Swiss J Geosci (2017) 110:833–850
DOI 10.1007/s00015-017-0280-5

Jurassic stratigraphy of the Belluno Basin and Friuli Platform: a perspective on far-field compression in the Adria passive margin

Vincenzo Picotti[1] · **Miriam Cobianchi**[2]

Received: 9 May 2017 / Accepted: 20 July 2017 / Published online: 21 August 2017

Abstract Anomalous patterns of the sedimentary architecture have been recognized in passive margins, and only recently they have been associated with plate reorganization or compressional deformations propagating from distant margins. With the aim of discussing the sedimentary architecture and the potential tectonic perturbations to the passive margin pattern, we present the revision of the stratigraphy of a fossil passive margin, involved in the retrobelt of the Alpine orogeny. The main events at the transition from rifted to passive margin have been controlled by palaeoceanography, i.e. the trophic state of surface waters that hampered the carbonate photozoan productivity for a long period between Toarcian and Callovian. Toward the latest Bajocian–earliest Bathonian, the platform productivity increased, dominated by ooids. A regressional trend up to the Middle Bathonian allowed the rapid infilling of the previous rift basin. The successive aggradation in the platform was still dominated by non-skeletal grains until the Early Oxfordian. The Middle Oxfordian to Early Kimmeridgian was a time of recovery of the palaeoceanographic conditions allowing the establishment of a hydrozoan/coral rich platform. The sedimentation rates in the platform increased at the margin of the productive Friuli–Adriatic Platform. From Late Kimmeridgian on, the sedimentation rates at the platform margin returned to the pre-Oxfordian values. At the scale of the whole Adriatic Platform, the Middle Oxfordian to Early Kimmeridgian interval is variable in thickness from 0 to 800 m, and it depicts a couple of folds of around 80–100 km of wavelength. The subsidence analysis of wells and composite logs from literature suggests this interval as a perturbation to the passive margin trend of around 3 Myr of duration. We interpret this folding event, superimposed to the passive margin subsidence, as the far field expression of the transition from intraoceanic to continental obduction, occurred at the eastern Adria active margin.

Keywords Belluno basin and Friuli–adriatic carbonate platform · Stratigraphy · Palaeoceanographic control · Jurassic Adria passive margin · Vardar obduction far-field stress transmittal

1 Introduction

The classic models of passive margin evolution depict a stratigraphy progressively less influenced by the previous rift structures and dominated by thermal subsidence, with the pull of the adjacent cooling oceanic lithosphere. Therefore, the resulting subsidence pattern is simple, thickening toward the continent to ocean transition (COT, e.g. Manatschal and Nievergelt 1997) and thinning toward a hinge located near the coastline and mostly influenced by sea-level oscillations (e.g. Pitman 1978).

A first criticism to this approach was presented by Cloetingh (1988), who provides thermomechanical models to suggest the same stratigraphic architecture could derive from intraplate stresses, folding the lithosphere with large to very large wavelength. This concept has been later explored

---

Editorial handling: W. Winkler.

✉ Vincenzo Picotti
vpicotti@erdw.ethz.ch

[1] Earth Sciences Department, ETH Zürich, Sonneggstrasse 5, 8092 Zurich, Switzerland

[2] Dipartimento di Scienze della Terra e dell'Ambiente, Università degli Studi di Pavia, Via Ferrata 1, 27100 Pavia, Italy

and demonstrated both in the continental and oceanic lithospheres (e.g. Stephenson and Cloetingh 1991; Beekman et al. 1996) and finally proposed as a viable tectonic model (Cloething et al. 1999). Since then, crustal to lithospheric buckling has been documented in various settings, mostly with the help of regional seismic profiles, close to subduction zones and overprinting flexural basins (e.g. Bertotti et al. 2001) or in continents and associated passive margins (e.g. India, Müller et al. 2015). A Special Publication of the Geological Society of London (Johnson et al. 2008) highlighted the importance of compressional reactivation of passive margins. Numerical and analogue models have been provided by Cloetingh et al. (2008) to describe folded and faulted rift basins and passive margins, including the Paris Basin and the Black Sea, as well as the Pannonian Basin. They concluded that basin inversion and lithospheric folding control the post rift subsidence in many examples and they are expression of intraplate deformation. On the other hand, Doré et al. (2008) reviewed several mechanisms for the observed North Sea inversion, and concluded that the far-field compressional stresses from the coeval orogens, although attractive for explaining the episodicity of the compressional structures, are difficult to explain, for the unclear spatial and temporal relationships with the orogens and the difficult stress transmission pathways. Hillis (2008), instead, clearly documented the Neogene to Recent compressional strain on the Australian passive margins, and they related it to the plate boundary forces. More recently, Cloething and Burov (2011) reviewed the role of lithospheric folding on the evolution of sedimentary basin. These authors defined basins associated with this buckling process as peculiar for their relatively short temporal scales involved (few Ma) and for their spatial scales spanning tens to hundreds of km, depending on the rheology of the lithosphere and its thermo-mechanical age. These features are evidenced in the subsidence pattern, with acceleration of subsidence in the depocenters and uplift and erosion from flanking highs.

Notwithstanding the recent literature, a description of the effects of propagating compressional stresses in ancient passive margins, later deformed into an orogen, is missing, mostly because of the difficulty in reconstructing the sediment architecture at a basin scale.

In this paper, we intend to bridge this gap, starting from the detailed nannofossil stratigraphy of the Belluno Basin (Cobianchi 2002) to obtain a larger picture of the Jurassic stratigraphic architecture of the rifted to passive Adriatic margin. We propose a revision of the stratigraphy of the Belluno Basin (Fig. 1) to calibrate the major tectono-sedimentary evolutionary steps and widen the view to the whole Friuli–Adriatic Carbonate Platform. This put the basis to stratigraphically calibrate possible scenarios for the tectonic interpretation of the sedimentary successions.

In particular, we provide (i) a detailed revision of the stratigraphy of the Belluno Basin and the Friuli–Adriatic Platform (Fig. 1), a rift structure in the Eastern Southern Alps of Italy that formed and deepened throughout the Jurassic in the western part of the Tethyan ocean. (ii) We present and discuss the dynamics of the platform thanks to detailed biostratigraphy of the basin and slope. Once the stratigraphic architecture at the transition from rifting to passive margin is well established, and (iii) taking into account the adjacent Friuli–Adriatic Platform, we discuss the factors controlling the Jurassic stratigraphic architecture of the Adria margin prior to the Cretaceous to Tertiary subduction and collision.

For this long-lived shallow water platform, Vlahovič et al. (2005) reviewed the Mesozoic evolution. They were the first to relate the Late Jurassic facies differentiations to a compressional environment without further details, since it was not the main focus of their paper.

2 Materials and methods

Although the biostratigraphy of the measured sections has been long available (Cobianchi 2002), a discussion of its consequences for the stratigraphic correlations and its sedimentological implications is still missing. This paper takes also into account and critically discusses all the available stratigraphic data in the literature, thus providing an updated review of the area. Starting from the new correlations, we first present platform to basin stratigraphic evolution, describing the variations in sedimentary environments and the lateral/vertical transitions. In some cases, we could propose also palaeobathymetric estimates for the Belluno Basin. Since we document the near filling of the Basin at the beginning of Bathonian, we consider the thickness differences between the post Bathonian successions, thinner in the basin and thicker at platform, as indication of rough estimates of palaeobathymetry. These are considered minimum values, since they do not take into account the residual bathymetry of the top Bathonian in the basin and the possible compaction of basinal sediments, but are anyway provided just for a better defining of the sedimentary evolution of the basin.

To discuss the tectono-stratigraphy of the Adria rifted to passive margin between the Belluno Basin and the Friuli–Adriatic Platform, we present some subsidence curves from the platform. We choose this carbonate platform for several reasons. First, in this environment always near sea-level, there is no need of palaeobathymetric correction, usually associated with large uncertainties. Second, carbonate platforms undergo early diagenesis, therefore the burial compaction is minimal and associated to pressure solution, not much effective in the study area, since the low post-

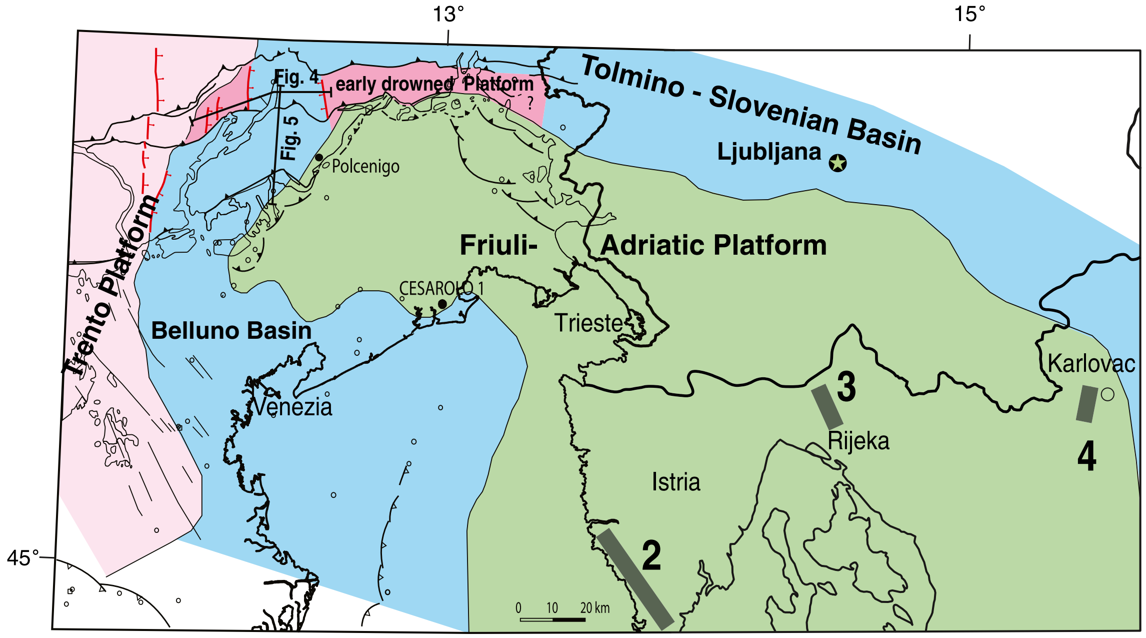

Fig. 1 Jurassic palaeogeographic domains projected over the present day geography. The original spaces are shortened in the north by Alpine and in the east by Dinaride structures. The *red faults* are Jurassic rift structures recognized in the field. The studied stratigraphic sections are aligned along the two perpendicular tracks and are spatially represented in Figs. 4 and Fig. 5, respectively. The four sites chosen for the subsidence analysis of Fig. 6 are Cesarolo 1 well, and the composite sections Istria *2*, Gorsky Kotar *3* and Karlovac *4*. Open dots are HC exploration wells, locally used for reconstructing the geological features in the subsurface

Jurassic burial. Finally, the Friuli–Adriatic platform is one of the widest palaeogeographic domain in the Adria plate, and it allows us to cover around 200 km of the original Jurassic spaces in west to east direction.

The subsidence curves are derived from stratigraphic logs of the Friuli–Adriatic Platforms presented in the regional synthesis by Vlahovič et al. (2005). The stratigraphy presented by the quoted authors is the synthetic representation of a wide area, shown in our Fig. 1 with a grey stretch, therefore providing a regional meaning to our subsidence curves. Particular attention was devoted to reconstruct the eroded stratigraphic interval in the two sections, where an important erosional unconformity was remarked by the occurrence of a bauxitic interval. For the assessment of the missing interval, we adopted a minimum value, averaging measured erosion rate in tropical carbonates, with dissolution of 100 m/Ma (see Viles and Trudgill 1984). The westernmost subsidence curve has been constructed after the Cesarolo 1 well, described by Cati et al. (1987) and slightly reinterpreted in the present paper.

3 Geological setting

The Jurassic successions studied are located in the eastern part of the Southern Alps of Italy, an Adria-vergent fold-and thrust belt derived from the retrowedge collision and inversion of the Adria Tethyan passive margin. This latter rifted off Pangea from the Triassic to the Early Jurassic. Actually, the Adria margins recorded two rifting events: the first, Permian to Middle Triassic, was associated to a Tethyan ocean opening to the east of Adria (Meliata, and then Vardar, e.g. Channell and Kozur 1997). The second formed the rifted to passive margin under study and was associated to the opening of a Tethyan branch to the west of Adria (Piedmont-Ligurian or Alpine-Tethys, see Bertotti et al. 1993). The wide Norian peritidal platform of the Dolomia Principale/Hauptdolomit (Bernoulli and Jenkyns 1974; Winterer and Bosellini 1981) was dissected by several north-south faults that separated areas with different subsidence rates, resulting in a horst and graben submarine topography. From west to east four different domains bounded by rift faults were formed (e.g. Auboin 1963; Bernoulli and Jenkyns 1974): the more subsident Lombardian Basin, the Trento Platform, a carbonate swell evolving during the Middle Jurassic into a pelagic plateau, the narrow pelagic Belluno Basin and the Friuli Platform. This latter (Fig. 1), characterised by shallow water sedimentation throughout the Jurassic and most of the Cretaceous, represents the northwestern part of the larger Adriatic carbonate platform of Vlahovič et al. (2005). Several studies have demonstrated that this sector of the Alps maintained the original pre-Alpine geographic order of the domains and the platform-basin juxtaposition across faults during the subsequent fold and thrust belt evolution (e.g. Picotti et al. 1995; Schumacher et al. 1997, see Fig. 1). The same physiographic-structural elements occurring in the Southern Alps have been also recognized in the subsurface of the Venetian-Friulian plain (Cati et al. 1987; Masetti et al. 2012).

Different successions developed in each structural domain, in particular this study deals with the stratigraphy of the Belluno Basin during the Middle–Late Jurassic. However, in order to better describe the evolution and interaction of the Belluno Basin with the Trento Plateau to west and the Friuli–Adriatic Platform to east, also data coming from these domains will be included.

The Belluno Basin is a fault-bounded rift basin that formed during the Late Triassic and Early Jurassic as part of the Adria rifted margin (Bernoulli and Jenkyns 1974; Winterer and Bosellini 1981). The basin is narrow, 20–50 km wide (Fig. 1) and less subsident than the coeval basin to the west (Lombardian Basin, see Bertotti et al. 1993). The Belluno Basin has been described by Bosellini et al. (1981) as an equivalent of the "Tongue of the Ocean", the deep trench dissecting the Bahama banks. This is true only until the Bajocian (Middle Jurassic) when the Trento Platform drowned becoming a submerged plateau and the only productive carbonate platform was the Friuli to the east. This latter was established in the Early Jurassic on the less subsiding blocks, east of the Belluno Basin.

4 Middle to Upper Jurassic stratigraphy of the Belluno Basin and adjacent platforms

The sections shown in Figs. 2 and 3 (and located along the transects in Fig. 1) are studied in detail for their stratigraphic features. Age calibration is based on the analyses of the calcareous nannofossil content from 279 samples performed by Cobianchi (2002), to which we refer for the detailed description of the nannofossil biostratigraphy. The bio-chronostratigraphic schemes proposed respectively by Mattioli and Erba (1999), Chiari et al. (2007) and Casellato (2010) are used in this paper to improve the age calibration of the sections.

The studied succession of the Belluno Basin starts with the Igne Fm, which overlies the Lower Jurassic Soverzene Fm and is abruptly overlain by the Vajont Oolitic Limestone (Vajont Lms). It consists of thin-bedded couplets of pelagic marl and limestone. Limestones, upwards replaced by dolomitic limestones to dolostones, are peloidal wackepackstone with sponge spicules, pelagic bivalves, ostracods, echinoid fragments, lagenids, ammonoid protoconchs. In the upper portion of the unit the visible chert sharply increases for the increasing of the radiolarian abundance, locally ranging from 20 to 40%.

An abundant fauna of ammonites and *Aulacoceras*, described by Boyer (1913) and Ferasin (1956), assigned the unit to the Toarcian–Aalenian interval. Subsequently, based on new ammonite finding, Casati and Tomai (1969) ascribed the top of the Igne Fm to the Early Bajocian.

Based on the abundant and well-preserved calcareous nannofossils, Cobianchi (2002) assigned the Igne Fm to the interval from the Early Toarcian (first occurrence of *Carinolithus superbus*) to the Bajocian. However, in the measured sections, the top of the unit displays different ages as a consequence of the erosional nature of the boundary with the overlying Vajont Lms. The youngest age was documented in the Vajont Gorge section (Fig. 2); here the topmost of the Igne Fm is barren in calcareous nannofossils, owing to the strong late diagenetic dolomitization. However, the youngest bioevents, recorded at 13.6 m below the top, is the first occurrence of *Watznaueria manivitae,* which documents the late Early Bajocian age (Fig. 2, Mattioli and Erba 1999). The non-decompacted sedimentation rates reconstructed in this section for the Toarcian and Aalenian interval of the Igne Fm are respectively 3.4 and 2.7 m/Myr. If we apply an average sedimentation rate of 3 m/Myr, the 13.6 m above the FO of *W. manivitae* can represent the entire Bajocian, only 2 Myr long (Cohen et al. 2013), or even the base of the Bathonian. Therefore, notwithstanding the downcutting erosion of the basal Vajont Lms makes it difficult to date the top Igne, a Late Bajocian age for the top of the Igne Fm is very likely. Finally, the unconformity at the base of the Vajont Lms is documented not only by its erosional geometry but also by the features of the clasts (endolithic boring documenting hard-ground bioerosion) ripped off from the topmost unconformable surface of the Igne Fm into the basal Vajont Lms.

The Vajont Lms, observed in all the studied section, is spanning from few to 400 m of thickness and it consists of poorly bedded to massive oolitic lime grainstones and lime packstones with frequent oncoids, peloids, lumps, micritic intraclasts and skeletal grains. Bosellini et al. (1981) interpreted the Vajont Lms as a turbiditic deposit, locally interbedded with hemipelagic mudstone, which filled progressively the Belluno Basin. In our stratigraphy, we limit the Vajont Lms to the body embedded within the Igne Fm and the first hemipelagic mudstone that is correlated with the overlying Fonzaso Fm. Therefore, we see no pelagic interbeds in the Vajont Lms, and we rather interpret it as an apron transported downslope mainly by hyperconcentrated currents (grain flows), poorly bedded because of the frequent amalgamation surfaces. In the Ponte Serra section (Fig. 2), 2 m of peloidal wackestone, representing the distal facies of the Vajont body, stratigraphically cover a red condensed and nodular ammonite rich unit of Late Bajocian–Early Bathonian age formed over the former

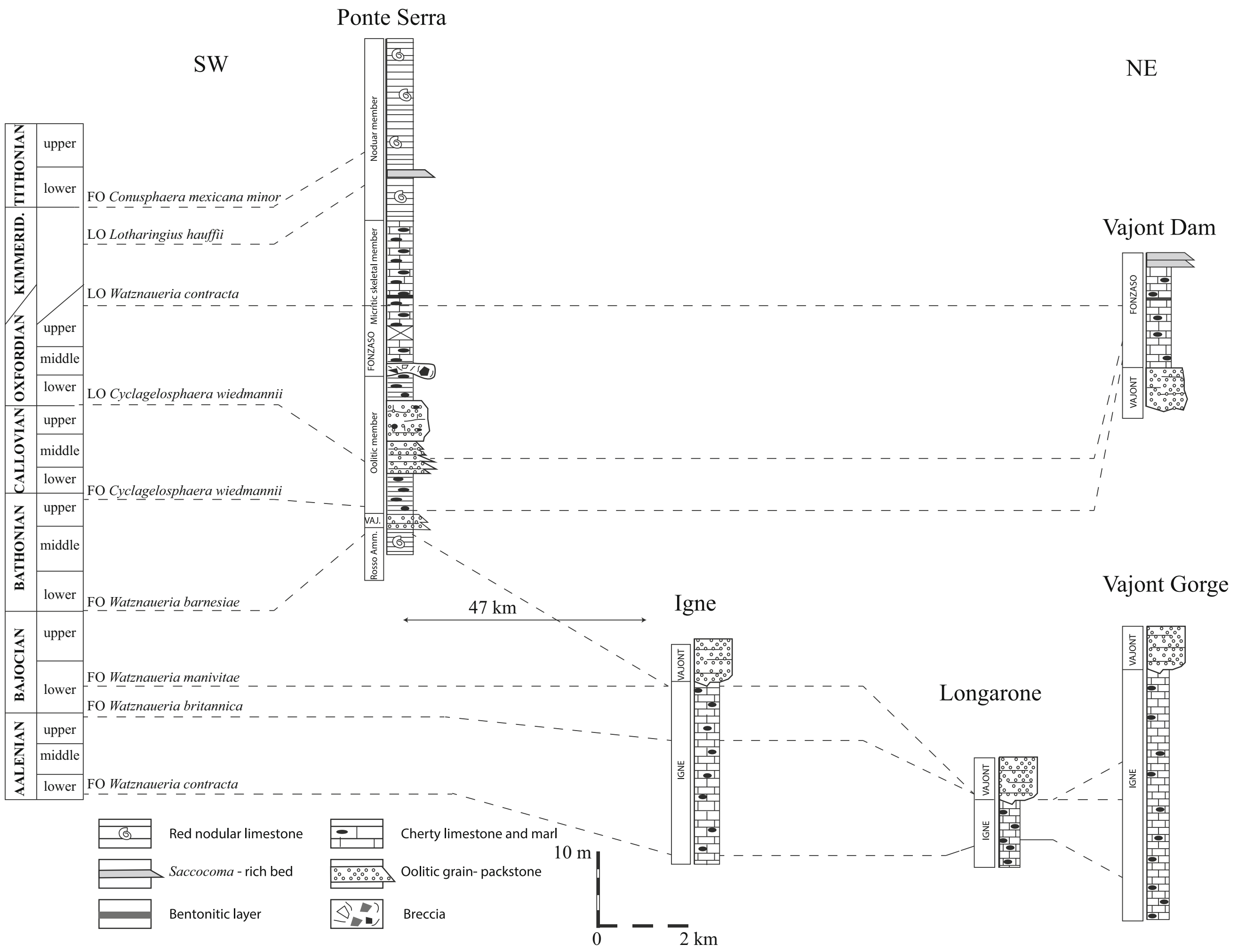

Fig. 2 The studied stratigraphic sections along a west to east profile. See text for details

Trento Platform. At the top surface of this condensed unit, Cobianchi and Picotti (2002) reported the finding of several intact shells of the irregular echinoid *Cyclolampas* cf. *castanea*. This monospecific assemblage was formed and preserved by burial of the Vajont deposits, documenting its sudden emplacement.

Casati and Tomai (1969) dated the Vajont Lms to the Late Bajocian–Bathonian interval based on the co-occurrence of *Protopeneroplis striata* and *Trocolina* sp. Bosellini et al. (1981) assigned it to a generic Bajocian–Callovian interval, based on its stratigraphic position. Zempolich (1993) found a ?*Docidoceras* sp. ind. at around 150 m from the base of the Vajont Lms. The distribution of this genus is ambiguous in the recentmost database, spanning the Late Aalenian to the top Bajocian (171.6–168.4 Ma), or the Early Bajocian (http://fossilworks.org/bridge.pl?a=taxonInfo&taxon_no=14794). Zempolich and Erba (1999) attributed the Vajont Lms to the latest Aalenian–Late Bajocian interval, based on few and poorly preserved nannofossil assemblages from the Col Visentin section. Cobianchi (2002) documented an age for the Vajont Lms spanning between the Early Bathonian (FO of *Watznaueria barnesiae* at Ponte Serra Section) and the early Late Bathonian (FO of *Cyclagelosphaera wiedmannii*, Mattioli and Erba 1999). Based on the palaeontological evidences, the Vajont Lms is Late Bajocian to Middle Bathonian in age: therefore, older age assigned by Zempolich and Erba (1999) could be due to nannofossil assemblages reworked from the underlying Igne Fm, the scoured substrate.

The Fonzaso Fm was studied in detail at the Ponte Serra section, which represents the type locality of the formation, and at the Vajont Dam, Soccher and Col Visentin sections (Figs. 2 and 3). This unit attains a variable thickness (20–80 m), but it covers the whole Belluno Basin. The Fonzaso Fm, which abruptly overlies the Vajont Lms and grades upward into the Maiolica Fm, is characterised by cherty limestones and marls, rich in grey and red chert,

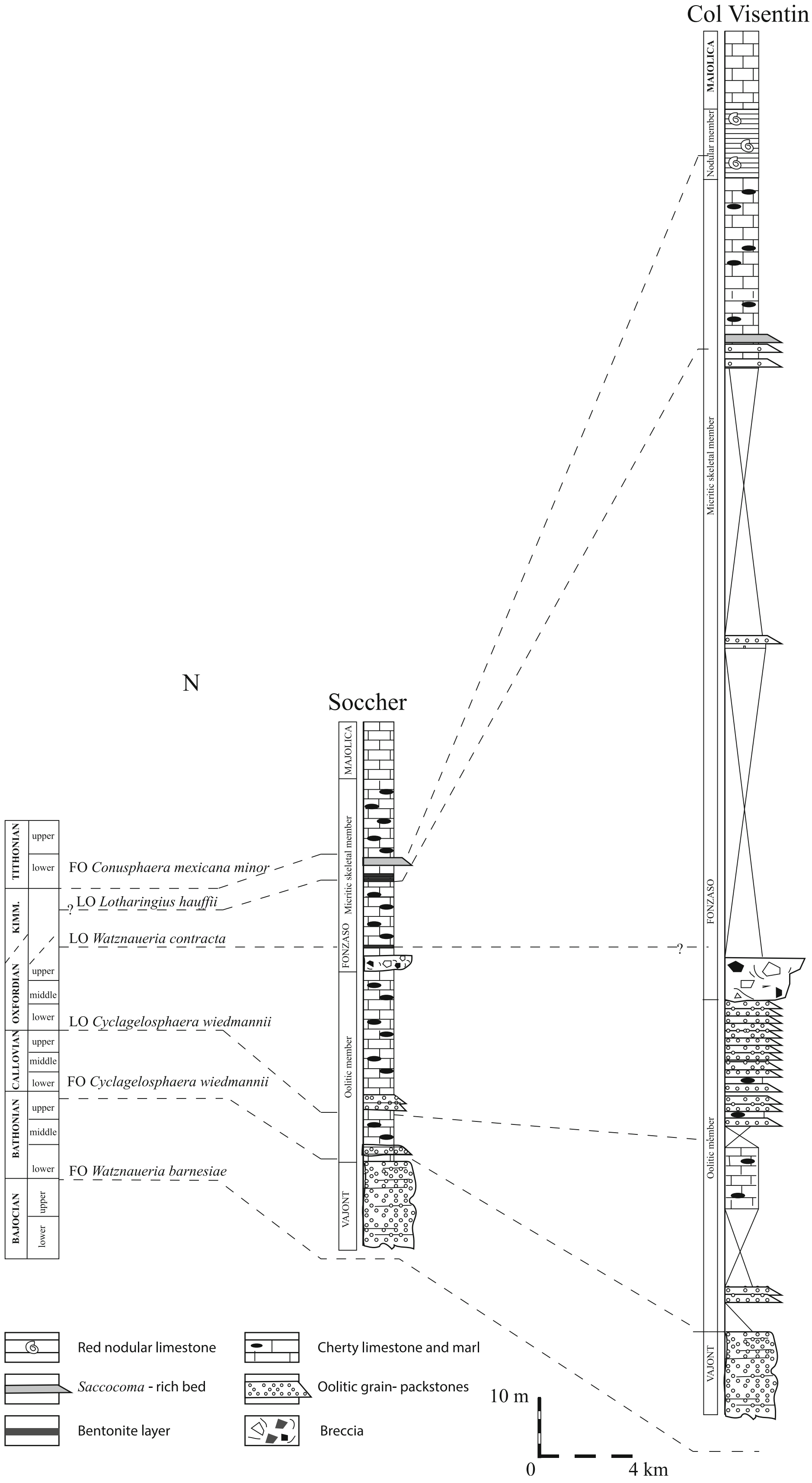

Fig. 3 The studied stratigraphic sections along a north to south profile. See text for details

interbedded with turbiditic calcarenites. A compositional change of the resedimented debris occurs from a lower portion of the unit, where it consists essentially of ooids, to a middle portion that is enriched in skeletal fragments. This change is here used to subdivide the unit into informal members.

The lower oolitic member consists of thin-bedded red and green cherty limestones, with red marly interbeds and red chert. These layers are interbedded locally with white peloidal and oolitic grainstone showing parallel and wavy lamination. Grains are mostly composed of concentric ooids, with minor miliolids and agglutinated foraminifers. Based on the distribution of the nannoplankton in the studied sections (Figs. 2 and 3, and Cobianchi 2002), this member spans the Late Bathonian to the Early Oxfordian.

The skeletal member starts with a bioclastic matrix-supported breccia, grading to a grainstone at the top, with thickness ranging from 1 (Ponte Serra section) to 10 m (Col Visentin section). Clasts consist of corals, calcareous sponges, calcareous algae and micritic intraclasts, embedded in a whitish micritic matrix. This basal breccia is overlain by a thinning upward interval of well-bedded light grey mudstones and bioclastic grainstones, followed by radiolarian-rich grey-green lime mudstones, with marly interbeds, and abundant chert nodules and ribbons. Based on the distribution of the nannoplankton in the studied sections (Figs. 2 and 3, and Cobianchi 2002), this unit spans the Middle Oxfordian to the Kimmeridgian.

At the western tip of the basin (Ponte Serra section) and at the base of slope (Col Visentin section, Figs. 2 and 3) the skeletal member grades upward into a more condensed interval of thin bedded to nodular reddish radiolarian-rich limestones, with green and red marly interbeds. In this upper member (nodular member in Figs. 2 and 3) *Saccocoma*-rich beds occur, as it is often the case in the Kimmeridgian to Tithonian (Nicosia and Parisi 1979). Della and Martire (1985) also reported a Kimmeridgian to Early Tithonian age for this nodular member. In the upper portion of this member, some thin beds of whitish bentonites are interbedded, derived from original volcanic ashes (Bernoulli and Peters 1970). These ash layers are widely represented in this interval of the Alpine Tethys and they are likely related to the Vardar island-arc volcanism (Pellenard et al. 2013, see next chapter). The age of the Fonzaso unit was attributed to the Callovian–Kimmeridgian interval by Casati and Tomai (1969) and Bosellini et al. (1981). Beccaro et al. (2008) dated the lower interval of the Fonzaso at Ponte Serra to the Callovian thanks to a rich radiolarian fauna. The detailed study of the nannofossil content, performed by Cobianchi (2002), allowed us to ascribe the Fonzaso Fm to the Late Bathonian–Early Tithonian interval. In the lower portion of the unit, the FO of *Cyclagelosphaera wiedmannii* was documented both in the Soccher and Ponte Serra sections. This event falls in the early Late Bathonian (Mattioli and Erba 1999). Upwards, always within the oolitic member, the LO of *Cyclagelosphaera wiedmannii* was recorded, which corresponds to the Callovian/Oxfordian boundary (Reale and Monechi 1994; Chiari et al. 2007; Casellato 2010). The breccia, marking the onset of the skeletal member, is Oxfordian in age because it occurs above the LO of *C. wiedmannii* and below the LO of *Watznaueria contracta*. Unfortunately, in literature the calibration of this latter event is not well established, also because in the last part of its range *W. contracta* appears to be rare. Bartolini et al. (1995) in the Terminilletto section documented the LO of *W. contracta* in a Middle–Upper Oxfordian range. According to Chiari et al. (2007), the LO of *Watznaueria contracta* falls in a transitional zone spanning the radiolarian Unitary Zones (UAZ) 9 and 10, in a range that includes the Upper Oxfordian and the base of the Kimmeridgian. Then, even if this event is not well calibrated, it anyway falls in a range that includes the Middle–Upper Oxfordian to lowermost Kimmeridgian. In all the sections studied, this event precedes slightly the lower bentonite bed implying that this latter may still be Oxfordian in age.

In the middle portion of the third member the FOs of *Conusphaera mexicana minor* and *Conusphaera mexicana mexicana*, documenting the Lower Tithonian, were observed (Cobianchi 2002). At Col Visentin and Soccher, the Upper Tithonian white micritic limestones of the Maiolica Fm overlies the Fonzaso Fm. The former, with thicknesses ranging 250–350 m, encompasses almost the whole Early Cretaceous (Erba and Quadrio 1987).

5 Discussion

5.1 Birth and infilling of the Belluno rift Basin

The Belluno Basin is just one of the rift structures formed in the Southalpine realm since the Late Triassic (Bertotti et al. 1993). As typical of the wide rifted margins (sensu Buck 1991), both hangingwall (the Belluno basin) and footwall (the adjacent platforms) were subsident (Brun 1999). During the Early Jurassic rifting, shallow water carbonate formed, named Calcari Grigi both at the Trento and the Friuli Platform, deposited over the footwall, whereas in the hangingwall deeper water sediments, the Soverzene Fm in the Belluno Basin, occurred (Fig. 4). In the Sinemurian, drowning of the eastern sector of the Trento Platform occurred (see Masetti et al. 2012), with backstepping of the platform margins that brought about the final basin configuration, with the easternmost 10 km of the former Trento Platform that hosted only patchy crinoidal sand waves in an open shelf (Figs. 1, 4).

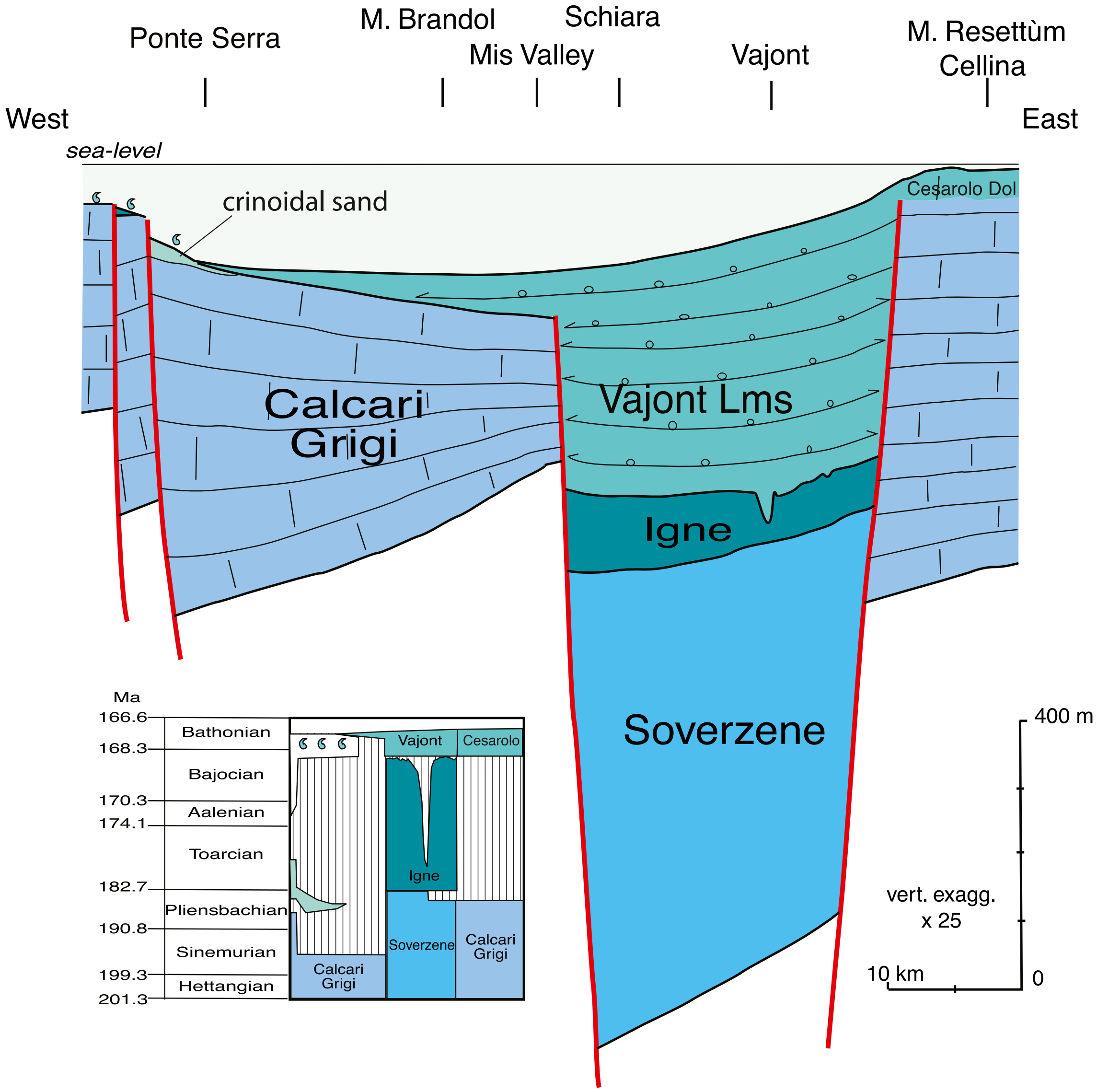

Fig. 4 Stratigraphic and geologic cross section along the west-east track shown in Fig. 1, with datum at the Middle Bathonian. In the bottom left inset, the chronostratigraphic chart corresponding to the section. Note the strong vertical scale exaggeration

The final drowning of the Calcari Grigi on the Trento Platform occurred at the end of the Pliensbachian (Dal Piaz 1907, *fide* Della and Martire 1985; Cobianchi and Picotti 2001). For the remaining Toarcian to Bajocian, the Belluno Basin was starving, with a reduced interval of limestones–marls couplets (Igne Fm). The platform contribution was very limited and coeval successions in the platform surrounding the Belluno Basin, i.e. the eastern Trento and western Friuli platforms, are not known. The palaeoceanographic conditions in this sector of the Tethys have been considered unsuitable for the carbonate productivity during this Toarcian to Bajocian time (Zempolich 1993: Bartolini et al. 1996; Cobianchi and Picotti 2001).

At Ponte Serra, i.e. the easternmost edge of the Trento Platform, a thin condensed unit developed, consisting of Upper Bajocian–Lower Bathonian reddish nodular limestones, rich in ammonoids and globigerinids (see Figs. 2, 4). This unit belongs to the wider pelagic domain of the Trento platform, consisting of a condensed succession of Bajocian to Callovian, and corresponding to the lower member of the Rosso Ammonitico Veronese (Martire 1996; Martire et al. 2006). From the Toarcian–Aalenian on, the Trento Platform drowned (Zempolich 1993; Picotti and Cobianchi 1996; Cobianchi and Picotti 2001) and its bathymetry was deeper than the photic zone: this is the reason why in the literature the name changes into Trento plateau (Winterer and Bosellini 1981). The Upper Bajocian condensed unit is transgressively covering the drowned platform (Fig. 4), and our data suggest that this transgression brought also new accommodation space on the margin of the Friuli Platform, giving rise to ooidal production and shedding toward the Belluno Basin (Vajont Lms). In the available literature (e.g. Bosellini et al. 1981; Masetti et al. 2012), there is confusion in defining the Vajont Lms, since these authors included also the oolitic interbeds of the lower member of the Fonzaso Fm. In this review, following the precise age assignment to the Late Bathonian of the base of the Fonzaso Fm, we better define the Vajont Lms as a Upper Bajocian to Middle Bathonian unit. The occurrence of the Vajont Lms abruptly covering the condensed Rosso Ammonitico Veronese at Ponte Serra documents sharp facies changes at the end of the Early Bathonian. These gravity-driven flows originated from the Friuli Platform at the time of maximum progradation of the slope apron of the Vajont Lms (Fig. 4). The occurrence of the Vajont Lms at Ponte Serra documents the spilling of the sediments over the margin of the Trento Plateu after the filling of the previous bathymetry of the Belluno Basin, where almost 400 m of oolitic limestones occur (see Fig. 4). Therefore, the infilling of the Belluno Basin is mostly constrained between the Late Bajocian and the Early Bathonian (Fig. 4), whereas the Vajont Lms continued up to the end of the Middle Bathonian. This sedimentary body shows an abrupt increase of sedimentation rate from 3 m/Myr of the underlying Igne Fm to around 300 m/Myr of the Vajont Lms.

At the Friuli Platform margin, a unit of prevailing dolostones, not better dated than Middle Jurassic, is known from the subsurface (Cesarolo 1 well, Fig. 1 for location and Fig. 5; Cesarolo Dolomite in Cati et al. 1987), where ghosts of ooids have been described. Due to the lack of exposure of coeval shallow water carbonates in the Friuli Alps, this is the only possible shallow water counterpart of the Vajont Lms, as it has been generally proposed in the literature (Bosellini et al. 1981, who called it Ternowaner Oolite). The Vajont Lms sedimentation rate is two orders of magnitude higher than any other basinal carbonates, including the syn-rift Soverzene Fm that was well supplied from the surrounding Calcari Grigi platforms during Early to Middle Lias, a time of good carbonate productivity (see Figs. 4, 5; Cobianchi and Picotti 2001). The Vajont Lms consists of ooidal sand-size deposits mostly, and this suggests the reduction of peritidal environments in the platform, usually exporting mud. Therefore, the shallow bottom of the Friuli Platform was swept by ooidal shoals, likely controlled by tidal currents, and, to explain the very efficient offshore transportation of the ooids, not only a high ooid productivity is required, but also a low accommodation space in the platform. For this reason, we interpret the Vajont Lms as a prograding slope apron deriving from the reworking of the platform margins, at a time when most of the Friuli Platform was swept by strong currents. Interestingly, in the second order stratigraphic cycles of both Boreal and Tethyan realm, the Early Bathonian is the onset of a regression that culminate in the Middle Bathonian (Jacquin et al. 1998). Therefore, the Vajont apron developed as lowstand shelf/slope wedge. At the third order scale, the sea-level oscillations could have been more complex, as suggested by the stratigraphic reconstruction of the European margin, where similar ooidal shelf wedges coevally developed (e.g. Gonzalez and Wetzel 1996). Unfortunately, our case study does not allow to enter into the third-order frequency. Following this interpretation, we think that the counterpart of the Vajont Lms on the Friuli Platform could not form a thick body during the Late Bajocian–Middle Bathonian. Most of the Cesarolo Dolomite should have started to aggrade only after the mid-Bathonian peak regression, mostly developing between Late Bathonian and Early Oxfordian (see Fig. 5), thus coeval with the Fonzaso Fm (Oolitic member) in the basin.

5.2 Aggradation of the Friuli Platform margin and deepening of the adjacent basins

In the Belluno Basin, the Callovian to middle Oxfordian lower member of the Fonzaso Fm record several intervals of oolitic grainstones interbedded within the radiolarian-rich pelagic limestones (Oolitic member, Figs. 2, 3). These gravity-driven deposits, derived from the Cesarolo Dolomite (Fig. 5), reached the most distal sector at Ponte Serra in the Late Callovian–Early Oxfordian, whereas they encompass the whole Callovian–Middle Oxfordian at the base of slope of the Friuli Platform (Col Visentin, Figs. 3, 5). This younging of the top of the gravity-driven deposits from distal to proximal suggests a backstepping trend of the platform margin, as already shown in the seismic profiles of the subsurface by Cati et al. (1987, see Fig. 5).

At the Middle–Upper Oxfordian, a lime mud-supported breccia occurs all over the basin with thicknesses ranging from 1 m at Ponte Serra section, to 2.5 m at Soccher and finally 10 m at Col Visentin, with a clear thickening toward the slope. The clasts include angular pieces of coral and sponge boundstones (*Ellipsactinia* sp.), rip-up clasts of slope sediments and skeletal grains from the platform. This breccia represents a single event of failure of the platform margin and it is a unicum in the stratigraphy of the Belluno Basin. No outcrops of the Oxfordian platform margin are available, and the few published seismic lines do not show platform edge collapses. Therefore, we can only interpret this breccia body as the most important failure of the Jurassic margin of the Friuli Platform, given the volumes involved (see e.g. Reijmer et al. 2015). A possible explanation for it is a (series of) ground shaking due to effective earthquakes, affecting a slope whose angle was increasing, thanks to the change from the shoal-rimmed Cesarolo Dolomite to the reefal-rimmed Ellipsactinia Lms (Fig. 5).

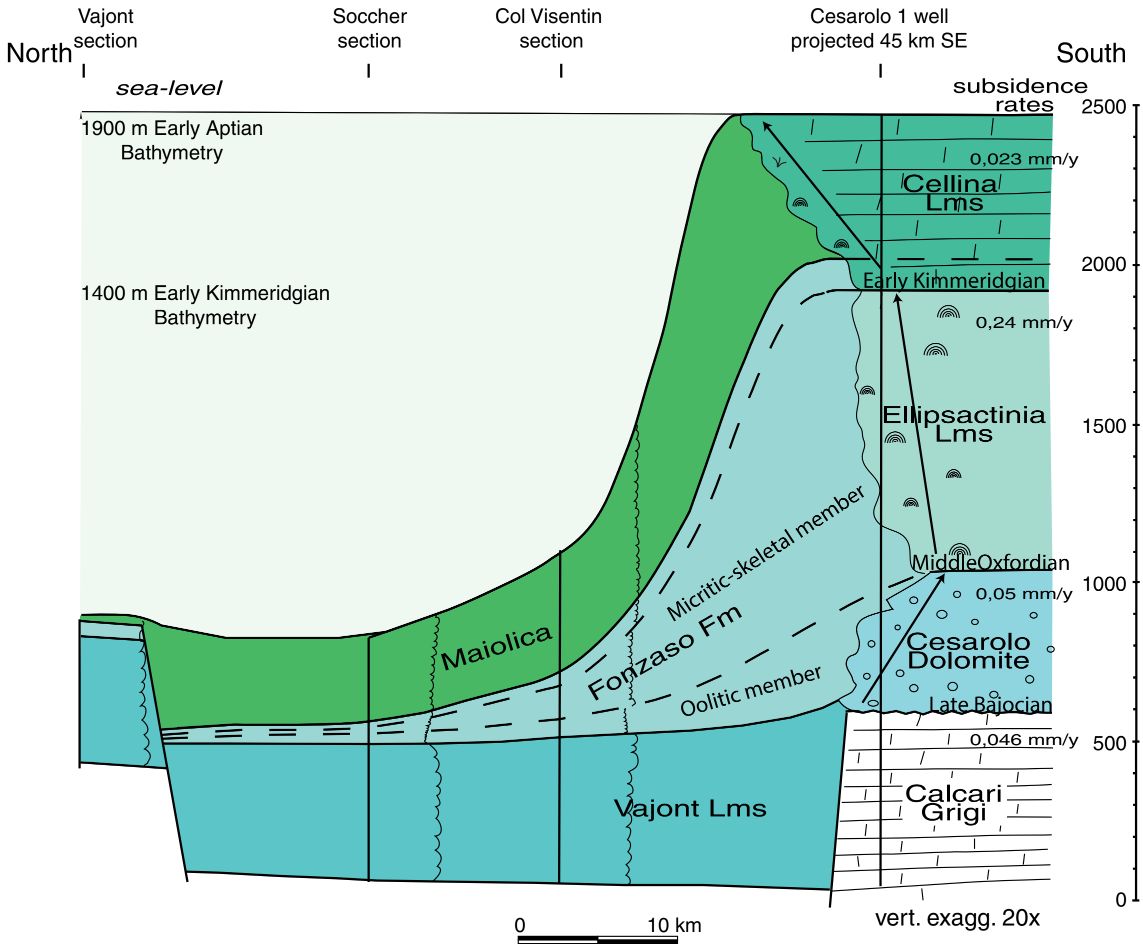

Fig. 5 Stratigraphic and geologic cross section along the north-south track shown in Fig. 1, with datum at the Early Aptian. Note the Cesarolo 1 well has been projected into the section. Note the strong vertical scale exaggeration

During the Early Kimmeridgian, prevailing hemipelagic sedimentation dominated the basin. The only gravity-driven deposits are found at the slope section of Col Visentin. The Upper Oxfordian–Lower Kimmeridgian platform is very thick (850 in the Cesarolo 1 well), showing a sedimentation rate much higher than the previous platforms (240 m/Myr against 50 m/Myr of the underlying Cesarolo Dolomite). This fast aggrading margin was typically dominated by calcareous sponge of the genus *Ellipsactinia* and corals. This evolution limited the exportation toward the basin, starving and deepening it from a bathymetry of around 500 m at the Middle Oxfordian to around 1400 m at the end of Kimmeridgian (Fig. 5). In the only outcrop known of the top of the Ellipsactinia Lms at Polcenigo (Fig. 1), described by Sartorio (1987), few tens of meters of boundstones with *Ellipsactinia* and corals occur, with a topmost nerineid mound. A drowning succession on top of the Ellipsactinia Lms consists of less than one meter of pinkish nodular to bedded limestones, bearing an ammonite of the late Early Kimmeridgian (*Taramelliceras compsum*, Sartorio 1987). This unit marks the basal boundary to the subsequent unit, the Cellina Limestone that in the Cesarolo 1 well (Cati et al. 1987) was not well dated. This latter unit consists of a large peritidal platform both in the outcrops (Cuvillier et al. 1968) and in the subsurface (Cati et al. 1987) (Fig. 5). Thus, the drowning succession, topping the marginal facies of the Ellipsactinia Lms represent the maximum transgression of the relative sea-level, followed by a regression, due to the establishment of the healthy Cellina platform. Its equivalent margin, consisting again of a coral–hydrozoan reef and associated talus, described by Ferasin (1958) and more recently by Schindler and Conrad (1994), shifted about 8 km northwest, re-establishing at the Middle Jurassic location. The early growth of the Cellina platform finds its basinal counterpart in the Upper Kimmerigian to Lower Tithonian nodular member of the Fonzaso Fm. This is a condensed interval with rosso ammonitico facies, developed on the more elevated areas, such as the Ponte Serra section at the distal part of the basin and the Col Visentin section, located at the slope. After this condensed interval, the sedimentation rates in the basin abruptly increased, starting at the Late Tithonian, due to the combined factors of the increasing exportation from the platform and production of planktonic organisms (nannoconid bloom, Erba and Quadrio 1987).

5.3 Jurassic subsidence history of the Friuli–Adriatic Platform: tectonic perturbations in the Adria passive margin

The Middle–Late Oxfordian to Early Kimmeridgian increased sedimentation rate is not recorded all over the Adriatic Platform. In their regional review, Vlahovič et al. (2005) showed composite sections from Istria and Gorsky Kotar north of Rijeka, for the platform interior and Karlovac for the eastern Adriatic Platform margin. We have analysed these data for their subsidence history together with the Cesarolo 1 well for the Friuli Platform margin (Cati et al. 1987), and we present them in this section (Fig. 6, see Fig. 1 for location).

In Istria, an important emersion and erosion event occurs, recorded by bauxite deposits embedded between the Lower Oxfordian and the Upper Tithonian (Vlahovič et al. 2005). On the Gorsky Kotar section, located around 50 km to the east, the Middle Oxfordian to Lower Tithonian interval, missing on the Istria section, reaches thicknesses of more than 500 m, comparable to the 800 m of the Cesarolo 1 well (Fig. 6). Finally, the Karlovac section shows the absence of the whole Middle Jurassic and the Oxfordian, again due to emersion and erosion, but the shallow-water sedimentation recovers at the Kimmeridgian–Tithonian.

The overall picture is provided by a profile presented in Fig. 6e, where one can evaluate the large wavelength folding of the substrate, with around 80–100 km wavelength, a value that has been already observed (Cloething et al. 1999; Cloething and Burov 2011).

Subsidence during Early Jurassic was controlled by rifting with variable rates even in the Friuli–Adriatic Platform, possibly due to the activity of normal faults within the platform domain (Fig. 6, see Franceschi et al. 2014). In most of the Southalpine rifted margin, the normal faults were already inactive at the end of the Early Jurassic and the rift activity went focusing from Toarcian to Bajocian at the westernmost edge of the Southern Alps, more than 300 km west of the Friuli–Adriatic Platform, eventually leading to the breakup west of it (Bertotti et al. 1993). For this reason, in Fig. 6 we indicate the rifting stage only until the Toarcian, followed by a drifting that anyway is associated with oceanic lithosphere spreading only in the Middle Jurassic (Fig. 6). The cessation of the rift fault activity brought about variable subsidence patterns, from low and steady (e.g. Karlovac section in Fig. 6), to similar to the previous (Istria) or even null, but increasing toward the onset of Late Jurassic (Cesarolo 1), to a gradually increasing subsidence pattern throughout the Middle Jurassic (Gorski Kotar) (Fig. 6). From the Middle Oxfordian to the Kimmeridgian, the subsidence pattern changed dramatically. Istria and Karlovac sections record negative subsidence (uplift) and stop of sedimentation with emersion and erosion (Vlahovič et al. 2005), whereas Cesarolo 1 and Gorsky Kotar show a coeval abrupt increase of the sedimentation rates. From the Tithonian to the Early Cretaceous the subsidence returned to the previous values, with the exception of a short-lived variation at Karlovac (Fig. 6). These latter rates appear compatible with the thermal subsidence of the drifting stage (e.g. Stampfli 2000).

The subsidence history for the Middle Oxfordian to the Kimmeridgian, on the contrary, is not compatible with a passive margin subsidence of the Adria lithosphere. We interpret these movements as long wavelength folding, a compressional perturbation superimposed to the drifting trend and affecting this sector of the Adria passive margin. The wavelength measured from the profile in Fig. 6e is around 80–100 km, a value that is considered typical by Cloething and Burov (2011) for the folding of the whole lithospheric mantle in case of young (around 100 Ma) thermotectonic ages. This is well suitable in the case of this sector of the Adria lithosphere that was strongly reworked by thermotectonic events in the Early Permian and Middle Triassic, respectively 110–65 Ma earlier than the Middle Oxfordian.

The timing of this folding corresponds to important events at the eastern margin of the Adria plate (Fig. 7). In recent years, and following the first pioneering works (e.g. Mercier 1966; Bernoulli and Laubscher 1972), several papers highlighted the evolution of the orogenic belt forming the transition between the eastern Adria and Eurasia margins (e.g. Schmid et al. 2008; Mikes et al. 2008; Bortolotti et al. 2013; Gallhofer et al. 2017). These reconstructions are based on structural and stratigraphic relationships between the obducted ophiolites and the deformed units of the Adria plate. They include radiochronometric ages and geochemistry of magmatic products associated with the subduction(s) and metamorphic ages associated with obduction.

All these papers have in common the recognition of the important obduction of the West Vardar ophiolites (sensu Schmid et al. 2008) over the Adriatic plate. Obduction started as intraoceanic, and its evolution throughout the Middle Jurassic can be tracked with the stratigraphic age of the youngest oceanic sediments underneath the obducted ophiolites (Late Bajocian–Early Oxfordian, Schmid et al. 2008), and with the peak metamorphism of the metamorphic sole (174–157 Ma, Schmid et al. 2008; 176 to 158 Ma Bortolotti et al. 2013). In the Late Jurassic, the Adriatic continental lithosphere started to get involved in the obduction process (Fig. 7). This is documented by the

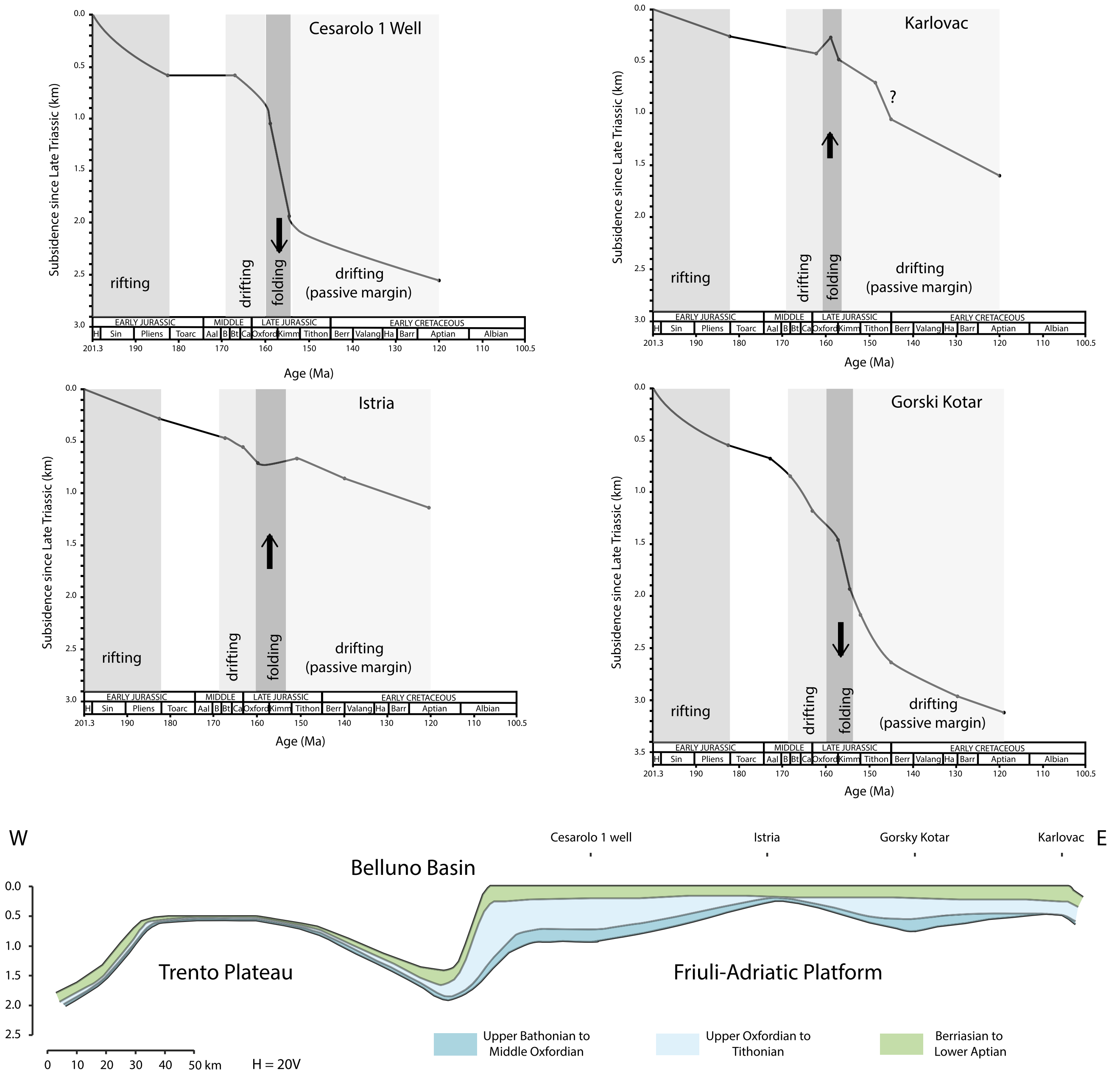

Fig. 6 Subsidence history for the chosen sites, located in Fig. 1. At the *bottom*, a stratigraphic cross section across the whole studied area, with datum at the Early Aptian. Note the strong vertical scale exaggeration

absence of Late Jurassic age for the metamorphic sole (Bortolotti et al. 2013), but also by the sedimentary rocks on the Adria plate. In literature, in fact, occurrence of ophiolitic detritus in the Upper Jurassic clastic deposits is reported in the Bosnian flysch, to the east of the Friuli–Adriatic Carbonate Platform (Mikes et al. 2008), and in the Middle Oxfordian–Lower Kimmeridgian Sillenkopf Basin in the Northern Calcareous Alps near Salzburg (Gawlick et al. 2015) (see Fig. 7e). Furthermore, over the obducted ophiolitic bodies, shallow water platform carbonates have been described as Upper Oxfordian to Kimmeridgian, or, more generally, Upper Jurassic (e.g. Bortolotti et al. 2013, Gallhofer et al. 2017). These carbonate platforms postdate the obduction and their shallow bathymetry confirm the ophiolites were already thrusted over the thick continental lithosphere of the eastern margin of the Adria plate.

Finally, some papers deal with the magmatic activity peaking between around 160 and 155–153 Ma, intruding the oceanic lithosphere (e.g. Gallhofer et al. 2017) as well as the Eurasian margin (Rhodope, e.g. Burg 2012; Bonev et al. 2015). This magmatic activity is interpreted as a volcanic arc setting associated to the subduction (see

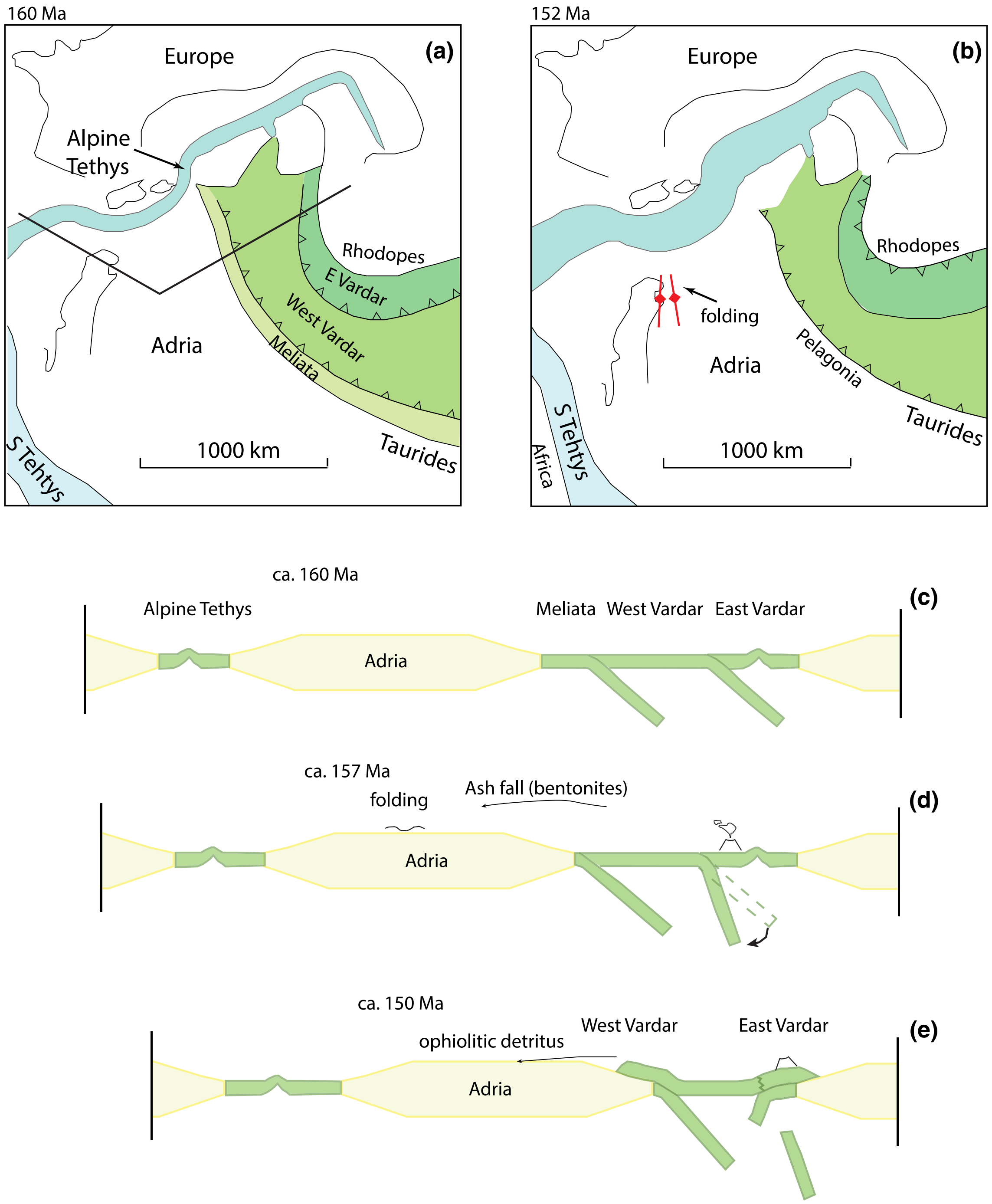

Fig. 7 Palaeogeographic setting at 160 (**a**) and 152 (**b**) Ma (modified after Gallhofer et al. 2017). Note in **a** the track of the next cross sections **c**–**e**. The cross sections (not to scale) are simplified reconstructions of the main events affecting the eastern Adria plate during the drifting of the Alpine Tethys at the western margin: **c** oceanic subduction of Meliata and west Vardar oceans. **d** impingement of Adria continental lithosphere into the subduction system and activity of the Vardar volcanic arc with explosive volcanism and ash fall over Adria and Europe. **e** obduction of the W Vardar against Adria and E Vardar against Rhodope

Fig. 7). The end of this magmatic activity has been associated to obduction of oceanic lithosphere over the Adria plate margin. The timing of the end of magmatic activity corresponds to the subsidence perturbations of the studied sector of the Adriatic lithosphere (Figs. 6, 7).

We have depicted a very short review of the main steps of the tectonic history of the eastern margin of the Adria plate, with the main relevant literature. A deeper discussion is beyond the scopes of this work. However, to better understand the role of the transition from oceanic to continental obduction, in Fig. 7 we present a palaeogeographic reconstruction based on the interpretation of Gallhofer et al. (2017) that in our view offers a suitable plate tectonic reconstruction of the Adria plate, linking the drifting of the Alpine Tethys and its Adriatic passive margins to the subduction and obduction to the east.

5.4 Other sedimentary evidences of tectonic activity in the margins and interior of plates

The Upper Jurassic sediments record tectonic movements not only in the Adriatic passive margin, and include several indicators.

Rhyolitic to trachytic ash layers weathered into bentonites (Bernoulli and Peters 1970) are very common in the Middle Oxfordian all over the Adria plate (Pellenard et al. 2013), but they are also found on the European plate (Paris basin, Subalpine basin, eastern France, Pellenard and Deconinck 2006). In the studied Belluno Basin, as well as in the Lombardian Basin, similar weathered ash layers are found also at the base of Early Kimmeridgian (Fig. 2 and Chiari et al. 2007). Overall, they have been correlated to the arc volcanism associated to the Vardar oceanic subduction (see Fig. 7 for a possible interpretation).

A coeval tectonic activity in terms of surface faulting is recorded by sudden thickness variations in the Oxfordian successions of the Adria plate both in the Southern Alps (e.g. Martire 1996), and in the northern Calcareous Alps (Austroalpine). Here, large breccia bodies and olistholiths in the mid-Oxfordian have been interpreted as evidences of compressional (Gawlick et al. 1999; Mandl 2000) or extensional faulting (Ortner et al. 2008). Whatever the interpretation of tectonic environment, these faults and associated breccias are coeval with the described buckling of the Adria lithosphere, and are possibly different expressions of the ongoing tectonics at its eastern margin.

On the European side, a Late Jurassic stress field reorganization was claimed (Ziegler 1990) to explain the widespread evidence of subsidence pulse, such in the Jura, with possible reactivation of basement faults (Allenbach 2002; Wetzel et al. 2003), or in the Helvetics (Rais et al. 2007).

Similar pulses of subsidence at the beginning of the Late Jurassic are recorded in the Anglo-Paris Basin (Rioult et al. 1991) and in the Paris Basin (Loup and Wildi 1994), as well as other parts of Europe and Iberia (e.g. Pittet and Strasser 1998). The occurrence of similar perturbations in the subsidence pattern of the European and Iberian plates points to a wider plate reorganization (e.g. Ziegler 1990), with the obduction processes in the eastern margin of the Adria plate that represents only part of it.

5.5 A geochronological problem

In the reconstruction of the subsidence curves, we adopted the recentmost available chronostratigraphic chart that shows the Oxfordian/Kimmeridgian boundary age to 157.3 ± 1.0 Ma (Cohen et al. 2013 updated). Accordingly, the timing of observed folding of the Southalpine passive margin, Middle Oxfordian to Early Kimmeridgian, would correspond to a geochronological timespan of around 160–155 Ma (Fig. 6).

The timing of obduction of the West Vardar ophiolites over the Adriatic continental margin is constrained by Schmid et al. (2008) and Bortolotti et al. (2013) between the Early Oxfordian (biostratigraphic age of the youngest oceanic deposits underneath the ophiolites) and the Late Oxfordian to Early Kimmeridgian (based on the biostratigraphic age of the carbonate platforms capping the obducted ophiolites). The metamorphic ages available from literature (Schmid et al. 2008, Bortolotti et al. 2013) also document the transition from intraoceanic to continental obduction occurred at 157 Ma. On the other hand, the end of the arc-volcanism, by most authors associated with the continental obduction, is recorded at 155–153 Ma (e.g. Bonev et al. 2015; Gallhofer et al. 2017).

Therefore, there is a mismatch between the age of the buckling of the Adria lithosphere reconstructed from biostratigraphy (Middle Oxfordian–Early Kimmeridgian, i.e 160–155 Ma according to Cohen et al. 2013 updated) and those of the obduction process (157–153 Ma), reconstructed through radiochronometric dating. These latter are 3–4 Ma younger than the former.

We acknowledge this point could be due to two alternative reasons: (1) folding is not associated to the obduction of the eastern Adria margin or (2) the geochronological dating of the Oxfordian and Kimmeridgian in the recent chronostratigraphic chart of Cohen et al. (2013) is not consistent with the biostratigraphy. This latter hypothesis could be raised also because of the absence of GSSP in the Late Jurassic, whose boundaries are mostly interpolated using cyclostratigraphy.

Recent papers highlighted discrepancies between the Late Jurassic radiochronometric ages and their stratigraphic position. Pellenard et al. (2013) provided a ^{40}Ar–^{39}Ar age of 156.1 ± 0.89 Ma for a Middle Oxfordian (*transversarium* Zone) bentonite layer of the Rosso Ammonitico Veronese of the Trento Plateau. The abovementioned authors discussed this age with respect to the chronostratigraphic chart and concluded with an evident 4 Ma discrepancy between their age and the interpolated age from the Cohen et al. (2013) chart.

The same 4 Ma discrepancy was noted by Gallhofer et al. (2017) when they discuss the onset of the continental obduction after the youngest island arc intrusion at

153 Ma. In the same region, on top of the obducted ophiolites, a shallow water carbonate was biostratigraphically dated at the Oxfordian/Early Kimmeridgian (Gallhofer et al. 2017), i.e. 157 Ma according to the stratigraphic chart of Cohen et al. (2013).

A similar geochronological problem has been recently raised by Tribuzio et al. (2016) for older stages of the Middle Jurassic. The authors U/Pb dated oceanic crustal rocks of the Ligurian Alpine Tethys, located west of the Southalpine rifted margin (Fig. 7) covered with radiolarian-rich sediments. Whilst the palaeontology documents a Bathonian age for these sediments, the underlying rocks provided U/Pb ages between 165 and 160 Ma, that is Callovian to Middle Oxfordian, according to the chronostratigraphic chart of Cohen et al. (2013 updated). This mismatch, again around 4 Ma, suggests the necessity of reconsidering the geochronology of the Middle–Late Jurassic.

If we accept the younging of the boundary ages of the Cohen et al. (2013) chart by around 4 Ma, then we can reconcile also our stratigraphic observations of peak activity between Middle Oxfordian and Early Kimmeridgian (Fig. 6), with the radiometric dated evolution of the eastern margin of Adria (see Fig. 7d, e).

6 Conclusions

The effects of stress transmittal from the margins toward the interior of the plates are known mostly from modelling experiments (e.g. Cloething and Burov 2011), but their role on the evolution of sedimentary basins is still poorly documented.

In this paper, we first set the timing of the main depositional events by providing a detailed stratigraphy for the Belluno Basin and the adjacent Trento and Friuli Platforms, at the rifted- to passive margin of the Adria plate in the Southern Alps of Italy. With the aim of assessing the wavelength of the movements affecting the study area, we enlarged the view to the whole northern Adriatic Platform, moving to the east toward the Jurassic active margin of Adria to reconstruct its stratigraphic architecture.

The transition from rifting to drifting in the study area is associated with important changes in the sedimentary style. On the other hand, the sea-level and palaeoceanography modulated the productivity of the carbonate system and the exportation potential toward the deep basins. The combined effects of these factors controlled the final basin architecture that we can summarize as follows.

The rift basin in the Early Jurassic was narrow and few hundreds of meters deep (Belluno Basin, see Fig. 4), supplied with carbonate sediments exported from the adjacent productive carbonate platforms. A long period of scarce productivity in the platform from the Toarcian to the Bajocian finally drowned the Trento platform to the west, and induced starvation in the Belluno Basin that was either not supplied by the Friuli Platform. Reasons for this starvation are likely due to the subsidence decrease at the footwall of the Belluno Basin, with less to null accommodation space in the platforms for the carbonate production. The most important factor hampering the carbonate factory, however, was the fluctuation in the trophic state of surficial waters in this part of the Tethyan sea (e.g. Bartolini et al. 1996).

Under these conditions of decreased subsidence and scarce carbonate productivity, a particular event occurred from Late Bajocian to Middle Bathonian. A strong bottom current regime at the edge of the Friuli Platform associated with a regressive trend of the sea-level produced the rapid filling of the Belluno Basin with ooids (Vajont oolitic Limestone) spilling over the edge of the drowned Trento Platform (Fig. 4).

After the slow Late Bathonian to Early Oxfordian recovery of the carbonate productivity in the Friuli Platform, the other important event is the development of a Middle Oxfordian to Lower Kimmeridgian photozoan (corals and calcareous hypercalcified sponges) *Ellipsactinia* platform. The coeval important subsidence pulse at the Friuli edge of the Adriatic Platform is documented by the five-fold increase of the sedimentation rate (Fig. 5). The effect on the adjacent Belluno Basin was starvation and consequent deepening, since most of the sediment was trapped on the subsiding platform. The Upper Kimmeridgian–Tithonian carbonate platform show a rapid decrease and a return to sedimentation rates similar to pre-Oxfordian times (Fig. 5).

In a section crossing the whole northern Adriatic Platform and from the subsidence analysis of four representative sections, the Middle Oxfordian to Kimmeridgian interval is laterally variable in thickness, from around 800 m at the western edge (Friuli Platform) to 0 in Istria and again thickening and thinning toward the east (Fig. 6). These stratigraphic data depict a couple of large-wavelength folds with around 80–100 km of length, followed by a Tithonian to Early Cretaceous interval of almost equal thickness, documenting the end of folding.

The timing of this folding corresponds to important tectonic variations at the eastern edge of the Adria plate (Fig. 7). For these reasons, we interpret the observed large-wavelength folding as the effect of stress transmittal to the plate interior at the transition from intraoceanic to continental obduction. Changes in rheological character of the subducting lithosphere allowed the involvement of larger volumes of rocks within the deformed zone, eventually coupling a larger section of the continental lithosphere with consequent folding in the studied sector of the Adria plate, quite far from the active margin.

Middle Oxfordian–Early Kimmeridgian evidence of tectonic or subsidence pulses are recorded in many places of the former Adria plate, especially to the north (present-day Austroalpine units, Gawlick et al. 1999, 2015), as well as in various areas of the Eurasian plate, where first Ziegler (1990) attributed the intense mobility recorded to an important plate reorganization.

The western Adria passive margin was strongly perturbed by this compressional event of around 3 Ma of duration. At the end of it, the normal thermal subsidence controlled the evolution of the Southern Alps passive margin until the Late Cretaceous, when the Alpine collision of the northern margin induced again other waves of compression all along the Adria plate (e.g. D'Argenio and Mindszenty 1995).

Acknowledgements The authors thank Prof. Stefan Schmid for the stimulating discussions on the evolution of the eastern margin of the Adria plate and for his kind critical reading of the manuscript. Discussions with J.P. Burg about metamorphic sole evolution and stress transmittal in obductions are warmly acknowledged. The authors are grateful to the Journal reviewers, Luca Martire and anonymous for their thorough comments.

References

Allenbach, R. P. (2002). The ups and downs of ''Tectonic Quiescence''—recognizing differential subsidence in the epicontinental sea of the Oxfordian in the Swiss Jura Mountains. *Sedimentary Geology, 150,* 323–342.

Auboin, J. (1963). Essai sur la paléogéographie post-triasique et l'évolution secondaire et tertiaire du versant sud des Alpes orientales (Alpes méridionales; Lombardie et Vénetie, Italie; Slovénie occidentale, Yougoslavie). *Bulletin Société Géologique de France, 75,* 730–766.

Bartolini, A., Baumgartner, P. O., & Hunziker, J. (1996). Middle and Late Jurassic carbon stable-isotope stratigraphy and radolarite sedimentation of the Umbria-Marche Basin (Central Italy). *Eclogae Geologicae Helvetiae, 89,* 811–844.

Bartolini, A., Baumgartner, P. O., & Mattioli, E. (1995). Middle and Late Jurassic Radiolarian Biostratigraphy of the Colle Bertone and Terminilletto sections (Umbria–Marche–Sabina Apennines, Central Italy): an integrated stratigraphical approach. In P. O. Baumgartner (Ed.), *Middle Jurassic to Lower Cretaceous Radiolaria of Tethys: Occurrences, systematics, biochronology. Mémoires de Géologie, Lausanne* (Vol. 23, pp. 817–832). Lausanne University

Beccaro, P., Diserens, M.-O., Gorican, S., & Martire, L. (2008). Callovian radiolarians from the lowermost Calcare selcifero di Fonzaso at Ponte Serra (Trento Plateau, Southern Alps, Italy). *Rivista Italiana di Palaeontologia e Stratigrafia, 114*(3), 489–504.

Bernoulli, D., & Jenkyns, H. (1974). Alpine, Mediterranean and central Atlantic Mesozoic facies in relation to the early evolution of the Tethys. In R. H. Dott, & R.H. Shaver (Eds.), *Modern and ancient Geosynclinal sedimentation*, *Society for Sedimentary Geology Special Publication* (Vol. 19, p. 129–160).

Bernoulli, D., & Laubscher, H. P. (1972). The Palinspastic Problem of the Hellenides. *Eclogae Geologicae Helvetiae, 65*(1), 107–118.

Bernoulli, D., & Peters, T. (1970). Traces of rhyolitic-trachytic volcanism in the Upper Jurassic of the Southern Alps. *Eclogae Geologicae Helvetiae, 63,* 609–621.

Bertotti, G., Picotti, V., Bernoulli, D., & Castellarin, A. (1993). From rifting to drifting: Tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous. *Sedimentary Geology, 86,* 53–76.

Bertotti, G., Picotti, V., Chilovi, C., Fantoni, R., Merlini, S., & Mosconi, A. (2001). Neogene to quaternary sedimentary basins in the South Adriatic (Central Mediterranean): Foredeeps and lithospheric buckling. *Tectonics, 20,* 771–787.

Bonev, N., Marchev, P., Moritz, R., & Collings, D. (2015). Jurassic subduction zone tectonics of the Rhodope Massif in the Thrace region (NE Greece) as revealed by new U-Pb and 40Ar/39Ar geochronology of the Evros ophiolite and high-grade basement rocks. *Gondwana Research, 27,* 760–775.

Bortolotti, V., Chiari, M., Marroni, M., Pandolfi, L., Principi, G., & Saccani, E. (2013). Geodynamic evolution of ophiolites from Albania and Greece (Dinaric-Hellenic belt): one, two, or more oceanic basins? *International Journal of Earth Sciences*, *102,* 783–811.

Bosellini, A., Masetti, D., & Sarti, M. (1981). A Jurassic, "Tongue of the Ocean" infilled by oolitic sands: The Belluno Trough, Venetian Alps, Italy. *Marine Geology, 44,* 59–95.

Boyer, G. R. (1913). Etude géologique des environs de Longarone (Alpes vénetiennes). *Bulletin Sociètè géologique de France, 13,* 451–485.

Brun, J. P. (1999). Narrow rifts versus wide rifts: inferences for the mechanics of rifting from laboratory experiments. *Philosophical Transactions Royal Society London, Series A-Mathematical Physical and Engineering Sciences, 357,* 695–710.

Buck, W. R. (1991). Modes of continental lithospheric extension. *Journal of Geophysical Research, 96*(B12), 20161–20178.

Burg, J. (2012). Rhodope: From Mesozoic convergence to Cenozoic extension. Review of petro-structural data in the geochronological frame. In E. Skourtsos, & G. S Lister (Eds.), *The Geology of Greece, Journal of the Virtual Explorer, Electronic Edition* (Vol. 42, paper 1).

Casati, P., & Tomai, M. (1969). Il Giurassico e il Cretacico del versante settentrionale del Vallone Bellunese e del gruppo del Monte Brandol. *Rivista Italiana di Paleontologia e Stratigrafia, 75,* 205–340.

Casellato, C. E. (2010). Calcareous nannofossil biostratigraphy of Upper Callovian–Lower Berriasian successions from the Southern Alps, North Italy. *Rivista Italiana di Paleontologia e Stratigrafia, 116,* 357–404.

Cati, A., Sartorio, D., & Venturini, S. (1987). Carbonate platforms in the subsurface of the Northern Adriatic area. *Memorie della Società Geologica Italiana, 40,* 295–308.

Channell, J. E. T., & Kozur, H. W. (1997). How many oceans? Meliata, Vardar, and Pindos oceans in Mesozoic Alpine palaeogeography. *Geology, 25,* 183–186.

Chiari, M., Cobianchi, M., & Picotti, V. (2007). Integrated stratigraphy (radiolarians and calcareous nannofossils) of the Middle to Upper Jurassic alpine radiolarites (Lombardian Basin, Italy): Constraints to their genetic interpretation. *Palaeogeography, Palaeoclimatology, Palaeoecology, 249,* 233–270.

Cloething, S., & Burov, E. (2011). Lithospheric folding and sedimentary basin evolution: a review and analysis of formation mechanisms. *Basin Research, 23,* 257–290.

Cloething, S., Burov, E., & Podlachikov, Y. (1999). Lithosphere folding: Primary response to compression? (from central Asia to Paris basin). *Tectonics, 18,* 1064–1083.

Cloetingh, S. (1988). Intraplate stresses: A tectonic cause for third-order cycles in Apparent Sea Level? In *Sea-Level Changes—An Integrated Approach, Society for Sedimentary Geology (SEPM) Special Pubblication* (Vol. 42, pp. 19–28).

Cloetingh, S., Beekman, F., Ziegler, P. A., Van Wees, J. D., & Soukoutis, D. (2008). Post-rift compressional reactivation potential of passive margins and extensional basins. In H. Johnson, A. G. Doré, R. W. Gatliff, R. Holdsworth, E. R. Lundin, & J. D. Ritchie (Eds.), *The Nature and Origin of Compression in Passive Margins, London, Special Pubblication* (Vol. 306, pp. 27–70). London: Geological Society.

Cobianchi, M. (2002). I nannofossili calcarei del Giurassico medio e superiore del bacino di Belluno (Alpi Calcaree Meridionali). *Atti Ticinensi di Scienze della Terra, 43,* 3–24.

Cobianchi, M., & Picotti, V. (2001). Sedimentary and biological response to sea-level and palaeoceanographic changes of a Lower and Middle Jurassic Tethyan platform margin (Southern Alps, Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology, 169,* 219–244.

Cobianchi M. & Picotti V. (2002). The Vajont gorge section: the Toarcian to Bajocian Igne Fm and the unconformable base of the Vajont limestone. In M. Santantonio (Ed.), *6th International Symposium on the Jurassic System*, *General Field Trip Guidebook*, Palermo 12–22 settembre 2002 (pp. 310–317).

Cohen, K. M., Finney, S. C., Gibbard, P. L., & Fan, J.-X. (2013). updated) The ICS international chronostratigraphic chart. *Episodes, 36,* 199–204.

Cuvillier, J., Foury, G., & Pignatti Morano, A. (1968). Foraminiferes noveaux du Jurassique superieur du Val Cellina (Frioul Occidental, Italie). *Geologica Romana, 7,* 141–155.

D'Argenio, B., & Mindszenty, A. (1995). Bauxites and related paleokarst: Tectonic and climatic event markers at regional unconformities. *Eclogae Geologicae Helvetiae, 88*(3), 453–499.

Della, Bruna G., & Martire, L. (1985). La successione giurassica (Pliensbachiano–Kimmeridgiano) delle Alpi Feltrine (Belluno). *Rivista Italiana Paleontologia Stratigrafia, 91*(1), 15–62.

Doré, A. G., Lundin, E. R., Kuznir, N. J., & Pascal, C. (2008). Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: pros, cons and some new ideas. In H. Johnson, A. G. Doré, R. W. Gatliff, R. Holdsworth, E. R. Lundin, & J. D. Ritchie (Eds.), *The Nature and Origin of Compression in Passive Margins, London, Special Pubblication* (Vol. 306, pp. 1–26). London: Geological Society.

Erba, E., & Quadrio, B. (1987). Biostratigrafia a Nannofossili calcarei, Calpionellidi e foraminiferi planctonici della Maiolica (Titoniano superior-Aptiano) nelle Prealpi bresciane (Italia Settentrionale). *Rivista Italiana di Paleontologia e Stratigrafia, 93,* 3–108.

Ferasin, F. (1956). Scogliere dolomitiche nel Malm superiore e nel Cretacico inferiore delle Prealpi venete. *Rendiconti della Accademia Nazionale dei Lincei, classe Scienze Fisiche Matematiche e Naturali, serie 8*, 21/3-4 (pp. 193–201).

Ferasin, F. (1958). Il "Complesso di Scogliera" Cretaceo del Veneto centro-orientale. *Memorie Istituto Geologia Mineralogia Università Padova, 21,* 1–54.

Franceschi, M., Massironi, M., Franceschi, P., & Picotti, V. (2014). Spatial analysis of thickness variability applied to an Early Jurassic carbonate platform in the central Southern Alps (Italy): A tool to unravel syn-sedimentary faulting. *Terra Nova, 26,* 239–246.

Gallhofer, D., von Quadt, A., Schmid, S. M., Guillong, M., Peytheva, I., & Seghedi, I. (2017). Magmatic and tectonic history of Jurassic ophiolites and associated granitoids from the South Apuseni Mountains (Romania). *Swiss Journal of Geosciences*. doi:10.1007/s00015-016-0231-6.

Gawlick, H.-J., Aubrecht, R., Schlagintweit, F., Missoni, S., & Plašienka, D. (2015). Ophiolitic detritus in Kimmeridgian resedimented limestones and its provenance from an eroded obducted ophiolitic nappe stack south of the Northern Calcareous Alps (Austria). *Geologica Carpathica, 66,* 473–487.

Gawlick, H.-J., Frisch, W., Vecsei, A., Steiger, T., & Böhm, F. (1999). The change from rifting to thrusting in the Northern Calcareous Alps as recorded in Jurassic sediments. *Geologische Rundschau, 87,* 644–657.

Gonzalez, G., & Wetzel, A. (1996). Stratigraphy and palaeogeography of the Hauptrogenstein and Klingnau Formations (middle Bajocian to late Bathonian), northern Switzerland. *Eclogae Geologicae Helvetiae, 89*(1), 695–720.

Hillis, R. R., Sandiford, M., Reynolds, S. D., & Quigley, M. C. (2008). Present-day stresses, seismicity and Neogene-to-Recent tectonics of Australia's 'passive' margins: intraplate deformation controlled by plate boundary forces. In H. Johnson, A. G. Doré, R. W. Gatliff, R. Holdsworth, E. R. Lundin, & J. D. Ritchie (Eds.), *The Nature and Origin of Compression in Passive Margins, Geological Society, London, Special Pubblication* (Vol. 306, pp. 71–90). London: Geological Society.

Jacquin, T., Dardeau, G., Durlet, C., de Graciansky, P.-C., & Hantzpergue, P. (1998). The North Sea Cycle: An overview of 2nd order transgressive/regressive facies cycles in western Europe. In P.C. de Graciansky et al. (Eds.), *Mesozoic and Cenozoic sequence stratigraphy of European basins, SEPM Special pubblication* (vol. 60, pp. 445–466).

Johnson, H., Doré, A. G., Gatliff, R. W., Holdsworth, R., Lundin, E. R., & Ritchie, J. D. (2008). *The nature and origin of compression in passive margins, London, Special Publication* (Vol. 306, p. 200). London: Geological Society.

Loup, B., & Wildi, W. (1994). Subsidence analysis in the Paris Basin: a key to Northwest European intracontinental basins? *Basin Research, 6,* 159–177.

Manatschal, G., & Nievergelt, P. (1997). A continent–ocean transition recorded in the Err and Platta nappes (Eastern Switzerland). *Eclogae Geologicae Helvetiae, 90,* 3–27.

Mandl, G. W. (2000). The Alpine sector of the Tethyan shelf—Examples of Triassic to Jurassic sedimentation and deFm from the Northern Calcareous Alps. *Milleilungen Osterreichiske Geologische Gessels, 92,* 61–77.

Martire, L. (1996). Stratigraphy, facies and synsedimentary tectonics in the Jurassic Rosso Ammonitico Veronese (Altopiano di Asiago, NE Italy). *Facies, 35,* 209–236.

Martire, L., Clari, P., Lozar, F., & Pavia, G. (2006). The Rosso Ammonitico Veronese (Middle–Upper Jurassic of the Trento Plateau): a proposal of lithostratigraphic ordering and formalization. *Rivista Italiana Paleontologia e Stratigrafia, 112*(2), 227–250.

Masetti, D., Fantoni, R., Romano, R., Sartorio, D., & Trevisani, E. (2012). Tectonostratigraphic evolution of the Jurassic extensional basins of the eastern southern Alps and Adriatic foreland based on an integrated study of surface and subsurface data. *American Association of Petroleum Geologists (AAPG) Bulletin, 96,* 2065–2089.

Mattioli, E., & Erba, E. (1999). Synthesis of calcareous nannofossil events in Tethyan Lower and Middle Jurassic successions. *Rivista Italiana di Paleontologia e Stratigrafia, 105,* 345–376.

Mercier, J. (1966). Mouvements orogeniques et magmatisme d'age Jurassique supérieur éocrétace dansles Zones Internes des Hellénides (Macédoine, Gréce). *Revue de Géographie Physique et de Géologie Dynamique, 8,* 265–278.

Mikes, T., Christ, D., Petri, R., Dunkl I., Frei D., Baldi-Beke M., Reitner, J., Wemmer, K., Hravatovič, H., & von Eynatten H. (2008). Provenance of Bosnian Flysch. *Swiss Journal of Geosciences,* 1–24. doi:10.1007/s.00015-008-1291-z.

Müller, R. D., Yatheesh, V., & Shuhail, M. (2015). The tectonic stress field evolution of India since the Oligocene. *Gondwana Research, 28,* 612–624.

Nicosia, U., & Parisi, G. (1979). *Saccocoma tenella* (Goldfuss)—Distribuzione stratigrafica e geografica. *Bollettino della Società Palaeontologica Italiana., 18,* 320–326.

Ortner, H., Ustaszewski, M., & Rittner, M. (2008). Late Jurassic tectonics and sedimentation: breccias in the Unken syncline, central Northern Calcareous Alps. *Swiss Journal of Geosciences, Supplement, 1*(101), 55–71.

Pellenard, P., & Deconinck, J. F. (2006). Mineralogical variability of Callovo-Oxfordian clays from the Paris Basin and the Subalpine Basin. *Comptes Rendus Geoscience, 338,* 854–866.

Pellenard, P., Nomade, S., Martire, L., De Oliveira Ramalho, F., Monna, F., & Guillou, H. (2013). The first ^{40}Ar–^{39}Ar date from Oxfordian ammonite-calibrated volcanic layers (bentonites) as a tie-point for the Late Jurassic. *Geological Magazine, 150,* 1136–1142.

Picotti, V., & Cobianchi, M. (1996). Jurassic periplatform sequences of the eastern Lombardian Basin (Southern Alps). The deep-sea record of the tectonic evolution, growth and demise history of a carbonate platform. *Memorie di Scienze Geologiche, 48,* 171–219.

Picotti, V., Prosser, G., & Castellarin, A. (1995). Structures and kinematics of the Giudicarie-Valtrompia fold and thrust belt. *Memorie di Scienze Geologiche, 47,* 95–109.

Pitman, W. C., III. (1978). The relationship between eustacy and stratigraphic sequences of passive margins. *Geological Society of America Bulletin, 89,* 1389–1403.

Pittet, B., & Strasser, A. (1998). Long-distance correlation by sequence stratigraphy and cyclostratigraphy: examples and implications (Oxfordian from the Swiss Jura, Spain and Normandy). *Geologische Rundschau, 86,* 852–874.

Rais, P., Louis-Schmid, S., Bernasconi, S. M., & Weissert, H. (2007). Palaeoceanographic and palaeoclimatic reorganization around the Middle–Late Jurassic transition. *Palaeogeography, Palaeoclimatology, Palaeoecology, 251,* 527–546.

Reale, V., & Monechi, S. (1994). *Cyclagelosphaera wiedmannii* new species, a marker for the Callovian. *Journal of Nannoplankton Research, 16,* 117–119.

Reijmer, J. J. G., Mulder, T., & Borgomano, J. (2015). Carbonate slopes and gravity deposits. *Sedimentary Geology, 317,* 1–8.

Rioult, M., Dugué, O., Jan du Chêne, R., Ponsot, C., Fily, G., Moron, J.-M., et al. (1991). Outcrop sequence stratigraphy of the Anglo-Paris Basin, Middle to Upper Jurassic (Normandy, Maine, Dorset). *Bulletin des Centres Recherches Exploration- Production Elf-Aquitaine, 15,* 101–194.

Sartorio, D. (1987). Reef and open episodes on a carbonate platform margin from Malm to Cenomanian: The Cansiglio example (Southern Alps). *Memorie della Società Geologica Italiana, 40,* 91–97.

Schindler, U., & Conrad, M. A. (1994). The Lower Cretaceous Dasycladales from the Northwestern Friuli Platform and their distribution in chronostratigraphic and cyclostratigraphic units. *Revue de Paléobiologie, 46,* 59–96.

Schmid, S. M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., et al. (2008). The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss Journal of Geosciences, 101,* 139–183.

Schumacher, M. E., Schönborn, G., Bernoulli, D., & Laubscher, H. R. (1997). Rifting and collision in the Southern Alps. In O. A. Pfiffner, R. Lehner, R. Heitzmann, S. Mueller, & A. Stecks (Eds.), *Results of NFP 20 deep structure of the Swiss Alps* (pp. 186–204). Basel: Birkhäuser Verlag.

Stampfli, G. M. (2000). Tethyan oceans. In E. Bozkurt, J. A. Winchester, & J. D. A. Piper (Eds.), *Tectonics and Magmatism in Turkey and the Surrounding Area, London, Special Publications* (Vol. 173, pp. 1–23). London: Geological Society.

Stephenson, R. A., & Cloetingh, S. A. P. L. (1991). Some examples and mechanical aspects of continental lithospheric folding. *Tectonophysics, 188,* 27–37.

Tribuzio, R., Garzetti, F., Corfu, F., Tiepolo, M., & Renna, M. R. (2016). U-Pb zircon geochronology of the Ligurian ophiolites (Northern Apennine, Italy): Implications for continental breakup to slow seafloor spreading. *Tectonophysics, 666,* 220–243.

Viles, H. A., & Trudgill, S. T. (1984). Long term remeasurements of micro-erosion meter rates, Aldabra Atoll, Indian Ocean. *Earth Surface Processes Landforms, 9,* 89–94.

Vlahovič, I., Tisljar, J., Velič, I., & Matičec, D. (2005). Evolution of the Adriatic Carbonate Platform: Palaeogeography, main events and depositional dynamics. *Palaeogeography, Palaeoclimatology, Palaeoecology, 220,* 333–360.

Wetzel, A., Allenbach, R., & Allia, V. (2003). Reactivated basement structures affecting the sedimentary facies in a tectonically ‘‘quiescent’’ epicontinental basin: an example from NW Switzerland. *Sedimentary Geology, 157,* 153–172.

Winterer, E. L., & Bosellini, A. (1981). Subsidence and sedimentation on Jurassic passive continental margin. *American Association of Petroleum Geologists (AAPG) Bulletin, 65,* 394–421.

Beekman, F., Bull, J. M., Cloetingh, S., & Scrutton, R. A. (1996). Crustal fault reactivation facilitating lithospheric folding/buckling in the central Indian Ocean. In P. G. Buchanan & D. A. Nieuwland (Eds.), *Modern Development in Structural Interpretation, Validation and Modelling, London Special Publication* (Vol. 99, pp. 251–263). London: Geological Society.

Zempolich, W.G. (1993). The drowning succession in Jurassic carbonates of the Venetian Alps, Italy: a record of supercontinent breakup, gradual eustatic rise, and eutrophication of shallow-water environments. In Loucks, R.G. & Sarg, J.F. (Eds.), *Carbonate sequence stratigraphy: recent developments and applications*, *American Association of Petroleum Geologists (AAPG) Memoires*, (Vol. 57, pp. 63–105).

Zempolich, W.G. & Erba, E. (1999). Sedimentologic and chemostratigraphic recognition of third-order sequences in resedimented carbonates: the Middle Jurassic Vajont Limestone, Venetian Alps, Italy. *Society for Sedimentary Geology (SEPM) Special Pubblication* (Vol. 63, pp. 335–370).

Ziegler, P. A. (1990). *Geological Atlas of Central and Western Europe* (p. 239). The Hague: Shell Internationale Petroleum Maatschapij.