

Conflicting tectonic interpretations of the central External Dinarides

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Abstract

The tectonic structure and orogenic evolution of the central part of the External (Outer) Dinarides in Croatia (northern Dalmatia, Velebit, and Lika) has been interpreted in different, sometimes conflicting ways. One of the recent models interprets the External Dinarides as a fold and thrust belt, characterized by the early orogenic thin-skinned contractional phase, followed by thick-skinned exhumation and related gravitational collapse of the thin-skinned cover. Another recent model offers the same tectonic style in the first phase of the orogenesis, followed by formation of a triangle zone and low angle north directed passive roof backthrusts in the intermediate phase, and final uplift because of antiformal south directed duplex stacking and multiple thrusting in the former tectonic basement. However, despite up-to-date geological cross section analysis, the later model seems to lack field data supporting it. This paper will discuss the need for such a complex and completely new regional tectonic interpretation that requires more thorough checking of existing observations previously published in numerous local studies and maps, and meticulous redebating of earlier interpretations before they are replaced. Moreover, it is concluded that the former model, reinterpreted here, combining the early-orogenic thin-skinned and late-orogenic crustal thick-skinned tectonics, seems to fit better both the seismological fault mechanism solutions and updated geological maps of the area.

Keywords: External Dinarides, geological structure, various models, active faults, seismotectonics

1. INTRODUCTION

The External (Outer) Dinarides can be considered as the detached and highly deformed upper crust of the central Adriatic microplate (Adria) during its subduction to the NE (KORBAR, 2009 and references therein). Possible multiphase reactivation of Triassic rift structures (lineaments), formed during separation of Adria from Gondwana, as well as movement of Adria within the western Tethys (VAN HINSBERGEN et al., 2020), strongly affected Mesozoic extension to Cenozoic compression of its central part. The process has strongly affected the stratigraphy and styles of tectonic deformations within the upper crust, and that is why the central part of the External Dinarides is divided into several major tectonic (tectonostratigraphic) units (SCHMID et al., 2008; KORBAR, 2009; Fig. 1). During the early-orogenic thin-skinned tectonic deformations, and progressive migration of the deformation front of the Dinaric (Alpine) orogen from the NE to the SW, sedimentary successions were detached on various decollements. The inactive thrust front of the central part of the External Dinarides is nowadays recognized offshore, SW of the outer NE Adriatic islands (Fig. 1). The axial zone of the External Dinarides is characterized by moderate earthquakes (Fig. 1) that are probably nucleated along the pre-orogenic crustal lineament that was reactivated during a late-orogenic transpressional stage (PICHA, 2002; KORBAR, 2009). Tectonic transport along the zone is probably still active during the present-day escape tectonics (PICHA, 2002). Thus, the pre-existing upper crustal structures related to the early orogenic deformations are masked during this latest stage of the geodynamic evolution of the External Dinarides.

In the last few years, BALLING et al. (2021a, b, 2023) published three papers dealing with the orogenic evolution of the central part of the External Dinarides, offering interpretation of the genesis of some important tectonostratigraphic units, and a completely new model of the orogenic evolution and the tectonic structure of this complex fold-and-thrust belt. The authors used state-of-the-art structural geology software, but the input data is not supported by verifiable field measurements. Although published by a group of distinguished structural geologists, the complexity of the belt advocates a more systematic approach to the new outcomes. Besides, since some interpretations are similar to those in the previous models, there is a need to give due credit to the previous authors.

In the first paper, BALLING et al. (2021a) argue for mantle delamination constrained by the uplifted Miocene marine terraces that the authors recognized during their trip along the eastern Adriatic coastal Dinarides. However, in the supplemental KML file of the paper there are hundreds of polygons marking "horizontal surfaces" that are supposed to be marine terraces, although there is neither evidence that any of the marked surfaces is of marine origin nor that they are of Miocene age. Besides, and more importantly, most of the "terraces" are not horizontal at all. Maybe the surfaces seem horizontal on the scale of the EU-DEM (25 m resolution and vertical accuracy of 7 m vertical), but on more detailed official topographic maps of the Republic of Croatia (e.g., DGU, 2023) it is clear that most of the small "horizontal surfaces" marked on the KML file of BALLING et al. (2021a) are neither horizontal nor flat, except for some small karst poljes, that are not terraces. However, the "terraces" are not in the focus of this paper.

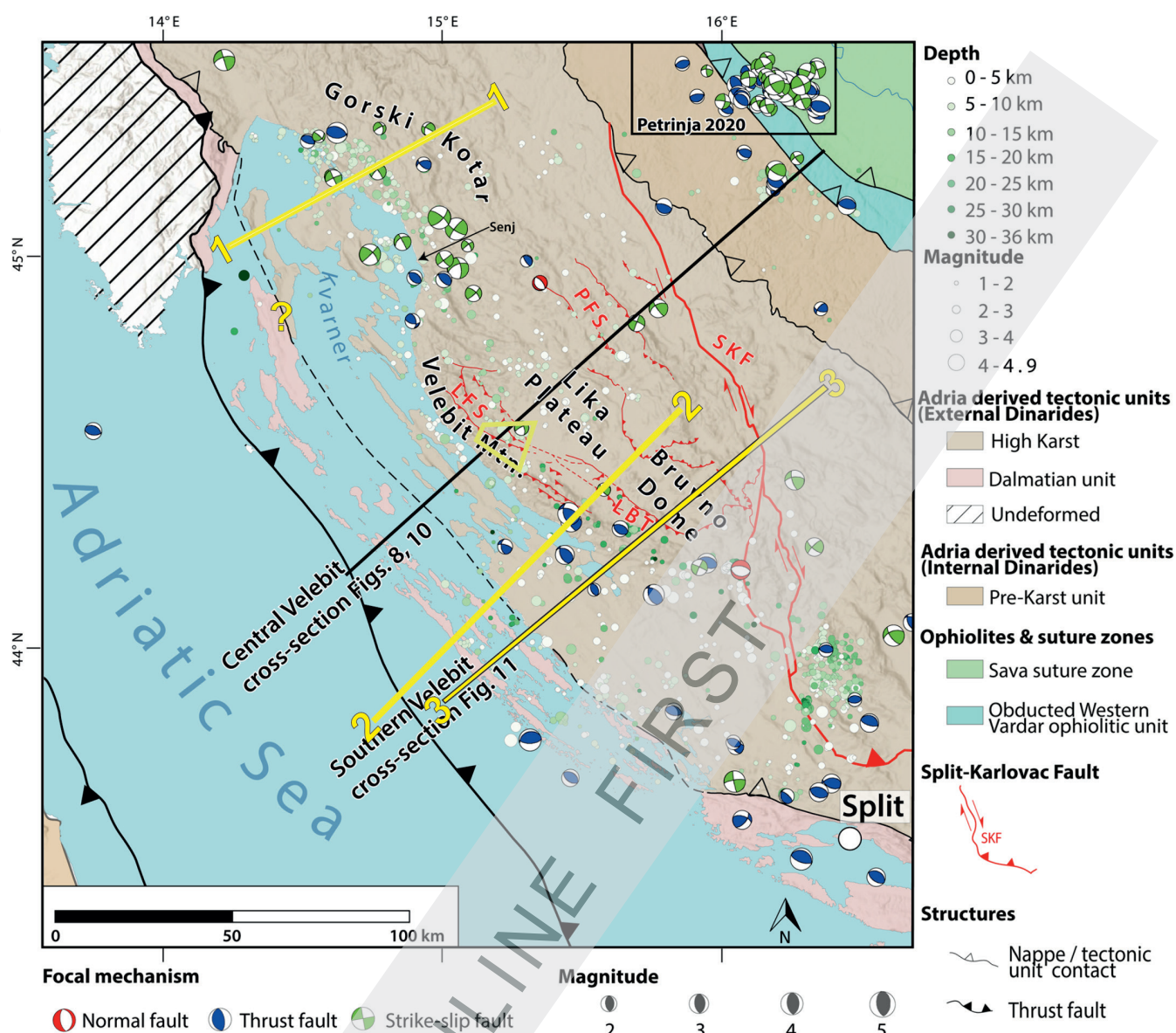


Figure 1. Tectonic map of the area of the central External Dinarides of BALLING et al. (2023), showing the main faults and the earthquakes epicenters with general magnitudes and focal depth as well as Focal Mechanism Solutions (FMS). Additions are in yellow: yellow lines mark the positions of the regional geophysical and geological cross-sections: 1 – ŠUMANOVAC et al. (2016), 2 – KORBAR (2009), both discussed in the text and shown on other figures, and 3 – BALLING et al. (2023) that is reinterpreted on Figure 4 (this paper); yellow polygon marks area shown on Figure 3; yellow question mark indicates the questionable boundary between the two traditional regional tectonic units that is drawn along minor faults by SCHMID et al. (2020), as especially obvious on the island of Cres in Kvarner (compare with map of FUČEK et al., 2015).

The focus is on the papers of BALLING et al. (2021b, 2023) that combine state-of-the-art structural geology tools and modern terminology for reinterpretation of comprehensive published data from the official geological maps, i.e., sheets and explanatory notes of Basic Geological Map (BGM) of former Yugoslavia at the 1:100,000 scale in the region of the central External Dinarides (BGM, 1965–1984), cited also in BALLING et al. (2021b, 2023). However, after a thorough reading of the papers, and cross-checking of the papers and maps cited in the paper, as an author of the previously published model (KORBAR, 2009), I felt I should add new data and the discussion to support that model, and also to point to some weak points of the latest model. Namely, that was already the third paper of Phillip Balling and a group of the co-authors in a series in which they proposed a completely new and the most complex model of the central part of the External Dinarides to

date, but with unverifiable data that are supposed to document the reinterpreted elements.

The model of BALLING et al. (2023) shows a greater complexity of structural architecture than previous interpretations, but it seems that the model is not supported either in the field geological data nor in the seismological data presented in the paper itself. In the following sections the most questionable issues are addressed.

2. DISCUSSION

2.1. Previous models and tectonic subdivision

Although there are several tectonic models for the External Dinarides published during the 20th century (KORBAR, 2009 and references therein), in this paper I will focus only to the most recent, modern models published in scientific journals

during the 21st century, which include also the most important issues of the previous models. One of these is a model of KORBAR (2009) and another one is a model of BALLING et al. (2021b, 2023).

BALLING et al. (2021b, 2023) used an overview tectonic map of SCHMID et al. (2020) rather than an older version that had a better fit to the local data (SCHMID et al., 2008). However, the former became very popular also among the other authors working in the External Dinarides, although the authors of the map did not consider modern data, especially the data published during the last decade on the new lithostratigraphical maps of the Republic of Croatia at the 1:50,000 scale that are much more detailed than the older BGM (1965 – 1984). The BGM is the only map that covers a complete investigated territory and is thus used by BALLING et al. (2021b, 2023), but the published sheets of the new lithostratigraphical map at the 1:50,000 scale should be used where available. For example, the new supra-regional map of SCHMID et al. (2020) proposed a new boundary between the Dalmatian and High Karst tectonic units that is not supported by published new local maps and scientific papers. Namely, in the central part of the island of Cres in the Kvarner area, the boundary is a local fault without such importance (FUČEK et al., 2015; Fig. 1).

Moreover, it is obvious that BALLING et al. (2023) did not give credit to the most important issues of the orogenic evolution of the region that are proposed in the previous models: (i) stratigraphically various detachments on evaporite horizons (Permian – Triassic and Jurassic – Cretaceous transition), (ii) early-orogenic foreland propagating thin-skinned tectonics (confirmed also by BALLING et al., 2023), and (iii) the general geotectonic setting of the Promina basin as a wedge-top (KORBAR, 2009).

Geophysical studies based on teleseismic data (ŠUMANOVAC et al., 2016; KAPURALIĆ et al., 2019), indicate crustal thickening in the area, that is also supported by gravimetry data and deep seismic profiles (PRELOGOVIĆ et al., 1995; TARI KOVAČIĆ & MRINJEK, 1994). This thickening is compatible with activity of crustal scale high angle transpressive faults that could be related to the major crustal NE Adriatic fault and exhumation along the crest of the External Dinarides (KORBAR, 2009; Fig. 2). In the model of BALLING et al. (2021b, 2023), the authors do not consider these previous data and interpretations and resolve the issue proposing an antiformal stack.

Besides, BALLING et al. (2023) introduces a new terminology for distinguishing structural units in this part of the External Dinarides (Lower High Karst and Upper High Karst), although CHOROWICZ (1974, 1975) had already proposed a subdivision into Inner Karst and High Karst. CHOROWICZ's subdivision was harmonized and accepted for the entire area of the External Dinarides in a review of KORBAR (2009), although the author was not fully consistent with the original names of the units, but proposed alternative names that were nevertheless compared with the traditional ones. I would like to highlight here a positive example of an acceptable reinterpretation of a traditional overall tectonic structure in the Northern Calcareous Alps, that is constrained by a comparison of a previous and a new model that illustrate

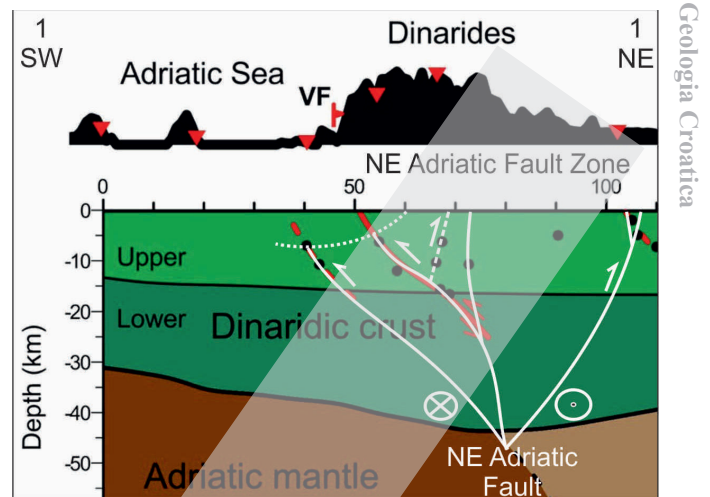


Figure 2. Simplified crustal geological section across the central External Dinarides (crop of fig. 12 of ŠUMANOVAC et al. (2016, coloured, black dots = hypocenters), modified with supposed active crustal transpressional faults along a supposed NE Adriatic Fault Zone (KORBAR, 2009, white lines and general dextral slip, for details see text and Fig. 4 in this paper). VF – Velebit Fault = NE Adriatic fault. Location is indicated on Figure 1.

less shortening for the previously considered large scale thrusting of this well-known fold and thrust belt (FERNANDEZ et al., 2024).

2.2. Reinterpretation of the data from the Basic Geological Maps 1:100,000 – Velebit Fault System and "Lika backthrust"

Some of the main input data for the presented modelling are from the reinterpreted Basic Geological Maps 1:100,000 (BGM) that are cited in BALLING et al. (2023), which in the researched area are in principle very well made based on comprehensive fieldwork and the results of many local studies performed during the 20th century. However, many of the data presented on BGM sheets and accompanying explanatory notes (with references therein) were neglected by BALLING et al. (2023).

Geological boundaries mapped over any distance (if done reliably with continuous outcrop conditions or adequate constraints) have more significant regional value than a local outcrop observation (FERNANDEZ et al., 2009; STEWART, 2020). It is especially true in carbonate rocks of the External Dinarides. There are numerous well-defined but local fault planes visible within open outcrops in carbonate rocks in the forested area (e.g., quarries) that have only a very local significance and disappear within a few metres, thus probably bounding small blocks. Therefore, the interpretation of regional-scale geometry is much better constrained by the relationship between fault traces and relief. For example, there are many local measurements in the Kvarner area of the External Dinarides (KORBAR et al., 2020, supplementary file), that resemble tectonically important fault planes, but do not have a significance for drawing of the main faults on the geological map.

The abovementioned criticism mainly refers to the reinterpretation of the important faults that were originally interpreted as steep normal faults on the BGM (see also CHOROWICZ, 1974; KORBAR, 2009). However, according

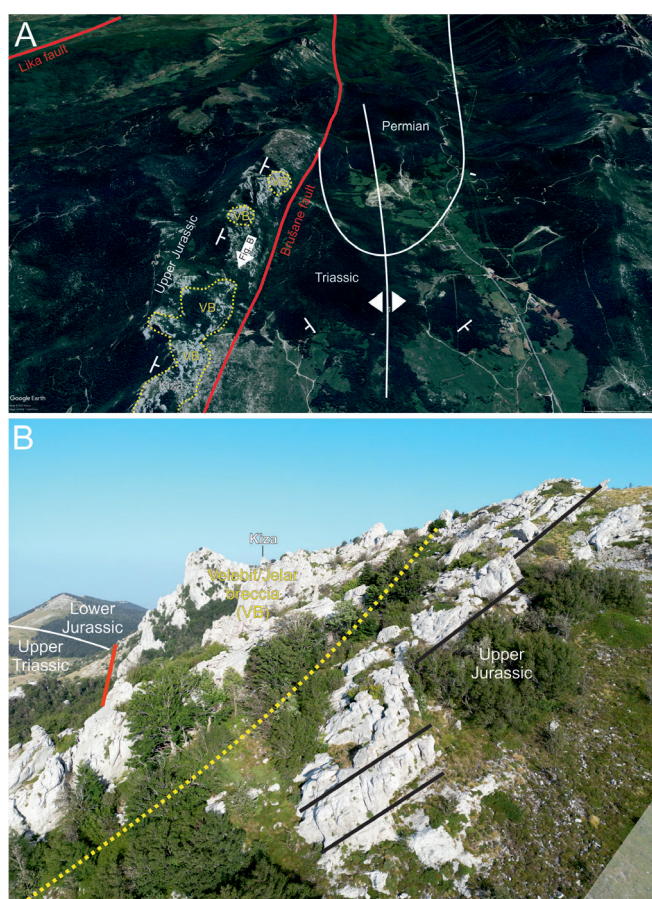


Figure 3. **a** Interpreted aerial panoramic western view to the Brušane anticline area (central Velebit Mt., compare with BGM sheet Gospić (SOKAČ et al., 1974) and fig. 6 of BALLING et al., 2023). Note rectilinear trace (red line) of the Brušane fault, one of the main faults of the VFS that is conjugated to the Lika fault (indicated in the background). Erosional remnants of the Jelar/Velebit breccia (VB) are not in contact with the Brušane fault; **b** Interpreted eastern view on Dabarski kukovi (marked by a white arrow on "a") that are built of massive Cenozoic Jelar/Velebit breccia (VB) resting unconformably(?) on top of well-bedded Upper Jurassic platform carbonates (black lines). Note the steep Brušane fault to the south (red line).

to BALLING et al. (2021b, 2023), the so-called "Lika Fault System" (LFS) is composed of several relatively shallowly dipping passive roof backthrust faults that are thrust top-to-north in the hinterland (so-called the "Lika backthrust"), and even further to north, as far as the Plitvice Fault System (PFS) or the "Plitvice backthrust" (Fig. 1).

For the purpose of forward modelling, BALLING et al. (2023) use several selected field measurements (without the information about locations) to re-interpret the LFS and PFS as gently SW dipping and top-to-north directed backthrusts, but without detailed structural elaborations on the outcrops or new geological maps, although these are shown subvertical on the all sheets of the BGM (produced by various authors). The Velebit Fault System (VFS) seems conjugated to the Lika fault (Brušane fault, Paklenica fault etc.) and could indeed be composed of SW dipping reverse faults (VELIĆ et al., 2014), but the fault planes are certainly very steep, which is revealed also by the rather rectilinear traces on the map, regardless of the relief cut by the faults. The steep fault planes of the VFS are also clearly visible in panoramic view, along the slopes of the central part of Velebit Mt. (SOKAČ et al., 1974; Fig. 3).

Besides, the Lika fault dissects the older Dinaric thrust (nappe) that encompass the Bruvno dome from the north and east (BGM: ŠUŠNJAR et al., 1973; CHOROWICZ, 1974; fig. 4 of KORBAR, 2009). Noteworthy, the Inner Karst nappe encompassing the Bruvno dome from the north and east does not include Palaeozoic clastics that are exposed only in the core of the Bruvno dome and along the Velebit structure – the two thick-skinned units separated by the subvertical Lika fault (ŠUŠNJAR et al., 1973; CHOROWICZ, 1974; KORBAR, 2009). However, BALLING et al. (2023) reinterpreted the Lika fault as a single nappe encompassing the Bruvno dome also from the south, although, even according to the authors, the detachment horizons are different, i.e., the older thrust sheet (northern) was detached at Lower Triassic and was thrust to the south, while the younger thrust sheet (southern) includes also the Palaeozoic strata and was thrust to the north.

The "Plitvice backthrust" or "Plitvice Fault System" (PFS) of BALLING et al. (2023; fig. 1), is also obviously a subvertical fault since its trace appears rectilinear on the regional geological maps (BGM), and thus probably belongs to the Plitvice – Una Spring fault zone along the northern margin of the transpressional system of the NE Adriatic Fault Zone (Fig. 4). The selected measurements that are supposed to elaborate the gently inclined PFS are used as the main input data for the model of BALLING et al. (2023), but the locations of the measurements are not provided (neither are provided in the cited graduate student diploma). Consequently, the entire modelling and final interpretation of BALLING et al. (2023) took place in an unusual direction, which led to an unusual interpretation, or, as the authors themselves stated, contrary to the similar systems modeled so far elsewhere in the world.

2.3. The Bruvno structure

Another questionable structure modelled by BALLING et al. (2021b, 2023) is a complex duplex system of multiple thrust faults forming an antiformal stack of the Bruvno dome, that is interpreted as the latest phase compressional structure responsible for the uplift of Velebit Mt. and its hinterland. The relative timing of the formation of the dome is also proposed by other authors (KORBAR, 2009), however, published data imply that this is a para-autochthonous pop-up structure (ŠUŠNJAR et al., 1973; SOKAČ et al., 1976). The Bruvno duplex shown by BALLING et al. (2021b, 2023) consists of as many as 5 thrust faults within Palaeozoic clastics, stacked one above the other, of which the structurally highest one intersects the Bruvno borehole located in the central part of the dome (for position see fig. 4 of KORBAR, 2009; fig. 2 of BALLING et al. (2023); Fig. 4). The fact is, instead, that there are no reported faults within the more than 3 km deep Bruvno borehole, that was drilled through Carboniferous and probably older clastics. Such an undocumented interpretation certainly strongly contributes to the unnecessary complexity of the resulting model, which can be performed in a much simpler way.

For example, KORBAR (2009) also considered the large-scale thrusting in the first phase of the orogenesis as BALLING et al. (2021b, 2023) that affected only thin-skinned Cretaceous and younger units within the High Karst unit (Lower High Karst of BALLING et al., 2023), and Triassic and younger units within the Inner Karst unit (Upper High Karst of BALLING

et al., 2023). However, the Palaeozoic (Carboniferous and Permian) units were probably deformed later, during the late-orogenic thick-skinned tectonics, responsible for the uplift of the Velebit Mt. core and the Bruvno dome (KORBAR, 2009).

2.4. Split – Karlovac Fault

The regional transverse Split – Karlovac fault (SKF) was proposed by CHOROWICZ (1977), but there were no later papers published with the details that would characterize its character, geometry, and more detail descriptions on the most important localities. BALLING et al. (2021b) regarded the fault as a dextral strike-slip fault without field measurements and/or new geological maps and combined state-of-the-art structural geology tools to re-interpret the role of that still controversial regional tectonic feature in the tectonic evolution of the region (Fig. 1).

Besides, BALLING et al. (2021b) offer evidence for the supposed Cretaceous deposits in the footwall of Plavno tectonic window by using a single photomicrograph that is determined as Cretaceous foraminifera that should be the final proof of the window that is also shown on the BGM. However, the single equatorial transection of the foraminifera is an unreliable biostratigraphic element, i.e., it could be determined as the Lower Triassic index fossil *Meandrosira dinarica* that is a common microfossil in the area (KOCHANOSKY-DEVIDÉ & PANTIĆ, 1965). Moreover, my own observations (including Mirko BELAK *pers. comm.*, 2006), suggest that the supposed Cretaceous deposits in the Plavno tectonic window lithologically resemble Lower Triassic deposits, implying that the Plavno need not be a tectonic window at all.

BALLING et al. (2021b) claim that the thrusts are south directed east of the SKF, while west of it there are mostly north directed backthrusts at the surface. However, according to the BGM sheets (see also HERAK & BAHUN, 1979), there are SW directed thrusts west of the SKF (Stražbenica, Čemernica, etc., ŠUŠNJAR et al., 1973; CHOROWICZ, 1974, fig. 5 of KORBAR, 2009). Large thrusts that include Permian clastics can be found in Gorski kotar (HERAK et al., 1961). Further to the west, in southern Slovenia and northern Istria, there are also obvious frontal nappes of the External Dinarides (KORBAR, 2009 and references therein; PLACER et al., 2010). Noteworthy, the north directed low-angle and long-traveling backthrust in the External Dinarides are recognized so far only by BALLING et al. (2021b, 2023).

2.5. Velebit/Lika/Jelar breccia

The massive Cenozoic (Oligocene?) carbonate breccia that outcrops along the SW and NE slopes of Velebit Mt. and the Lika area is traditionally referred to as the Jelar deposits/formation/breccia (BAHUN, 1962, 1963, 1974; HERAK & BAHUN, 1979; KORBAR, 2009 and references therein). In the work of BALLING et al. (2023) it is stated, without any evidence, that the "Velebit breccia" and "Lika breccia", are two different formations that crop out on the SW and NE slopes of Velebit Mt., respectively. However, even the data mentioned sporadically in the paper of BALLING et al. (2023) indicates that such a distinction is not acceptable. It is clear from the geological maps (see overview map of the synonymous Velebit breccia of VLAHOVIĆ et al., 2012) that the breccia belt

periclinally and almost continuously encompasses Velebit Mt. and appears in places separately in the Lika area (Velebit hinterland). Besides, the breccia has a similar tectonostratigraphic position since it rests unconformably on top of the Upper Jurassic carbonates on the SW (Fig. 3) as well as on the NE slopes, and has a similar composition in both these areas (VLAHOVIĆ et al., 2012), implying that they are probably of the same genesis (see KORBAR, 2009). In the case that the Velebit breccia would be related to the VFS faults (fig. 6 of BALLING et al., 2023), the clasts in the breccia would also be from the Permian and Triassic rocks outcropping along the fault contact with the outcrops of Upper Jurassic, but that is not the case (VLAHOVIĆ et al., 2012). Instead, the breccia belt is dissected by the VFZ faults that are thus younger than the breccia, and the erosional remnants of the breccia are not consistently in contact with the Brušane fault (SOKAČ et al., 1974; Fig. 3).

However, there are differences in the composition of this type of breccia outcropping around Velebit Mt. (typical Jelar/Velebit breccia), and those outcropping in the eastern Lika area (upper stream of Una River, BAHUN, 1985). Thus, the composition of the widespread Cenozoic breccia in the central part of the External Dinarides depends on the thickness of the thin-skinned stratigraphic succession in the highly deformed hanging walls of the thin-skinned nappes formed in the first phase of the orogeny (KORBAR, 2009). Namely, the lithoclasts probably collapsed during the secondary phase of the orogenesis, i.e., thick-skinned uplift of the whole sedimentary succession (including the Palaeozoic), resulting in extension within the previously thin-skinned upper parts of the succession due to the supposed gravitational reactivation of the early-orogenic compressional detachments (KORBAR, 2009). If so, the extension resulted in the local deposition of large masses of collapse breccia that include older stratigraphical members in eastern Lika (Inner Karst = Upper High Karst of BALLING et al., 2023) than in the Velebit Mt. area (High Karst = Lower High Karst of BALLING et al., 2023). In the Velebit area (including Lika polje), typical Jelar/Velebit breccia clasts originate from all stratigraphic members from the Lower Cretaceous to Dinaric flysch, since the detachment was within the Jurassic – Cretaceous transition. In the eastern Lika area (Una Spring area), where the detachment was within Permian evaporites, the breccias are characterized by the older stratigraphic members in the clasts, e.g., Lower Triassic clastics and younger carbonates. Thus, in the eastern Lika the breccia could indeed be re-named, e.g., Lika or Una Breccia, since the composition differs from the typical Jelar/Velebit breccia on Velebit Mt, although the main mechanism of the origin of both is probably the same (KORBAR, 2009 and references therein). Nevertheless, all the Cenozoic tectonic breccia mentioned above could be broadly and traditionally recognized as the Jelar Group.

2.6. Relative timing of deformations within the "foreland" and the main crest of the External Dinarides

According to BALLING et al. (2021b, 2023) there are three main phases of the orogenic deformation along the main crest of the External Dinarides: early-orogenic south directed thin-

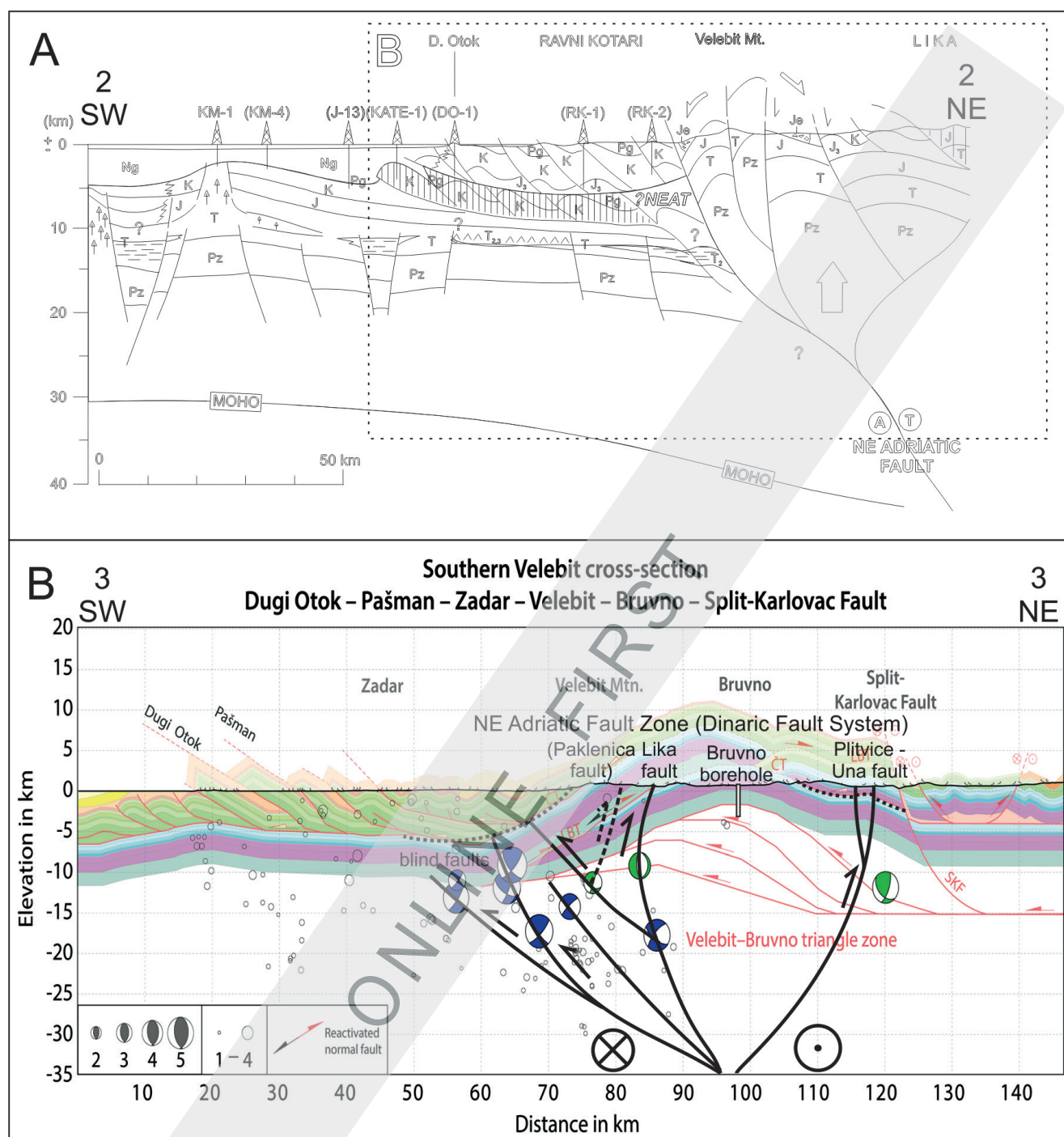


Figure 4. Geological sections across the central part of the External Dinarides of **a** KORBAR (2009, fig. 5) with an indication of the frame of "b", broken frame), and **b** BALLING et al. (2023, fig. 11), coloured in the background, and the crustal transpressional faults (thick black lines, modified after KORBAR, 2009). Locations are indicated on Figure 1.

skinned thrusting (the same was proposed by KORBAR (2009), the newly proposed north-directed thin-skinned backthrust during an intermediate phase, and the latest again south directed "thick-skinned" antiformal nappe stack within the Palaeozoic basement along a "triangle zone". The latest nappe stack is supposed by BALLING et al. (2023) to cause the uplift of the thin-skinned Palaeozoic and Mesozoic successions along Velebit Mt. and the exhumation of the Bruvno dome. The latest (exhumation) phase was also suggested by KORBAR (2009), who proposed late-orogenic uplift accommodated by relatively steep transpressional faults,

that are also responsible for the recent seismicity (see next section).

Although the frontal thrust of the External Dinarides is situated in the Adriatic Sea, SW of the outer Dalmatian islands (Fig. 1), BALLING et al. (2021b, 2023) consider the islands as a foreland of the Velebit structure. However, even according to their model, Velebit was uplifted in the latest phase within the triangle zone. It should be emphasized that, according to the latest previous model (KORBAR, 2009), the thin-skinned structures of the northern Dalmatian islands were also formed before the uplift of Velebit Mt., the complex thick-skinned

structure along the main crest of the External Dinarides. That is why the northern Dalmatian islands also belong to the External Dinarides, rather than to its recent foreland, as proposed by BALLING et al. (2021b, 2023).

2.7. Discrepancy between the latest model and the seismological data

The most challenging issue in the model presented by BALLING et al. (2023) is the discrepancy in the position of the earthquake hypocenters, and especially their focal mechanism solutions (FMS), with the interpreted faults that are active in the underground of southern Velebit (fig. 11 of BALLING et al., 2023; Fig. 4). Even in a tentative comparison it is clear that the main faults in the previous models overlap better with the hypocenters and the Fault Mechanism Solutions (FMS) than in the new model of BALLING et al. (2023). This is particularly illustrated by one of the strongest recent earthquakes (01/11/2020, M_L 4.6), with computed FMS showing clearly a relatively steep reverse slip. Besides, there was an even stronger recent earthquake (M_L 4.8 on 11th of February 2025) in the same area with the FMS showing a clear subvertical strike-slip along generally E – W or N – S trending faults deeper in the crust (PMF, 2025). This newly registered strike-slip mechanism in combination with the former predominantly oblique slip and reverse dip-slip solutions (HERAK, 2025), further points to the presumed transpressional active tectonic regime in the wider Velebit area (KORBAR, 2009).

Comparison of the spatial position of the hypocenters with the interpreted active faults and its FMS (HERAK, 2025) is the main test of any seismotectonic model. Therefore, due to the apparent inconsistency of these two elements, the model of BALLING et al. (2023) is not reliable, and the FMS has a better fit to the deeper and steeper crustal transpressional faults of KORBAR (2009) than to the shallow thrusts of the so-called Velebit – Bruvno triangle zone proposed by BALLING et al. (2023). Namely, it seems that major crustal thick-skinned steep reverse (transpressional) faults, striking NW – SE along the main crest of the External Dinarides, fit well with the modern hypocenters and FMS (Fig. 4). Thus, active faulting is probably related to the still active late-orogenic transpression that is responsible for the exhumation and uplift of the main crest of the External Dinarides, rather than multiple low-angle thrusting within the Palaeozoic basement. A similar mechanism is proposed in the NW Zagros (MOUTHEREAU et al., 2012), but a more detailed comparison is beyond the scope of this paper but should be performed in future analyses.

2.8. Updated tectonic model

Possibly still active and deeply penetrating transpressional faults striking along the Velebit Mt. were originally proposed by KORBAR (2009) and are reinterpreted in this paper according to the new idea of blind active faulting in the SW front of the NE Adriatic Fault Zone, since they probably do not dissect the thin-skinned early-orogenic cover (Fig. 4). The hypocentral depths between 8 and more than 20 km, as well as its distribution, support the interpretation. The focal mechanisms (FMS) imply that the faults are mostly relatively steep, reverse, oblique and strike-slip, thus they probably

accommodated transpression within the upper crust. However, there must be lower crustal or even a deeper driver of the upper crustal dynamics mentioned above, and that is why the NE Adriatic Fault, separating the Dinaric and Adriatic segments of the Adria, is proposed (KORBAR, 2009).

The active faults are probably blind SW of Velebit Mt. since they are not shown on the geological maps. Thus, the thin-skinned cover probably gravitationally glided down (stripped) along the former low-angle compressional detachments during the late-orogenic uplift of Velebit Mt. In the first phase of the uplift, the gravitational extension on the flanks of the uplifting Velebit structure (thick arrows on Fig. 4a) could result in the gravitational collapses within the thin-skinned cover and therefore deposition of the late-orogenic Jelar/Velebit breccia (KORBAR, 2009) that encompasses the Velebit Mt. central ridge (VLAHOVIĆ et al., 2012). However, some branches of the late-orogenic and possibly still active transpressional faults dissect the breccia belt (SOKAČ et al., 1974; Fig. 3), while the thin-skinned orogenic cover is completely eroded along the central crest of the mountain, along with its exhumed tectonic basement (Fig. 4b).

There are mapped active dextral strike-slip seismogenic faults in the NW part of the External Dinarides, striking generally NW – SE, that are referred to the Dinaric Fault System (MOULIN et al., 2016). The active faults are characterized by subvertical fault planes along a crustal fault zone (VIČIĆ et al., 2019) that obviously dissect the thin-skinned cover and continue further to the SE in the Kvarner area (KORBAR et al., 2020). The fault zone could be equivalent to the NE Adriatic Fault Zone of KORBAR (2009), that also strikes along the Velebit Mt. and its wider hinterland (Fig. 4). It is still not clear why the seismicity is weak along the Velebit Mt. (HERAK, 2025). However, some of the active faults within such a wide zone may be currently locked (VIČIĆ et al., 2019).

Interestingly, the NE Adriatic Fault Zone resembles the active and slowly-deforming wide shear zone of eastern California (GARVUE et al., 2024). If so, Velebit Mt. and other positive flower structures along the zone could be formed along the complex system of the active strike-slip faults and several restraining bends. The restraining bends could be formed at the crossing points of the main pre-orogenic crustal faults that were not all reactivated in the first compressional phase of the Dinaric orogenesis, but probably completely covered by the thin-skinned early-orogenic highly deformed topmost sedimentary successions (KORBAR, 2009; BALLING et al., 2021b, 2023).

The subvertical active dextral strike-slip faults are well documented in the NW part of the External Dinarides and could also have a continuation along Velebit Mt. and its wider hinterland. However, such faults are not mapped on the surface, but some of the active faults could be blind, since they do not dissect everywhere the thin-skinned tectonic cover. Moreover, recent seismicity, in combination with the former predominantly reverse oblique-slip mechanisms, also imply an overall transpressional active tectonic regime in the central External Dinarides, but further targeted multidisciplinary research should be performed.

CONCLUSION

BALLING et al. (2021b, 2023) deal with the orogenic evolution of the central part of the External Dinarides, offering a complex new model and the tectonic structure of the area that combine state-of-the-art structural geology tools and modern terminology. However, the new model is constrained neither by comprehensive data from the official geological maps in the region, nor with the new data and necessary local structural geology studies that could contribute to the elucidation of the still not completely understood tectonic evolution in the region.

BALLING et al. (2023) introduces a new terminology for distinguishing structural units in this part of the External Dinarides, although previous authors already proposed almost the same subdivision that was harmonized and proposed previously for the entire area of the External Dinarides (KORBAR, 2009 and references therein).

The so-called Lika fault and the other faults of the Velebit Fault System (VFS) were originally interpreted as subvertical normal faults (ŠUŠNJAR et al., 1973; SOKAČ et al., 1974) but are re-interpreted by BALLING et al. (2023) as low angle backthrusts, although the faults have rather long rectilinear routes, regardless of the relief cut by the faults. Besides, the Lika fault dissects the older Dinaric low-angle thrusts (nappes) that encompass the Bruvno dome from the north and east (CHOROWICZ, 1974; KORBAR, 2009).

BALLING et al. (2023) reinterpret and divide an important tectonostratigraphic unit in Velebit Mt. and Lika polje, i.e., the Jelar/Velebit breccia. However, the breccia has a similar stratigraphy and composition, regardless of the location on the northern or southern slopes of the huge but dissected Velebit anticline, and therefore it likely has the same genesis. KORBAR (2009) proposes that the late-orogenic uplift (exhumation) resulted by gravitational reactivation of the thin-skinned detachment (stripping), related collapses within the thin-skinned cover, and the deposition of the late-orogenic breccia above the detachment.

The Bruvno dome is interpreted by BALLING et al. (2023) as the latest phase compressional structure of the supposed Velebit – Bruvno triangle zone that consists of as many as five low-angle thrust faults within the Palaeozoic basement of the earlier thin-skinned cover, although there are no thrusts reported from the more than 3 km deep Bruvno well. Thus, the Palaeozoic (Carboniferous and Permian) units were rather deformed along steeply dipping and deeply penetrating crustal faults reactivated during the late-orogenic thick-skinned tectonics, responsible for the uplift of the Velebit Mt. core and the Bruvno dome.

The most problematic issue in the model presented by BALLING et al. (2023) is the discrepancy in the spatial position of the earthquake hypocenters, and especially their focal mechanism solutions (FMS), with the interpreted low-angle faults. An updated older model (KORBAR, 2009) offers steeper faults that fit better with the hypocenters and FMS. However, the supposedly still active crustal transpressional faults along the main crest of the External Dinarides probably did not dissect the early-orogenic thin-skinned cover along the SW foothills of the huge Velebit anticline, and thus are probably mostly blind and active below the thin-skinned cover that was “stripped” from the main ridge of Velebit Mt.

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