbonate platforms.
Carbonate platform
Slope to basin
e
A NW
Uplift
Isolated Basins Minimum sed. input
Uplift
Erosion
B
Volcanic Arc (?)
Accretionary Prism (?)
SE C
A-C sources
AMA source
Permian Adria Plate
Adria Plate Today
Subducting Palaeotethys Oceanic Crust
Minimum distance ~160 km (Bennett et al., 2008)
~2
0 (km)
~25
~50
Kuril Arc
NW
Backarc
Present Arc
Paleo Arc
Subduction Zone
SE
0 (km)
25
50
Vp (km/s)
2 3.5 5.5 6.5 7.5 8
1
2
0 (km)
100
200
300
400

Figure 4 Conceptual models of the formation and Permian-Jurassic evolution of the underplated gabbros. **a,** Late Carboniferous palinspastic sketch illustrating the Adria s.str. and Apulia s.str. microplates and surroundings; due to the inception of back-arc spreading the underplating possibly started during the widening of the Palaeotethys Ocean. **b,** During Permian times the increasing underplated volume provides substantial uplift in the areas where the major volumes are localized. In Mid Permian, the opening of the Neothethys western branch stops the underplating and prevents breakup completion. Sedimentation in internal basins is limited and localized, mostly consisting of erosional products of the exposed basement. **c,** In a period of tectonic stasis due to the closing of the northern Palaeotethys branch, post-underplating subsidence has produced its effects and Triassic evaporites are deposited above the basement. **d,** During Late Triassic and Lower Jurassic the regions that undergone higher uplifts in the previous period allow the Dinaric carbonate platform to grow longer, while in adjacent areas slope and deeper environments are found. The opening of the Umbria-Marche and Lagonegro basins is lateral (westwards) to the Adria s.str. microplate but likely contributes to tectonic subsidence of the western Adria basins. **e,** Regional model section across the subducting Palaeotethys oceanic crust and the study area during Permian (for location see figure 4b) compared with the P-wave velocity model across the Kuril arc (Nakanishi et al., 2009) and its interpretation – 1: Post-fractionation and delaminated underplating; 2: Mafic underplating (Thybo and Artemieva, 2013). Palaeogeographic maps are modified after Moix et al. (2008), Stampfli and Hochard (2009), Stampfli et al. (2013).

Assuming an Airy-type response within the crust (Watts, 2001) we can estimate (see methods section) the maximum uplift induced by the underplating load to be ~2000 m in the Dinaric domain. This estimate is supported by the differential growth of the Dinaric platform in respect to the Adriatic domain. In the first case, above the thicker and wider AMA source, we find a wide and continuous Dinaric carbonate platform lasting from Late Triassic to Paleogene (Scisciani and Esestime, 2017). In the Adriatic domain, above the thinner sources that we interpret as causative of the A and B anomalies, we find scattered duration of the carbonate platforms and structural highs (Figure 3) whose spatial distribution coincides with locations of the A and B anomalies and causative sources. The drowning of these latter domains was likely driven by faster cooling of the thinner underplated material accelerating upper crustal subsidence (Schuster and Stüwe, 2008) with possible later contributions from the western Jurassic rifting systems (Figure 3d).

In this framework, strong magnetic sources are lacking at the base of the southernmost Apulian s.str. crust (Figure 1c; Caratori Tontini et al., 2004; Milano and Fedi, 2016) because during Permian times the Apulia s.str. microplate pertained to the Cimmerian terranes and was in between the Palaeotethys and the newly-opening Neothethys (Stampfli et al., 2013), away from the Adria underplating (Figure 4b). If the Apulian promontory was in the same position relative to the Adriatic Sea as today, it should testify this with magnetic signatures like those found in the Central Adriatic Sea (Figure 1) and/or with massive Permian magmatic intrusions like those observed in the Alps (Cassinis et al., 2012) or resulting from our models. Such evidences are lacking because only one thin level of volcanic deposits is found interlayered in shallow-water carbonates of Apulian affinity across the complete Permian sequence drilled by the Gargano 1 borehole (Scisciani and Esestime, 2017). On the contrary, the C anomaly is apparently related to the

Apulian platform (Figure 3) but it is actually related to the Permian underplating beneath the Adria s.str. microplate and thus pertains to the westward-subducting Adria s.str. crust.

Geometries of the modeled volumes may suggest a tectonic underplating process (Menant et al., 2019) related to the Palaeotethys subduction beneath the Permian Adria. In this scenario, the outcropping gabbros and the underplated volume would represent the lower Palaeotethys oceanic crust tectonically stacked during its subduction beneath Adria. Despite the observed topographic uplift seems to support this view (Menant et al., 2020), a tectonic origin for the underplating can be ruled out because of the timing, thickness and gabbroic nature of the underplated material. In fact, the ~20 km thick gabbroic volumes are significantly younger than the Palaeotethys oceanic crust. Furthermore, the thin and deep gabbroic oceanic crust is not involved by tectonic stacking that should allow underplating only of the upper basaltic layers (Menant et al., 2019) that are missing across the entire study area.

An alternative view could regard the AMA source as a fossil seamount pertaining to the Palaeotethys ocean that was exposed by erosion of the accretionary prism once the Palaeotethys was closed. The size of the AMA source is compatible with other cases along the Palaeotethys suture (Moix et al., 2008; Federici et al., 2010; Moix et al., 2013; Eyuboglu et al., 2018) but the basaltic, ophiolitic and metamorphic facies that usually are found in such cases are missing in the Central Adriatic area. Moreover, a seamount origin for the outcropping gabbros is further discredited by their trace element concentration that supports an Island-Arc origin (Figure S2).

Another plausible alternative scenario can relate the AMA underplating to the northwestern termination of the Pindos ocean – i.e. the Budva rift (Stampfli and Kozur, 2006; Moix et al., 2008). Given the Budva-Adria s.str. proximity in Late Triassic-Early Jurassic times (figure 4), if the Budva rift survived to the Pindos subduction, its attenuated lithosphere may have carried the AMA underplated gabbros towards the external Dinarides during later transcurrent deformation (Stampfli and Kozur, 2006). In such case however, the AMA anomaly and its causative source should locate at least in the external Dinarides or, given the Cenozoic Adria-Eurasia collision, it should be even more internal on the Dinaric chain. Furthermore, this hypothesis is not matched by the Triassic evaporites postdating the underplated gabbros as resulting from our modeling (figure 2).

Finally, we propose that the emplacement of the underplated material is related to the Palaeotethys-Adria s.str. convergence in the form of a back-arc extension (Figure 4e). Such scenario was common in the northern Palaeotethys margin (Stampfli et al., 2004) due to the acceleration of Palaeotethys slab rollback after the end of Gondwana and Laurasia convergence and collapse of the Laurasian active margin (Vavassis et al., 2000). The back-arc regions firstly evolved towards shallowing or exhumation of the lower crust over large areas (including the Adria s.str. region) in a Basin and Range fashion (Zandt et al., 1995), and finally towards opening of the small Triassic back-arc oceans (Meliata, Maliak, Pindos-Huglu) (Stampfli and Kozur, 2006).

If this rifting was completed laterally (southwards) to the Adria s.str. microplate or if it evolved discontinuously and completion of the breakup was aborted only in this region remains unclear. However, in the first case the evidences would have been consumed by the Adria subduction beneath Dinarides, whilst in the second case this portion of the Adria s.str. microplate was very close to formation of new oceanic crust, as testified by intrusive bodies reaching shallow depths, but in late Permian-early Triassic a rapid change in the geodynamic context has stopped rift completion. We suggest that this event is the opening of the northwesternmost Neotethys branch that sets the stage to close the gap between the Apulia s.str. and Adria s.str. microplates to form the wider Adria as it is today, accelerates the closure of the Palaeotethys ocean and stops the extensional tectonics in the Adria s.str. area (Figure 4c-d).

If the linkage between the AMA source and the sources of the A- C anomalies is accepted, then some constraints are provided to the extent of the Adria s.str. microplate. In fact, the boundary between Adria s.str. and Apulia s.str. should be located south of the C anomaly. In this area surrounding the Gargano promontory the lithosphere thickens southwards (Calcagnile and Panza, 1981) and broad E-W transform deformation was related to inherited discontinuities in the deep crust (Di Bucci et al., 2006). Furthermore, a significant GPS velocity increase was observed between the areas north and south of the Gargano promontory (Oldow et al., 2002) and recent findings suggest that the Adria plate as intended today extending from the Alps to the Apulian promontory, is fragmented in two subplates rotating in opposite directions and whose boundaries are located in the Gargano promontory area (Handy et al., 2019). We interpret all these features as indicative of the boundary between the Adria s.str. and Apulia s.str. grossly corresponding with the E-W transform zone, but whose eventual upper crustal evidences were masked by the Cenozoic Apenninic orogenesis. In this view, this area locates a Mesozoic plate boundary that is still affecting the geodynamic evolution of the area.

The case of the Adria plate demonstrates that underplating processes in collisional dynamics may contribute to continental crust accretion and, in the long term, to preserve crustal thickness. This is the case in the Pacific-Okhotsk plate boundary as it was in the Palaeotethys-Adria s.str. collision. Underplating contribution is showcased by the long-living Dinaric platform whose evolution since Permian times would have been completely different without the underplated volume that, by providing significant uplift and crustal buoyancy, has controlled the topography/bathymetry ultimately allowing for platform growth and palaeogeographic differentiation. In the long-term evolution of the plate, the underplated volume has probably played a key role also in the Adria-Eurasia collision by partial transfer of crustal volumes from the Adria plate to the Dinaric belt.

Methods

Forward modeling of the magnetic anomaly

In our modeling, we set a maximum magnetic susceptibility threshold of 0.05 ±0.005 (SI units) compatibly with estimates from Minelli et al. (2018) and modeling in the Central Apennines by Mancinelli et al. (2019). All the other bodies modeled across the sections were given susceptibility values ranging between 0 and 0.055 SI units.

A fundamental constraint when modeling magnetic anomalies is given by the Curie isotherm. Here, we set a magnetite Curie temperature of 600 °C (Frost and Shive, 1986; Shive et al., 1992). To locate the Curie isotherm we assume an average crustal thermal conductivity of 2.5 W m^{-1} K^{-1} (Turcotte and Schubert, 2002; Pauselli et al., 2006; Pauselli and Ranalli, 2017) and calculate the conductive thermal gradient using heat flow data from Central Italy (Pauselli et al., 2019), the Adriatic Sea (Della Vedova et al., 2001) and heat flow values from Bosnia and Herzegovina (Atlas of geothermal resources in Europe, 2002). We also use thermal gradient data over Croatia (Kurevija et al., 2014).

The observed conductive heat flow (q) is given by:

$$q = -k \frac{\partial T}{\partial Z}$$

where k is the thermal conductivity of crustal rocks and $\partial T/\partial Z$ is the thermal gradient (Fourier, 1822).

The resulting Curie depth is estimated to range between 35-40 km in the Apenninic and Adriatic areas, where lower heat flow values (30-40 mW m^{-2}) are observed, and ~20 km in the northeastern part of the investigated area of Bosnia and Herzegovina, where the highest thermal gradient (30 K km^{-1}) and heat flow values (~75 mW m^{-2}) are found. Considering that the Moho discontinuity represents a magnetic boundary preventing any contribution from the mantle to generate anomalies (Wasilewski et al., 1979; Wasilewski and Mayhew, 1992), these estimates allow to assume that the observed magnetic anomalies may come from sources located within the entire crust in the Apenninic, Adriatic and Croatian onshore domains, while sources in the northeastern area are located within the upper crust.

For the modeling we set the following parameters of the magnetic field: field intensity (H) 36.8 A/m, inclination (FI) 58°, declination (FD) -0.1°. In modeling the magnetic anomalies we consider both induced (M_i) and remanent magnetization (M_r). The first is attributed to each body above the Curie depth through the magnetic susceptibility ($M_i = S \times H$). The remanent magnetization is attributed only to large underplated volumes above the 400°C isotherm because at higher temperatures M_r contributions are unlikely due to its unstable and viscous signature (Pullaiah et al., 1975; Schlinger, 1985; Minelli et al., 2018). Given the uncertainties about magnetization values of the underplated gabbros (Bronner et al., 2011), we assume an effective average M_r value of 1.8 A m^{-1} with a magnetization vector inclination of 0° and declination of 12° according to the Permian paleopole (Van der Voo, 1990).

The high magnetic susceptibilities used to model the main sources of the AMA and surrounding magnetic anomalies exclude the possibility of a granitic composition for these bodies (Punturo et al., 2017) and are similar to susceptibility values observed on samples from the Ivrea-Verbano area (Rochette, 1994).

Volume estimates of the magnetic anomalies sources

To estimate the volume of the causative source for the observed magnetic anomalies we use the minimum values of thickness and lateral extent (SW-NE direction) of the source as resulting from the modeled sections (white dashed squares in figure 2). Furthermore, we consider the distance between section 1 and 3 (~180 km) to represent the third dimension of the source along the NW-SE direction. Only volumes with magnetic susceptibility ≥ 0.05 (SI units) are considered. From the volume estimate we exclude the volumes outside the white dashed boxes in figure 2 – i.e. the northernmost wedge-shaped anomalous sources and the A-C sources, due to their marked lateral variability. This approach provides a conservative estimate of the AMA source volume (0.3×10^6 km^3) and of the underplated material beneath the Adriatic Sea and Italian onshore (0.2×10^6 km^3). Throughout the text, when we refer to sources we imply both the AMA and the Western Adriatic Sea and Italian onshore sources related to the A-C positive anomalies.

Uplift estimates caused by underplating

Uplift estimate is produced assuming an Airy-type response of the crust to the underplating load (see text for discussion) given by

$$u = v \frac{(\rho_m - \rho_x)}{(\rho_m - \rho_w)}$$

Where u is the induced uplift, v is the thickness of the underplated body, ρ_m is the density of the mantle (3200 kg m^{-3}), ρ_x is the density of the underplated body (2900 kg m^{-3}) and ρ_w is the density of water (1030 kg m^{-3}) (Watts, 2001). Table 1 shows the estimated uplift due to underplated material thickness ranging between 2 and 25 km. If a regional uplift is assumed to be ~700 m due to the basal layer of the source averaging 5 km thickness in all the modeled sections, the maximum uplift beneath the AMA source ranges between 2700 and 2000 m for underplating thickness of 25 and 20 km, respectively. Above the sources for the A-C anomalies in Western Adriatic Sea and onshore Italy, the maximum estimated uplift is ~700 m because of the average underplating thickness of 10 km across all modeled sections (Figure 2).

v (km)	2	5	10	15	20	25
u (m)	276	691	1382	2074	2765	3456

Table 1. Airy-type crustal uplift u (m) compared to the thickness of the causative underplated material v (km).

Acknowledgments and data availability

All the data used in this work are available from literature and published maps.

Authors contributions

Competing interests

The authors declare no competing interests.

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Supplementary material for the manuscript

Back-arc underplating provides crustal accretion affecting topographic and sedimentary domains.

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This supplementary material consists of 2 figures and supplementary text.

Figure S1

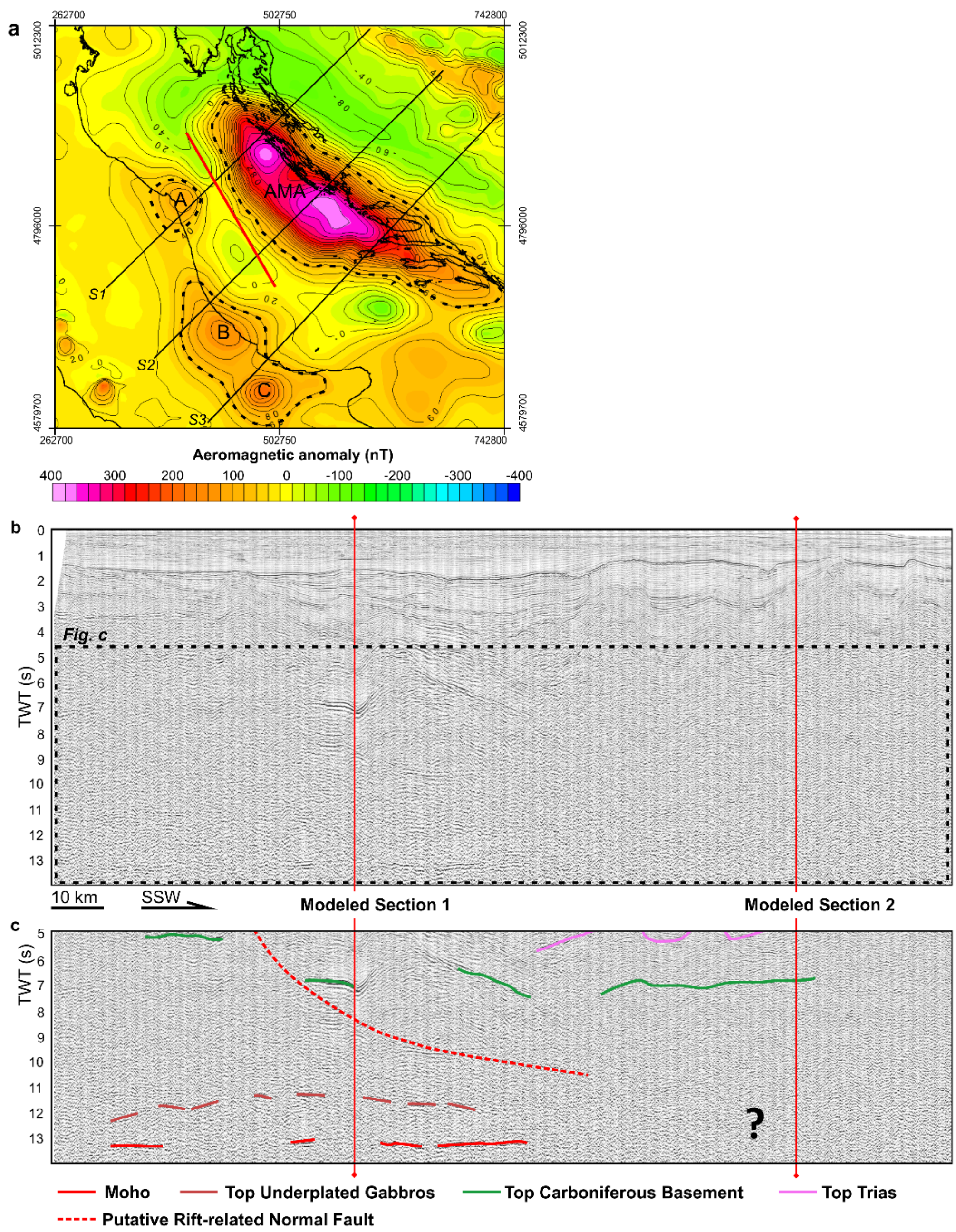

Figure S1. **Location and interpretation of the seismic reflection profile CROP M17C. a,** Location of the CROP M17C profile (red line) across the study area. **b,** clean image of the CROP M17C profile between 0 and 14 sec TWT. Red vertical lines locate the intersection with modeled sections 1 and 2. **c,** Interpretative sketch of the main horizons between 5 and 14 sec TWT.

Figure S1 shows the interpretation of the deep main horizons in the study area. This line represents the best deep (> 6 s TWT) seismic data across the entire Central Adriatic Sea because in its northernmost portion some deep reflectors are traceable. In particular, we locate the ~13 sec TWT horizon that we interpret as representative of the Moho discontinuity, we also locate some discontinuous reflections above the Moho between 11 and 12 sec TWT (brown horizons) and some other shallow reflections interpreted as the top of the carboniferous basement (green horizons) and the top of the Triassic sequence (pink horizons) in the southern region.

Figure S2

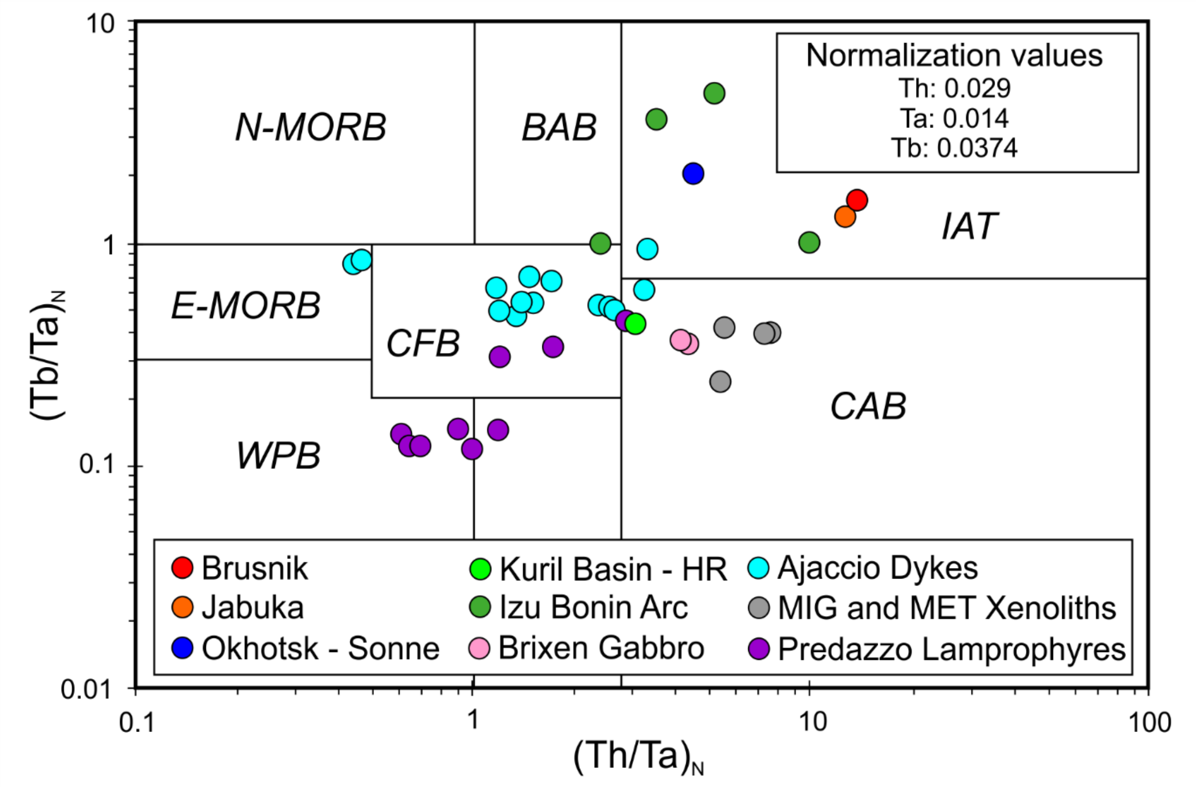

Figure S2. **$(Th/Ta)_N$ vs $(Tb/Ta)_N$ ratios (Thièblemont et al., 1994) for the gabbros outcropping in Jabuka and Brusnik islands compared with surrounding known Permian-Triassic volcanics and intrusives and with the Okhotsk-Kuril arc and the Izu Bonin arc volcanics.** N-MORB filed – N-Type MORB; E-MORB field – E-Type MORB; BAB field – Oceanic back-arc basin basalt; WPB field – Within-plate basalt (transitional and alkaline); CFB field – Continental tholeiite; IAT – Island-arc tholeiite; CAB – Subduction-related calc-alkaline lava. These data exclude a basaltic composition and a seamount origin for the gabbros outcropping in Jabuka and Brusnik (see Figure 1 for their locations). Brusnik and Jabuka compositional data are from Radić and Lugović (2004). Data from the Sonne volcanoes in the Okhotsk Sea and from the Hydrographer Ridge (HR) in the Kuril Basin correspond to samples 126-1-1, 126-1-2, DR7-1-1, DR7-1-2 and DR83-1-1 from Werner et al. (2020). Data from the Ajaccio dykes and Brixen gabbros are from Boscaini et al. (2020). Data from the Predazzo lamprophyre are from Casetta et al. (2019). Data from the Migmatite (MI) and Metapelite (ME) xenoliths are from the Euganeans hills (Sassi et al., 2020). Data from the Izu Bonin arc are from Straub (2003). All data are normalized against Cl Chondrites (Sun and McDonough, 1989).

Figure S2 shows that when compared against data from an actual island-arc system in the Okhotsk Sea and Kuril Basin (Werner et al., 2020), the trace element composition of the Jabuka and Brusnik gabbros suggests that these are related to an internal back-arc area of the island-arc system. In fact, Jabuka and Brusnik samples shows a better fit with the Sonne samples (~300 km from the Kuril arc) rather than with the Hydrographer Ridge (HR) samples (~80 km from the Kuril arc). Moreover, the Jabuka and Brusnik samples are comparable also with the Izu Bonin back-arc volcanics (Straub, 2003). Finally, the trace element composition of the gabbros from jabuka and Brusnik do not compare with the composition of the surrounding known Permian-Triassic volcanics and intrusives where such data are available.

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