The boeotian flysch revisited: New constraints on ophiolite obduction in central Greece

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THE BOEOTIAN FLYSCH REVISITED: NEW CONSTRAINTS ON OPHIOLITE OBDUCTION IN CENTRAL GREECE

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ABSTRACT

This paper reports new data on biostratigraphy, stratigraphy and syn-sedimentary deformation of the so-called "Boeotian Flysch" cropping out in key areas in Central Greece (Levadhia, Parnassus, Iti). Because of its age, sedimentary evolution and mechanisms of the syn-sedimentary deformation, the Boeotian Flysch represents a key element providing useful hints on the Cretaceous paleogeography reconstruction of the Dinaric-Hellenic Chain and in particular on the obduction at the Jurassic-Cretaceous transition in the eastern continental margin of the Adria plate.

We provide here a new detailed study of different features of the Boeotian Flysch, with particular emphasis on reconstructing and dating its stratigraphy. In particular, we recognized two distinct turbiditic systems: the Lower Boeotian Flysch (Tithonian?-Aptian) and the Upper Boeotian Flysch (Cenomanian-Coniacian), which are separated by a main unconformity marking a sedimentary hiatus lasting from Aptian *p.p.* to Albian. By means of the improvement of the age, stratigraphy and deformation history of this syn-tectonic turbidite deposit, we therefore contribute to better define the chronology of the early phases of the continental stage of obduction, and the following continental collision between Adria and Eurasia.

The analyses of the collected data allowed us to propose for the Boeotian Flysch a deposition within an obduction-related foredeep basin associated with a flexural depression/flexural bulge due to crustal loading of westerly-directed ophiolite obduction.

INTRODUCTION

The ophiolites cropping out along the Dinaric-Hellenic collisional belt are arranged as discontinuous large bodies encompassing more than 1000 km in length along the strike of the belt (Fig. 1). The current position of these rocks onto the Adria continental crust is commonly regarded as the consequence of Early Jurassic convergence between Adria and Eurasia which eventually led to intra-oceanic subduction and finally to westward obduction of portions of the Western Tethys oceanic lithosphere onto the Adria continental margin, with strong impact on its sedimentary and structural evolution (Aubouin et al., 1970b; Bernoulli and Laubscher, 1972; Robertson and Dixon, 1984; Robertson and Shallo, 2000; Bortolotti et al., 2005; Schmid et al., 2008; Robertson, 2012; and many others). Obduction led to flexure of the underlying lithosphere that progressively controlled sedimentation into deep basins facing the advancing ophiolite slab. Basin deepening and accumulation of ophiolite-bearing mass flow deposits marked progressive ophiolite emplacement onto the Adria continental margin (Baumgartner, 1985; Thiébault and Clément, 1992; Thiébault et al., 1994; de Bono, 1998; Bortolotti et al., 2013).

In Greece the first well-developed basin characterized by ophiolite-derived sediments set in the continental margin environment is represented by the so-called Boeotian Flysch of Late Jurassic-Early Cretaceous age. Sedimentary hiatuses, syn-sedimentary deformations and high facies variability characterizing this succession can be interpreted as the beginning of deformation in the basins facing the advancing ophiolitic thrust sheet.

A detailed knowledge of the age, stratigraphy and deformation history of this syn-tectonic turbidite deposit allows definition of the chronology of the early phases of continental stage of obduction and the following continental collision between Adria and Eurasia. The ages and tectonic-stratigraphic reconstruction obtained from the Boeotian Flysch also have significance in the Cretaceous paleogeographic reconstruction of this sector of the Dinaric-Hellenic Chain.

This paper reports new data on biostratigraphy, stratigraphy and syn-sedimentary deformation concerning the Boeotian Flysch cropping out in the key areas of Levadhia, Amfikleia and Koumaritsi (Helicon, Parnassus and Iti Mountains, Central Greece; Fig. 2). The improved knowledge of the Boeotian Flysch provides more details on the obduction mechanism at the Jurassic-Cretaceous transition in the eastern continental margin of the Adria plate.

GEOLOGICAL SETTING

The Hellenides consist of two main tectono-stratigraphic domains (Brunn 1956): the "Internal Hellenides" to the east and the "External Hellenides" to the west (Fig. 1). The Internal Hellenides comprise, from east to west (Robertson and Dixon, 1984; Robertson et al., 1991; Pamić et al., 1998; Robertson, 2002; Bortolotti and Principi, 2005; Schmid et al., 2008; Bortolotti et al., 2013 and references therein): *i-* the Rhodope and the Serbo-Macedonian massifs (terranes with European affinities); *ii-* the Vardar zone, notably consisting of a complex thrust-sheet array built up by ophiolites and deep sea sediments which represents relics of the Vardar Ocean; *iii-* the Pelagonian zone (also known as Pelagonia or Pelagonian Platform), which is regarded as the eastern continental margin of the Adria Plate or as an intervening microcontinent between two oceanic basins: the Vardar

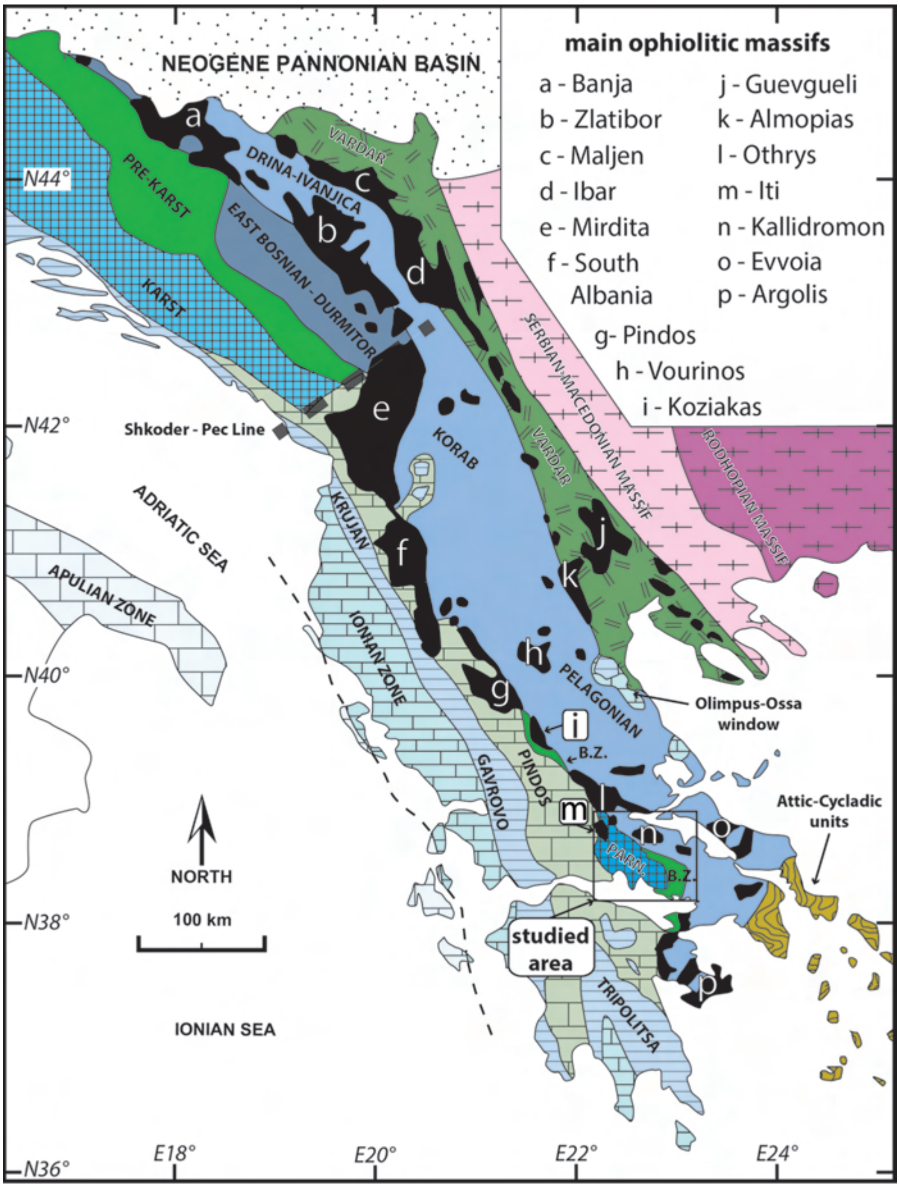

Fig. 1 - Tectonic sketch map of the Dinaric-Hellenic Orogenic Belt showing main zones and distribution of ophiolitic massifs (in solid black). B.Z.- Boeotian Zone; PARN.- Parnassus Zone (Modified after Bortolotti et al., 2013).

and the Pindos oceans, to the east and west respectively. The Internal Hellenides record widespread deformation and metamorphism of Late Jurassic-Early Cretaceous age following the westward obduction of the Vardar Ocean above the Pelagonian zone (Schermer, 1993; Most, 2003; Kilias et al., 2010). Deformations in the Internal Hellenides resulting from the obduction event were sealed by widespread carbonate sedimentation of Late Cretaceous age (Carras et al., 2004).

The External Hellenides form a west-verging fold and thrust belt of Tertiary times built up by units detached from the eastern margin of the Adria Plate. A nappe pile of Mesozoic to Paleogene carbonate sequences topped by Tertiary siliciclastic turbidite deposits characterizes these units. From east to west and from top to bottom this nappe pile includes the Parnassus, Pindos, Gavrovo-Tripolitsa and Ionian units. The External Hellenides suffered high-pressure metamorphism of Late Cretaceous-Eocene age as recorded in the Olympos-Ossa tectonic window and in the Pelion Peninsula following the westward emplacement of the Internal Hellenides (Schermer et al., 1990; Lips et al., 1998; Kilias et al., 2010).

The Jurassic ophiolite bodies of the Hellenides can be divided into an "Eastern Ophiolite Belt" (EOB) and a "Western Ophiolite Belt" (WOB) (Spray et al., 1984; Ferrière et al., 2012). Ophiolite masses of the EOB coincide with the Vardar zone and they are thrust above the eastern margin of the Pelagonian zone. Ophiolites of the WOB overthrust both onto the western margin of the Pelagonian zone and onto the Eocene turbidite deposit of the Pindos zone (Fig. 1).

Whereas a consensus exists on the location of the root zone of the EOB ophiolites in the Vardar Zone the genesis of the WOB is matter of debate. Some authors regard the WOB as rooted in the Pindos zone, implying the existence in the Jurassic times of two oceanic basins separated by the "Pelagonian Microcontinent": the Pindos Ocean to the west and the Vardar Ocean to the east (Smith et al., 1975, Smith, 1993; Robertson and Shallo, 2000; Robertson, 2002; Stampfli and Borel, 2004; Dilek et al., 2005; 2007; Saccani and Photiades, 2005; Rassios and Moores 2006; Saccani et al. 2008). Alternatively both EOB and WOB are interpreted as derived from a unique oceanic basin (i.e. the Vardar Ocean) located to the east of the Pelagonian Zone,

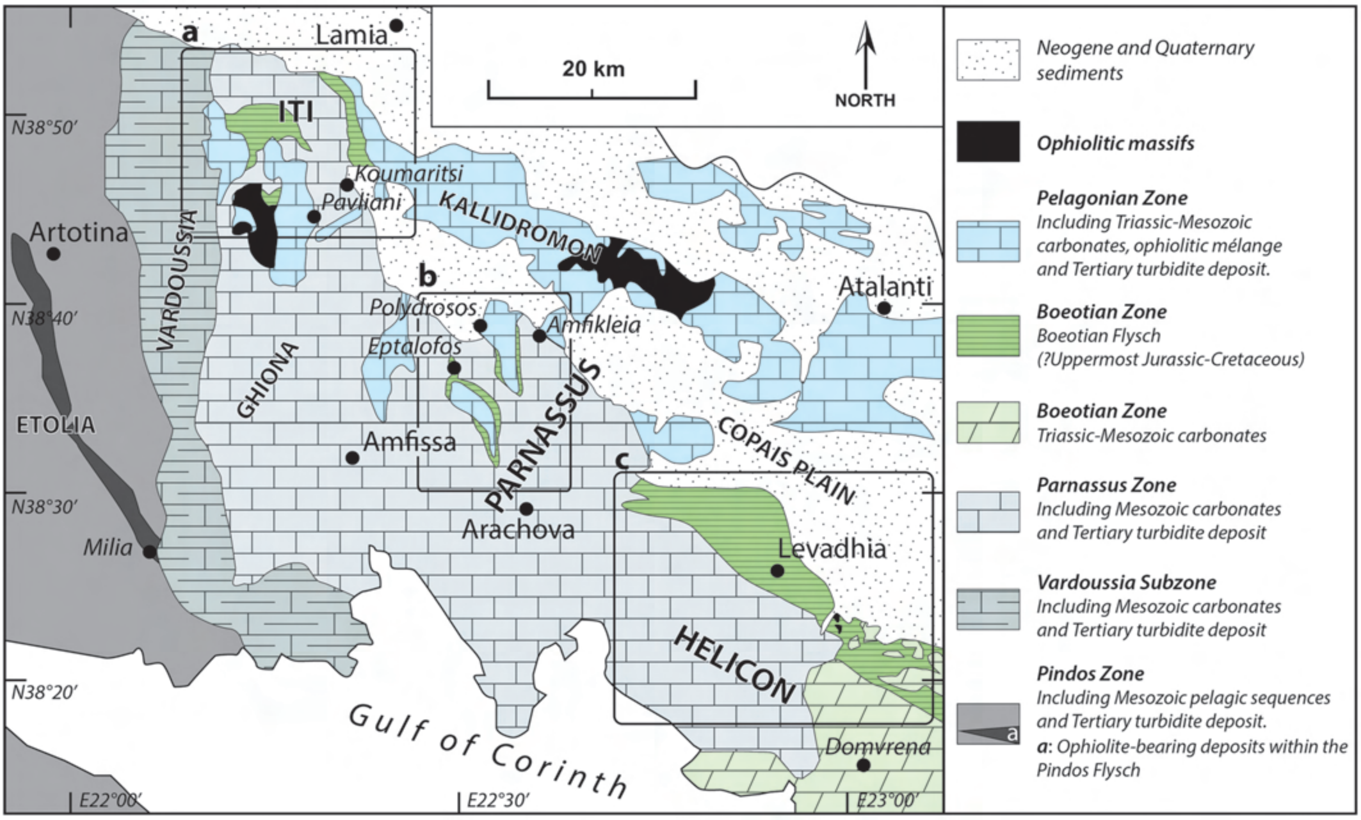

Fig. 2 - Geological sketch map of the study area (modified after Celet, 1977; Jacobshagen, 1986; Richter et al., 1996). Boxes emphasize the occurrence areas of the Boeotian Flysch (a- Iti Mountains area; b- North Parnassus area; c- Levadhia area).

which, in this hypothesis, represents the eastern margin of the Adria Plate. In this scenario, the ophiolites of WOB represent a far-travelled nappe with its roots in the Vardar Zone (Bernoulli and Laubscher, 1972; Ferrière, 1982; Ricou et al., 1998; Bortolotti et al., 2005; 2013; Schmid et al. 2008; Kilias et al., 2010; Schefer et al., 2010; Ferrière et al., 2012).

The Boeotian basin is classically located between the Pelagonian and Parnassus platforms (south of the Sperchios River) or on the eastern border of the Pindos basin to the north (Celet et al, 1976; Clément, 1977; Fleury, 1980; Robertson and Dixon, 1984; Richter et al., 1996). The position of the Boeotian Flysch between the Pelagonian and Parnassus/Pindos zones is intriguing because it represents a discriminant item in the long-lasting dispute on whether a single or multiple oceans existed between Adria and the European margin. Considering the Pelagonian sequence as a continental terrane originally located between two oceanic basins, the Boeotian Flysch would have deposited on the western tip of Pelagonia microcontinent facing to the west the Pindos oceanic basin, probably sharing an oceanic basement (Celet et al., 1976; Wigniolle, 1977b; Robertson and Degnan, 1993; Pe-Piper and Piper, 2002). On the other hand, considering the Pelagonian sequence as a Mesozoic carbonate platform located at the eastern edge of the Adria continent, the Boeotian basin would represent a foreland basin set on continental crust down-flexured after obduction tectonic (Ferrière et al., 2012; Bortolotti et al., 2013).

THE BOEOTIAN FLYSCH IN THE LEVADHIA-PARNASSUS-ITI AREA

The first reporting of a turbidite deposit of Late Jurassic-Early Cretaceous age between the internal and external units of the Dinaric-Hellenic belt (i.e. Durmitor and Prekarst thrust sheets; Fig. 1) was done by Blanchet (1966) in Bosnia. Soon after, new investigations allowed discovering new outcrops and defining the stratigraphy and chronostratigraphy of the so-called Bosnian Flysch (Charvet, 1967; Cadet, 1968; Rampnoux, 1969; Blanchet et al., 1969). The importance of the Bosnian Flysch in the paleotectonic reconstruction of the Dinarids led those authors to coin a new zone *sensu* Aubouin (1965), that is the Bosnian Zone (Blanchet et al., 1969; Blanchet, 1970; Aubouin et al., 1970a).

Similarly, the existence of a "flysch" of Early Cretaceous age was first guessed by Tataris (1967) and successively well documented by Clément (1971) in Boeotia. The report of a Tithonian-Berriasian turbidite deposit in Boeotia was the first report of a long series of outcrops running from Perachora Peninsula (Clément, 1972) to the south up to Othrys (Celet et al., 1976), Koziakas (Aubouin and Bonneau, 1977) and Pindos mountains (Terry and Mercier, 1971) to the north. Early Cretaceous mass flow deposits know as Firza Flysch were reported in the Northern Albania (south of the Shkoder-Péc Line; Dercourt, 1967) as sedimented above a sedimentary mélange (Simoni Mélange; Gardin et al., 1996) that in turn unconformably cover the Mirdita ophiolites (WOB). North of the Shkoder-Péc Line this kind of deposits only reappears again in the northernmost Albania (Vermoshi Flysch of Barremian age; Peza et al., 1990; Marroni et al., 2009) and then in Montenegro and Bosnia as equivalent to the Bosnian Flysch.

All these reports permitted to delineate the extension of the basin of the so-called Boeotian Flysch, and similarly to the Bosnian Flysch, led to definition of a new geotectonic zone located between the Pelagonian thrust sheets to the east and the Parnassus and Pindos thrust sheets to the west (i.e. the Boeotian Zone; Celet et al., 1976).

While the Parnassus carbonate platform persisted in shallow water conditions until the Late Cretaceous, the Pelagonian and Boeotian basins underwent a rapid deepening in the Late Jurassic. The neritic sedimentation in the Boeotian basin ended in the late Oxfordian-early Kimmeridgian, followed by radiolarite, red pelite and limestone that, according to Celet and Clément (1971), represent the substratum of the Boeotian Flysch in Boeotia. The onset of the turbidite sedimentation recorded along scattered outcrops from Perachora Peninsula to Pindos Mountains is late Tithonian to Berriasian and Valanginian (Terry and Mercier, 1971; Wigniolle, 1977a; Celet et al., 1976; Richter et al., 1994). After a major hiatus in the late Early Cretaceous the sedimentation resumed in the Cenomanian and lasted until the Santonian (Bléhaut, 1975; Celet et al., 1976; Wigniolle, 1977a; Rothenhöfer, 1985; Richter et al., 1996). Hierarchically, two turbiditic systems (*sensu* Mutti and Normark, 1987) are recognizable in the Boeotian Flysch separated by a main system boundary of Aptian *p.p.*-Albian age.

Unfortunately, the strong deformation characterizing all the outcrops of the Boeotian Flysch hampered precise stratigraphic descriptions. However, it is plausible that it was represented by small thicknesses (500 to 800 m) then disrupted by tectonics and scattered as small slivers between the Internal and External Hellenides.

Stratigraphy

The stratigraphic reconstruction was possible only comparing, with the aid of biostratigraphy, isolated outcrops. With the support of calcareous nannofossil biostratigraphy (Fig. 3) we report the stratigraphic reconstruction of the Boeotian Flysch cropping out in the Levadhia, Parnassus and Iti areas (Fig. 2). In particular, the outcrops along the Levadhia-Arachova road are particularly well preserved allowing a detailed description of the turbidite facies associations. Two turbiditic systems were recognized in the studied areas: an Early Cretaceous portion, for which we propose the informal name of “Lower Boeotian Flysch”, is unconformably capped by Late Cretaceous sediments representing the upper portion of the Boeotian turbidite complex. For this latter turbidite system, we propose the informal name of “Upper Boeotian Flysch”.

In the Levadhia area, the Lower and Upper Boeotian Flysch are tectonically imbricated along with Tertiary turbidite deposit and Late Cretaceous carbonate thrust sheets pertaining to the Parnassus and Boeotian zones respectively. This structural array is capped by a roof thrust underlying carbonate units of the Helicon Mountains (Parnassus and Boeotian zones). In the Parnassus and Iti areas, a similar pile consisting of Boeotian units and Tertiary turbidite deposits of the Pindos, Parnassus and Pelagonian zones, is overthrust by Pelagonian carbonates.

The Early Cretaceous Boeotian Turbidite System (Lower Boeotian Flysch - LBF)

The lithostratigraphic units of the Lower Boeotian Flysch (LBF) are described below from bottom to top.

Unit LBFa

This unit is well exposed along the Levadhia-Amfissa road cut between approximately 4.5 km west of Levadhia (N38°26’28”; E22°48’50”; Figs. 2, 9a, 10c). This outcrop was at first described by Richter et al. (1996) as *Buntpelit-Sandstein-Kalkstein* sequence.

In the Levadhia area, the observed thickness of this unit is approximately 100 m. Calcareous turbiditic beds with rhythmic bedding dominate the lower portion of the Unit (see stratigraphic column in Fig. 4). The lithologies are represented by calcarenite, marl and siliceous limestone with minor occurrences of thin ophiolite-bearing litharenite (< 15 cm). The litharenitic strata progressively increase in frequency and thickness (up to 50 cm) toward the top of the unit alternating with sandy marl and reddish carbonate-free shale and lower contents of calcarenite and thin limestone levels (< 20 cm). T_{d-e} and subordinately T_{c-e} base missing Bouma sequences characterized the carbonate-dominated turbidite strata, whereas T_{a-b} and T_b characterize the litharenitic strata. Coarse sand to conglomeratic litharenite beds represent amalgamation of different turbidite events with sometimes traction carpet structures typical of F4 facies of Mutti (1992). Presence of coal fragments (mm- to dm-sized) is common suggesting proximity to terrestrial terrigenous input and possibly direct river discharge into the basin. The sand+limestone to shale ratio is generally > 1. Those sedimentological features point to low density and high-density turbidity currents as main types of genetic flow for carbonatic and litharenitic strata respectively.

Microscopic observation of the sandstone confirms the presence of two main interacting and alternating sedimentary sources. Micrite and ultramafic rock fragments along with rare quartz and plagioclase clasts characterize the calcareous turbiditic strata. The litharenite strata mainly differ for a dominant content in ultramafic rock fragments. The ophiolite-derived clasts are usually sub-rounded to well-rounded and are affected by serpentinization and chloritization, whereas carbonate rock fragments are usually angular to sub-angular often recrystallized into sparite.

The substratum of this Unit, that is the substratum of the Boeotian Flysch, does not crop out in the studied areas. The increase in shale and limestone content and decrease of litharenite marks the gradual transition to the upper Unit LBFb.

The nannofossil assemblages of the samples from LBFa contain poorly preserved (heavily overgrown) and rare specimens of *Assipetra infracretacea*, *Calcicalathina oblongata*, *Cruciellipsis cuvillieri*, *Cyclagelosphaera* sp., *C. margerelii*, *Diazomatolithus lehmanii*, *Micrantholithus hoschulzii/obtusus*, *Eiffellithus* sp., *Retecapsa crenulata*, *Watznaueria* sp., *W. barnesae*, *W. britannica*, *Zeugrhabdotus embergeri* and very rare Nannoconids that suggest Berriasian to Valanginian ages for this unit.

Unit LBFb

Good exposures of this Unit were studied along the Levadhia-Amfissa road cut from 7 km to 10 km west of Levadhia (Fig. 2). This unit represents the most abundant Early Cretaceous facies of the Boeotian Flysch in the studied areas and its minimum thickness could be roughly estimated

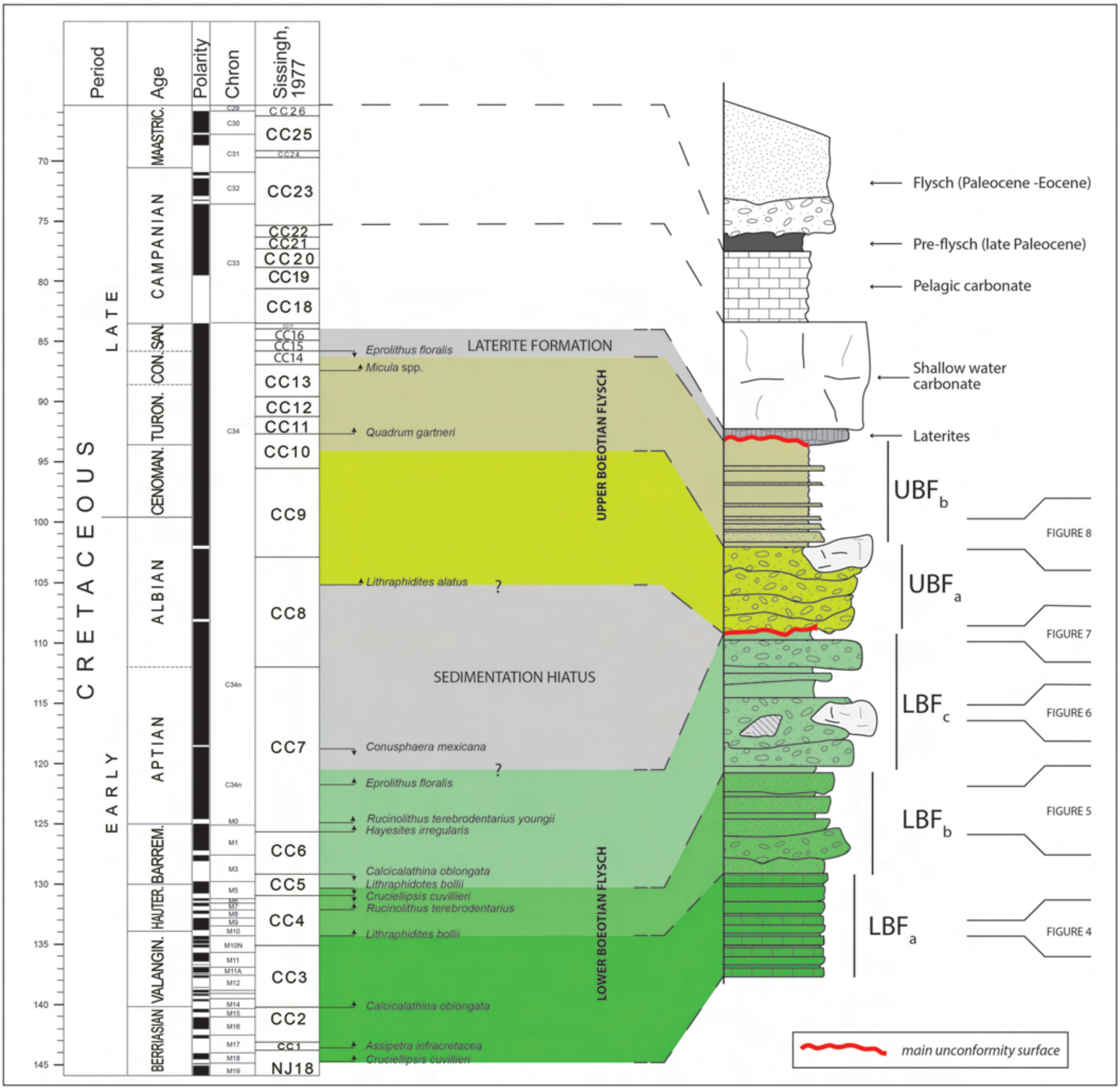

Fig. 3 - Litho-, bio-, and chrono-stratigraphy of the Boeotian Flysch in the studied localities. Age and nannofossil biostratigraphy within the studied sections are shown on the left (only diagnostic species are shown); nannofossils zonation after Sissingh (1977). On the right schematic lithostratigraphy of the Boeotian Flysch and associate Cretaceous-Tertiary units are shown along with references to detailed lithostratigraphic columns. Data concerning Late Cretaceous carbonate sedimentation from Steuber et al. (1993); data on Tertiary turbidite deposits from Richter and Risch (1981) and Richter et al. (1996). See text for details.

in more than 200 m. Lithologies consist of fine grained and thin-bedded (10 to 20 cm) calciturbidites alternating with micritic limestone, carbonate-free shale and marl (Figs. 5, 9b, 10a and b). Medium to coarse-grained sandstone, poorly cemented and with litharenitic composition has variable frequency along the unit. Coal fragments were occasionally found in the coarse-grained sandstone. Sandstones describe a fining and thinning upward sequence and are associated, mainly toward the base and the top of the unit, with cohesive debris flow deposits. These latter represent the more proximal sedimentary inputs from the advancing orogenic wedge, dominated by ophiolitic units, and are characterized by facies F1 to F3 (Mutti, 1992); then the flow is transformed either into a gravelly high density turbidity current (facies F4 of Mutti, 1992) or into a sandy high density turbidity current producing facies F8 (Mutti, 1992) which represents the litharenitic medium- to coarse-grained sandstone strata. On the other hand, calciturbidites resulted from low-density turbidite currents producing mainly T_{c-e} to T_{d-e} base missing Bouma sequences. Cohesive to granular debris flow deposits with bulk carbonatic compositions were observed in the lower part of the unit along with some metric slide blocks of Kimmeridgian-Berriasian carbonate (Richter et al., 1996). Coeval micritic limestone and shaly rip-up clasts

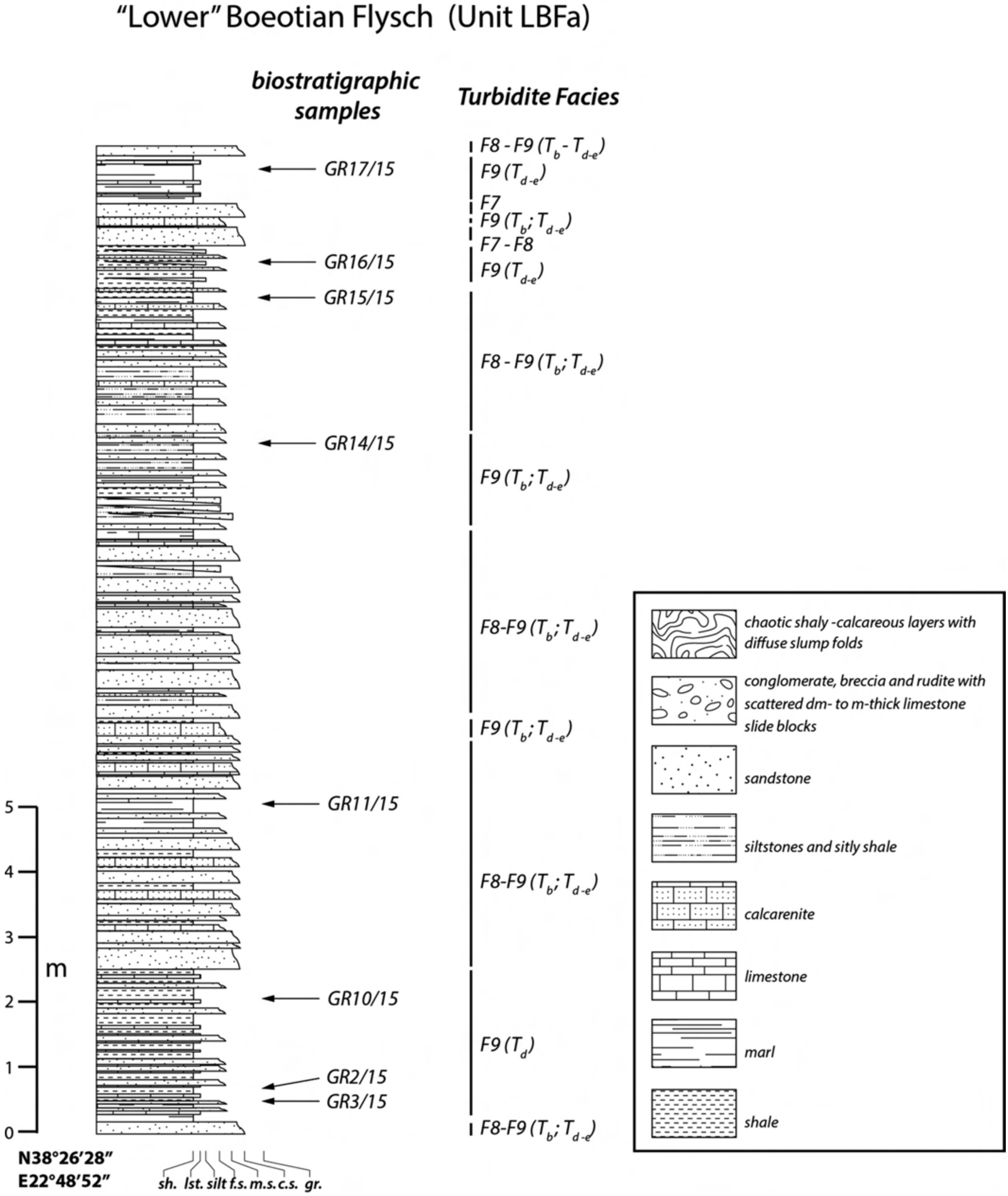

Fig. 4 - Lithostratigraphic column of Unit LBFa measured along the Levadhia-Amphissa road cut. Location of nannofossil samples and definition of the turbiditic facies (after the model proposed by Mutti, 1992) are reported on the right.

in the coarse-grained sandstone and debris flow deposits may indicate intrabasinal redeposition. The top of the unit is characterized by an increase of whitish shaly to marly levels, cohesive debris flow deposits and diffuse syn-sedimentary deformations as slumping folds, angular unconformities and normal faults, which mark the transition to the Unit LBFc. Arenite to shale ratio is < 1 in the lower part of the unit and decreases drastically upward (<< 1).

Petrographic composition of the litharenite and calcarenite is the same as described for Unit LBFa.

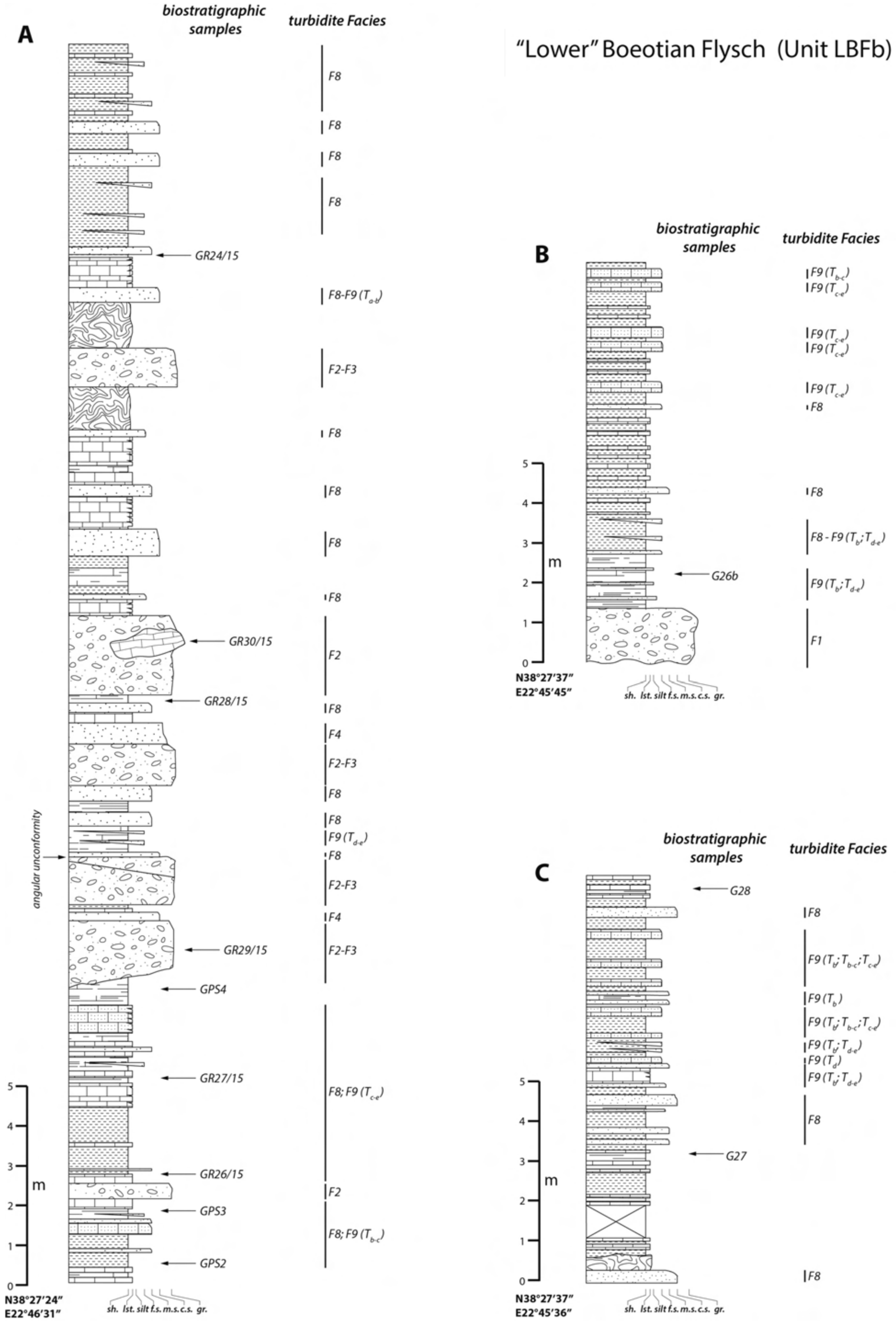

Fig. 5 - Lithostratigraphic columns of Unit LBFb measured in different locations along the Levadhia-Amphissa road cut (for lithology symbols refer to Fig. 4). Location of nannofossil samples and definition of the turbiditic facies are reported on the right.

The nannofossil assemblages found in this unit coming from different samples are represented by *Assipetra infracretacea*, *Braarudosphaera regularis*, *Calcicalathina oblongata*, *Cyclagelosphaera margerelii*, *Cruciellipsis cuvillieri*, *Diazomatolithus lehmanii*, *Lithraphidites carniolensis*, *L. bollii*, *Nannoconus steinmannii*, *Retecapsa crenulata*, *Rhagodiscus dekaenelii*, *Watznaueria barnesae*, *W. britannica*, *Zeugrhabdotus embergeri*, that indicate ages ranging from the Valanginian to the upper part of Hauterivian. The lower part of this unit was dated to middle-late Berriasian by Clément (1983) whereas Richter et al. (1996) dated the matrix of a cohesive debris flow deposit, located more or less in the same stratigraphic position, to a generic Berriasian age.

Unit LBFc

The uppermost portion of the Early Cretaceous Boeotian Flysch was observed in the Parnassus area, approximately 5 km SSW of Amfikleia (N38°35'46"; E22°33'39"; Fig. 2), 2 km north of Levadhia (N38°27'35"; E22°51'32") and on the northern slope of the Iti Mountain (N38°47'05"; E22°22'53").

The transition from Unit LBFb is marked by the almost complete disappearance of the micritic limestone and the drastic reduction of calciturbidites (see stratigraphic column in Fig. 6). This transition is accompanied by an increase of metric to plurimetric cohesive debris flow deposits representative of facies F1 to F3 (Mutti, 1992) interlayered with abundant blackish shale horizons. Clasts of the debris flow deposits consist of ultramafic and radiolarite rock fragments from the ophiolitic suite and carbonate rock fragments. Ophiolite-derived clasts are usually well rounded to sub-rounded and are locally associated with relatively delicate, terrestrial material (laterite, coal) suggesting their elaboration in a subaerial environment before redeposition in the turbidite basin (Fig. 9c). Sub-angular carbonate fragments, commonly represented by isolated coral fragments and gastropods, are locally associated with large reefal carbonate slide blocks (up to 5 m) suggesting provenance from an eroding carbonate platform. Sandstone with the litharenitic composition described in Unit LBFa and LBFb are also present showing incomplete $T_{a\text{-}b}$ Bouma sequences and gravelly dominated strata with traction carpet structures (F4 facies; Mutti, 1992). In general, the unit shows a thickening coarsening upward sequence. Arenite to shale ratio varies from << 1 in the lower part and increases up to ≥ 1 in the upper part of the unit.

The nannofossil assemblages in this unit, characterized by the occurrence of *Assipetra infracretacea*, *Braarudosphaera regularis*, *Conusphaera mexicana*, *Haqius circumradiatus*, *Helenea chiastia*, *Lithraphidites carniolensis*, *Micrantholithus obtusus/hoschulzii*, *M. spinuletus*, *Nannoconus bermudezii*, *N. minutus*, *N. steinmannii*, *Retecapsa angustiforata*, *Rhagodiscus robustus*, *Watznaueria barnesae*, *W. fossacinta*, *W.* cf *manivitae*, *Zeugrhabdotus embergeri*, allow the attribution to lower Barremian. The terminal portion of the unit, sampled just below the unconformable contact with UBF, gave nannofossil assemblages constituted by rare and poorly preserved specimens of *Assipetra infracretacea*, *Rucinolithus terebrodentarius* and *R. terebrodentarius yongii*, *Eprolithus floralis*, *Hayesites irregularis*, *Helenea chiastia*, *Lithraphidites carniolensis*, *L.* sp., *Manivitella pemmatoidea*, *Watznaueria* spp., *Zeugrhabdotus embergeri*, of lower Aptian age. The carbonate clasts collected in the debris flow deposits of early Barremian age are characterized by algae bioconstruction with presence of

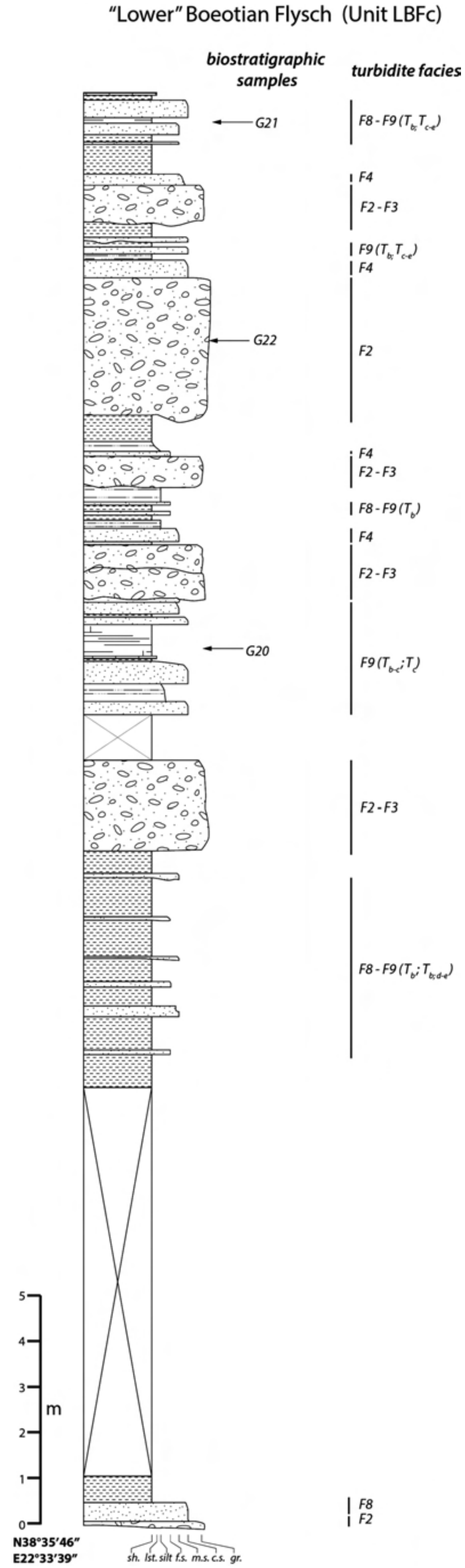

Fig. 6 - Lithostratigraphic column of Unit LBFc measured in the northern Parnassus area (for lithology symbols refer to Fig. 4). Location of nannofossil samples and definition of the turbiditic facies are reported on the right.

Thaumatoporella, Rivulariaceae, Coscinoconus alpinus LEUPOLD and *Mercierella? dacica* DRAGASTAN. This allows identifying the provenance area from a dismantling circum-reef facies of Kimmeridgian-Berriasian age.

The Late Cretaceous Boeotian Turbidite System (Upper Boeotian Flysch - UBF)

Sedimentation resumed above the Early Cretaceous Boeotian Flysch in the Cenomanian and lasted until Santonian age (Clément, 1972; Celet et al., 1976; Wigniolle, 1977a; Richter et al., 1996). These deposits are here regarded as a different turbiditic system unconformably set above the LBF after a sedimentation hiatus in the Aptian *p.p.*-Albian.

The primary contact between LBF and UBF was observed along the road connecting Pavliani to Lamia at about 1.5 km north of the Koumaritsi village (N38°47'05"; E22°22'53"; Fig. 2). The tilted strata of the Lower Boeotian Flysch, here represented by Unit LBFc, are covered by the lowermost UBF strata through an angular unconformity marked by reddish erosion surfaces (Fig. 7).

Two main lithostratigraphic units were recognized in the UBF (Unit UBFa and Unit UBFb) showing as a whole a thinning and fining upward sequence.

Unit UBFa

This unit is well exposed along the Levadhia-Amfissa road cut approximately 4.5 km west (N38°26'31"; E22°48'31"; Figs. 2, 9d-e) and in scattered outcrops in eastern slopes of the Iti mountain near Koumaritsi village.

The basal unit of the Upper Boeotian Flysch is represented by an approximately 30 m thick sequence of predominantly conglomerate alternating with shale and minor sandstone and micritic limestone layers (Fig. 8). In the Koumaritsi section (Fig. 7) the UBF starts with approximately 8 m of alternating shale and fine grained sandstone (T_d; T_{c-e}) passing upward to up than 20 meters of conglomerates arranged in a coarsening thickening upward sequence (F1-F3 facies of Mutti, 1992). Conglomerates elements consist of well-rounded ophiolitic clasts (mainly serpentinite) and fragments and entire specimen of gastropods, mollusks and corals (Fig. 9d). Metric-sized slide blocks of reefal limestone are also common (Fig. 9e).

The macrofossil association in the conglomerates in the Levadhia outcrop was studied in detail by Kollmann (1984), which attributed the section, along with the reefal limestone, to the Cenomanian. In the Aliartos area (20 km west of Levadhia), the UBFa unit overlies unconformably the Late Jurassic *Cladocoropsis*-limestone of the Boeotian zone (Steuber et al., 1993).

The nannofossil assemblages recorded in this unit allow the attribution to late Albian-Cenomanian age, as they contain common but overgrown *Lithraphidites* referable to *Lithraphidites* cf *acutus*, *L. alatus*, *L. carniolensis*, *L.* cf *pseudoquadratus*, *L.* sp., and rare *Watznaueriaceae* and *Nannoconids*.

Unit UBFb

This unit is well exposed along the Levadhia-Amfissa road cut (N38°26'34"; E22°48'24"; Fig. 2), in scattered outcrops in northern slopes of the Iti Mountain (N38°49'8"; E22°17'44") and in small tectonic sliver in the northern Parnassus (N38°36'35"; E22°29'51") slope. The visible thickness of the unit is more than 80 m.

The unit is represented by a regular succession of reddish shaly marl and ophiolite bearing sandstone and minor calcarenite and limestone. The turbiditic strata are more frequent at the base of the unit with F8-F9 and occasional F7 facies and decrease gradually toward the top of the unit

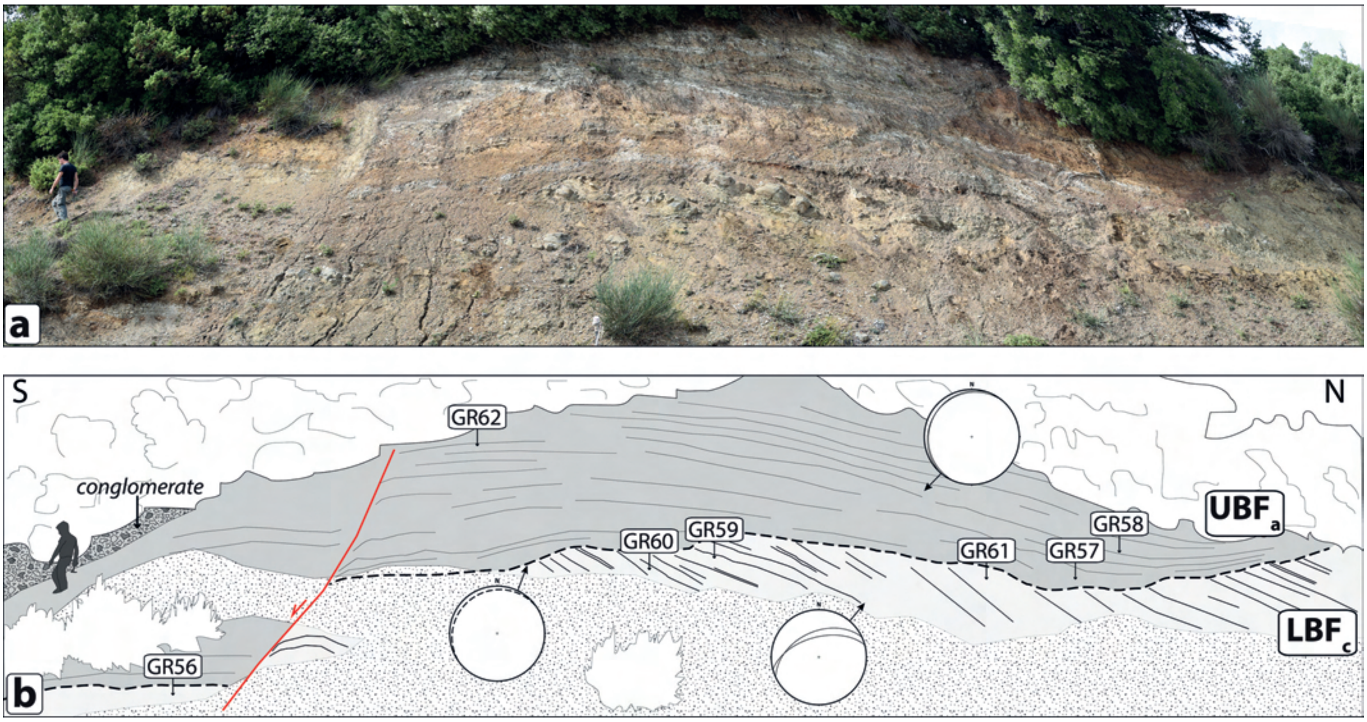

Fig. 7 - (a) Unconformity between the Lower Boeotian Flysch and Upper Boeotian Flysch north of Koumaritsi village (Mt. Iti area). (b) Line drawing with biostratigraphic sample locations. Bedding surfaces of LBFc and UBFa and main orientation of the interposed unconformity surface are shown by inset stereonets (Schmidt, lower emisphere).

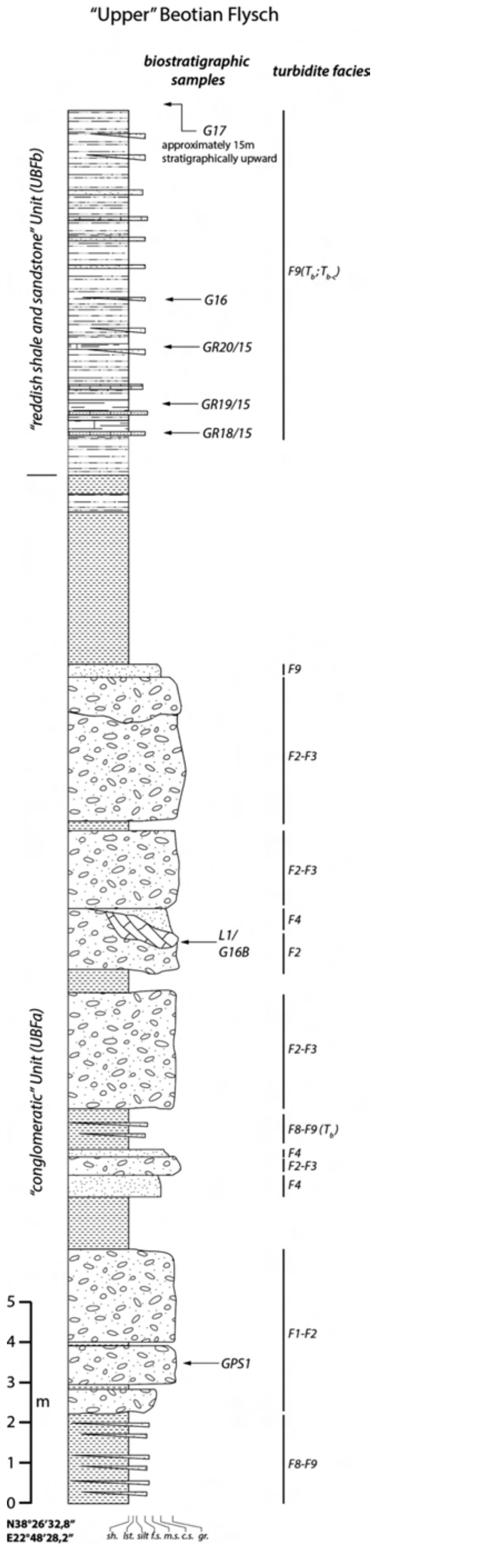

Fig. 8 - Lithostratigraphic column of Units UBFa - UBFb measured along the Levadhia-Amphissa road cut (for lithology symbols refer to Fig. 4). Location of nannofossil samples and definition of the turbiditic facies are reported on the right.

depicting a fining upward sequence (Fig. 8).

Nannofossil assemblages allow the attribution of the UBFb unit in the Levadhia area to Turonian-Coniacian age, as they contain *Cyclagelosphaera margerelii*, *Eprolithus floralis*, *Quadrum gartneri*, *Micula adumbrata*, *M.* sp., *Nannoconus* sp., *Watznaueria* spp.

The unit gradually passes in the Iti Mountain to shallow marine rudist-bearing limestone of Campanian-Maastrichtian age through the interposition of coarse limestone and ophiolite-bearing breccia of Coniacian-Santonian age (Wigniolle, 1977a). In the Levadhia area the sedimentation of shallow water limestone of late Santonian-Campanian age is preceded by subaerial exposure of the UBF with formation of silcrete and laterite horizons (Steuber, 1992; Fig. 9f).

SYN-SEDIMENTARY DEFORMATION

Though various post-deposition tectonic events affect the Boeotian Flysch, widespread syn-sedimentary deformations are still well recognizable. Those deformations are relative to different and subsequent episodes that affected the LBF from Berriasian throughout Aptian. Older extensional deformations were recognized only in units LBFa and LBFb whereas compressive structures developed in LBFc.

Slumping events (Fig. 10a), formation of local wedge shaped strata and repeated angular unconformities (Figs. 10b, 11), as well as zones of bedding disruption by fluid expulsion represent evidence of deposition of the LBFa and LBFb on a mobile sea floor.

The basal unit of the Lower Boeotian Flysch (LBFa) is affected by a well-developed system of about N-S trending normal faults, which points to syn-sedimentary tectonics. In the normal fault zone of Fig. 10c-d two sub parallel fault planes are shown. It can be noted that across the two faults the strata thickness increases downwards, whereas the strata-relative vertical throw decreases upwards (1 to 5 in Fig. 10d). This is a clear evidence of cumulated episodes of faulting during sedimentation. The eastern fault is sealed by bed 5 (Fig. 10d) whereas faulting continues on the western plane. No striae were observed on the fault planes. The diffraction at the upper fault tip shown in the figure is indicative of little confinement load due to a near surface faulting.

A more complex tectonic evolution is shown in Fig. 10b. Here the syn-sedimentary activity of normal faults led to the formation of wedge-shaped strata, erosive surfaces and angular unconformities (Fig. 11a-c).

A post-depositional deformation was detected in the uppermost portion of LBFc just before the deposition of the basal conglomerates of UBF. Well lithified LBFc sediments were tilted and extensively eroded with formation of a reddish surface exemplifying a sedimentation hiatus of Aptian-Albian age (Fig. 7). The resulting angular unconformity (30°-36°) with the above UBF sediments represents a clear evidence of a tectonic climax that ended the sedimentation within the Lower Boeotian Flysch basin.

The LBF and UBF units have been successively deformed together under a generalized compressional stress field, with development of folds and major thrusting of the LBF onto UBF (Fig. 9a), which tilted and locally reactivated the syn-sedimentary normal fault systems of units LBFa and LBFb (Fig. 11d). Syn-sedimentary fault data were processed with stereographic software to subtract the post-depositional deformations. The resulting fault attitudes point to an average E-W extension (Fig. 12).

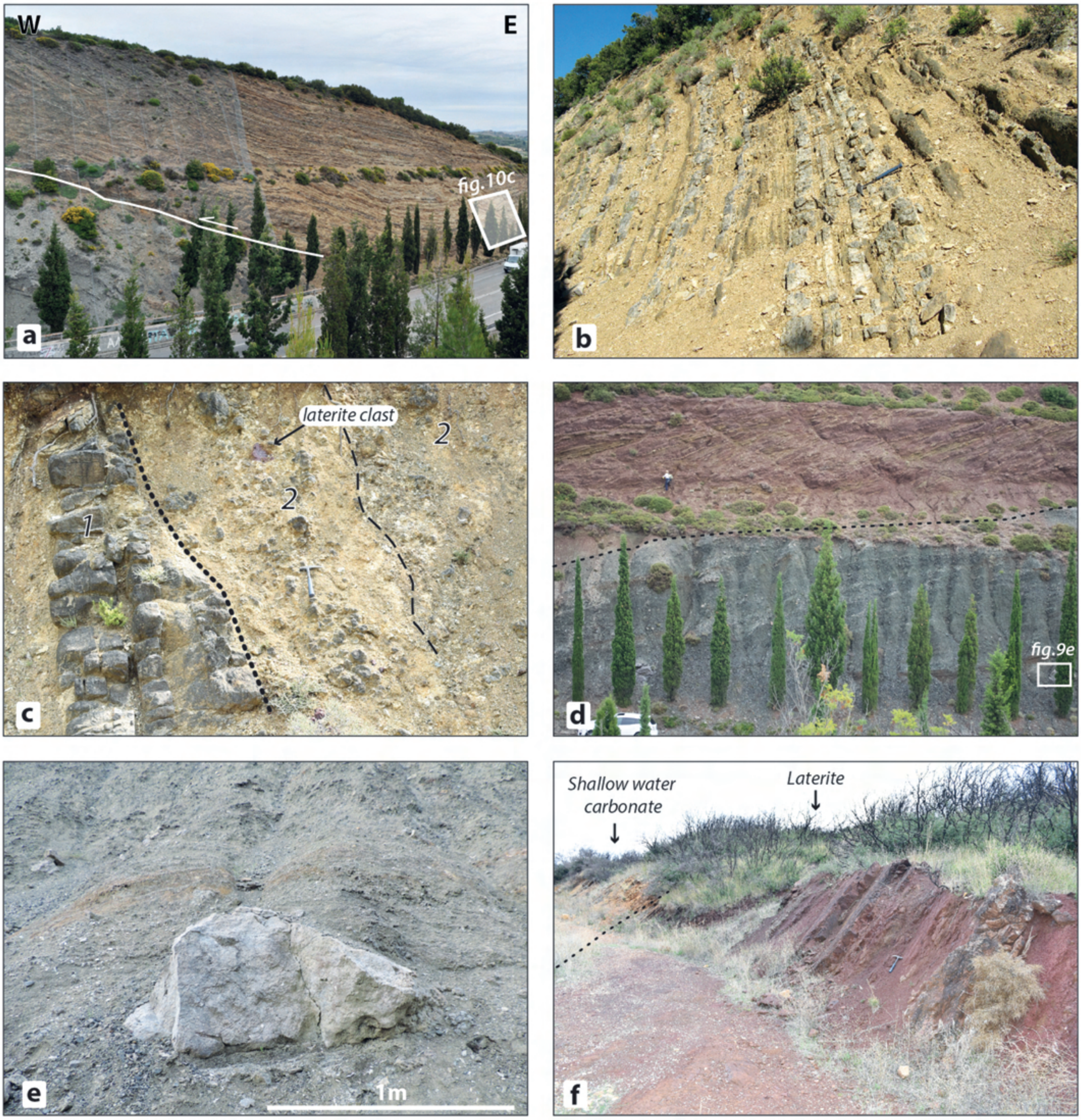

Fig. 9 - (a) Tectonic contact of the LBFa (hanging wall) and UBFb (footwall) exposed along the Levadhia-Amphissa road cut. (b) Shaly-calcareous facies of the Unit LBFb (see Fig. 5b for details). (c) Amalgamated cohesive debris flow deposits (2) of Unit LBFc showing erosive contact (dotted line) with underlying high density turbidite deposits (1). Elements of debris flow deposits are represented by shallow water limestone and less frequent terrestrial materials (laterite) embedded in abundant shaly-calcareous matrix. (d) Tectonized contact between conglomerates of Unit UBFa and reddish shaly-arenaceous facies of Unit UBFb. (e) Slide block of Cenomanian reefal limestone within conglomerates of UBFa. (f) Laterites and silcrete at the base of shallow water limestone (Late Cretaceous) unconformably overlying Unit UBFb in the Levadhia area.

DISCUSSION

The collected data on the Boeotian Flysch were compared with consolidated geological constraints from geological literature in order to contribute to the reconstruction of the tectonic and sedimentary evolution from obduction to continental collision in Central Greece. In particular the reconstructed evolution of the Boeotian basin was compared with the main events recorded in the Parnassus and Pelagonian successions.

The carbonate sequence located between the Parnassus platform to the west and the Pelagonian platform to the east could be identified as a distinct isopic zone (Boeotian Zone, Fig. 13) starting from the Middle-Late Jurassic transition (Celet et al., 1976; 1988). At that time, the compressional regime related with the inception of the intra-oceanic stage

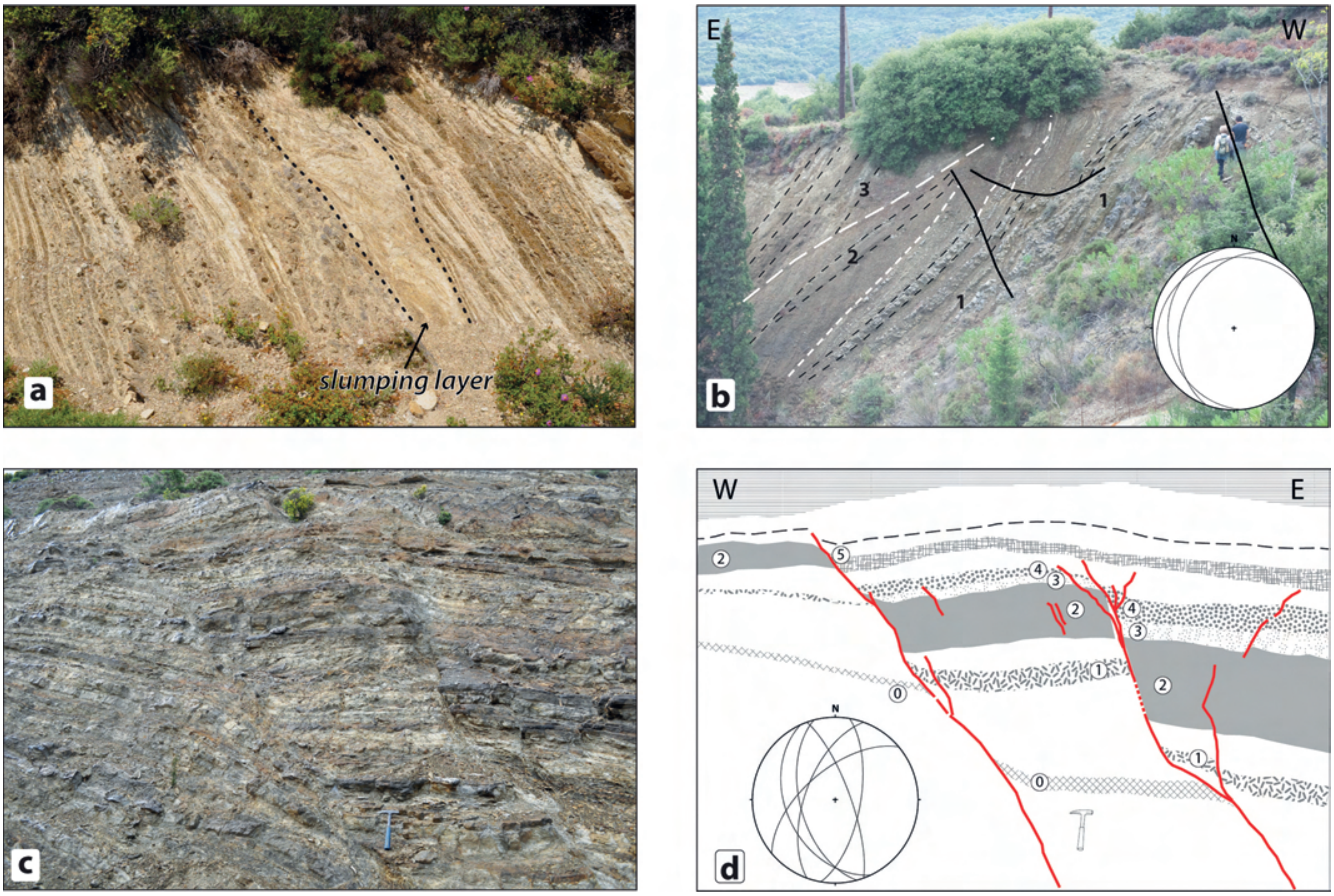

Fig. 10 - Exemplificative syn-sedimentary deformations in the Lower Boeotian Flysch. (a) Slump layer within a shaly-marly facies of Unit LBFb. (b) Normal faults (solid black lines) and associated wedge shaped strata in Unit LBFb. Stereonet shows the attitude of the normal faults in the photo. White dashed lines represent angular unconformity surfaces between strata packages 1-2 and 2-3. (c) Normal faults in Unit LBFa and (d) line drawing. The inset stereonet shows the attitude of the faults detected in Unit LBFa (Schmidt, lower emisphere). See text for explanation.

of obduction triggered the forebulge of the carbonate platform located to the west with local emersion events and formation of a bauxite horizon (b_1 bauxite horizon in the Parnassus and in more external portions of the Pelagonian platforms; Clément, 1983; Carras and Tselepidis, 2001). The uplift of the carbonate platform was accompanied by normal faulting and deepening in the more internal areas, associated with drowning of large portions of the former Pelagonian platform and final identification of a pelagic Boeotian basin between the Parnassus and Pelagonian platforms (Celet et al., 1976; Clément, 1983) (Fig. 2).

The second bauxite horizon (b_2) of late Tithonian-Berriasian age (Carras and Tselepidis, 2001) was recorded only in the Parnassus platform and is possibly related with a new tectonic pulse, as demonstrated by the high sea-level stage in this period (Haq, 2014). At the same time, pelagic conditions established progressively in the Pelagonian domain as the obducting oceanic slabs advanced onto the continental margin (Baumgartner, 1985; Baumgartner et al., 1995; de Bono, 1998). This scenario would be in accordance with the further deepening in the Boeotian basin that accompanied and assisted the onset of turbidite sedimentation.

Our data show that the Boeotian Flysch is represented by a complex array of tectonic slivers sandwiched between the Internal and External Hellenides that so far hampered precise lithostratigraphic study of the entire basin. A tentative reconstruction of the geometry and tectono-sedimentary evolution of the Boeotian Flysch was possible only by means of biostratigraphic sampling on both scattered and more continuous outcrops distributed on a large area ranging from Iti Mountains to the north up to Helicon Mountains to the south.

Biostratigraphic and detailed lithostratigraphic analyses demonstrated that two distinct turbiditic systems (LBF and UBF) exist within the classical definition of Boeotian Flysch. LBF ranges in age from Tithonian?-Berriasian up to Aptian and shows a general coarsening upward sequence along with an increasing syn-sedimentary deformation.

The onset of turbidite deposition in the studied areas is not well constrained by our data because the LBF is always detached from its substratum. However, Clément (1983) and Danelian and Robertson (1998) described an outcrop from Makariotissa Monastery north of the Dromvrena valley (Fig. 2) in which strongly deformed Tithonian to Berriasian shaly-silty sequences of the Boeotian Flysch overlie the radiolarian chert of Bathonian age which in turn overlay the neritic Triassic-Jurassic carbonate sequence of the Boeotian Zone. In summary, in spite of strong tectonic obliteration, the carbonatic units of the Boeotian zone likely represented the substratum of the turbidite deposit.

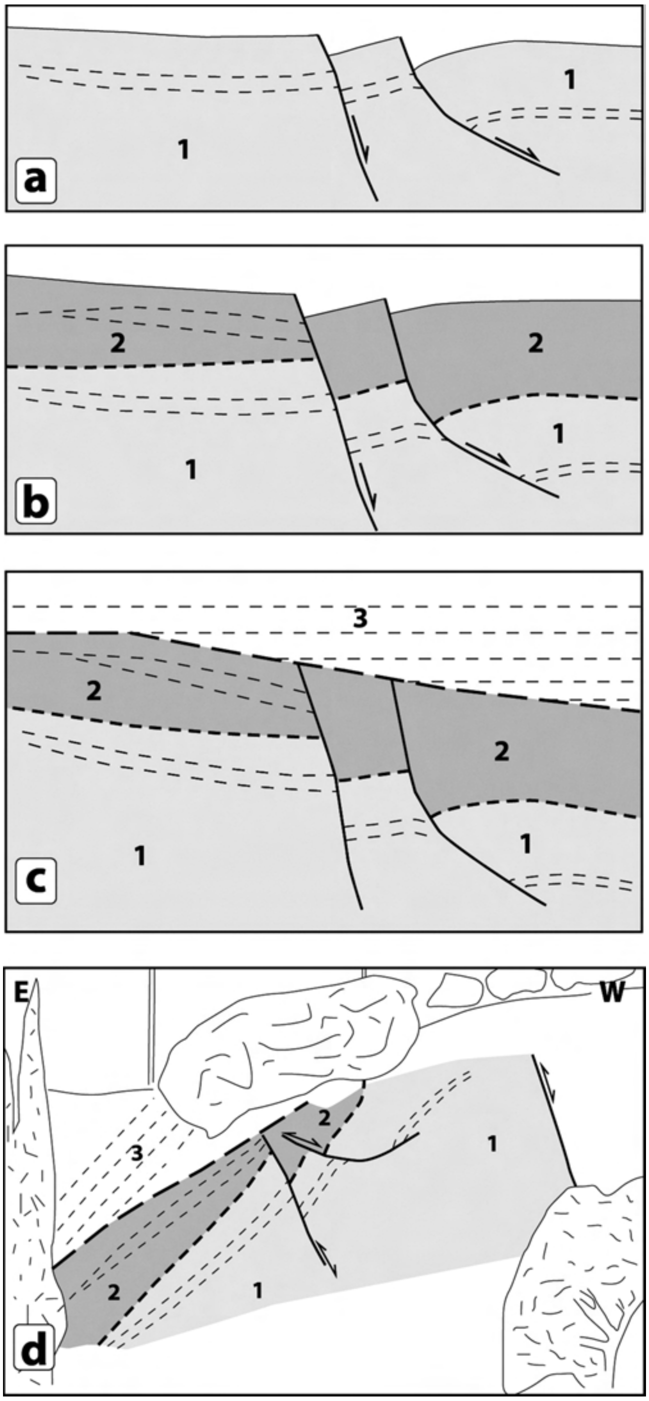

Fig. 11 - Sketch illustrating the tectonic evolution of LBFb in the outcrop of Fig. 10b. (a) Layer 1 is faulted during sedimentation with development of growth strata. (b) Layer 1 is locally eroded, and faulting continues during deposition of layer 2. (c) Layer 2 is locally eroded and then sea bottom is tilted; angular unconformity marks the passage to layer 3. (d) Post-depositional tectonics led to deformation under compressive stress and local reactivation of the former syn-sedimentary faults.

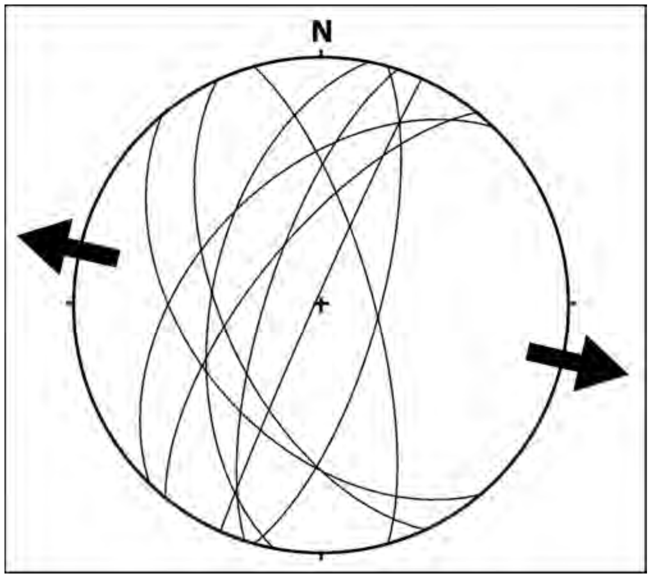

Fig. 12 - Stereonet of syn-sedimentary normal faults described in text back-tilted considering the older faulted layers as paleohorizontal surfaces. Rotations around vertical axis were not considered. The resulting fault distribution indicates extension along a roughly E-W direction (black arrows). Schmidt, lower emisphere.

Besides its structural position, the LBF sedimentation to the west of the obducting ophiolitic slab and to the east of the Parnassus Platform is also demonstrated by the westward younging of the earliest ophiolite detritus above the Pelagonian continental units (Baumgartner, 1985; Thiébault and Clément, 1992; Thiébault et al., 1994; de Bono, 1998). The trend of ophiolite-bearing debris followed the advancing of the obducting slab and reached its climax with the formation of the Boeotian Flysch. The distribution of ophiolitic debris that we observed within the LBF clearly shows a progressive increase in frequency and size toward the top (from sub-mm lithoclasts to olistoliths). Similarly, the carbonate inputs vary from calcarenites at the base (LBFa) to pebbles and metric boulder upward (LBFb and LBFc). We consider the source area of low-density calcareous turbidites located in the distal Parnassus platform that also suffered in the Early Cretaceous episodic events of emersion and erosion (e.g., bauxite horizon b_{2-3}; Carras and Tselepidis, 2001). Ophiolite-bearing mass flows and large size carbonate inputs possibly derived from ophiolitic units covered by ephemeral reefs that were immediately dismantled and redeposited onto the clastic wedge (Fig. 13a).

Some authors proposed paleogeographic models involving the presence of oceanic basins between the Parnassus and Pelagonian zones (Pindos Ocean: Jones and Robertson, 1991; Robertson et al., 1991; Sharp and Robertson, 2006) and between Parnassus and Gavrovo platforms (Kerassia-Milia Ocean: Robertson and Degnan, 1993; Pe-Piper and Piper, 2002). According to those authors, the Boeotian Flysch would have sedimented after eastward obduction of the Pindos Ophiolite onto the Pelagonian margin and so, necessarily, above obducted ophiolites. Anyway, this situation is widely in disagreement with our data and hardly reconcilable with the current structural position of the Boeotian Flysch. From a general point of view, it should be noted that in the hypothesis of an eastward Jurassic obduction event involving oceanic crust located to the west of the Pelagonian platform it should be admitted that the Pindos deep basin sequences sedimented on top of a substratum represented, even if locally, by oceanic crust. Moreover, the hypothetical marginal successions located on the western border of the Parnassus platform (Vardussia serie) and on the western margins of the Pelagonian Continent (likely represented by the Koziakas serie as stressed by Ferrière et al., 2012) would have had registered the obduction event. However, this hypothesis is disproved by the absence of ophiolites in the

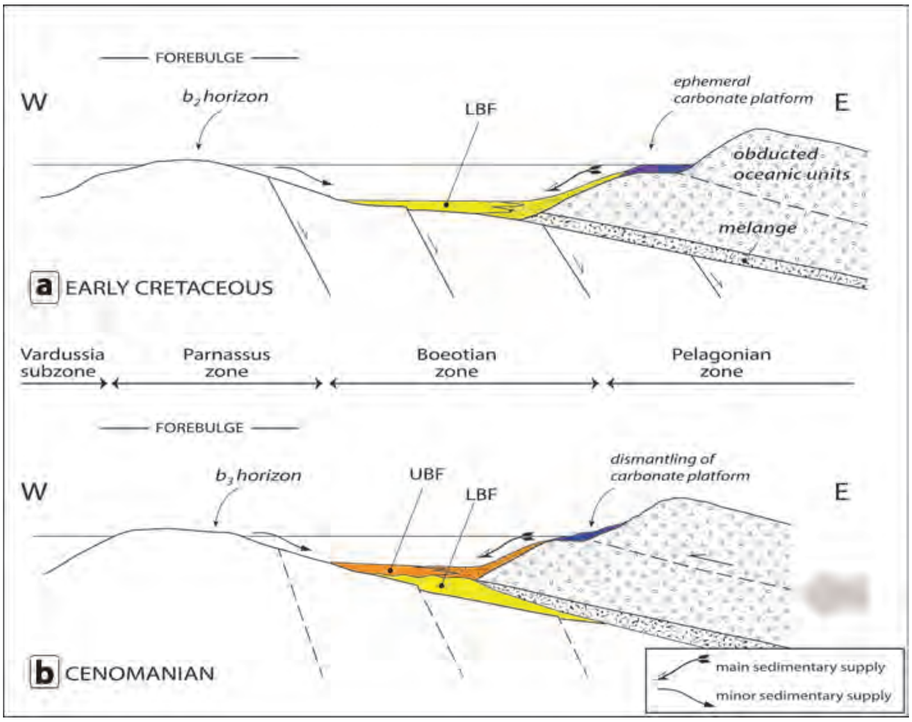

Fig. 13 - Geodynamic reconstruction of the "Boeotian Flysch" during Early Cretaceous (a) and Late Cretaceous (b). LBF: Lower Boeotian Flysch; UBF: Upper Boeotian Flysch; b_2: second bauxite horizon in the Parnassus succession; b_3: third bauxite horizon in the Parnassus succession. See text for details.

Jurassic sections of the Pindos basin and in the presumed marginal successions of Vardoussia and Koziakas (Ferrière et al., 2012). Our data agree with other evidences (see Bortolotti et al., 2013 for discussion) in favor of a westward emplacement model considering the EOB and WOB ophiolites originated from the same oceanic basin to the east (i.e. Vardar Ocean).

The older deformations that we documented in the LBF are related to development of normal faults causing differential strata thicknesses across a growth fault, local tilting of the sea bottom, angular unconformities and slump folds (Figs. 10 and 11). Those deformations are likely associated to faulting of the basin substratum in response to the load of the advancing oceanic thrust sheets (Fig. 13a). Syn-sedimentary deformation reached its climax in the Barremian-Aptian time span during deposition of Unit LBFc and was followed by tectonic deformation that stopped sedimentation of the Lower Boeotian Flysch. This tectonic phase is possibly related with renewed westward translation of the oceanic thrust sheets (Fig. 13b).

Subsequent deposition in the Boeotian through was preceded by a stage of tectonics and erosion that gave rise to a first order unconformity of Aptian *p.p.*-Albian age. A similar situation was recognized in the Bosnian Flysch, where the Early Cretaceous Vranduk Formation is separated from the Late Cretaceous Ugar Formation through a sedimentation hiatus of Albian-Cenomanian age (Mikes et al., 2008). With the same tectonic phase could be correlated the generalized emersion of the Parnassus platform that gave rise to a large sedimentation hiatus (from Aptian to at least early Turonian) and erosion, karst and bauxite deposition (b_3 bauxite horizon, Carras and Tselipidis, 2001). This important tectonic phase could be possibly related with the ongoing continental collision between Adria and Eurasia.

The lower unit of the Upper Boeotian Flysch (UBFa) still recorded the effects of tectonics as testified by redeposition of large blocks of Urgonian reef limestone onto deformed terrains of both LBF and Boeotian Zone limestone (Steuber et al., 1993). The well-rounded ophiolite pebbles and relatively delicate terrestrial clasts as laterite and coal that we observed suggest that the deposition happened through direct discharge of high-energy rivers in the turbidite basin (hyperpycnal flows).

After unit UBFa deposition, sedimentation recorded a waning sedimentary supply passing from low-density turbidite currents as the main sedimentation mechanism to a shale-dominated starved pelagic basin (unit UBFb, Turonian-Coniacian). Possibly related with renewed tectonic activity (or alternatively with short-term sea level fall; Haq, 2014) is also the local subaerial exposure of the Upper Boeotian Flysch with laterite development in the Levadhia area and deposition of coarse-grained mixed ophiolitic-carbonate breccia of Coniacian-Santonian age in the Iti Mountains (Wigniolle, 1977a). Subsequently, a generalized late Santonian-Campanian transgression flooded all the studied area (Steuber, 1992) with development of Campanian rudist-bearing platforms. Finally, from late Campanian-Maastrictian age a generalized transition from platform to pelagic conditions occurred (Steuber et al., 1993), which preceded the almost synchronous turbidite sedimentation onset of late Paleocene in the Pelagonian, Parnassus and Pindos zones (Richter and Risch, 1981; Richter et al., 1996).

The first evidence of Ophiolite existence in the Parnassus Zone is represented by post-Eocene emplacement of the ophiolitic thrust sheets in the Iti Mountains (Wigniolle, 1977a). Similarly, ophiolitic slide blocks and debris flow deposits of Eocene age recorded within the Pindos Flysch in Etolia represent the first occurrence of ophiolite in this zone (Beck, 1980; Bortolotti et al., 2009).

FINAL REMARKS

The stratigraphic and biostratigraphic data obtained from the Boeotian Flysch cropping out in Boeotia allowed us to define important hints on the reconstruction of the tectono-sedimentary evolution of the Adria continental margin during the early phases of continental stage of obduction and the following continental collision between Adria and Eurasia. The following points could be remarked:

– Two "Boeotian" turbiditic systems existed within the so-called "Boeotian Flysch" separated by a main sedimentary hiatus of Aptian *p.p.*-Albian age.
– Sedimentation of the "Lower Boeotian Flysch" started at the Jurassic-Cretaceous transition and lasted until the early Aptian. The turbiditic sedimentation in the Boeotian basin resumed with the "Upper Boeotian Flysch" in the Cenomanian and lasted until the Coniacian, then replaced by shallow marine sedimentation of Late Cretaceous age.
– The older deformation recognized in the "Lower Boeotian Flysch" testifies the existence of a tectonically active sedimentary basin characterized by widespread syn-sedimentary deformation of Early Cretaceous age. This observation, along with the widespread ophiolite bearing mass flow deposits within the Lower Boeotian Flysch, points to the presence of the nearby obducted ophiolite thrust sheet at that age.
– The end of sedimentation in the Lower Boeotian Flysch is marked by an increasing tectonic activity in the inner sectors that eventually led to dismantling of penecontemporaneous and older (Kimmeridgian-Berriasian) carbonate platforms previously set onto the obducted ophiolite slab and then resedimented in the Lower Boeotian Flysch.
– The Pelagonian Unit to the east recorded ophiolite bearing deposit depicting a westward younging trend that span from Late Jurassic to Early Cretaceous (Baumgartner and Bernoulli, 1976; Baumgartner et al., 1995), whereas to the west the Parnassus carbonate platform persisted in shallow water conditions until the Senonian.
– The Pindos and Parnassus Jurassic to Cretaceous sections do not record any evidence of ophiolite. Ophiolites in the Parnassus Mountains were overthrust only in Tertiary times after Paleocene-Eocene turbidite deposition. Similarly, the first evidence of ophiolites in the Pindos zone are represented by slide blocks and debris flow deposits of Eocene times (Bortolotti et al., 2009, Nirta et al., 2010).

Based on the above remarks we consider the Boeotian Flysch sequence deposited within an obduction-related foredeep basin associated with a flexural depression/flexural bulge due to crustal loading of westerly-directed ophiolite obduction. We also tentatively correlate the Aptian *p.p.*-Albian unconformity separating the LBF from the UBF to the ongoing continental collision between Adria and Eurasia.

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