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ORIGINAL PAPER

# Emplacement of the Jurassic Mirdita ophiolites (southern Albania): evidence from associated clastic and carbonate sediments

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**Abstract** Sedimentology can shed light on the emplacement of oceanic lithosphere (i.e. ophiolites) onto continental crust and post-emplacement settings. An example chosen here is the well-exposed Jurassic Mirdita ophiolite in southern Albania. Successions studied in five different ophiolitic massifs (Voskopoja, Luniku, Shpati, Rehove and Morava) document variable depositional processes and palaeoenvironments in the light of evidence from comparable settings elsewhere (e.g. N Albania; N Greece). Ophiolitic extrusive rocks (pillow basalts and lava breccias) locally retain an intact cover of oceanic radiolarian chert (in the Shpati massif). Elsewhere, ophiolite-derived clastics typically overlie basaltic extrusives or ultramafic rocks directly. The oldest dated sediments are calpionellid- and ammonite-bearing pelagic carbonates of latest (?) Jurassic-Berrasian age. Similar calpionellid limestones elsewhere (N Albania; N Greece) post-date the regional ophiolite emplacement. At one locality in S Albania (Voskopoja), calpionellid limestones are gradationally underlain by thick ophiolite-derived breccias (containing both ultramafic and mafic clasts) that were derived by mass wasting of subaqueous fault scarps during or soon after the latest stages of ophiolite emplacement. An intercalation of serpentinite-rich debris flows at this locality is indicative of mobilisation of hydrated oceanic ultramafic rocks. Some of the ophiolite-derived conglomerates (e.g. Shpati massif) include well-rounded serpentinite and basalt clasts suggestive of a high-energy, shallow-water origin. The Berriasian pelagic limestones (at Voskopoja) experienced reworking and slumping probably related to shallowing and a switch to neritic deposition. Mixed ophiolite-derived clastic and neritic carbonate sediments accumulated later, during the Early Cretaceous (mainly Barremian-Aptian) in variable deltaic, lagoonal and shallow-marine settings. These sediments were influenced by local tectonics or eustatic sea-level change. Terrigenous sediment gradually encroached from neighbouring landmasses as the ophiolite was faulted or eroded. An Aptian transgression was followed by regression, creating a local unconformity (e.g. at Boboshtica). A Turonian marine transgression initiated widespread Upper Cretaceous shelf carbonate deposition. In the regional context, the southern Albania ophiolites appear to have been rapidly emplaced onto a continental margin in a subaqueous setting during the Late Jurassic (Late Oxfordian-Late Tithonian). This was followed by gradual emergence, probably in response to thinning of the ophiolite by erosion and/or exhumation. The sedimentary cover of the south Albanian ophiolites is consistent with rapid, relatively short-distance emplacement of a regional-scale ophiolite over a local Pelagonian-Korabi microcontinent.

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## Introduction and regional setting

Our present understanding of the processes of ophiolite emplacement, for example, of the classic Eastern Mediterranean ophiolites (Fig. 1) comes largely from the underlying units especially the metamorphic sole and the melange beneath (e.g. Robertson 2006). However, the sedimentary covers of ophiolites can also provide important clues concerning ophiolite emplacement, including tectonic setting, palaeoenvironments and the timing of events. This paper provides new evidence from key outcrops of the Jurassic Mirdita ophiolites exposed in southern Albania (Fig. 2). Field, petrographical and palaeontological evidence will be summarised for each of the ophiolitic massifs because each one shows significantly different features. This will be followed by an overall interpretation in the light of regional comparisons. Our main aim is to provide a well-constrained body of data and interpretation that need to be taken into account in any regional model of Balkan ophiolite emplacement.

The Mirdita ophiolites of northern, central and southern Albania form part of the belt of Jurassic ophiolites that extends from the region of former Yugoslavia south-eastwards through Albania and Greece (e.g. Robertson 2002; Beccaluva et al. 2005; Bortolotti et al. 2005; Dilek et al. 2008a, b). In northern Albania, extrusive rocks of both mid-ocean ridge (MOR)-type and supra-subduction zone (SSZ)-type ophiolites are covered by radiolarian cherts that, taken together, are well dated as Late Bajocian-Early Oxfordian in age (Kellici et al. 1994; Marcucci et al. 1994; Marcucci and Prela 1996; Prela 1994; Chiari et al. 2002). In contrast, the ophiolites of southern Albania (Fig. 2) do not fall neatly into either MOR-type or SSZ-type settings but instead show more composite or "intermediate" characteristics (Hoeck et al. 2002, 2009; Koller et al. 2006; our unpublished data). Most of the ophiolitic massifs in southern Albania expose ultramafic mantle ranging from mainly lherzolitic rocks (e.g. Voskopoja), to massifs consisting only of harzburgite (e.g. Devolli) (Hoeck et al. 2009). In addition, locally exposed crustal units comprise layered and massive gabbros, sheeted dykes, basaltic extrusives and radiolarian cherts.

The ophiolitic massifs of southern Albania are covered by sequences of ophiolite-derived clastic sediments (Geological Map of Albania 1983, 2002; Shallo and Vranaj 1994). These sediments have been described as being mainly composed of serpentinite with less common basalt-derived clastic material and were dated as Tithonian-Early

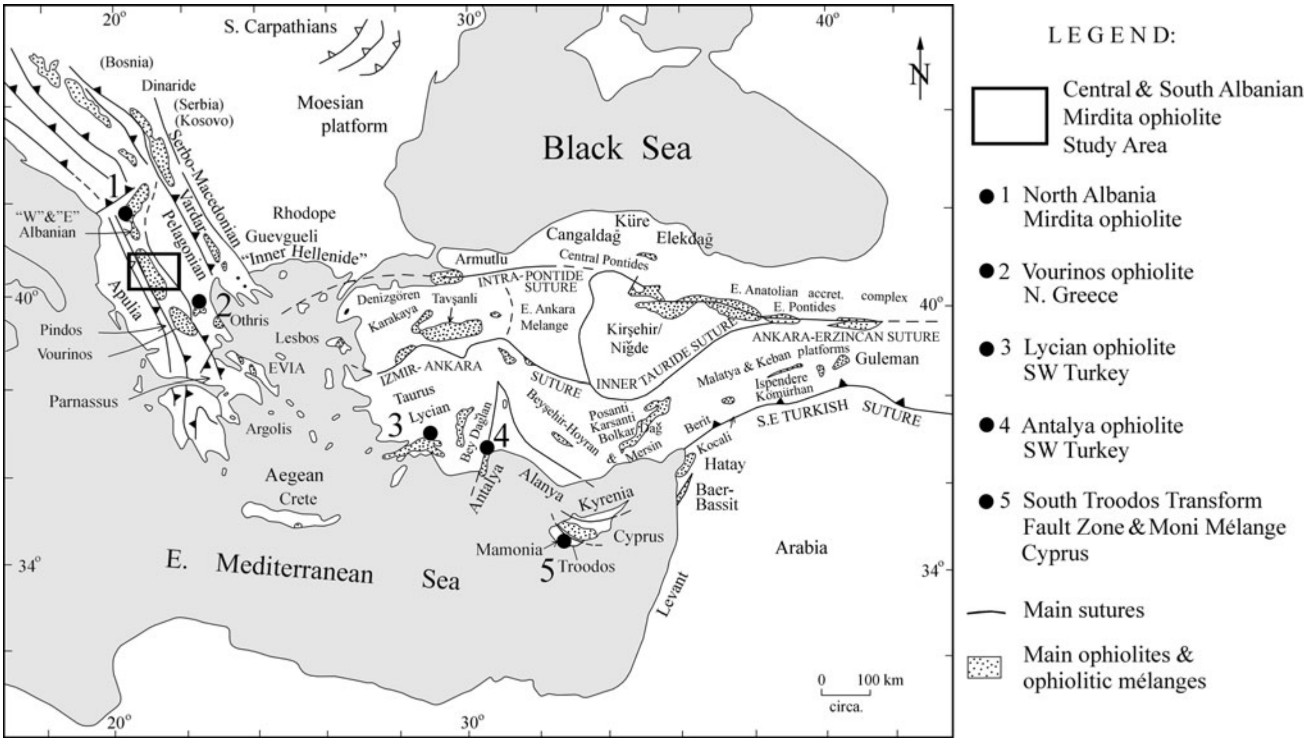


**Fig. 1** Outline tectonic map showing the main ophiolites and suture zones in the Eastern Mediterranean region. The study area in southern Albania is shown by the box. Areas characterised by ophiolite-derived clastic sediments in other areas of the Eastern Mediterranean region are numbered 1–5 and discussed in the text

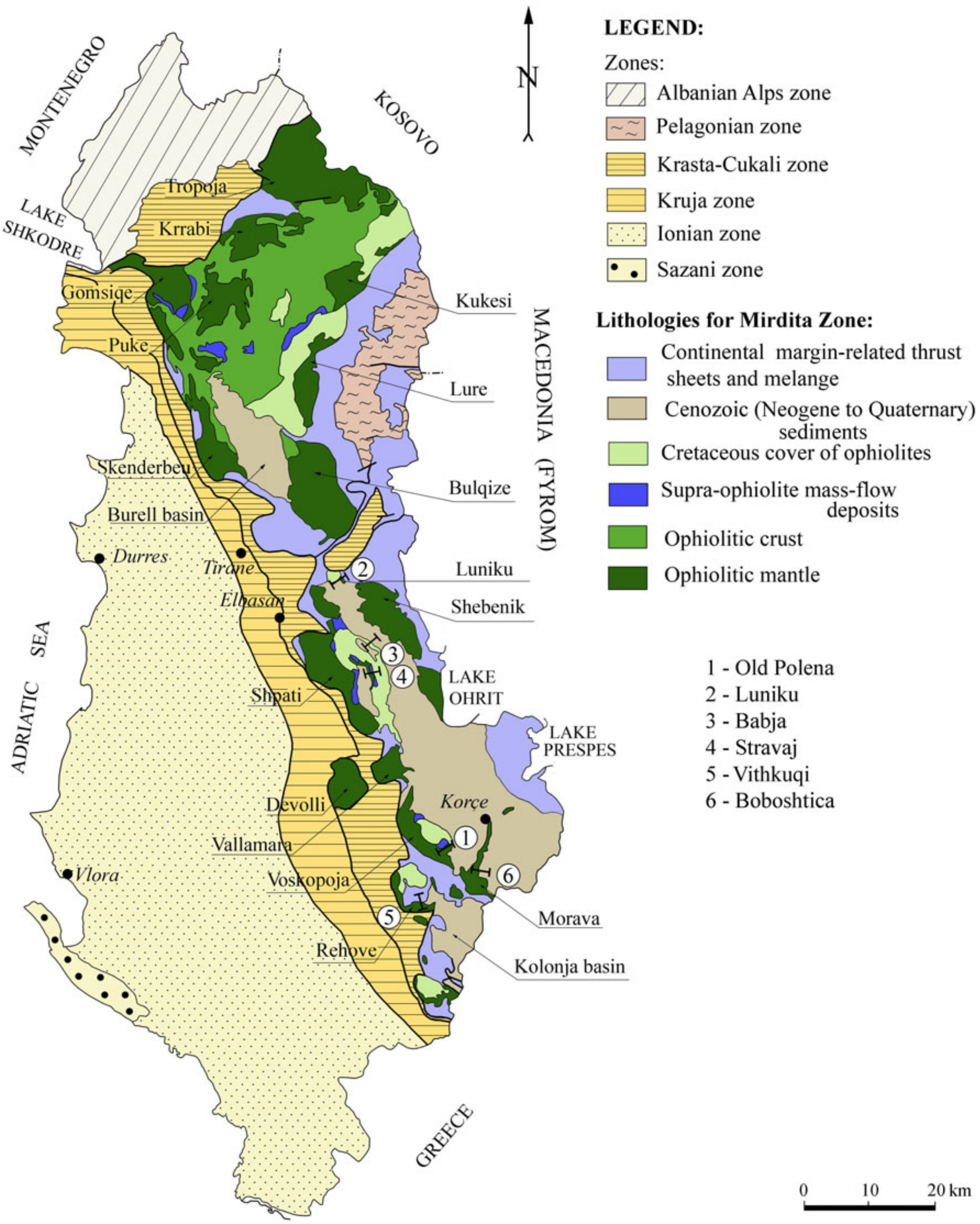


**Fig. 2** Simplified geological map showing the main tectonic units of Albania including the Jurassic ophiolites. The locations of the ophiolite-derived clastic sediments discussed here are within the boxes numbered 1–6

Cretaceous in age (Shallo et al. 1990, Shallo 1991). The clastic sediments are in turn overlain by transgressive shallow-water limestones of reportedly Barremian-Aptian age, followed by Upper Cretaceous (Turonian and younger) *Globotruncana*-bearing pelagic limestones (Peza and Theodhori 1993).

## Successions in individual ophiolite massifs

### Voskopoja ophiolitic massif

Coarse ophiolite-derived clastic sediments form a relatively large outcrop near the southern end of the Voskopoja ophiolitic massif, in the vicinity of Old Polena (Figs. 2, 3a). The clastic sequence is faulted against mylonitic lherzolite that is locally brecciated and cut by isolated dolerite dykes (Fig. 4a). Where well exposed, these coarse sediments are estimated to be ~400 m thick but may locally reach 700 m, very much more than known elsewhere. Chemical analysis shows that the clasts have MORB-like compositions suggestive of original genesis at a "normal" spreading axis (Hoeck et al. 2002, 2009; our unpublished data). The sediments at Voskopoja exhibit several unique features that are critical to any interpretation.

The breccias and conglomerates are virtually massive and unstratified, without finer-grained interbeds (Fig. 5a). Near the exposed base, the conglomerates and breccias contain a high proportion of angular, to subangular and subrounded clasts (<3 m in size) that are mainly composed of serpentinite and gabbro. Higher in the sequence, angular to subangular clasts of basalt dominate, commonly 1–5 m in size. The matrix consists of angular, poorly sorted grains of basalt, altered volcanic glass (hyaloclastite) and chlorite set in a reddish, unfossiliferous calcareous mudstone.

The coherent sequence of breccias and conglomerates is overlain by a chaotic interval (<30–50 m thick) that is dominated by irregularly shaped blocks of serpentinised ultramafic rocks and less common basalt and limestone, all embedded in a soft-weathering serpentinite matrix. Larger blocks of sheared serpentinite (up to several metres in size) characterise the base of this unit.

More stratified breccias and conglomerates (up to 150 m thick) are developed above this, dominated by angular to subangular basaltic clasts (mostly <10 cm in size). Irregular lenses of red, fine-grained limestone contain scattered serpentinite clasts (Fig. 5b). Elongate basalt clasts tend to be aligned subparallel to bedding. Breccias and conglomerates contain silt to sand-sized material composed of variable mixtures of mostly angular to subrounded grains of serpentinite and micritic limestone, plus minor basalt, altered hyaloclastite and chlorite grains set in a reddish, ferruginous micritic matrix. Rare fragments of serpentinite-derived siltstone and cataclastic serpentinite are also present.

Upwards, weakly stratified pelagic limestones are interbedded with ophiolite-derived clastic sediment. These coarse clastic rocks (~30 m thick) include lenticular slabs and irregular clasts of pink limestone (up to ~80 cm long by <25 cm thick). In thin section, one red pelagic limestone clast was seen to be packed with tightly imbricated thin-walled shell fragments (Fig. 6, no. 1), crystalline limestone grains, echinoderm debris and scattered grains of basalt, while another is dominated by curved thin-walled bivalve shells set in a pink micritic matrix. A further limestone clast contains abundant *Saccocoma* debris (Fig. 6, no. 2), calcified sponge spicules, calcified radiolarians and shell fragments in a micritic matrix rich in calpionellids.

The breccias and conglomerates are overlain by reddish-pink, argillaceous pelagic limestone. The basal contact of the limestone ranges from sharp and conformable to transitional over ~5 m vertically. The argillaceous limestones then pass upwards into purer, pink to grey pelagic limestone with nodular chert (Fig. 5c). Some of this pelagic limestone takes the form of displaced blocks (up to several tens of metres long by ~5 m thick) that are internally sheared, faulted and brecciated. Some of the blocks are mantled with limestone talus and enveloped in ophiolite-derived clastic sediments. Where the matrix to the blocks is well exposed (on steep slopes), it comprises crudely stratified matrix-supported ophiolite-derived breccias, including angular clasts of pink limestone (Fig. 5d). The ophiolite-derived breccias and conglomerates finally grade upwards into matrix-supported conglomerates (debris flows) with smaller clasts (<10 cm), interbedded with poorly lithified, thin-bedded ophiolite-derived sandstone and marl.

The pink pelagic limestones contain abundant *Calpionella alpina* and *Remaniella ferasini* belonging to the upper part of the Calpionella zone of Berriasian age that includes the *Remaniella* subzone sensu Remane et al. (1986), or the subzones Alpina and Ferasini (cf. Pop 1994, 1998; Fig. 6, nos. 3–5). An ammonite, *Berriasella jacobi*, of Early Berriasian age, was recovered from the pink pelagic limestones (A Lukender, personal communication 2010; work in progress). Locally abundant *Saccocoma* and thin-shelled pelagic bivalves ("filaments") are typical of Kimmeridgian-Early Tithonian Tethyan limestones elsewhere (e.g. Dragastan 1975; Sartorio and Venturini 1988; Michalik et al. 2009). The maximum known age range of *Saccocoma* is Oxfordian-Valanginian (Dragastan 1975). However, *Saccocoma* is best considered as an indicator of high siliceous productivity rather than a precise stratigraphic marker.

Pink limestones higher in the overall succession are also rich in benthic foraminifera including forms identified as *Choffatella decipiens, Vercorsella scarsellai* and *Montseciella arabica. Choffatella decipiens* is known from Hauterivian-Early Aptian time (Luperto Sinni 1979; Schroeder et al. 1982; Arnaud-Vanneau and Masse 1989; Masse et al. 1992), while *Vercorsella scarsellai* is Hauterivian-Albian (Brönnimann and Conrad 1968; Chiocchini et al. 1983; Luperto Sinni and Masse 1984; Arnaud-Vanneau and Premoli Silva 1995) and the orbitolinid foraminifer *Montseciella arabica* is restricted to Late Barremian-earliest Aptian (Correira et al. 1982; Baud et al. 1994). *Calamophylliopsis fotisalensis*, a coral, occurs commonly from Barremian to Aptian, while the rudist *Pchelintsevia renauxiana* (d'Orbigny) spans a similar time

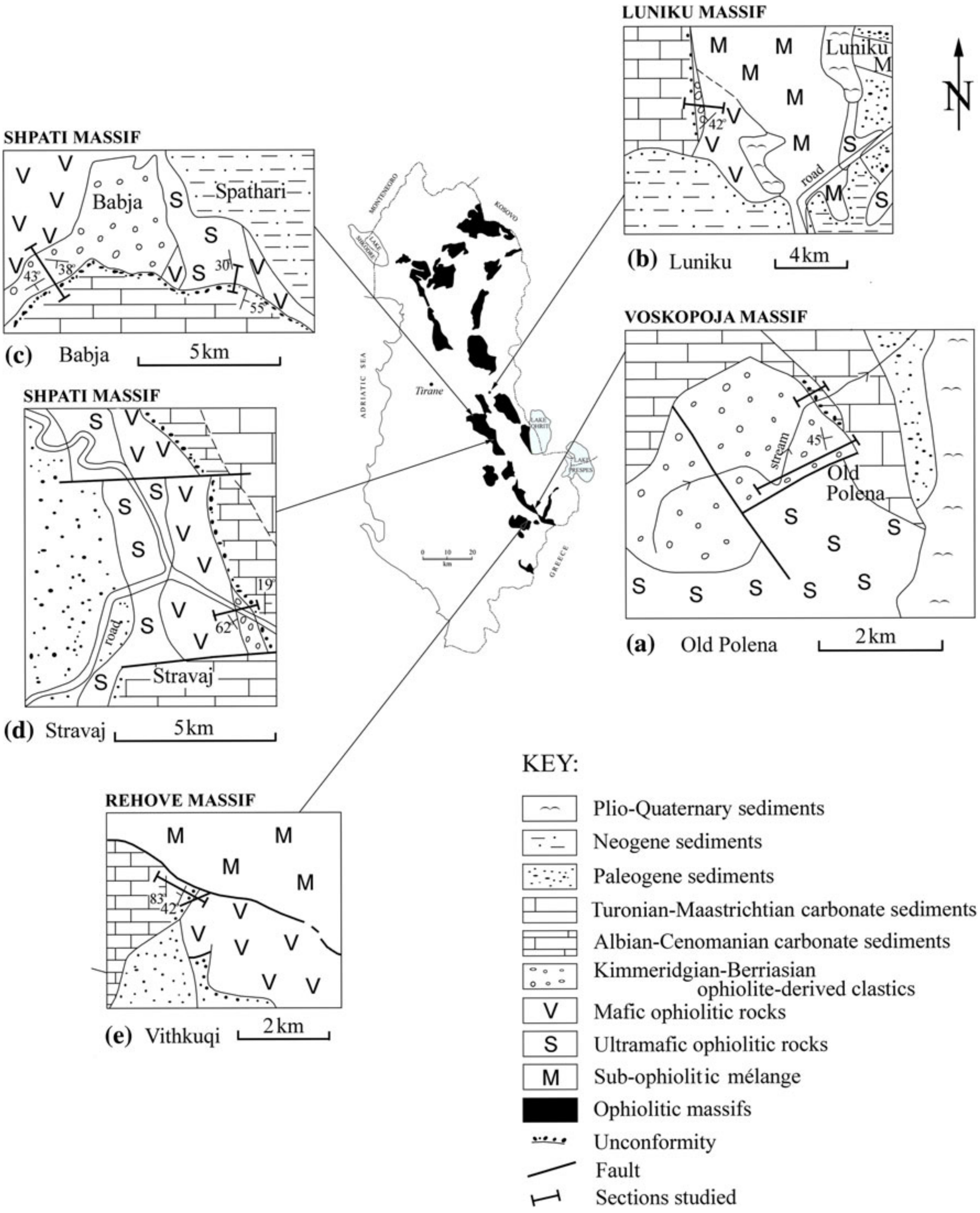


**Fig. 3** Geological sketch maps of the local areas studied based on the Geological Map of Albania (1983, 2002) and our observations. **a** Old Polena, **b** Luniku, **c** Shpati, **d** Stravaj, **e** Vithkuqi. Insert main ultramafic ophiolitic massifs in Albania

range. The limestones at Voskopoja therefore record an overall shallowing-upwards succession, probably extending from latest (?) Jurassic-Berriasian to Early Aptian, coupled with much instability and down-slope reworking.

The above succession is interrupted by a prominent unconformity marking the top of the Early Cretaceous succession. Above is a conglomerate (<20 m thick) that contains well-rounded clasts (mainly serpentinite), together with occasional reworked rudist bivalves. The succession then continues with ophiolite-derived clastic sediments interbedded with marly limestones containing Turonian neritic fossils (e.g. *Itruvia canaliculata, Hippurites requieni*, *Radiolites radiosus, R. neamonti* and *Sauvagesia charpey*) (Peza and Theodhori 1993).

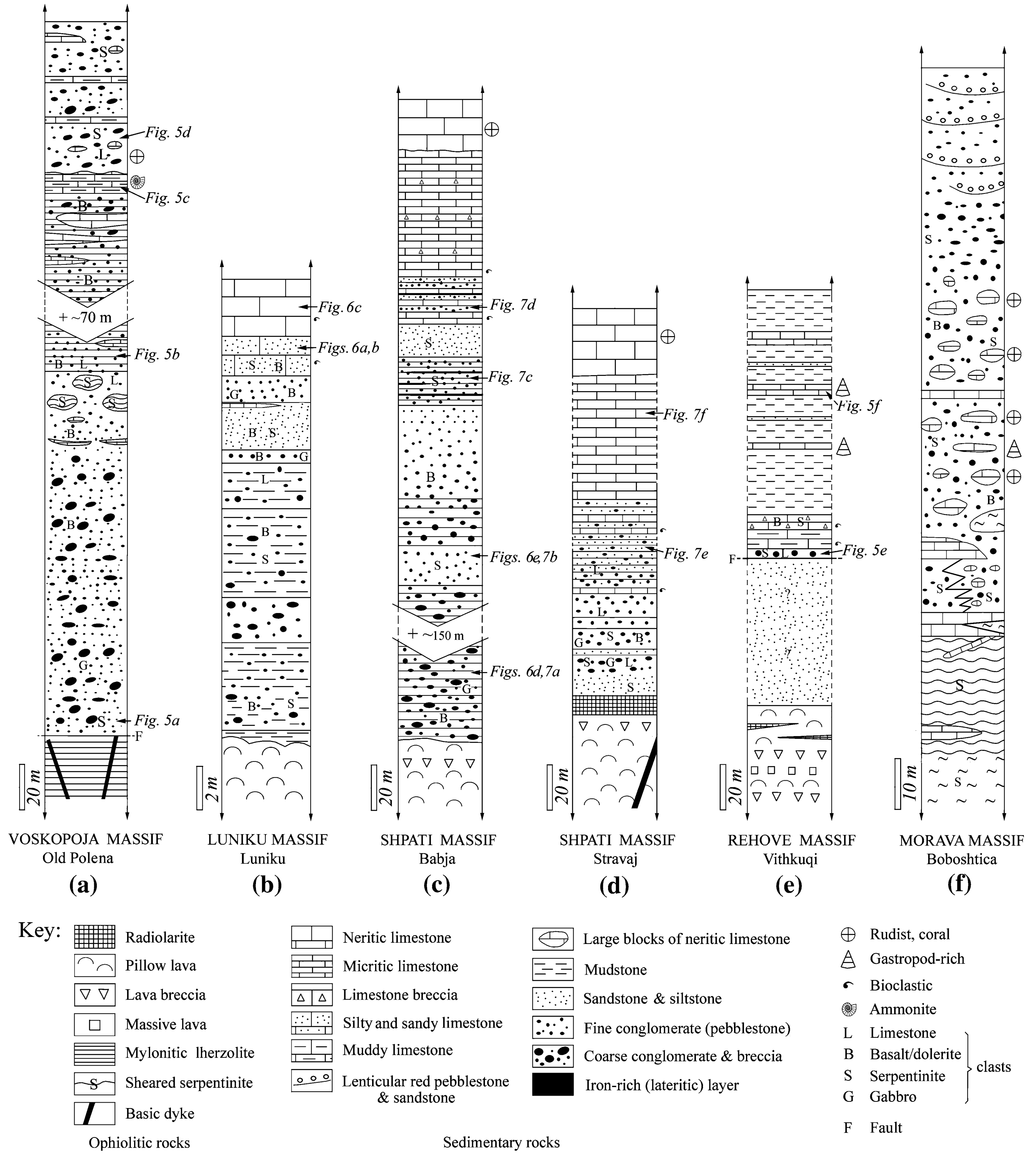


**Fig. 4** Measured logs of the ophiolite-related sediments and their younger sedimentary cover. **a** Old Polena (Voskopoja massif), **b** Luniku (Luniku massif), **c** Babja (Shpati massif), **d** Stravaj (Shpati massif), **e** Vithkuqi (Rehove massif), **f** Boboshtica (Morava massif)

## Luniku ophiolitic massif

The Luniku ophiolite is a small fault-bounded massif in the Librazhd area, near the north-western end of the Shebenik ophiolite massif (Geological Map of Albania 1983, 2002; Hoeck et al. 2007, 2009; Koller et al. 2009; Figs. 2, 3b). It exhibits a tectonically reduced sequence of mainly gabbros, sheeted dykes and basaltic, partly boninitic extrusives, cut by boninitic dykes. Exposures of the ophiolite-derived clastic sediments are restricted to small stream-cuttings on

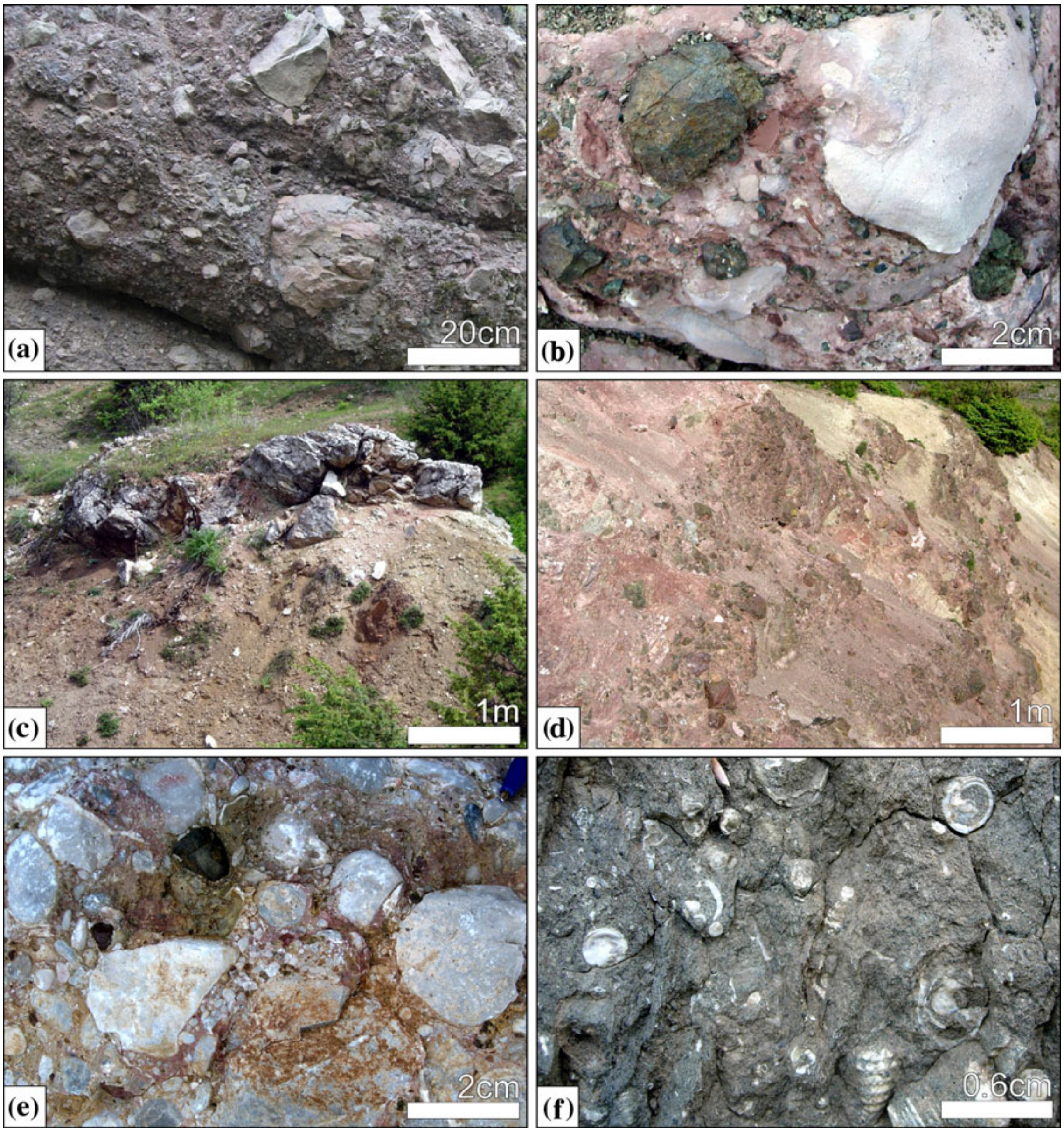
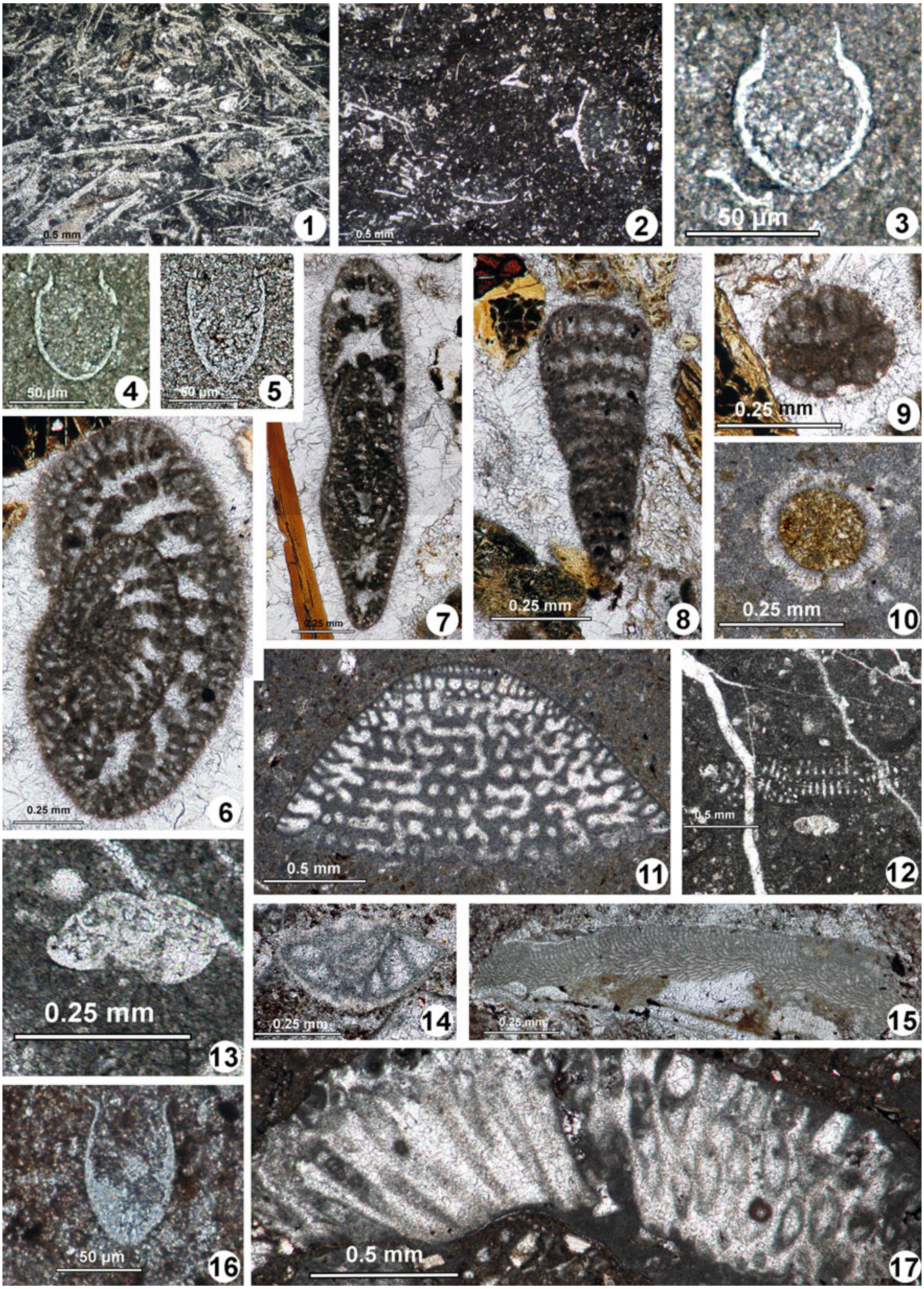


**Fig. 5** Field photographs. **a** Basalt-derived talus breccia; lower part of sequence at Old Polena (Voskopoja), **b** Basalt-derived breccia-conglomerate with a matrix of pink micrite; upper part of ophiolite-derived clastic sequence at Old Polena (Voskopoja), **c** Detached, internally deformed block of pelagic limestone within ophiolite-derived clastic sediment; near Old Polena (Voskopoja), **d** Chaotic matrix-supported ophiolite-derived mass-flows that form the matrix to the interval containing pelagic limestone blocks (see **c**), 1 km N of Old Polena (Voskopoja), **e** Lowest exposed conglomerate containing poorly sorted clasts of neritic limestone and ophiolitic lithologies (e.g. basalt; serpentinite). The matrix is rich in detrital chromite; near Vithkuqi (Rehove), **f** Calcareous silty and sandy mudstone rich in reworked gastropods; mixed carbonate-clastic succession near Vithkuqi (Rehove)

the steeply sloping northern flank of the Luniku river valley (Figs. 3b, 4b).

In one 15 m-thick section logged in detail, pillow basalt is overlain by ophiolite-derived clastic sediments, with subordinate carbonate sediments. The uppermost pillow lavas are highly altered and overlain by a chloritic layer (~1 m thick), which includes small (<10 cm) angular, to subrounded clasts of basalt, dolerite and serpentinite. A thin layer (~1 m thick) of serpentinite breccia and conglomerate follows (clasts <20 cm). The coarse clastic sediments fine upwards into pebbly conglomerate (<5 cm clasts), in which clasts are dispersed through a brown muddy matrix and then overlain by thin fissile mudstones that contain small (<10 cm) rounded, partially disaggregated pebbles of micritic limestone. Several thin iron oxide–rich horizons (<0.2 m thick) are also present. A thin



conglomerate above this includes well-rounded clasts of dolerite and gabbro (<2.5 cm in size). Overlying well-bedded ophiolite-derived sandstone (2 m thick) includes angular to rounded clasts of basalt and serpentinite set in a fine-grained clastic matrix. There are also several thin interbeds (<10 cm thick individually) of pale micritic limestone. Above comes pebbly conglomerate with small (<5 cm), well-rounded clasts of ophiolitic rocks (mainly

◀ **Fig. 6** Photomicrographs of microfossils. **1** Packstone containing thin shells of planktonic bivalves. ?Late Jurassic (Kimmeridgian-Early Tithonian); thin section A09/870, Voskopja; **2** *Saccocoma*-bearing wackestone (?Kimmeridgian-Early Tithonian); thin section A09/868, Voskopoja; **3** and **4** *Calpionella alpina* Lorenz (Early Berriasian); thin section A03/401, Voskopoja; **5** *Remaniella ferasini* (Catalano) (Early Berriasian); thin section A04/531, Voskopoja; **6** and **7** *Choffatella decipiens* Schlumberger (Hauterivian to Early Aptian); thin section A03/452, Luniku; **8** and **9** *Vercorsella scarsellai* (De Castro) (Barremian-Albian); associated with *Choffatella decipiens* in the same sample (Barremian-Early Aptian); thin section A03/452, Luniku; **10** *Salpingoporella dinarica* Radoičić (Valanginian-Aptian ?Barremian-Aptian in the sample studied); thin section A09/884, Luniku; **11** *Montseciella arabica* (Henson) (Late Barremian-Early Aptian); thin section A04/514, Luniku; **12** *Cuneolina pavonia* d'Orbigny and *Rotalipora* cf. *ticinensis* (Gandolfi) (Late Albian); thin section A09/897, Babja; **13** Rotaliporid foraminifer (*Rotalipora* cf. *ticinensis* (Gandolfi) (Late Albian); thin section A09/897, Babja; **14** *Protopeneroplis* cf. *ultragranulata* (Gorbatchik) (Middle Tithonian-Barremian); associated with other Early Cretaceous microfossils in the same sample); thin section A09/906, Shpati; **15** *Sporolithon rude* (Lemoine) (Hauterivian-Albian); associated with *Tintinnopsella carpathica* in the same sample (? Hauterivian); thin section A09/908, Shpati; **16** *Tintinnopsella carpathica* (Murgeanu and Filipescu) (Tithonian-Late Valanginian-Hauterivian); associated with *Sporolithon rude* (? Hauterivian) in the some sample; thin section A09/908, Shpati; **17** *Suppiluliumaella* sp. (?Barremian-Aptian); thin section A09/907, Shpati

gabbro and dolerite), red calcilutite and green silty limestone with abundant ophiolite-derived grains, especially chromite. Pale grey transgressive neritic limestones are exposed on inaccessible cliffs above this.

Thin sections of sediments above the ophiolitic extrusives reveal facies ranging from calcareous sandstones to sandy bioclastic limestones. The calcareous sandstones contain variable mixtures of serpentinite, dolerite, basalt, altered volcanic glass, radiolarian chert, crystalline limestone, micritic limestone, quartzite and also muscovite-schist clasts (Figs. 7a, b). The biogenic components are mainly carbonate grains including benthic foraminifera, bivalves, gastropods, echinoderm plates and spines, and also occasional ostracods. In several sections, many grains are coated with microbial carbonate ("oolitic coatings") but lack micrite (other than as detrital clasts) indicating relatively high-energy conditions. Detrital grains in the calcareous sandstones are mainly serpentinite with subordinate basalt (commonly chloritised), red- or brown-coloured, altered volcanic glass, red radiolarite, detrital crystalline limestone, micritic pellets and opaque grains (mainly iron oxide and chrome spinel). On the other hand, several sections contain abundant micrite suggestive of low-energy conditions. Detrital quartz is minimal, although scattered grains of quartzitic sandstone (litharenite) and polycrystalline quartz are present in several thin sections. The detrital grains are set in a matrix of white-, pink- or reddish-coloured micrite that is variably recrystallised to calcite spar. Occasional thin interbeds of white fine-grained micritic limestone include benthic foraminifera, curved thin shell fragments, echinoderm plates and scattered tiny angular ophiolite-derived grains (Fig. 7c).

The bioclastic limestones contain a rich assemblage of well-preserved benthic foraminifera (Table 1), including *Choffatella decipiens* of inferred Hauterivian-Early Aptian age (Fig. 6, nos. 6, 7), associated with *Vercorsella scarsellai* (De Castro) of Barremian-Albian age (see Luperto Sinni 1979; Schroeder et al. 1982; Arnaud-Vanneau and Masse 1989; Masse et al. 1992; Fig. 6, nos. 8, 9). One thin section was observed to obtain a sparse matrix including calpionellids, together with *Lenticulina* sp. and *Gaudryina* ?) sp., suggesting an earliest Cretaceous age. The neritic limestones contain the calcareous algae *Salpingoporella dinarica* of Valanginian-Aptian age (most abundant in Barremian-Early Aptian) (Granier and Deloffre 1993; Bucur 1999; Fig. 6, no. 10) and also *Montseciella arabica* (Henson) of Late Barremian-Early Aptian age (Fig. 6, no. 11). Also present is the peyssonneliacean alga, *Polystrata alba*, although this is a long-ranging form, known for example from Barremian to Oligocene (Bucur and Băluţă 1986) and latest Jurassic to Miocene (Dieni et al. 1979). Dasycladacea are locally abundant and have the potential to narrow the age range given further work. An overall Barremian-Early Aptian age is inferred for the calcareous sediments overlying the Luniku ophiolite, although as elsewhere the underlying ophiolite-derived clastics remain undated and Late Jurassic sediments may also be present. However, a previous suggestion that benthic foraminifera of Oxfordian-Kimmeridgian age are present at Luniku (Hoeck et al. 2009) was not confirmed by this study.

## Shpati ophiolitic massif

Ophiolite-related clastic sediments are exposed in the northern and central areas of the Shpati ophiolitic massif (Geological Map of Albania 1983, 2002; Figs. 2, 3c). The sections studied in these two areas differ considerably although they are located within a single, structurally intact ophiolite.

Exceptionally complete and intact successions are exposed for over ~2.5 km along strike in the north-west, between Babja and Spathari (SW of Librazhd). These ophiolite-related sediments depositionally overlie pillow basalt and lava breccia (>100 m thick) near Babja (Fig. 4c), whereas they cover ultramafic rocks further east near Spathari (Fig. 3c). In the section exposed near Babja (Fig. 4c), clastic facies (~300–350 m thick) comprise crudely bedded to massive clast-supported conglomerates that form repeated depositional units ~0.5–1 m thick. The clasts are poorly sorted and range variably from well-rounded, to subrounded, to subangular, to angular. Basalt and microdolerite predominate (Figs. 7d, 8b), together with

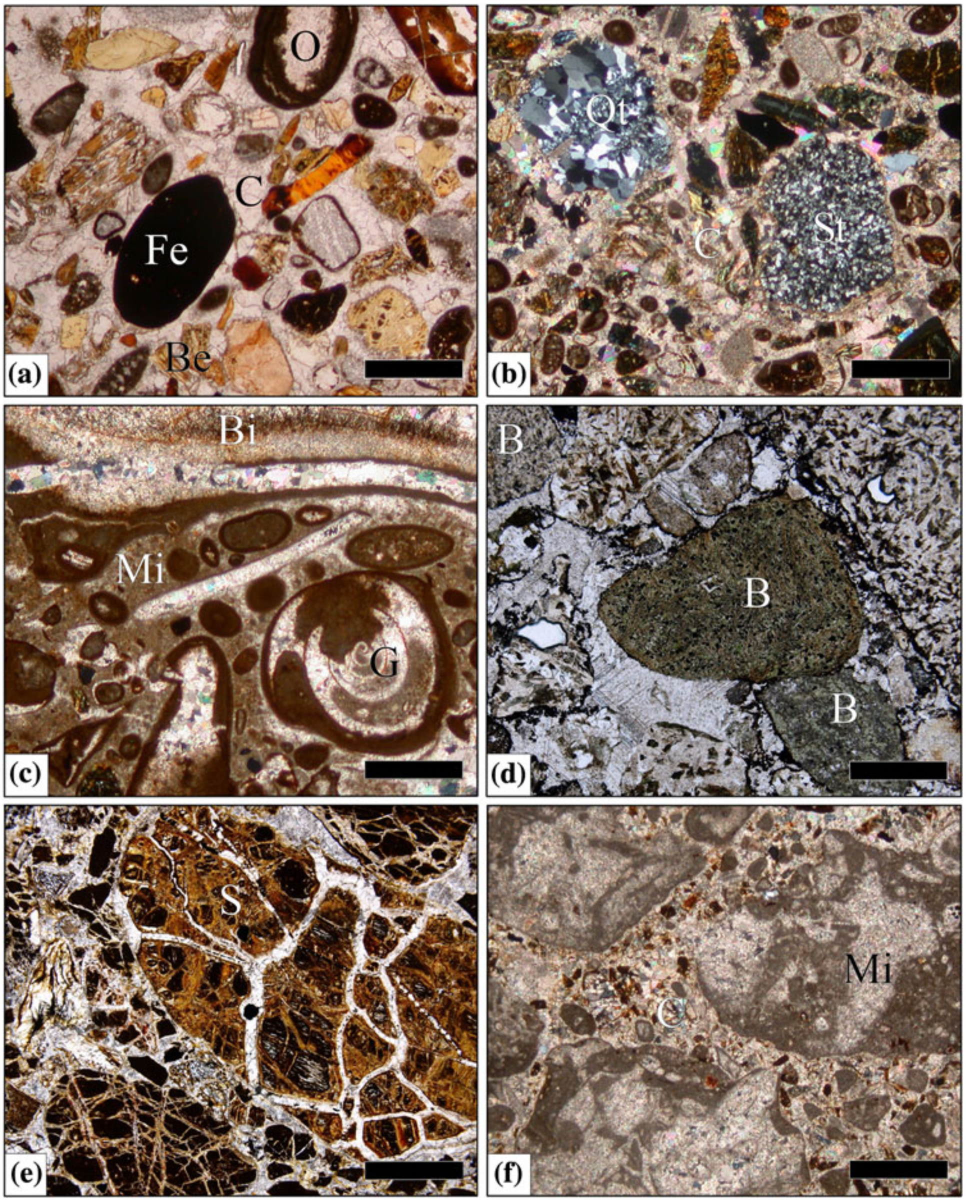


**Fig. 7** Photomicrographs of thin sections. **a** Detrital ophiolite-derived grains, including serpentinite, together with neritic grains (e.g. shells, benthic foraminifera and oolitically coated grains) and sparse grains of limestone and quartz; Lower Cretaceous; Luniku massif, **b** similar to **a**, but highlighting the occurrence of quartzose siltstone and metamorphic quartzite. Mélange as exposed beneath the ophiolite is the likely source of this relatively coarse terrigenous sediment; Luniku massif, **c** Neritic limestone with gastropods, shell fragments and pellets, all showing micritic envelopes and set in a lime mud matrix; Lower Cretaceous; Luniku massif, **d** Basalt-derived conglomerate from near the base of the succession at Babja (Shpati). Note the moderately well rounded, but poorly sorted nature of the grains, consistent with emplacement by mass-flow, **e** Serpentinite-derived conglomerate higher in the succession at Babja (Shpati). Note the relatively rounded grains and strong alteration of harzburgite, **f** Biomicrite including partially recrystallised biogenic grains, reworked in a fine packstone rich in calc-silt and biogenic grains. Such reworking is typical of the Lower Cretaceous shallow-marine to lagoonal successions; Stravaj (Shpati massif). Viewed under crossed polarisors except c (plane-polarised light). Key to letters: *B* Basalt, *Be* Benthic foram; *Bi* Bivalve (partially recrystallised), *C* Calcite spar cement, *Fe* Iron-rich pellet, *G* Gastropod, *Mi* Micritic matrix (partially recrystallised), *O* Oolitically coated shell fragment; *S* Serpentinite, *St* Siltstone lithoclast, *Qt* Quartzite lithoclast

rare gabbro, gabbro pegmatite and microgabbro. Individual clasts are mostly <20 cm across but can reach 1 m. A weak clast imbrication is rarely visible in several depositional units. Thin sections of the matrix reveal mainly basalt-derived sediments, commonly as rounded grains set in an unfossiliferous, red ferruginous muddy matrix, with the addition of a late-stage calcite spar cement.

Upwards, there is then an abrupt change to an interval of serpentinite-derived conglomerate (>20 m thick) in which clasts are smaller (<15 cm), quite well rounded and set

**Table 1** Summary of the sample numbers, sample location, fossil taxa identified and the assigned ages

| Sample | Massif | Locality | Name | Age |
|---|---|---|---|---|
| A00/187 | Voskopoja | 700 m SW Old Polena | *Saccocoma* sp. | Late Jurassic (probably Kimmeridgian-Early Tithonian) |
| A03/401 | Voskopoja | Old Polena | *Calpionella alpina* (Lorenz)<br>?*Lorenziella* sp.<br>*Tintinopsella carpathica* (Murgeanu & Filipescu)<br>*Colomisphaera carpathica* (Borza) | Early Berriasian |
| A03/406 | Voskopoja | Gores | Sclerosponge n.g | Barremian-Aptian (?) |
| A03/407 | Voskopoja | Gores | *Berriasella jacobi* | Early Berriasian |
| A03/452 | Luniku | W-slope | *Vercorsella scarsellai* (De Castro)<br>*Choffatella decipiens* (Schlumberger)<br>?*Everticyclammina* sp.<br>*Mayncina* sp. | Barremian-Aptian |
| A04/511 | Luniku | W-slope | *Vercorsella scarsellai* (De Castro)<br>*Choffatella decipiens* (Schlumberger)<br>*Terquemella* sp. | Barremian-Aptian |
| A04/512 | Luniku | W-slope | *Choffatella decipiens* (Schlumberger)<br>*Vercorsella scarsellai* (De Castro)<br>*Vercorsella* sp.<br>?*Ammobaculites* sp.<br>*Spiroloculina* sp. | Barremian-Aptian |
| A04/514 | Luniku | W-slope | ?*Reophax* sp.<br>*Vercorsella scarsellai* (De Castro)<br>*Montseciella arabica* (Henson) | Late Barremian-Early Aptian |
| A04/531 | Voskopoja | Old Polena | *Calpionella alpina* Lorenz<br>*Remaniella ferasini* (Catalano)<br>*Colomisphaera carpathica* (Borza) | Early Berriasian |
| A04/535 | Voskopoja | Gores | Branching coral n.g. | Barremian-Aptian (?) |
| A06/635 | Voskopoja | Gores | *Calamophylliopsis fotisalensis* (Bendukize) | Barremian-Aptian |
| A09/857 | Morava | | *Pchelintsevia renauxiana* (d'Orbigny) | Late Barremian-Early Aptian |
| A09/868 | Voskopoja | Gores | *Saccocoma* sp. | Late Jurassic (probably Kimmeridgian-Early Tithonian) |
| A09/870 | Voskopoja | Gores | "Filaments" | Late Jurassic (probably Kimmeridgian-Early Tithonian) |
| A09/872 | Voskopoja | Gores | *Pchelintsevia renauxiana* (d'Orbigny) | Late Barremian-Early Aptian |
| A09/873 | Voskopoja | Gores | *Vercorsella* sp.<br>*Terquemella* sp.<br>*Koskinobulina socialis* (Cherchi & Schroeder) | Probably Early Cretaceous |
| A09/874 | Rehove | | Nerinea | ?Barremian |
| A09/881 | Rehove | | *Paraglauconia lujani* (Verneuil) | Early Aptian |
| A09/884 | Luniku | Western slope | *Carpathoporella* sp.<br>*Choffatella decipiens* (Schlumberger)<br>?*Mayncina* sp.<br>*Commaliama* sp.<br>*Nezzazatinella* sp.<br>*Textularia* sp.<br>*Glomospira* sp.<br>Miliolids<br>*Salpingoporella dinarica* (Radoicic)<br>*Salpingoporella* cf. *muehlbergii* (Lorenz) | Barremian-Aptian |

**Table 1** continued

| Sample | Massif | Locality | Name | Age |
|---|---|---|---|---|
| A09/894 | Shpati | Babja | ?*Coscinophragma* sp.<br>Dasyclad green algae<br>*Polystrata alba* (Pfender) | Probably Early Cretaceous |
| A09/895 | Shpati | Babja | *Lenticulina* sp.<br>?*Gaudryina* sp.<br>Very rare sections of calpionellids | Probably basal Cretaceous |
| A09/897 | Shpati | Babja | Mixing of planktonic and benthic foraminifera<br>?*Rotalipora* cf. *ticinensis* (Gandolfi)<br>?*Rotalipora* sp.<br>*Cuneolina pavonia* (d'Orbigny)<br>?*Moncharmontia* sp. | ?Late Albian to ?Coniacian |
| A09/906 | Shpati | Stravaj | Unidentified Dasyclad green algae<br>*Salpingoporella/Suppiluliumaella* sp.<br>*Similiclypeina conradi* (Bucur)<br>*Protopeneroplis* cf. *ultragranulata* (Gorbatchik)<br>*Carpathoporella* sp.<br>*Favreina* sp.<br>*Lithocodium-Bacinella* sp. | Early Cretaceous (probably Berriasian—Early Valanginian) |
| A09/907 | Shpati | Stravaj | *Protopeneroplis* cf. *ultragranulata* (Gorbatchik)<br>*Suppiluliumaella* sp.<br>*Carpathoporella* sp.<br>*Koskinobulina socialis* (Cherchi & Schroeder) | Early Cretaceous (probably Berriasian—Early Valanginian) |
| A09/908 | Shpati | Stravaj | *Salpingoporella pygmaea* (Guembel) (forma *exilis* Dragastan)<br>*Sporolithon rude* (Lemoine)<br>*Carpathoporella* sp.<br>*Tintinnopsella carpathica* (Murgeanu & Filipescu) | Probably Hauterivian |
| A09/917 | Shpati | Stravaj | *Evericyclammina* sp.<br>*Vercorsella scarsellai* (De Castro)<br>*Salpingoporella pygmaea* (Guembel) (forma *exilis* Dragastan)<br>*Carpathoporella* sp.<br>Rivulariacean-type cyanobacteria | Early Cretaceous (probably Barremian-Aptian) |
| A09/918 | Shpati | Stravaj | *Everticyclammina* sp.<br>*Montseciella arabica* (Henson) | Late Barremian-Early Aptian |

See text for explanation

in a matrix of coarse ophiolite-derived sandstone or pink micritic carbonate (Figs. 7e, 8a). There is a return to mafic clasts (basalt, dolerite and gabbro) that generally decrease in size upwards. Well-stratified serpentinite-derived conglomerates (~20 m thick) follow (Fig. 8c), with several thin (<16 cm), reddish-coloured iron oxide–rich interbeds (mainly too thin to show on Fig. 4c).

The sediments then pass upwards into coarse, well-cemented pebbly sandstones and siltstones that contain abundant serpentinite and reworked micritic grains in a partially recrystallised micritic matrix. Grey, then pink to reddish micritic or bioclastic limestone appears above this, rich in shell fragments and detrital chromite grains. The bioclastic limestones include reworked grains of micrite, shell fragments, echinoderms, serpentinite, chloritised basalt, iron oxide granules and chrome spinel, set in calcite spar cement. Thin micritic interbeds contain calpionellids of Early Cretaceous age, rare small benthic foraminifera and sparse detrital ophiolite grains.

The succession grades upwards into an interval (~20 m thick) made up of interbedded conglomerates (Fig. 8d), pebbly sandstones, reddish or pink bioclastic limestone with occasional thin, reddish iron-rich (lateritic) layers. The sandstones and limestones contain abundant detrital

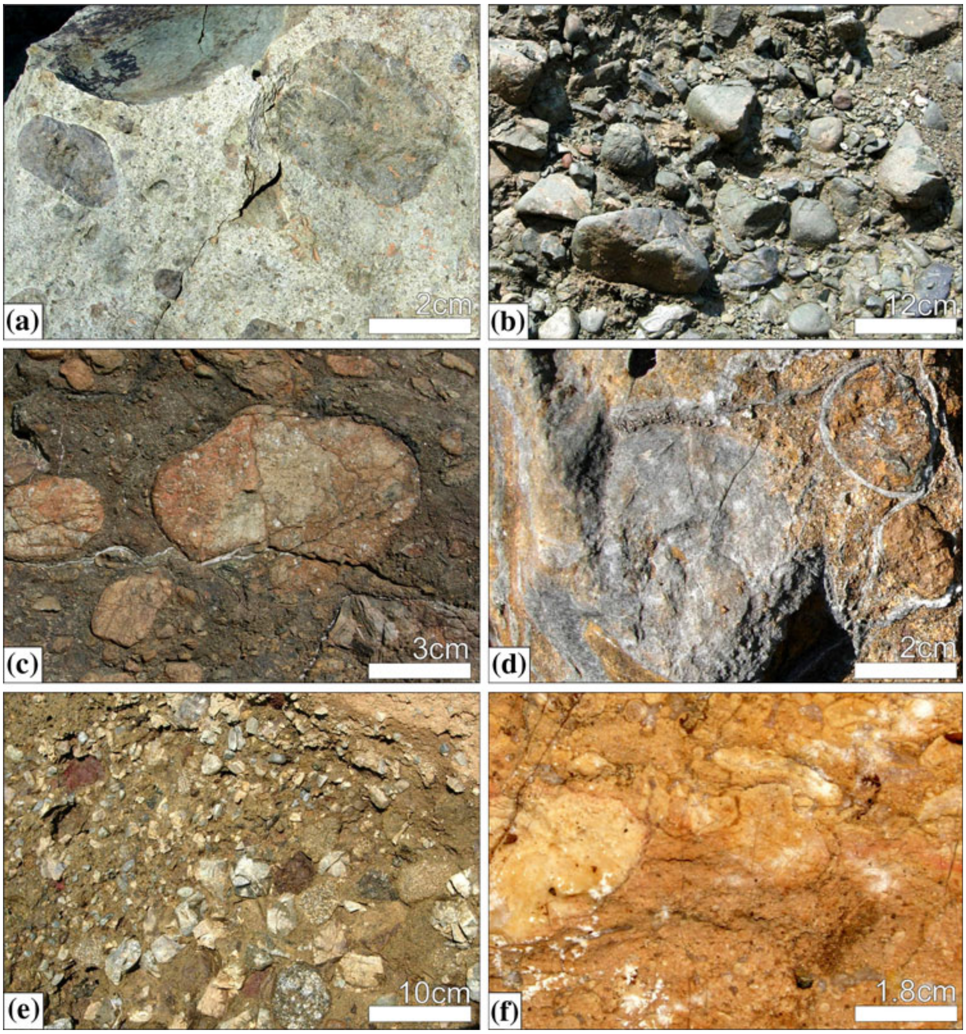


**Fig. 8** Field photographs from Shpati massif. **a** Matrix-supported serpentinite-derived conglomerate; clasts are harzburgite; matrix is detrital serpentinite; lower part of the succession at Babja, **b** Clast-supported basalt-derived conglomerate; matrix is also basalt derived; mid-part of the succession at Babja, **c** Matrix-supported serpentinite-derived conglomerate; clasts are harzburgite; matrix is detrital serpentinite; upper part of the succession at Babja, **d** Weathered serpentinite clasts coated with carbonate (microbial) (right), together with micritic limestone clast (left) in an matrix of altered serpentinite and carbonate; upper deltaic interval at Babja; **e** Heterogeneous ophiolitic clasts (e.g. basalt, dolerite, gabbro, serpentinite) in an argillaceous matrix, Stravaj, **f** Reworked micritic limestone rich in detrital chromite grains; upper deltaic interval; Stravaj

chromite while the iron-rich layers contain scatted clasts of serpentinitised ultramafic rocks. Benthic foraminifera include *Protopeneroplis ultragranulata* of Middle Tithonian-Barremian (Bucur 1993), but more commonly Berriasian-Lower Valanginian age (see Table 1).

The succession continues into pink or grey micritic, locally bioclastic, limestones interbedded with intraformational conglomerates composed of micritic limestone clasts (<15 cm in size). In thin section, these clasts contain benthic foraminifera, small shell fragments and planktic foraminifera (see Table 1). The benthic foraminifer *Cuneolina pavonia* (Fig. 6, no. 12) is indicative of an Albian-Coniacian age (Chiocchini et al. 1983; Husinec and Sokac 2006; Sari et al. 2009) and occurs together with the planktic foraminifer *Roralipora* cf. *ticinensis*, an index species for the Late Albian (Sliter 1989; Grötsch et al. 1993; Fig. 6, no. 13). Upper Cretaceous (Turonian and younger) limestones rich in rudist bivalves and corals occur above this but the contact is not well exposed.

A significantly different succession is exposed near Spathari, only several kilometres to the east of Babja (Fig. 3c). Above the ophiolite, an intact succession (not shown in Fig. 4) is dominated by serpentinite conglomerate (~200 m thick), made up of well-rounded, but poorly sorted clasts of serpentinised harzburgite (up to 40 cm in size), set in a subordinate sparse matrix of well-cemented, sand-sized, rounded, detrital serpentinite grains. In some samples, some of the individual serpentinised ultramafic rock clasts are highly weathered (reddened) and cemented by calcite spar. The grain size of pebbles generally decreases upwards into an interval characterised by interbeds of serpentinite-derived sandstone/pebblestone and micritic limestone. This is followed by grey to pink micritic limestones with abundant detrital and bioclastic grains.

A very different sequence is exposed ~25 km further south, near Stravaj (Fig. 3d). In the uppermost part of the ophiolite, there is mainly pillow basalt with subordinate pillow disintegration breccia, cut by isolated dolerite dykes. The breccias, up to 10 m thick, are mainly made up of basalt, together with altered volcanic glass (hyaloclastite) and chloritic grains, set in a matrix of volcaniclastic siltstone rich in tiny, angular detrital grains of plagioclase and clinopyroxene. Detrital grains near the top of the extrusive sequence include basalt, hyaloclastite, dolerite, radiolarite and rare pelagic micrite clasts with calcified "ghosts" of radiolarians.

Unusually, the pillow breccias are overlain by reddish-coloured ribbon radiolarites (Fig. 4d) with shaly partings (~8 m thick). The uppermost radiolarites grade upwards into several metres of soft weathering, fine- to medium-grained serpentinite-derived sandstones (up to 3.5 m thick). In thin section, they are made up of moderately well rounded grains of serpentinite and micritic limestone (partially recrystallised), plus rare basalt, clinopyroxene, radiolarite and a pre-existing serpentinite-derived siltstone. Coarse serpentinite-derived conglomerates follow above this (>10 m thick). Large serpentinite clasts near the base (<80 cm) are commonly well rounded, together with rare clasts of gabbro and micritic limestone (while basalt and dolerite are effectively absent).

Despite landslipping, a nearly continuous succession could be pieced together above the basal serpentinite-derived clastics by careful logging and local lithological correlation (Fig. 4d). In the lower part, medium- to thick-bedded calcite-cemented conglomerates, up to 70 m thick, are dominated by well-rounded clasts of basalt, gabbro, dolerite and neritic limestone (<15 cm in size). The matrix is mainly detrital serpentinite, with common rounded micritic grains, also rare small quartz grains and muscovite laths.

Above, there is a transition from conglomerates with a red/purple carbonate matrix, to pebbly sandstones (up to 15 m thick) with numerous clasts of grey micritic limestone rich in microfossils. This is followed by an interval (3–5 m thick) of volcaniclastic sandstone with several intercalations of pebbly conglomerates up to ~60 cm thick (Fig. 8e). Interbedded pink limestones contain scattered ophiolite-derived pebbles and sand grains. The carbonate becomes more abundant upwards and grades into thick-bedded pink or reddish bioclastic limestones (Fig. 8f).

Thin sections of the mixed clastic-carbonate sediments revealed well-rounded grains of limestone and oxidised (reddened) serpentinite plus occasional grains of altered basalt, radiolarite, detrital quartzose sandstone (litharenite), echinoderm debris and locally abundant benthic foraminifera, all set in a partially recrystallised micritic matrix. The pelagic micrite contains calpionellids, both in the matrix and as detrital grains. Several samples include shells fragments, echinoderm debris, polyzoans and microbial carbonate (see Table 1). The relative abundance of ophiolite-derived, versus bioclastic grains varies greatly in individual beds. Benthic foraminifera include *Protopeneroplis ultragranulata* that ranges in age from Middle Tithonian to Barremian (Bucur 1993), but is most common during Berriasian-Early Valanginian (Fig. 6, no. 14). In addition, *Montseciella arabica* is characteristic of Barremian-Early Aptian (Luperto Sinni 1979; Schroeder et al. 1982; Arnaud-Vanneau and Masse 1989; Masse et al. 1992). The red alga *Sporolithon rude* (Fig. 6, no. 15) ranges from Hauterivian to Albian (Tomas et al. 2007) and is associated with *Tintinnopsella carpathica* (Murgeanu & Filipescu) of Tithonian-Late Valanginian-Hauterivian age (Fig. 6, no. 16). In addition, *Suppiluliumaella* sp. is indicative of a Barremian (?) Aptian age (Fig. 6, no. 17). There is considerable evidence of reworking and redeposition of deeper water facies into neritic settings (Fig. 7f).

The fine-grained limestones above the neritic carbonates contain Albian planktonic foraminifera (e.g. *Hedbergella* sp., Peza and Theodhori 1993), followed by thick-bedded, to massive, Late Cretaceous limestones rich in ooids, corals and rudist bivalves.

### Rehove ophiolitic massif

An intact shallow-water sequence is exposed above ophiolite-derived clastic sediments further south in the Rehove ophiolitic massif, near Vithkuqi (Figs. 2, 3e). In this area, the ultramafic rocks are tectonically overlain by a well-exposed ophiolitic extrusive sequence. This comprises massive basalts, pillow lavas and pillow breccias, with occasional thin interbeds of ribbon cherts and ferromanganiferous mudstones (several metres long by <30 cm thick). Preliminary taxonomic study indicates the presence of Radiolaria of late Oxfordian-Kimmeridgian age (P. Dumitrica pers. com. 2010). There are widespread traces of hydrothermal copper mineralisation and related oxide sediments. Sand-sized material within the breccia is mainly composed of very angular, poorly sorted fragments of basalt, dolerite and microgabbro with lesser amounts of altered hyaloclastite, radiolarite, plagioclase and clinopyroxene.

The base of the overlying clastic sequence is faulted out in the only known section (Fig. 4e). This begins with subrounded, to rounded, pebbles of ophiolite-derived lithologies and neritic limestone (mostly 5–10 cm in size) (Fig. 5e) and fines upwards into grey muddy bioclastic limestone over a short interval. Pebbly bioclastic limestones above this contain clasts aligned parallel to bedding and also scattered small, rounded ophiolite-derived pebbles (<3 cm in size). Thin sections exhibit variable mixtures of well-rounded, to subangular, poorly sorted grains of serpentinite, basalt, red radiolarite and quartz, together with subordinate grains of polycrystalline quartz, micaschist, quartzose sandstone, crystalline limestone (marble), pelagic limestone, plagioclase and pyroxene, all set in an unfossiliferous matrix of ferruginous silt. Other samples include variable amounts of bioclastic material, mainly shell fragments (bivalves and gastropods) and benthic foraminifera. Macrofossils include *Paraglauconia lujani* (Early Aptian) age and *Nerinea* (Barremian ?).

The succession above is mainly calcareous mudstone/siltstone with several intercalations of dark grey, organic-rich limestone, packed with bioclastic material, especially *Nerinea* gastropods and bivalve shell fragments (Fig. 5f). Scattered ophiolite-derived grains, especially chromite, occur throughout this limestone. Thin interbeds of fine-grained sandstones and siltstones are typically terrigenous with abundant quartz and common muscovite. Similar sediments, of reportedly Barremian-Aptian age, are known elsewhere in the Korça and Kolonja regions (Peza and Theodhori 1993).

### Morava ophiolitic massif

The uppermost levels of the Morava ophiolitic massif, exposed south of Korçe, near Boboshtica (Fig. 2), are characterised by strongly sheared and locally cataclastically deformed serpentinised lherzolite. This is unconformably overlain by poorly lithified, matrix-supported mega-conglomerates. The logged section (Fig. 4f) is affected by several neotectonic features, including small high-angle faults and low-angle extensional sheet cracks.

The exposed mega-conglomerate is restricted to a local depression in the surface of the eroded ultramafic rocks (~100 m long by 10 m thick) where it is dominated by rounded, to subrounded, highly fossiliferous neritic limestone clasts, up to 2 m in size. The clasts contain corals and rudists, both in life position and as displaced fragments set in a matrix of pink micrite. Some boulders include pelecypods and gastropods, together with detrital basalt and serpentinite. The matrix is serpentinite breccia and limestone debris with variable amounts of pink micrite. Thin sections revealed fragments of bivalves, corals, rudists, coralline algae and both benthic and planktic foraminifera, together with common reworked grains of pelagic limestone that include calpionellids of Early Cretaceous age. The presence of the rudist *Pchelintsevia renauxiana* (d'Orbigny) suggests a Barremian to Early Aptian age. Ophiolite-derived material is mainly serpentinite with rare basalt and chlorite grains. Upwards, the limestone clast size diminishes, while angular clasts of serpentinite (up to 40 cm in size) become more abundant. There is then an incoming of lenticular, reddish non-marine ophiolite-derived sandstones and conglomerates, in places directly transgressive on eroded ultramafic ophiolite.

## Comparable ophiolite-derived clastic sediments

Below, we highlight comparisons that aid the interpretation of the south Albanian ophiolite-related sediments.

In northern Albania (Fig. 1), intact successions of the Jurassic Mirdita ophiolite are overlain by radiolarian cherts, with a maximum known age range of Bajocian-Early Oxfordian (Marcucci et al. 1994; Prela 1994; Marcucci and Prela 1996; Chiari et al. 2002). They are followed, with a depositional contact, by sedimentary melange ('olistostromes'), variously known as the Heterogeneous unit (Shallo 1991, 1992), or the Simoni melange (Bortolotti et al. 1996). This includes exotic blocks of many lithologies derived from the ophiolite (e.g. ultramafic rocks) and the underlying melange (e.g. terrigenous sandstone; chert; basalt) and even from the continental margin beneath (e.g. granitic rocks). The sedimentary melange is interpreted as a series of huge subaqueous debris flows that record the timing of emplacement of the ophiolite over the adjacent continental margin (Robertson and Shallo 2000). The sedimentary melange (near Kurbnesh) includes "megablocks" of serpentinite that are reported to be depositionally overlain by debris flows made up of reef-slope material (~30 m thick); this contains clasts of shallow-water carbonates of Kimmeridgian (?)-Tithonian age. These neritic carbonates formed within the photic zone above the newly emplaced ophiolite ("Kurbnesh carbonate platform") but were later reworked into deeper water. The emplaced ophiolitic rocks and detritus were then covered by pelagic carbonates containing calpionellids of Late Tithonian to Late Valanginian age (Gardin et al. 1996). Interbedded calcareous turbidites ("Sandstone-Calcareous Flysch", "Firza Flysch") are indicative of continuing tectonic instability. An intact carbonate platform developed above this, beginning in Late Berriasian-Valanginian time (Gawlick et al. 2008; Schlagintweit et al. 2008).

The timing of ophiolite emplacement is, therefore, constrained as post-dating the youngest radiolarian cover sediments (Early Oxfordian) but essentially predating the depositionally overlying local neritic facies (Late Oxfordian to Kimmeridgian?-Tithonian) and the overlying Late Tithonian-Late Valanginian calcareous sandstones and calpionellid facies (pre-Late Tithonian); i.e. emplacement is likely to have taken place between Late Oxfordian and Early Tithonian time (~157–148 Ma). Similar-scale exotic rock-bearing debris flows are unknown in southern Albania.

In Greece, few of the ophiolites retain intact sedimentary covers. Exceptionally, in the Vourinos ophiolite the extrusive sequence is overlain by thin radiolarian cherts of ~ earliest Bajocian age (Chiari et al. 2003), followed by Early Cretaceous calpionellid-bearing pelagic limestones. Shallow-water carbonates and Upper Cretaceous pelagic limestones accumulated above this (Mavrides et al. 1979; Chiari et al. 2003; Carras et al. 2004; Rassios and Moores 2006). In this case, the ophiolite appears to have been emplaced at some time after the Bajocian and was then transgressed by calpionellid pelagic limestones.

The sedimentary covers of the ophiolites exposed further east in the Pelagonian zone and also in the eastern Almopias part of the adjacent Vardar Zone help to constrain the regional timing of ophiolite emplacement. Within the Pelagonian zone, the basal conglomerates are overlain by fossiliferous mudstones and carbonates of Late Albian to Cenomanian age, rich in corals, oysters and rudists. This was followed by the deposition of *Globotruncana*-bearing pelagic carbonates during Late Santonian-Early Campanian time (Mercier 1966; Galeos et al. 1994; Sharp 1994; Sharp and Robertson 2006).

In contrast, the sedimentary cover of the ophiolitic rocks exposed in the western Almopias zone further east (correlated with the Pelagonian zone), locally begins with neritic carbonates containing Late Oxfordian-Kimmeridgian corals (B. Rosen, in Sharp and Robertson 2006). This implies that the underlying ophiolitic rocks were emplaced prior to, or during, Late Oxfordian-Kimmeridgian time, in general agreement with the evidence from northern Albania. Overlying coarse-grained ophiolite-derived detritus and locally developed transgressive carbonates range in age from Oxfordian-Kimmeridgian to “Neocomian”-Barremian. Ophiolite-derived breccias and conglomerates are well developed in several units (e.g. Liki-Margarita and Klissochori units and near the base of the Kerassia and Kedronas units). These accumulated in variable fully marine, to shallow-marine and subaerial settings. Small carbonate build-ups formed and rapidly disintegrated leaving carbonate talus, as in northern Albania. However, in contrast to both southern and northern Albania, these Upper Jurassic-Lower Cretaceous detrital facies are associated with intermediate- to silicic-composition volcanic rocks and experienced syn-sedimentary deformation. This points to a contrasting tectonic setting (extensional or transtensional ?) after ophiolite emplacement (Sharp and Robertson 2006). Later, an overall marine transgression took place during Aptian-Albian time, followed by deepening during the Cenomanian-Turonian and the establishment of carbonate shelves and ramps consistent with deposition along the northeastern edge of the Pelagonian carbonate platform (see Sharp 1994; Sharp and Robertson 2006).

Ophiolite-related breccias have also been mentioned from mélange units that lie between the regional carbonate platform and overlying ophiolites in both Albania and Greece (e.g. Robertson and Shallo 2000; Dilek et al. 2005). A well-exposed example has recently come to light in Macedonia (FYROM), directly east of the Albanian border (i.e. several kilometres NW of Gorna Belica, itself 11 km NW of Struga on Lake Ohrid). A N–S outcrop (7 km N–S × 1 km E-W) that is mapped as Jurassic in age on the Ohrid Sheet (K34–102) of the geological map of former Yugoslavia is contiguous with a much larger outcrop in Albania mapped as Upper Jurassic-Lower Cretaceous ophiolitic mélange and related sediments (~20 km ESE of the Luniku ophiolite). The Macedonian outcrop comprises a coherent succession of ophiolite-derived breccias and conglomerates (>300 m thick), with no exposed stratigraphical base. Clasts are mainly gabbro, dolerite and basalt, typically <0.8 m thick. The clasts range from angular, to subangular, to locally well rounded. Most of the breccia outcrop is massive or weakly stratified. The upper part of the succession (~25 m) fines upwards through medium-bedded to thin-bedded ophiolite-derived sandstone and shale and then passes transitionally into red radiolarian chert and shale (<20 m thick) with interbeds of ophiolite-derived sandstone and shale. Preliminary taxonomic study indicates the presence of radiolarians of late Aalenian-?Bajocian, late Oxfordian and Oxfordian-Kimmeridgian age (P. Dumitrica, pers com, 2010). The succession passes depositionally into white pelagic limestone (up to 40 m thick), rich in calcified radiolarians, with lenticular chert intercalations. The limestone is strongly disrupted and in places interspersed with sheared serpentinite. The highest exposed levels of the breccia unit (exposed in the south of the outcrop) include disrupted, redeposited clasts, blocks and slabs (up to metre-sized) of radiolarian chert (still undated) and fine-grained limestone that were redeposited before being fully lithified.

The Macedonian outcrop is likely to represent oceanic crust-derived breccias and deep-sea cover sediments that were accreted separately (and earlier) from the regional emplacement of the ophiolites. As a consequence, they now occur within the regionally underlying melange unit. However, the breccias are similar in thickness, facies and composition to those associated with the Voskopja ophiolitic massif (see Fig. 4a). The Macedonian breccias accumulated adjacent to a major submarine fault scarp, presumably in a rifted ridge, or possibly a transform setting. Breccias of similar facies to those of the Vospopoja massif could therefore form independently of ophiolite emplacement and are indeed reported from the north Albanian ophiolites (Nicolas et al. 1999; Tremblay et al. 2009).

Several examples of clastic facies associated with the Upper Cretaceous ophiolites in the Eastern Mediterranean and Oman also have implications for ophiolite emplacement, although deep-sea sedimentary covers are rarely preserved, or dissimilar to those in south Albania (e.g. associated with the Lycian and Troodos ophiolites; see Fig. 1).

In SW Turkey, the dismembered Upper Cretaceous Antalya ophiolite is locally interleaved with ophiolite-derived breccias and conglomerates (Çınarcık Breccias). These are interpreted as ophiolite-derived debris flows that were shed from an emplacing ophiolite, probably in a transpressional setting (Robertson and Woodcock 1980). Most of the breccias are much more deformed than in south Albania reflecting their involvement in ophiolite emplacement.

In northern Oman, the uppermost extrusive rocks of the Semail ophiolite (exposed in Wadi Jizi) are overlain by thin Upper Cretaceous pelagic carbonates and radiolarites (Fleet and Robertson 1980). These sediments pass gradationally upwards into ophiolite-derived mudstones, siltstones and sandstones, and then into multiple debris flows made up of highly immature lava and sedimentary talus, up to several tens of metres thick in total (Robertson and Woodcock 1983a). The debris flows are interpreted to record the erosion and redeposition of the uppermost part of the ophiolite extrusives and cover sediments during the emplacement of the ophiolite while still in a subaqueous setting. However, the material shows no signs of reworking in contrast to the common well-rounded clasts, for example in the basal serpentinite conglomerates of the Shpati massif (Stravaj section).

Elsewhere, in northern Oman (in the “Alley zone”) the uppermost ophiolitic extrusives are overlain by debris flows that contain up-to-house-sized blocks of exotic rocks that are typical of the melange beneath the ophiolite (e.g. sheared radiolarian chert, marble, basalt, serpentinite). This material, known as the Batinah Melange, is inferred to have extruded through breaks in the emplacing ophiolite, followed by redeposition onto the seafloor as multiple gravity flows and exotic blocks (Robertson and Woodcock 1983b). This unit reflects the emplacement of the ophiolite over the adjacent continental margin and is very similar to the debris flows (“Heterogeneous Unit”, or “Simoni Mélange”) overlying the ophiolite in northern Oman.

## Interpretation of the south Albanian sequences in the regional context

The different sections studied in southern Albania potentially record several different scenarios for which the pros and cons are summarised in Figure 9.

### Ophiolite genesis and oceanic deposition (Late Early Jurassic-Early Late Jurassic)

The Mirdita ophiolites formed in the Tethyan Ocean around 165–160 Ma (Late Bathonian-Early Oxfordian), constrained mainly by isotopic dating of ophiolitic plagiogranites (Dilek et al. 2005, 2008a, b) and the ages of the overlying radiolarian cherts (Marcucci et al. 1994; Marcucci and Prela 1996; Prela 1994; Chiari et al. 2002).

The oceanic extrusives as a whole erupted on an irregular sea floor, as indicated by the interbedding of pillow lava, pillow breccia and massive flows in the Shpati and Rehove ophiolites.

Radiolarian sediments occasionally accumulated within the extrusives as seen in the Rehove ophiolite implying breaks in eruption. Hydrothermal ferromanganiferous sediment (umber) is locally associated with hydrothermal copper mineralisation, as seen in the Rehove ophiolite. Rarely preserved radiolarian cherts above the ophiolitic extrusives in southern Albania (e.g. in the Shpati massif, at Stravaj and at Lubonje in the southern Rehove massif) are likely to be of late Middle Jurassic to early Late Jurassic age, as in northern Albania and Greece (Marcucci et al. 1994; Marcucci and Prela 1996; Prela 1994; Chiari et al. 2002; see Danelian and Robertson 1998; our work in progress).

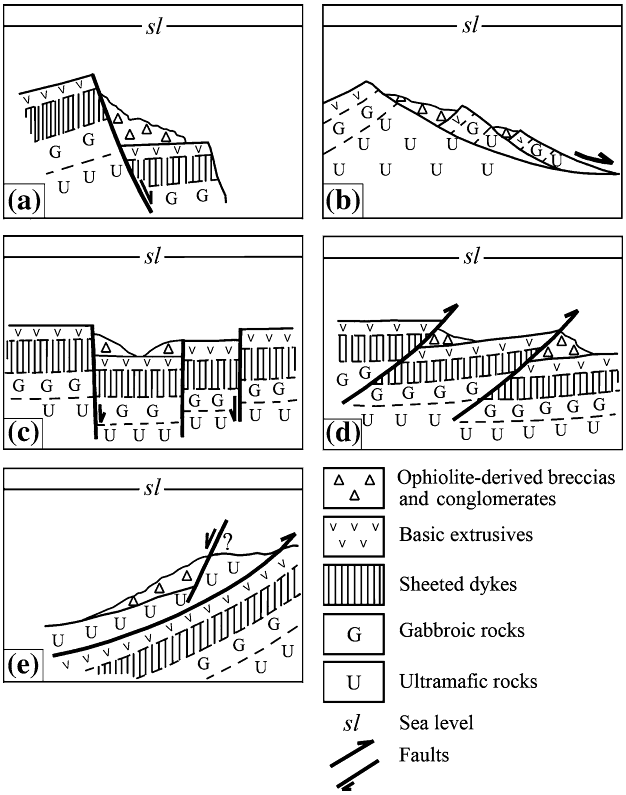


**Fig. 9** Possible modes of coarse ophiolite-derived clastic sedimentation. Faulting of oceanic crust related to extension and seafloor spreading, associated with either high-angle faults (**a**) or low-angle (detachment) faulting (**b**). Both probably apply to the formation of breccias within the ophiolite pseudostratigraphy, as reported from northern Albania but seem inapplicable to the south Albanian supra-ophiolite clastic sediments. Faulting of oceanic crust related to compression and ophiolite emplacement associated with either high-angle faulting (**c**) or reverse faulting (**d**). Model d is questioned by the texturally mature nature of clastic material (e.g. well-rounded clasts) and by the absence of associated overthrust ophiolite sheets. Subaqueous mass wasting of a highly irregular seafloor (**e**) that was created by ophiolite emplacement (i.e. infill of a relict palaeotopography). Fault scarps were eroded possibly following extensional collapse of newly emplaced ophiolite thrust sheets. Option e fits much of the data from the south Albanian clastic sediments and is consistent with results from northern Greece and northern Albania. Breccias could also form in strike-slip settings (e.g. transform fault) but this lacks supporting evidence from the study area

The south Albania ophiolites show evidence of crustal extension that took place at an oceanic spreading centre; this is potentially relevant to the ophiolite-derived clastic sedimentation in two ways.

First, the widespread high-temperature-derived mylonites (e.g. Voskopoja massif) indicate that crustal extension took place in an oceanic setting prior to the emplacement. Similar mylonites in northern Albania are interpreted to reflect extension at a slow-spreading ridge (Nicolas et al. 1999; Meshi et al. 2010). Inferred extensional detachments (Tremblay et al. 2009) may be comparable to the oceanic core-complexes (megamullions) that developed near spreading centre-fracture zone intersections on the Mid-Atlantic Ridge (Tucholke et al. 1998). As a result, intrusive rocks including gabbro and ultramafic rocks were exhumed to a relatively high level near the spreading centre. During and after ophiolite emplacement, ultramafic rocks could, therefore, be easily exposed to erosion without any need to first erode a thick crustal sequence (i.e. lavas, sheeted dykes etc.) or duplicate the crustal sequence by large-scale thrusting. This could explain the close proximity of mafic- and ultramafic-dominated clastics, both vertically and laterally, as seen in the northern part of the Shpati massif (e.g. at Babja). This interpretation is supported by the MORB-type (at Voskopoja), or “transitional-type” (at Stravaj) chemical compositions of the breccias, which by comparison with outcrops in northern Albania are consistent with formation at a rifted spreading axis.

Secondly, it is likely that the ocean floor would exhibit a strongly fault-controlled topography characterised by the development of subaqueous screes, as reported from northern Albania (Nicolas et al. 1999; Tremblay et al. 2009). Comparable fault-derived talus might also develop along transverse structures (e.g. transform faults of various scales), if present. The very thick breccia-conglomerate in the Voskopoja massif (Fig. 4a) records part of a vast subaqueous scree that was shed from different levels of the ophiolite pseudostratigraphy (e.g. ultramafics, dolerite, basalt). The associated ultramafic rocks show evidence of seafloor extension (e.g. mylonitic serpentinite) and represent a potential source area for the coarse clastic sediments. Similar breccias are inferred to have formed in an oceanic setting in the comparative Macedonian example (see above). One possibility is therefore that the Voskopoja breccias formed at a rifted spreading centre prior to ophiolite emplacement (see Fig. 9a or b). However, against this there is no angular discordance between the breccia-conglomerate and the gradationally overlying calpionellid limestones, which elsewhere, regionally overlie emplaced ophiolites (e.g. in northern Albania and northern Greece; see above). This suggests that the coarse clastic sediments effectively post-date the ophiolite emplacement.

## Ophiolite emplacement (Late Jurassic)

The regional ophiolite emplacement is constrained as Late Jurassic (Late Oxfordian to pre-Late Tithonian) from the cover sediments in northern Albania and northern Greece (see above). This is consistent with $^{40}$Ar/$^{39}$Ar dating of the ophiolitic metamorphic soles throughout Albania and Greece. This indicates that intra-oceanic slicing of young, still-hot oceanic lithosphere took place during Middle to Late Jurassic time ~174–159 Ma (i.e. Aalenian-Oxfordian) (Vergély et al. 1998; Dimo-Lahitte et al. 2001). A general south to north decrease in the age of the Albanian metamorphic soles has been inferred although there are apparent local variations (Vergély et al. 1998; Dimo-Lahitte et al. 2001).

It is possible that some of the basal ophiolitic clastic sediments in south Albania accumulated actually during the ophiolite emplacement, although all the dated sediments (?latest Jurassic-Berriasian) post-date this regional event.

## Syn- to early post-emplacement deposition (latest Jurassic?)

Throughout northern Albania and northern Greece, the ophiolitic rocks and associated debris flows, where present (in northern Albania), are overlain by relatively deep-marine calcareous facies, including pelagic carbonates and sandstone turbidites (see above) of Late Tithonian to Late Valanginian age. In south Albania, the pink calpionellid limestones, dated as latest Jurassic (?)-earliest Berriasian, are underlain with a gradational contact by the thickest-known (hundreds of metres) ophiolite-derived breccias. This implies that the breccias are themselves likely to have formed during latest Jurassic time; i.e. during or soon after the latest stages of regional ophiolite emplacement. The breccias were shed from subaqueous scarps created by the ophiolite emplacement. In general, the breccias and conglomerates infilled a rugged seafloor topography that remained after the emplacement.

In all areas, the dominant process of coarse ophiolite-derived clastic deposition involved mass movement, ranging from rock-fall in the Voskopoja massif, where clasts are unusually large, angular and unsorted, to more common multiple debris flows, as seen above the Shpati ophiolite. The rounding of ophiolite clasts in the lower part of the section below the calpionellid limestones at Voskopoja is attributed to down-slope gravity reworking, probably as multiple events. However, elsewhere (e.g. at Babja and Stravaj in the Shpati massif) some of the clasts (e.g. serpentinite, dolerite, gabbro and pelagic limestone) are very well rounded suggesting an origin in a high-energy, shallow-marine or even fluvial setting.

The occurrence of basalt-derived breccias as seen in the Shpati ophiolitic massif (near Spathari) could be explained by local uplift and reworking of underlying mafic oceanic crust. Similar conglomerates are mainly basalt-derived nearby, at Babja, again reflecting erosion of the uppermost levels of the ophiolite pseudostratigraphy. The local appearance of serpentinite-derived conglomerates above basaltic conglomerate in the Babja section could then be explained by downcutting through basalt to ultramafics below, especially if the crust had already thinned by seafloor extension at the spreading axis prior to emplacement (see above). Alternatively, the crust had already been duplicated by thrusting during its emplacement, exposing ultramafic rocks to erosion.

Elsewhere, in the Shpati massif (near Stravaj), the basal ultramafic-derived clastics (sandstones and conglomerates) could be explained by derivation from a faulted or upthrust ultramafic sheet (see Fig. 9c, d). However, none of the ophiolite-derived sediments studied show evidence of overthrusting by higher ophiolite thrust sheets and it is likely that, instead, all of the clastic sediments formed after the ophiolite emplacement was more or less complete.

The subaqueous breccias and conglomerates in the Voskopoja massif were followed by the emplacement of chaotic serpentinitic gravity flows ("olistostromes"). Ultramafic rocks were exposed on the seafloor as thrust sheets or possibly as serpentinite diapirs, mobilised (in response to hydration), mixed with mafic talus and then emplaced as subaqueous debris flows.

### Early post-emplacement pelagic deposition (latest Jurassic-Valanginian)

In the Voskopoja section, the ophiolite-derived breccias and conglomerates pass upwards into calpionellid pelagic carbonates. Reworked calpionellid grains and individual microfossils are widespread in the other sections studied indicating that similar pelagic limestones accumulated widely but were later largely eroded.

The calcareous sediments accumulated following a Tethyan-wide fall in the oceanic carbonate compensation depth during Kimmeridgian-Early Tithonian time (Bernoulli and Jenkyns 1974; Bosellini and Winterer 1975). The timing of the CCD fall is more or less coeval with the regional ophiolite emplacement; i.e. post-Early Oxfordian-pre-Late Tithonian. The pelagic calpionellid limestones dated as Late Tithonian?-Early Berriasian in the south Albanian sections studied are assumed to have accumulated soon after the latest stages of ophiolite emplacement. By then, the underlying continental margin had subsided owing to flexural subsidence beneath the emplaced ophiolite (e.g. Stockmal et al. 1986) such that the initial cover sediments accumulated in a relatively deep, open-marine setting. Comparable flexural subsidence is documented in other ophiolites including Oman and Newfoundland.

In the Voskopoja section, the ophiolite-derived talus was gradually covered by pelagic limestones of latest (?) Jurassic-Berriasian age. The local presence of radiolarians, *Saccocoma* debris, sponge spicules, thin-shelled bivalves and also of diagenetic chert, indicate that the accumulation took place in a nutrient-rich, productive sea. Also in the Voskopoja section, the pelagic carbonates show evidence of large-scale slumping and sliding of poorly consolidated material, indicative of an unstable seafloor. The possible cause was shallowing to shelf depths where benthic foraminifera flourished, driven by isostatically controlled uplift.

### Later post-emplacement shallow-marine to subaerial deposition (Early Cretaceous)

The coarse ophiolite-derived clastics and, where preserved, the calpionellid limestones (at Voshopoja; see above) were covered by shallow-marine deltaic and lagoonal, to non-marine sediments in several of the ophiolitic massifs, mostly during Barremian-Aptian time. The contact with the underlying sediments is transitional. The ophiolite-derived sediments typically become finer and more texturally mature upwards, followed by an incoming of thin interbeds of shallow water, to lagoonal carbonate (e.g. in the Shpati massif). The shallowing is likely to have been a response to isostatic rebound of the emplaced ophiolite that accompanied partial erosion or extensional exhumation. Coeval volcanism and inferred extension elsewhere (i.e. in northern Greece) may reflect ophiolite exhumation or the onset of an unrelated extensional stress regime (see above). However, eustatic sea-level change may also have played a role (see Fig. 10).

The red–grey limestones in the upper part of the Voskopoja section contain abundant benthic foraminifera and calcareous algae. Similar shallow-water bioclastic limestones are interbedded with ophiolite-derived clastic sediments in the much thinner Luniku section. The presence of oolitic microbial coatings on ophiolite-derived and bioclastic grains indicates accumulation in shallow water within the photic zone (<10 s of metres). Pebbles were derived from various ophiolitic rocks including highly "depleted" harzburgite/dunite and "enriched" lherzolite. Chemical evidence from these grains (Hoeck et al. 2009) is consistent with a variable or "composite" magmatic character for the southern Albanian ophiolites, which show features of both MOR-type and SSZ-type ophiolites (Hoeck et al. 2002).

In the Shpati massif (at Babja-Spathari and Stravaj), mixed carbonate-clastic sediments, up to 60 m thick,

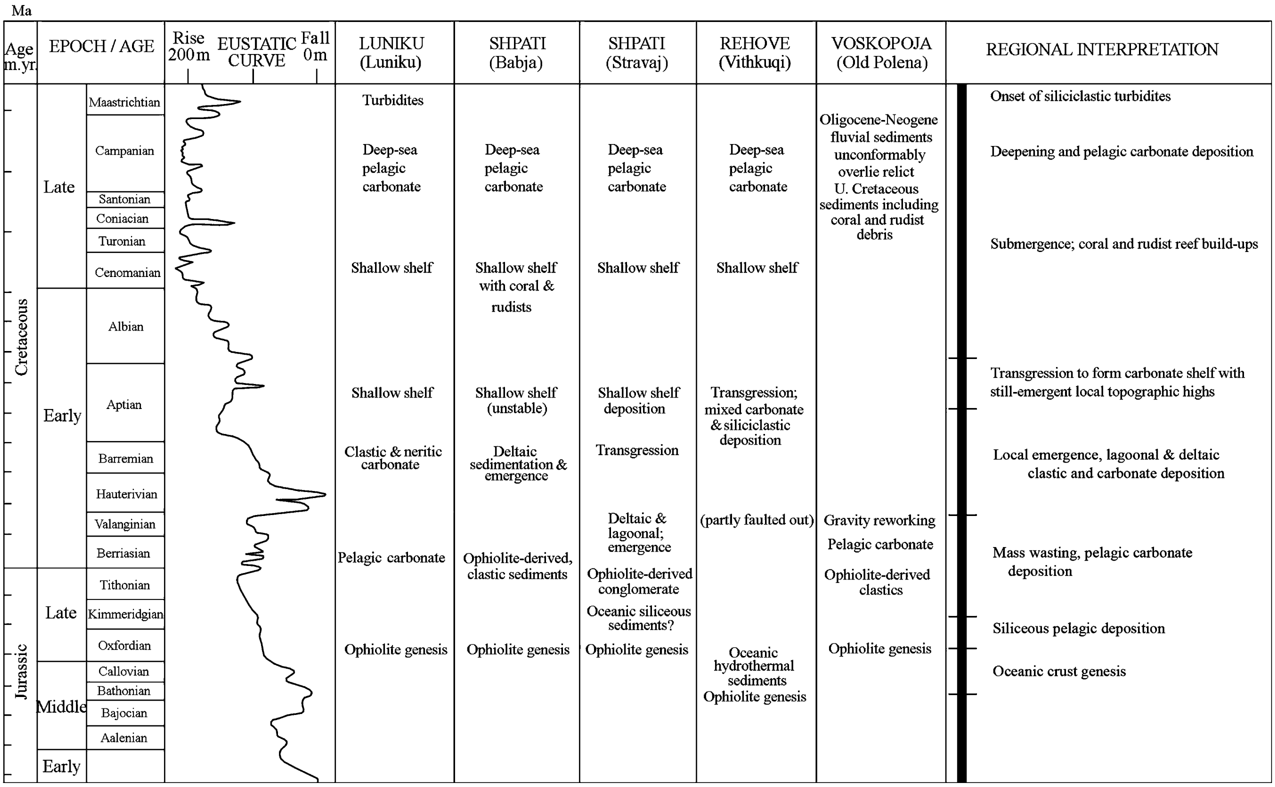


**Fig. 10** Time-activity diagram summarising inferred palaeoenvironmental and tectonic processes and interpretations. The sea-level curve is from Haq et al. (1987). See text for discussion

accumulated in a low-energy shallow-marine setting. Ophiolite-derived and bioclastic grains were reworked, rounded and coated with microbial carbonate. Local concentrations of shelly material could reflect storm activity. Ultramafic rocks were weathered on land, as reflected in highly oxidised and rounded clasts and the abundance of detrital grains of chrome spinel. Thin, reddish-coloured iron oxide–rich deposits accumulated during periods of subaerial exposure and terrestrial weathering, as observed in the Babja-Spathari outcrops and at Stravaj further south. Comparable, but generally thicker lateritic deposits are reported from above the ophiolites in other areas including Greece and former Yugoslavia (Skarpelis 2006).

Chrome spinels from the mixed clastic/carbonate sediments from Luniku, Shpati and Morava have a predominantly harzburgitic composition, with high Cr# and low Mg#. In addition, some of the spinels were probably derived from dunite and chromitites and/or boninites (Hoeck et al. 2010). Spinels derived from lherzolites are apparently absent. This suggests that these clastic sediments were largely derived from the mafic/ultramafic rocks typical of the SSZ-type ophiolites that characterise the eastern belt of Albanian ophiolites. Ophiolitic rocks of this composition are assumed to have been exposed further east in an area undergoing subaerial erosion. The chromite was concentrated as it was resistant to breakdown in contrast to ferromagnesian minerals (e.g. olivine, pyroxene) and was carried seawards into a shallow sea.

For some time the ophiolite surface was close to sea-level, with small gravel deltas building from emergent areas into small shallow-marine lagoons. Cyclic repetitions of graded conglomerates, sands and shallow-marine carbonates, as seen in the Shpati massif (at Stravaj) reflect small-scale fluctuations in relative sea level that were either eustatically or tectonically controlled (see Fig. 10).

## First regional marine transgression (Aptian-Albian)

The mixed carbonate-clastic sediments were gradually transgressed by a first cycle of fully open-marine carbonates of Aptian-Albian age (e.g. at Babja, Shpati; see Fig. 10). The mixed clastic-carbonate sediments are covered by pink micritic limestone (up to 60 m), rich in benthic foraminifera and neritic macrofossils in the Shpati massif (at Babja and Stravaj). However, some parts of the ophiolite probably remained emergent giving rise to abundant iron oxide that was reworked into the nearby marine basin. The seafloor, as seen in the Babja section, remained tectonically unstable and micritic limestones were locally reworked as intraformational debris flows, interbedded with undisturbed micritic carbonates. Colonial rudist build-ups of Barremian-Aptian age are recorded in some areas (Peza 1985, 1992; Peza et al. 1999).

The depositional contact with the ophiolite in the Rehove massif is faulted such that the base of the sedimentary sequence is missing (near Vithkuqi). The lowest exposed conglomerate there contains well-rounded clasts of neritic limestones and detrital ophiolitic lithologies. The succession passes into alternating shallow-marine limestones, commonly rich in gastropods and terrigenous sandy, silty and argillaceous sediment derived from a neighbouring continental area. These sediments provide the first evidence of incoming of abundant terrigenous sediment presumably in response to erosion or faulting of the ophiolite.

### Second regional marine transgression (Late Cretaceous)

Late Jurassic to Early Cretaceous pelagic and neritic sediments were eroded during a marine regression, as documented in the Voskopoja and Morava massifs. Bioclastic conglomerates with a Turonian-aged pelagic matrix then accumulated there indicating a second cycle of transgression (see Fig. 10). Elsewhere, Lower Cretaceous pink limestones pass, with a sharp conformable contact, into widespread Upper Cretaceous limestone rich in coral and rudist bivalves, as seen in the Shpati massif, at Stravaj (Geological Map of Albania 1983, 2002). Rudist reefs were developed during the Turonian in several areas (Peza 1992; Peza et al. 1999). During the Late Cretaceous, the ophiolites were entirely submerged prior the onset of deformation related to regional continental collision during latest Cretaceous-Maastrichtian time.

## Conclusions: implications for ophiolite emplacement

In the light of comparisons with other ophiolites, especially in northern Albania and northern Greece, the sediments overlying the ophiolites of southern Albania are interpreted to reflect processes that mainly took place during and after the emplacement of the oceanic crust onto a continental margin (Figs. 9e, 11). The ophiolites remained submerged after the latest stages of emplacement probably in response to isostatic loading of the continental crust beneath. Ophiolite-derived breccias accumulated along a major subaqueous fault scarp (Voskopoja) soon after the latest stages of ophiolite emplacement and were then covered by pelagic carbonates (Tithonian (?)-Berriasian). The MORB- or transitional-type chemical compositions of the ophiolitic clasts (e.g. basalts and dolerites) suggest that most of the clastic sediments formed on the emplaced western or "transitional" belt of the Albanian ophiolites. In contrast, the detrital chrome spinels in the Lower Cretaceous sediments were mainly derived from depleted mantle tectonites (harzburgites), typical of the supra-subduction zone-type ophiolites of the eastern belt.

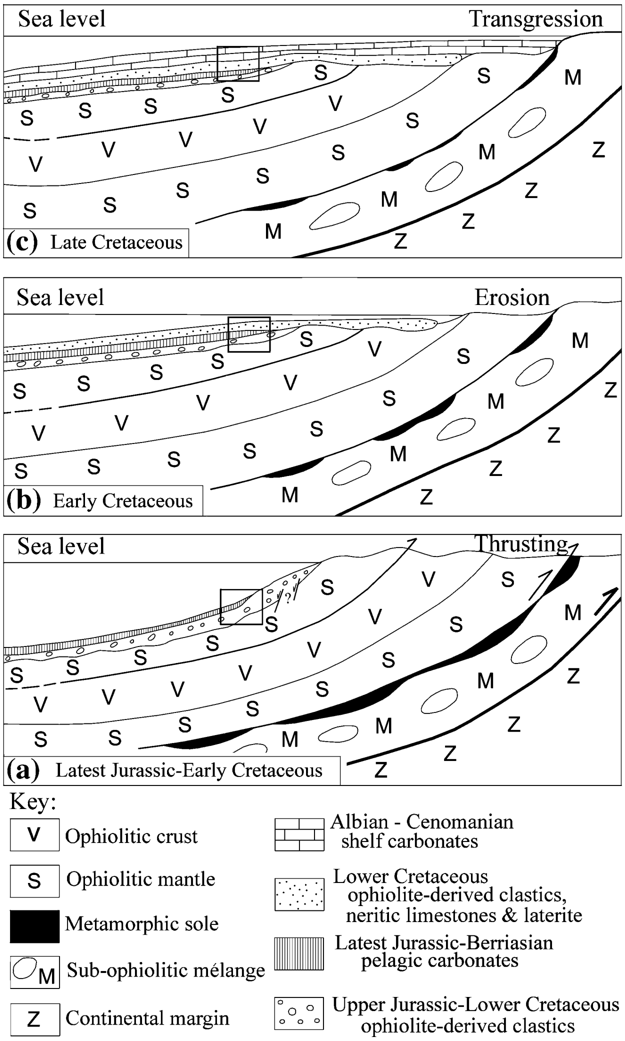


**Fig. 11** Summary of proposed interpretation of the Upper Jurassic-Lower Cretaceous ophiolite-derived clastics and related facies is southern Albania. **a** ?Latest Jurassic-Early Cretaceous. Following oceanic crust genesis and deposition of oceanic radiolarian sediments, the ophiolite was emplaced exposing crust and mantle rocks on the seafloor in different local areas where they underwent mass wasting and were then covered by pelagic, calpionellid limestones, **b** Early Cretaceous. The ophiolite emerged and was locally weathered to form lateritic deposits and eroding, generating clastic sediments that were deposited in shallow-marine deltaic and lagoonal settings where neritic carbonates also accumulated, **c** Late Cretaceous. The ophiolite was transgressed by shallow-marine carbonates while continental rocks were exposed elsewhere, shedding terrigenous clastic sediment into the area. Extensional faulting during and after ophiolite emplacement is likely to have played a role in generating the clastic sediments, possibly related to local gravity sliding or ophiolite exhumation. The box indicates the approximate position of the study area

After the formation of the breccias, the ophiolite massif gradually emerged into shallow water associated with tectonic instability (e.g. slumping and sliding at Voskopoja). This was a probable response to isostatic rebound, triggered by regional erosion or tectonic exhumation. Parts of the ophiolite were subaerially exposed and weathered while others remained just below sea level during later Early Cretaceous time (Barremian-Aptian). Neritic carbonates accumulated in open-marine lagoons subject to influxes of ophiolite-derived clastic sediment. The cyclicity of the carbonate and clastic sedimentation is likely to have been influenced by fluctuations in eustatic sea level.

The evidence from southern Albania is consistent with Late Jurassic emplacement of a regional-scale ophiolite (Fig. 11). The sediments studied here do not provide any unambiguous directional evidence as to whether the Albanian ophiolites were emplaced from a Vardar ocean far to the north-east or from a Mirdita ocean to the south-west (in present co-ordinates) (see Robertson 2006 for discussion). However, the evidence is consistent with interpretations in which the ophiolites were rapidly emplaced during Late Oxfordian-Early Tithonian time ($\sim$157–148 Ma at most) rather than being episodically emplaced over a much longer time period (e.g. Gawlick et al. 2008; Schmid et al. 2008). Relatively short-distance (tens of kilometres) emplacement onto a small Korabi-Pelagonian microcontinent (e.g. Robertson and Shallo 1991) is favoured rather than long-distance (hundreds of kilometres) over a much larger Apulian continent.

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