Exotic clasts of Upper Cretaceous Southalpine units (N Italy) point to uplift and erosion of uppermost Austroalpine (Eastalpine and Transdanubian) and E-Southalpine sources

FRANCESCO MASSARI[1, ✉], GIUSEPPE CADEL[2] and CRISTINA STEFANI[1]

[1]University of Padova, Geoscience Department, Via G. Gradenigo, 6, I-35131 Padova, Italy
[2]Università Statale di Milano, Dipartimento di Scienze della Terra, Via Mangiagalli, 34, I-20133 Milano, Italy

Abstract: This study aims at identifying the source area(s) of two populations of exotic pebbles/cobbles present as drift-wood dropstones in the upper Turonian to Coniacian pelagic layers of the Scaglia Rossa, as well as gravity flow deposits in the Santonian Sirone Conglomerate of the Lombardian Flysch. The clast assemblage indicates that the main source(s) were the structurally highest Austroalpine units of the Eo-Alpine orogenic edifice of the Eastern Alps and the Transdanubian Range; the erosion of such units produced Gosau-type gravels that, after local elaboration in high-energy settings, were resedimented into the Southalpine basins. Despite the affinities shown by the clast composition with the lithofacies of the Lombardian stratigraphic succession, origin from a central-Southalpine early orogenic retrobelt edifice can be reasonably excluded, since the onset of uplift and denudation of the Southern Alps occurred in the Late Oligocene. In Santonian times, a complementary source fed the Sirone Conglomerate and likely contributed the Kainach Gosau basin with clasts of Southalpine rocks. This source is inferred to have coincided with an emerging belt located in the eastern Southalpine domain, produced by transpression along the proto-Periadriatic Lineament. Ophiolitic detritus may have reached the Central Alpine and Southalpine areas during the Early Cretaceous; in contrast, the exhumation and uplift of the Koralpe–Wölz high-pressure belt and of its uppermost Austroalpine nappe cover at 89–84 Ma, likely separated the Southalpine retrobelt basins from 'northern' sources.

Keywords: Cretaceous paleogeography, Southalpine conglomerates, clast microfacies, ophiolitic detritus, Upper Austroalpine and Southalpine sources, Transdanubian Range, proto-Periadriatic Lineament

Introduction

Compositional analysis and dating of the spectrum of clasts in pebble populations, especially those of an exotic nature, are important tools for provenance studies, and are particularly of crucial value for the reconstruction of the paleogeography, as well as the geological history of ancient mountain belts. This is especially true in the case of source areas now eroded, covered by other tectonic units, or buried by younger sediments (Zuffa 1980, 1985; Lewis 1984; von Eynatten & Gaupp 1999; Krische et al. 2014). The presence of rock fragments of particular lithofacies may sometimes have a high diagnostic potential for the identification of source areas and may significantly change existing paleogeographic reconstructions. Furthermore, the heavy mineral content of terrigenous sediments provides important information on the presence and evolution of physical connections and divisions between depocentres that, in the area under examination, had been predominantly constrained by regional tectonics.

The main subject of this study is the description and illustration of the litho- and microfacies of pebbles/cobbles contained in the Santonian Sirone Conglomerate of the Lombardian Flysch, as well as an upper Turonian to Coniacian stratigraphic interval of the Scaglia Rossa of the Venetian Prealps, with the aim of reconstructing the relevant source rocks and areas compatibly within the limits implied by this type of analysis. Source reconstruction implies an attempt at palinspastic restoration of the Late Cretaceous situation, which is a hard task, since it should take into account the main post-Cretaceous movements, such as the south-vergent thrusts of the Southern Alps and the Tertiary strike-slip movements along the Periadriatic and Giudicarie lines. In any case, we think that our reconstruction based on clast compositional analysis could represent an important contribution to shedding light on some aspects of the Late Cretaceous Alpine paleogeography.

Geological setting

The Lombardian and Dolomites flysch

The Upper Cretaceous Lombardian Flysch of the Southern Alps may be defined as a system of submarine fan and basin plain deposits, overlying an upward-deepening pelagic to hemipelagic succession of Jurassic to Early Cretaceous age deposited on the distal continental margin of Adria (Bichsel &

✉ corresponding author: Francesco Massari
francesco.massari@unipd.it

Häring 1981; Gelati et al. 1982; Bersezio & Fornaciari 1987; Bernoulli & Winkler 1990). The Lombardian Flysch basin has been generally considered a flexural basin on the Adriatic plate developed in the Alpine retrobelt area, in front of an Upper Cretaceous 'Orobic' belt (Fig. 1) of south-verging folds and thrusts (Bersezio & Fornaciari 1987, 1988; Doglioni & Bosellini 1987; Bernoulli & Winkler 1990; Bersezio et al. 1993; Wagreich & Faupl 1994; Berra & Carminati 2010; D'Adda et al. 2011; Zanchetta et al. 2011).

In the following description of the stratigraphy of the Lombardian Flysch, reference is made predominantly to Bersezio & Fornaciari (1987) and Bernoulli & Winkler (1990). In the Brianza area and the Bergamasc Alps, flysch sedimentation began with either uppermost Cenomanian or lowermost Turonian fan-fringe sediments (Flysch Rosso, Sommaschio Formation). Submarine unconformities, such as large slumps and chaotic deposits in the Cenomanian flysch, point to submarine erosion and mass wasting, possibly in connection with minor decollement and deformation in the sedimentary cover of the Southern Alps (Bersezio & Fornaciari 1988; Bernoulli & Winkler 1990). The fan-fringe sediments are overlain by a thick sequence of basin-plain turbidites (Pontida Formation, Turonian), which in turn grade into the Coniacian Sarnico

Sandstone that is made up of medium- to thick-bedded, coarse-grained sandstones and conglomerates. The unit represents a non-channelized midfan system (Bichsel & Häring 1981), which grades upwards into the Sirone Conglomerate. The latter was dated to late Coniacian–early Santonian by Venzo (1951); more recently, Erba & Fornaciari (1988) found nannofloras of the *Reinardtites anthophorus* and *Calculites obscurus* biozones and extended its age to the entire Santonian. The Sirone Conglomerate ranges in thickness from 80 to 150 metres, and has been interpreted as a channelized system of the prograding Sarnico Sandstone submarine fan (Häring 1978; Bichsel & Häring 1981). It consists of lens-shaped conglomerate bodies alternating with thin-bedded, fine-grained interchannel and levee deposits and common small crevasse channels (Häring 1978; Bichsel & Häring 1981; Bersezio & Fornaciari 1987; Bernoulli & Winkler 1990). Outside the Brianza area, the Sirone Conglomerate has been crossed by the Lisanza 1 borehole (AGIP 1981), which had been drilled near the southern end of the Lake Maggiore. Moreover, sparse outcrops of pebbly sandstone and sublithic to lithic arenite, attributed to the Sirone Conglomerate, have been signalled in the 50,000 Geological Sheet Mendrisio in the area between Torre and Balerna, NW of Como (Bernoulli et al. 2018).
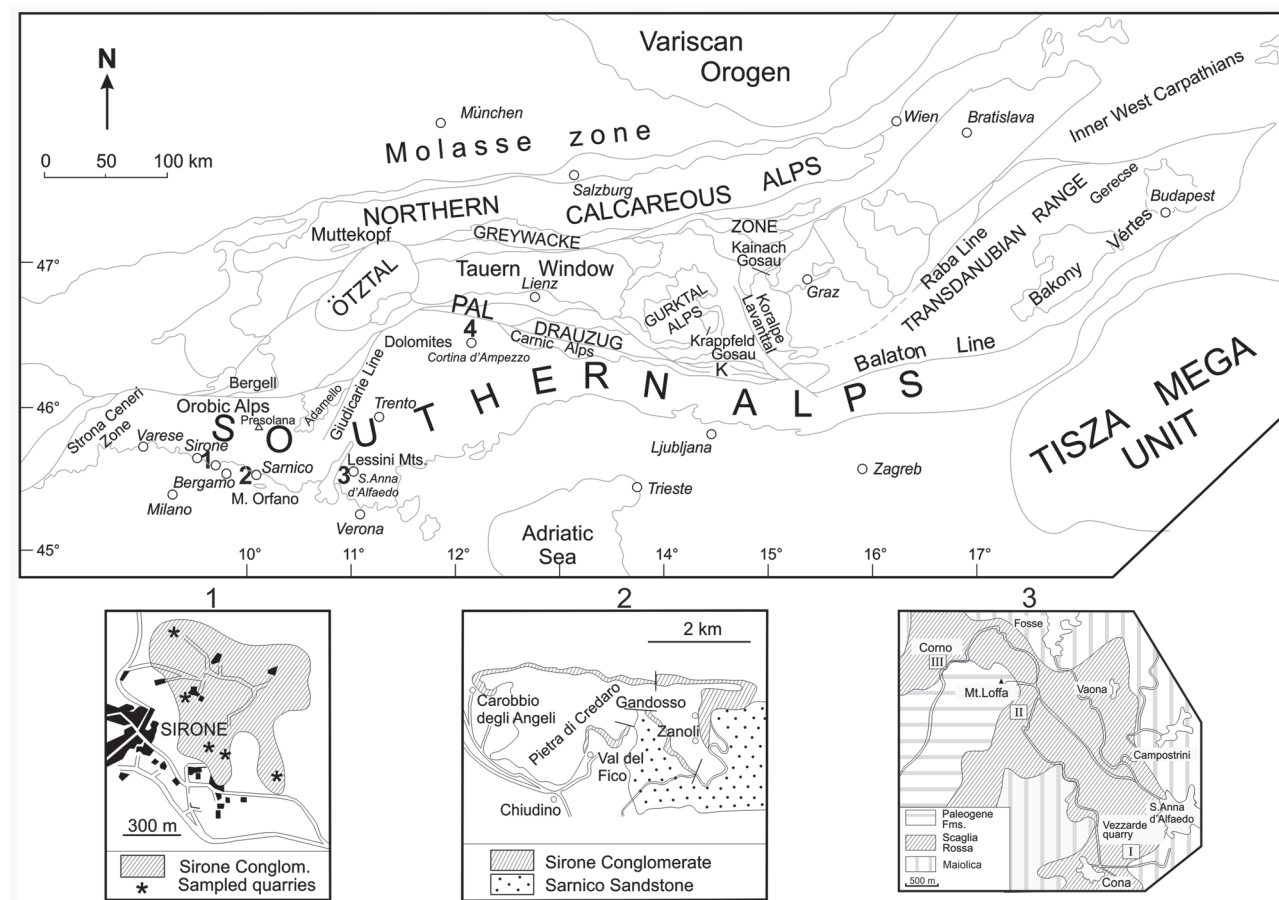

Fig. 1. Upper part: index map of main geographic and geological names used in the text. PAL: Periadriatic Lineament; K: Karawanken. Small boxes in the lower part indicate the sampled locations of the Sirone Conglomerate (1 and 2) and of the exotic clasts in the Scaglia Rossa (3); these localities (1–3) are also indicated in the index map, where 4 refers to the locality Ra Stua, 10.5 km NNW of Cortina d'Ampezzo.

The Sirone Conglomerate contains a redeposited shallow-water fauna of Santonian age, including rudists (*Hippurites*, *Radiolites*), bivalves, and gastropods (*Actaeonella*, *Nerinea*) (De Alessandri 1899; Venzo 1954). This resedimented fauna shows that source areas were rimmed by more or less extensive carbonate shelves (Castellarin 1972; Bernoulli et al. 1987). From the Sirone Conglomerate, Aubouin et al. (1970) reported the presence of pebbles of Paleozoic lithofacies of the eastern Southern Alps (quartzite, phyllite, Devonian Tentaculite limestone, phtanite, greywacke, etc.) and elements comparable to the central Southalpine Mesozoic lithofacies (Triassic dolostones, *Conchodon* Dolostone, Liassic oolitic limestone, Dogger-Malm radiolarites, and Lower Cretaceous Maiolica). Cadel (1974) identified quartz-wacke, greywacke, siltstone, and subarkose, which were possibly derived from Carboniferous and/or Permo–Schytian formations; litharenite with volcanic fragments; dolostones and limestones from Triassic–Jurassic formations; black and red chert from Jurassic units like the Medolo of the Lombardic succession or older units; Albian–Cenomanian marly limestone in Scaglia Rossa facies; reef limestone with rudists and corals of Santonian age; eruptive rocks, including rhyolite, dacite and andesite, inferred to have been derived mainly from Permian units; in the sandstones associated with conglomerates, he identified fragments of slate, phyllite, and micaschist, in addition to clasts of sedimentary rocks.

Recession of the turbidite fans in the late Santonian and Campanian led to the deposition of outer-fan deposits (Flysch di Bergamo, Pietra di Credaro) followed by hemipelagic and bioclastic slope sedimentation in the latest Campanian to early Maastrichtian.

The paleocurrent pattern of the Lombardian Flysch (Bichsel 1980; Bichsel & Häring 1981) indicates an input from the North and North-East, as well as a deflection into a predominantly westerly direction along the basin axis (Fig. 2).

Bersezio & Fornaciari (1987) reported paleocurrents consistent from the East, both in the Sarnico Sandstone and in the Sirone Conglomerate, while Aubouin et al. (1970) reported a preponderance of the ENE–WSW direction, indicating an almost longitudinal flow.

Bernoulli & Winkler (1990) pointed out that the main components of the heavy mineral assemblage of the upper Cenomanian to Turonian flysch sequences indicate provenance from presumably Variscan high-grade terranes. They also established that the source area of the Sarnico Sandstone/ Sirone Conglomerate was characterized by a shallow continental crust dominated by low-grade metamorphic terranes (and sediments) and granitic rocks.

Heavy mineral assemblages point again to high-grade metamorphic source terranes for the sandstones of the late Santonian to Campanian Bergamo Flysch. The changes in composition between the Sarnico/Sirone system, as well as the underlying and overlying formations are accompanied by unconformities, suggesting significant changes in paleogeography (Bernoulli & Winkler 1990) and possibly in dispersal paths.

Most importantly, chromite is rare or completely lacking in the post-Turonian deposits of the Lombardian Flysch, indicating that the basin was largely sheltered from the influx of ophiolitic detritus in post-Turonian times, which is in contrast to the Lower Austroalpine flysch basins (Bernoulli & Winkler 1990).

Castellarin (1976) and Castellarin et al. (1976, 2006) showed that isolated outcrops of a coarse Turonian to Maastrichtian flysch (Giudicarie Flysch), which are similar in facies to the Lombardian Flysch, are present near the present-day northern segment of the Giudicarie Line, between Malé (Val di Sole) and Rumo (Val di Non). According to Castellarin et al. (1976), the conglomerates of this flysch contain clasts of various lithofacies, including chert (mostly radiolarian chert or radiolarite),
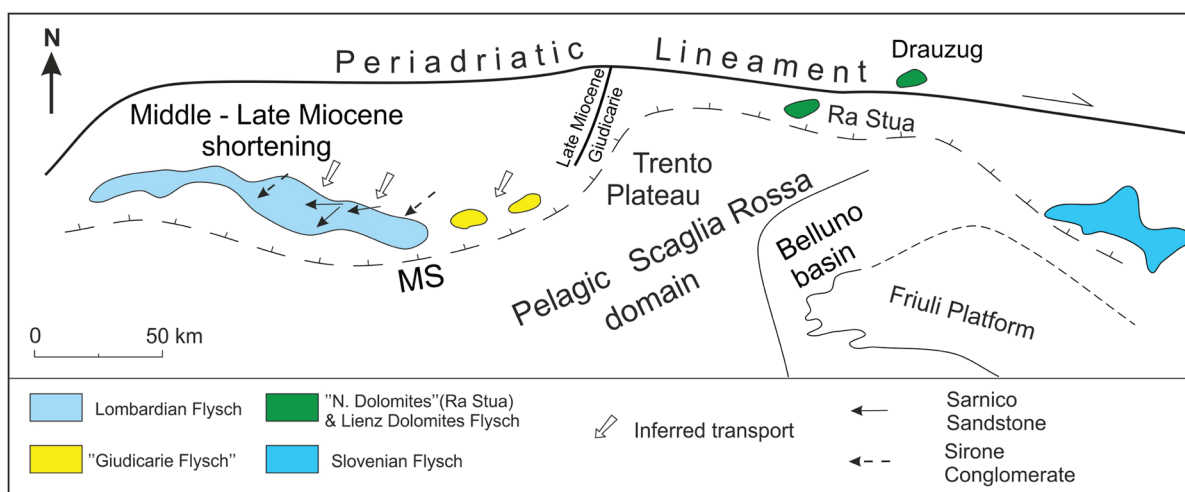

Fig. 2. Schematic, non-palinspastic reconstruction of the paleogeography in the Southalpine area during the Late Cretaceous. Arrows in the Lombardian Flysch and Giudicarie area show approximate paleoflow directions (from Bichsel 1980 and Bichsel & Haring 1981, simplified); flysch in the N Dolomites crops out near Cortina d'Ampezzo [localities of Ra Stua and Antruiles]. MS: tectonically-controlled marginal scarps separating the Scaglia Rossa domain from the flysch basins.

polycrystalline metamorphic quartz (from micaschist, paragneiss and/or orthogneiss), quartzite, slate and siltstone, phyllite, carbonaceous phyllite, acid intrusive rocks (or orthogneiss), aplite, mafic intrusive rocks, porphyroid, and acid and mafic volcanic rocks; clasts of carbonate rocks include Upper Triassic biogenic and stromatolitic dolostone, neritic limestone probably of Liassic age, nodular limestone similar to the upper Rosso Ammonitico Veronese with Kimmeridgian and Tithonian fossils, and Maiolica-type limestone with Neocomian calpionellids or Aptian foraminiferal assemblages. Castellarin et al. (2006) remarked that the conglomerate at the top of the Turonian towards the (?)Santonian lower unit of the 'Giudicarie Flysch' is comparable in composition to the Sirone Conglomerate.

Other records are represented by the flysch remnants of the Northern Dolomites (Aptian–Albian siliciclastics of Ra Stua – about 10.5 km NNW of Cortina d'Ampezzo – and Turonian–Campanian hybrid arenites of Antruiles – about 10 km W of Cortina d'Ampezzo), and by the turbidites of the Lienz Dolomites and Slovenian basin (Fig. 2). It is important to stress that the 'Giudicarie' flysch is not an extension of the Lombardian Flysch basin to the north, but was displaced to its present position by Neogene transfer faults along the Giudicarie system. Therefore, the outcrops of Lombardy, Rumo–Malè, Ra Stua–Antruiles, Lienz Dolomites, and Slovenia formed a continuous approximately E–W-belt before the dislocations along the Insubric/Pusteria and Giudicarie systems. The various flysch deposits terminated against marginal fault scarps of the pelagic Scaglia Rossa domain (Castellarin et al. 1976; Fig. 2).

Pebble analysis of the conglomerates of the Lombardian Flysch (Bichsel & Häring 1981) and the Insubric Flysch (Castellarin 1976; Castellarin et al. 1976) led the authors to the conclusion of a provenance from an area with facies development identical to that of the Lombardian Zone or the Austroalpine nappes. Similar conclusions were reached by Bernoulli & Winkler (1990).

It is also worth noting that the mineralogical and petrographic composition of the Lombardian Flysch shows a close affinity with the Pietraforte Fm. (Northern Apennines), a flysch unit laid down in an external sector of the Ligurian ocean, close to the Adriatic margin (Bortolotti & Malesani 1967; Valloni & Zuffa 1984; Gardin et al. 1994). The two units likely belonged to the same basin, with the Pietraforte presumably recording the downcurrent, distal deposition from more diluted flows with respect to the coarser-grained proximal facies of the Lombardian area laid down by higher-concentrated flows.

The Upper Cretaceous Scaglia Rossa

As mentioned above, the Lombardian Flysch terminates against tectonically-controlled marginal scarps bounding the Scaglia Rossa pelagic domain, within which the Trento Plateau was an extensive, long-lived structural high (Fig. 2; Castellarin et al. 1976, 2006). On this plateau, exotic clasts were found embedded in pelagic limestones of the Scaglia Rossa. The outcrops are situated in the surroundings of the village of S. Anna di Alfaedo (Valpolicella, Lessini Mounts N of Verona; Fig. 1); the clasts are embedded in three horizons within a 7–8 m thick stratigraphic interval, ranging in age from late Turonian (*Marginotruncana schneegansi* Zone) to Coniacian (lower part of the *Dicarinella concavata* Zone).

The exotic pebbles/cobbles are rounded, lack a preferred orientation, and appear either isolated or clustered in the pelagic host rock (Fig. 3a); they are associated with calcareous tubes of Teredinids (Massari & Savazzi 1981; Fig. 3b) and locally with debris of *Inoceramus* shells. Most clasts are pebbles 3–4 cm in diameter, but the size ranges from less than 1 mm to cobbles up to 13 cm in diameter; exceptional lengths of up to 30 cm are reported by Sorbini (1968). Sometimes, the surface of carbonate pebbles is densely pitted with borings. Mesozoic limestones, dolostones, and chert are dominant (Massari & Medizza 1973). The association with woodborers
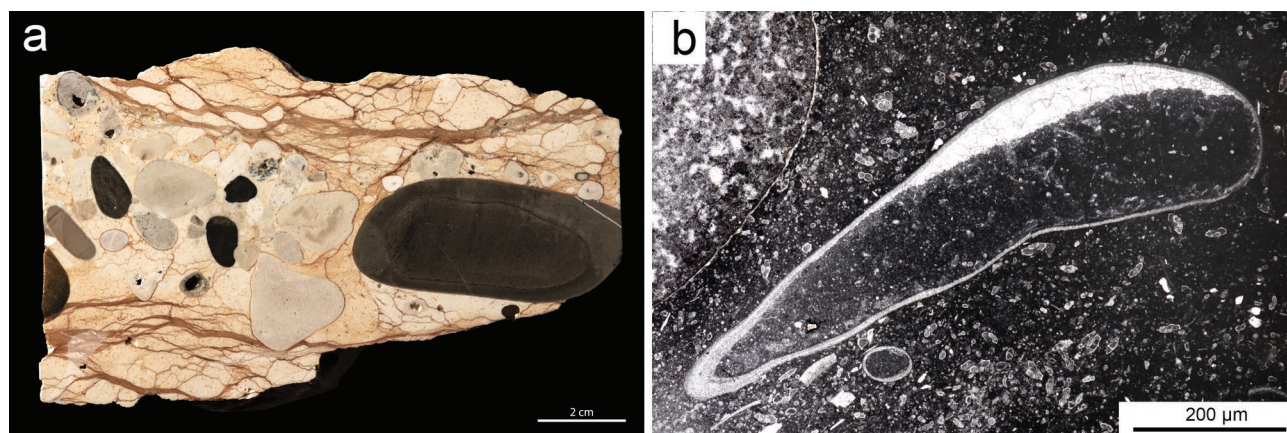

Fig. 3. a — Pebble cluster in the matrix of pelagic Scaglia Rossa limestone. Note the partial interpenetration of adjacent pebbles. Surroundings of S. Anna d'Alfaedo. **b** — Teredinid tubes associated with pebbles (SC 950, dry peel). Acronyms SC and SI in all the following figures refer to clasts from Scaglia Rossa and Sirone Conglomerate respectively.

or the lack of a siliciclastic matrix and any evidence of channeling indicate that driftwood was the most likely mechanism of transportation. The association with Teredinids testifies that driftwood transport had lasted long enough for these wood-boring organisms to become established (Massari & Savazzi 1981). We suggest that the clasts, entangled within tree roots, were brought to the ocean during river floods. Driftwood pebble transportation to the ocean over even great distances has also been demonstrated to occur by many authors, and the subsequent sinking of the clasts to the seabed as dropstones after waterlogging of the wood is well-documented in present-day and ancient pelagic environments (Emery 1955; Birkenmayer et al. 1960; Pratt 1970; Bennett et al. 1996; Bernoulli & Ulmer 2016). As observed by Bernoulli & Ulmer (2016), in an environment of relatively low sedimentation rates and oxidizing bottom water conditions, no trace of wood remains.

The compositional affinity of the clasts with those of the Lombardian Flysch suggests a common source in an emerged area drained by rivers and most likely forested.

Material and methods

Clasts (rounded pebbles and cobbles) studied for provenance analysis come from the Sirone Conglomerate of the Lombardian Flysch and the Scaglia Rossa pelagic limestones (Figs. 1, 2). In the former unit, they were sampled in a number of outcrops, situated in the surroundings of Sirone (small box 1 in Fig. 1) and in an area about 6 km west of Sarnico (small box 2 in Fig. 1) comprising the localities of Gandosso, Bossoletti, Molere, Zanoli, Carobbio degli Angeli, and Val del Fico, which are close to one another. Clasts in the Scaglia Rossa were collected in three upper Turonian to Coniacian horizons of the Scaglia Rossa quarried in the surroundings of S. Anna d'Alfaedo (Valpolicella, Lessini Mounts, N of Verona; small box 3 in Fig. 1), cropping out in the abandoned Vezzarde quarry near S. Anna d'Alfaedo [(I) in the small box 3], on the nearby slopes of the Mount Loffa (II), and in the locality 'Corno' (III). The three horizons are named by local quarrymen 'Corso Gentil', cropping out on the Mount Loffa, 'Corso Lastre Doppie', near the locality 'Corno', and 'Corso Dal Pel', in the Vezzarde quarry near S. Anna d'Alfaedo (Sorbini 1968). Most samples were obtained from large rock slabs of Scaglia Rossa, which were polished to allow a quick gross identification of the lithologies.

Textural descriptions and age attributions of lithofacies are based on the study of thin sections and dry-peels of 427 clasts from the Sirone Conglomerate and 3045 clasts from the Scaglia Rossa.

The age of the clasts could be determined with different degrees of accuracy and sometimes had to be left undetermined in the presence of poor, diagnostic fossil content. Formational assignments (Table 1 and Table S1 of the Electronic Supplement) were largely based on literature and personal field experience, when applicable. In terms of volume,

no rigorous attempt was made to calculate the relative abundance of the lithofacies present in the Sirone Conglomerate. On the other hand, an approximate evaluation was achieved for the principal classes of clasts contained in the Scaglia Rossa. Minor, insignificant, and unclassifiable lithofacies were not considered. Lithofacies were identified by a number (in order of age, from the oldest to the youngest), and summarized lithofacies descriptions, micro-faunas/floras, ages, formational attributions, possible analogues, and relevant references were eventually tabled (Table 1 and Table S1 of the Electronic Supplement).

Two samples from the locality Ra Stua (10.5 km NNW of Cortina d'Ampezzo, number 4 in Fig. 1; Fig. 2) were analysed for the identification of the heavy mineral assemblage after disaggregation by HCl acid. 200 transparent grains were identified under an optical microscope and, when necessary, verified with Raman spectroscopy. Lithofacies 48 was also processed as above; however, only an approximate evaluation of the heavy mineral content was possible, due to the great abundance of oxides and deep alteration of the grains.

Lithofacies and microfacies of the exotic clasts

A concise description of the identified lithofacies, their potential sources, and the inferred ages are presented in Table 1, while a more detailed description and relative microfacies, accompanied by a suggestion of ages and possible analogue units with relative references, is presented in Table S1 of the Electronic Supplement. The lithofacies are numbered 1 to 56, with each number representing an inferentially-homogeneous population of clasts. The number of clasts within each lithofacies from the Sirone Conglomerate (marked SI) and Scaglia Rossa (marked SC) is also indicated in Table S1 of the Electronic Supplement. A more detailed illustration is devoted in the text only to selected lithofacies that are deemed more significant in terms of provenance (see also Fig. 4 to Fig. 10).

Relative abundances

An approximate evaluation of the relative abundances of the main lithofacies contained in the Scaglia Rossa was attempted, based on the counting of 3045 clasts in 92 large and medium-sized dry peels of polished slabs. It is important to note that it was not possible to assess the frequency distribution by clast dimensional classes, given that the counting had been performed on sections which could not represent the real size of the intersected fragments. Moreover, counting results are largely biased in favour of the lithologies that tend to split into small particles, such as dolostones, which in fact appear with an overwhelming abundance. In any case, the data cannot reflect the real distribution of the lithologies in the source areas, since the preservation potential is influenced by the sensitivity to weathering, the different resistance to mechanical abrasion during transportation in high-energy environments,

Table 1: Summary of the identified lithofacies with concise indication of lithology, potential sources and inferred ages. Grst: grainstone; wckst: wackestone; pckst: packstone. A: Austroalpine; SA: Southern Alps; TSD: Transdanubian domain; SLO: Slovenian basin.

Lithofacies	Potential sources	Inferred age
1. Metasublitharenite	A–SA–TSD	Ordovician–Silurian?
2. Metalitharenite	A–SA	Ordovician–Silurian?
3. Carboniferous terrigenous/volcaniclastic facies	A–SA	early-Late Carboniferous
4. Subarkosic arenite/microrudite	A–SA–SLO	Late Carboniferous–Permian–Triassic
5. Rauhwacke	A–SA–TSD	Late Permian?–Triassic?
6. Oolitic grst	A–SA–TSD–SLO	Schythian?
7. Framestone with sphinctozoan sponges	A–SA	late Anisian–Ladinian
8. Wckst with *Austrocolomia*	A–SA–TSD–SLO	Anisian–Carnian
9. "Calcare Rosso"	SA	Middle Triassic
10. Silty microsparite with *Aulotortus*	A–SA	Middle–Late Triassic
11. Microsparite/micrite with *Aulosina oberhauseri*	A–SA–TSD	Carnian
12. Dolostone with *Griphoporella*	A–SA–TSD	Middle–Late Triassic
13. Microbial boundstone/floatstone	A–SA–TSD	Middle–Late Triassic
14. Wckst/pckst with *Aulotortus*	A–SA–TSD	Middle–Late Triassic
15 Coquinoid grst/pckst with *Alpinophragmium perforatum*	A–SA–TSD	Late Triassic
16. Coquinoid grst/pckst/wckst with *Aulotortus sinuosus*	A–SA–TSD	Late Triassic
17. Coquinoid pckst with *Kaeveria fluegeli*	A–SA	Rhaetian
18. Grst/pckst/wckst with *Triasina hantkeni*	A–SA–TSD	Rhaetian
19. Coquina with thick-shelled bivalves	A–SA–TSD	Rhaetian
20. Grst with ooids/oncoids and *Duostomina*	A–SA	late Rhaetian
21. Wckst with *Involutina liassica*	A–SA–TSD	Hettangian–Sinemurian
22. Wckst with *Licispirella violae*	A–SA–TSD–SLO	Hettangian–Sinemurian
23. Pckst/hybrid pckst with nodosarids and crinoid ossicles	A–SA–TSD	Sinemurian–Pliensbachian
24. Wckst with *Vidalina martana*	A–SA–TSD	Liassic
25. Stromatolite with sponge spicules	A–SA	Liassic
26. Wckst/pckst with sponge spicules	A–SA–SLO	Liassic
27. Peritidal grst/pckst with *Siphovalvulina*	A–SA	Sinemurian
28. Cherty spiculite	A	Early Jurassic?
29. Wckst with radiolarians	A	Early–Middle Jurassic
30. Platform wckst with *Nubecularia* and *Meandrovoluta*	A–TSD	Middle Jurassic
31. Pckst/wckst with pelagic bivalves	A–SA–TSD	Middle Jurassic
32. Cherty radiolarite	A–SA–TSD	Paleoz.?, Mid.–Late Triass.? – Mid.–Late Jur.?
33. Pelagic stromatolite with *Globochaete alpina*	A–SA–SLO	Bajocian–Callovian
34. Wckst/pckst with *Colomisphaera* spp.	A–SA	Oxfordian–Kimmeridgian
35. Radiolarian wckst with *Stomiosphaera moluccana*	A–SA	Oxfordian–Kimmeridgian
36. Grst/pckst with pelagic ooids	A	Oxfordian to early Kimmeridgian
37. Jurassic calcareous breccia with *Colomisphaera fibrata*	A–TSD	Middle–Late Jurassic
38. Wckst/pckst with Aptychus	A–SA	Kimmeridgian–Tithonian
39. Wckst with *Saccocoma/Globochaete* assoc.	A–SA–TSD	late Oxfordian–Kimmeridgian
40. Pckst/wckst with *Saccocoma/*radiolarian assoc.	A–SA–TSD	late Oxfordian–Kimmeridgian
41–45. Maiolica-type wckst with calpionellids	A–SA–TSD–SLO	late Tithon.–early Valanginian
46. Lower Cretaceous transgressive limestone	TSD	Early Cretaceous–late Aptian?
47. Urgonian-type limestone with orbitolinids	TSD	Albian
48. Upper Albian hybrid quartzarenite with *Pseudothalmanninella*	TSD	late Albian
49. Hybrid pckst with ?*Vidalina hispanica*	A	late Cenomanian–Coniacian
50. Gosau-type hybrid rudist floatstone	A–SLO	Santonian
51. Gosau-type hybrid floatst/grst/wckst with *Cuneolina pavonia*	A	Coniacian–Santonian
52. Gosau-type early-lithified lithic rudite	A–TSD	Coniacian–Santonian
53. Granitoid rock	A–SA–TSD	Early Permian?
54. Rhyolite	A–SA–TSD	Ordovician?, Early Permian?, Middle Triassic?
55. Dacite/andesite	A–SA–TSD	Late Carb.?, Early Permian?, Middle Triassic?
56. Mafic effusive rock	A–SA	Ordov.?, Silur.?, Dev.?, Carb.?, Mid. Triassic?

and the expected lack of lithologies prone to disgregation into very fine particles, such as clays, soft marls, etc. However, being aware of their poor significance, we opted to present the results anyways, believing that they could provide hints on the stratigraphy of the provenance area domain:

- Dolosparite, dolomicrosparite, dolomitic limestone (lithofacies 12): 87.4 %.
- Microsparite, either azoic or with sparse microfossils (lithofacies 10–11): 5.7 %.

- Biomicrite with radiolarians and/or sponge spicules (lithofacies 24, 26, 28, 29, 32, 34, 35, 39, 40): 2.5 %.
- Chert (lithofacies 28, 32): 2.1 %.
- Platform limestone of mostly Triassic and Jurassic age (lithofacies 6, 7, 13–21, 23, 27, 30): 1.7 %.
- Hybrid arenite with sparse planktonic foraminifers (lithofacies 48): 0.4 %.
- Maiolica-type limestone (lithofacies 41–45): 0.1 %.
- Shallow-water facies with Orbitolinidae and/or rudist debris (lithofacies 47, 50–52): 0.07 %.
- Others (mainly igneous and crystalline): 0.07 %.

Provenance-diagnostic lithofacies

Most of the studied lithofacies show analogies with those of units which are widespread along the southern margin of the Alpine Tethys and the Adria plate, and not specific to a particular paleogeographic domain of this area. However, some of them provide more specific information; they are outlined in the following paragraphs, and a more detailed description and accompanying comments are provided when necessary.

Carboniferous terrigenous/volcaniclastic facies (lithofacies 3 of Table 1)

Characteristics: Feldspathic litharenite and lithic microrudite/arenite showing tight packing (Fig. 4a, b). Extraclasts (angular to rounded) include: common fragments of mafic effusive rocks with plagioclase laths (intersertal texture) and occasional femic minerals in a glassy groundmass with sparse opaque minerals; quartz–feldspathic effusive rocks; rhyolite; micaceous quartzite; gneiss with occasional garnet; metaquartzarenite; arkose; siltstone and shale; isolated minerals, such as myrmekitic intergrowths, tourmaline. Pelsparite and biomicrite generally recrystallized to microspar with crinoids, bryozoans, brachiopods, thick-shelled molluscs, and rare Dasycladaceae; micrite with ostracods; dolosparite and dolomicrite; oolitic limestone with micritic matrix; wackestone with sparse radiolarians; radiolarian and spiculitic chert; radiolarian chert with Fe pigment and flattened radiolarians; microsparite with ghosts of radiolarians. Macroscopic colour: dark green, blackish green.

This lithofacies is restricted to the clast population of the Sirone Conglomerate.

Possible analogues: This lithofacies association shows a striking compositional analogy with the Carboniferous M. Terzo Sandstone, an informal member of the Dimon Fm. of Carnic Alps (Spalletta et al. 1980; Läufer et al. 1993; Germani 2007; Venturini & Spalletta 2015), grading laterally into the upper part of the Hochwipfel Fm. (Corradini et al. 2015), a Variscan flysch interpreted as a subduction-related foreland-basin fill.

The identified lithic components are closely similar to those recognized by Spalletta & Venturini (1988) and Krainer (1992)

in the Hochwipfel flysch of the Carnic Alps. The lithofacies also shows close resemblance in lithic components with the upper Visean Badstub Breccia of the Paleozoic of Nötsch, which is regarded as a Variscan molasse (Neubauer et al. 2022). Variscan flysch is present throughout the so-called Noric domain, which includes the Graz and Gurktal Paleozoic (Neubauer et al. 2022).

A wide paleogeographic domain of the synorogenic Variscan flysch can be inferred; however, the striking compositional analogy of the studied lithofacies with a member of the Carboniferous Dimon Fm. of Carnic Alps, which grades laterally to the upper part of the Hochwipfel Flysch, supports the assumption of an eastern Southalpine source area, a hypothesis strengthened by the presence in the Sirone Conglomerate of other clastic components typical of the Paleozoic of the eastern Southern Alps.

Inferred age: Bashkirian or latest Serpukhovian to Bashkirian.

Jurassic calcareous breccia (lithofacies 37 of Table 1)

Characteristics: Partly-silicified calcareous breccia with clasts of Triassic and Jurassic formations (Fig. 7e, f). Angular to subrounded extraclasts include: carbonate platform bioclastic limestone, oolitic packstone/grainstone, pelletal limestone, dolosparite, grainstone with *Thamatoporella parvovesiculifera*, wackestone with radiolarians and sponge spicules, radiolarian chert; isolated components, such as common ooids, oncoids, and foraminifers, such as *Trocholina*, *Trochammina*, *Siphovalvulina* are likewise considered as resedimented; obviously coeval components in the matrix are sponge spicules, radiolarians, *Colomisphaera fibrata*, crinoid ossicles, ostracods (Fig. 7e). Another subfacies (Fig. 7f) is almost devoid of microfossils and shows a fluidal structure of the fine-grained matrix, suggesting a debris flow origin.

The lithofacies suggests a link with submarine erosion of tectonically elevated area(s) and gravity-driven redeposition into adjacent basin(s).

Possible analogues: Lithofacies 37 is comparable to the calclithitic breccias reported in the Austroalpine domain of the Eastern Alps and the Transdanubian Range unit as related to Middle–Late Jurassic tectonics (e.g., Mandl 2000; Ortner et al. 2008; Császár et al. 2009, 2012; Missoni & Gawlick 2011; Steiner et al. 2021). In the Northern Calcareous Alps (NCA hereafter), Callovian to Tithonian breccias consist of tectonic-related mass-flow deposits with clasts of several Triassic and Jurassic stratigraphic units (Gawlick et al. 2009). In the Transdanubian Range, similar sedimentary breccias are reported in the Gerecse and Bakony Mountains (Császár et al. 2009, 2012), for example, the so-called 'Oxfordian Breccia', which is attributed to the tectonics associated with the closure of the 'Meliata Ocean'.

The causes of the Middle to Late Jurassic tectonic processes in the Austroalpine domain are still controversial, and several contrasting models have been proposed (Gawlick et al. 2015). Missoni & Gawlick (2011) correlated the Jurassic geodynamic
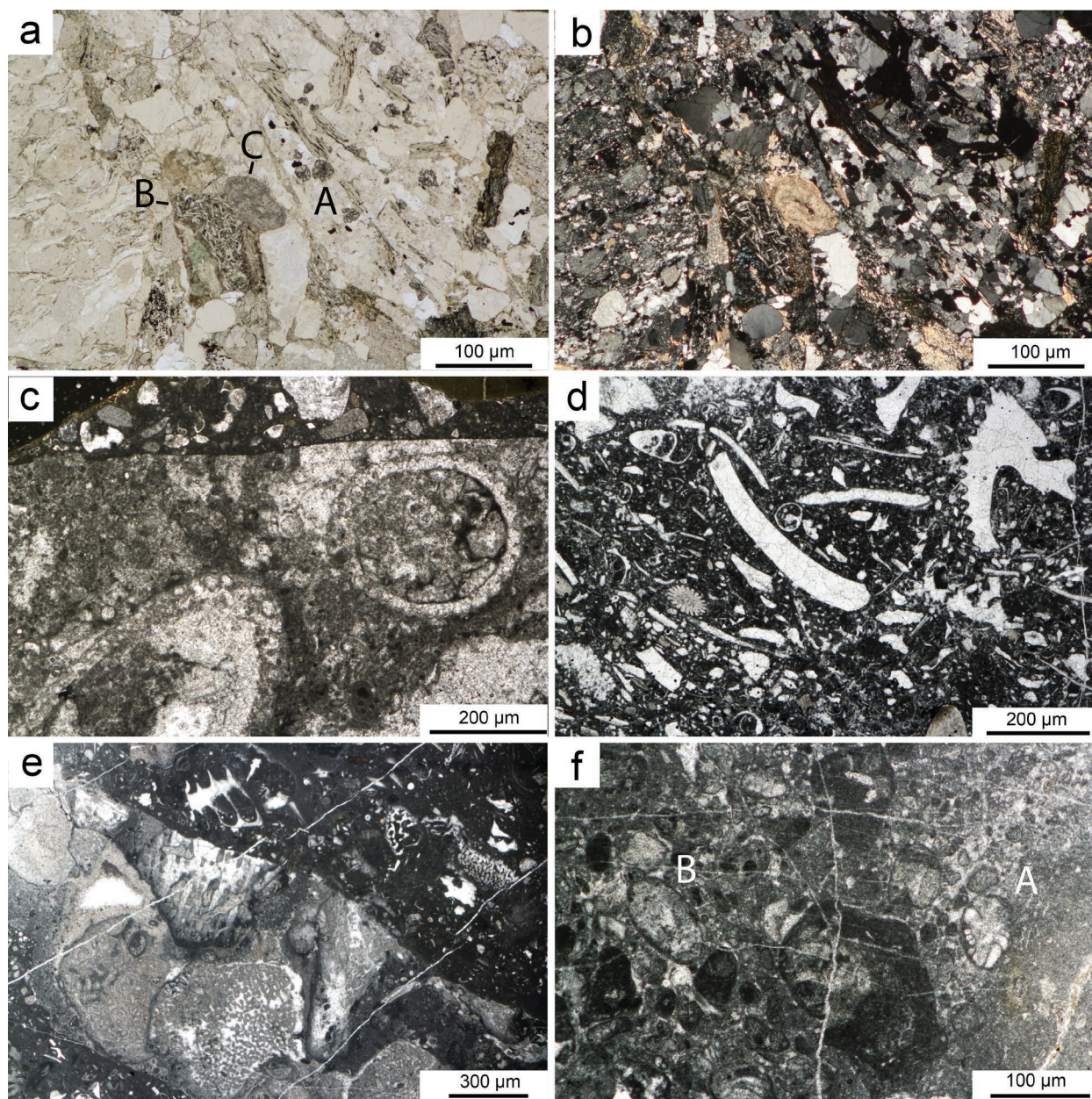
Fig. 4. a — Lithofacies 3 (inferred age: early Late Carboniferous). Feldspathic lithic microrudite. Note the fragment of garnet gneiss (A), mafic effusive rock (B) and crinoid ossicle (C). SI 225 (thin section). Parallel nicols. **b** — The same subject, crossed nicols. **c** — Lithofacies 12 (inferred age: Middle–Late Triassic). Dolomitic limestone with *Griphoporella*. SC744 (thin section). **d** — Lithofacies 15 (inferred age: Late Triassic). Coquinoid packstone with debris of molluscs and echinoids. SC 182 (thin section). **e** — Lithofacies 16 (inferred age: Late Triassic). Wackestone with detritus of reef dwellers, including bored Sphinctozoan sponges, corals, gastropods. SI333 (thin section). **f** — Lithofacies 18 (inferred age: Rhaetian). Packstone with Duostominidae (A) and *Aulotortus* (B). SI 140 (thin section).

evolution of the NCA with the partial closure of the western Neotethys Ocean. They pointed out that during the Middle to early Late Jurassic times the geodynamic scenario changed from divergent to convergent, with erosion of Triassic to Lower Jurassic sediments and their mobilization as slides and mass flows into deep-water trench-like basins formed in sequence in front of a propagating thrust belt. Other authors (e.g., Haas et al. 2011 and references therein) envisage a link of the breccias with the erosion of fault-blocks generated in a context of strike-slip faulting.

Inferred age: Middle–Late Jurassic.

Lower Cretaceous transgressive limestone (lithofacies 46 of Table 1)

This lithofacies is very rare and just one pebble was found in the Sirone Conglomerate.

Characteristics: red skeletal packstone/wackestone with *Hedbergella*, common microbored Nodosariidae (*Lenticulina*, *Nodosaria*), *Spirillina*, *Planiinvoluta*, small gastropods, debris
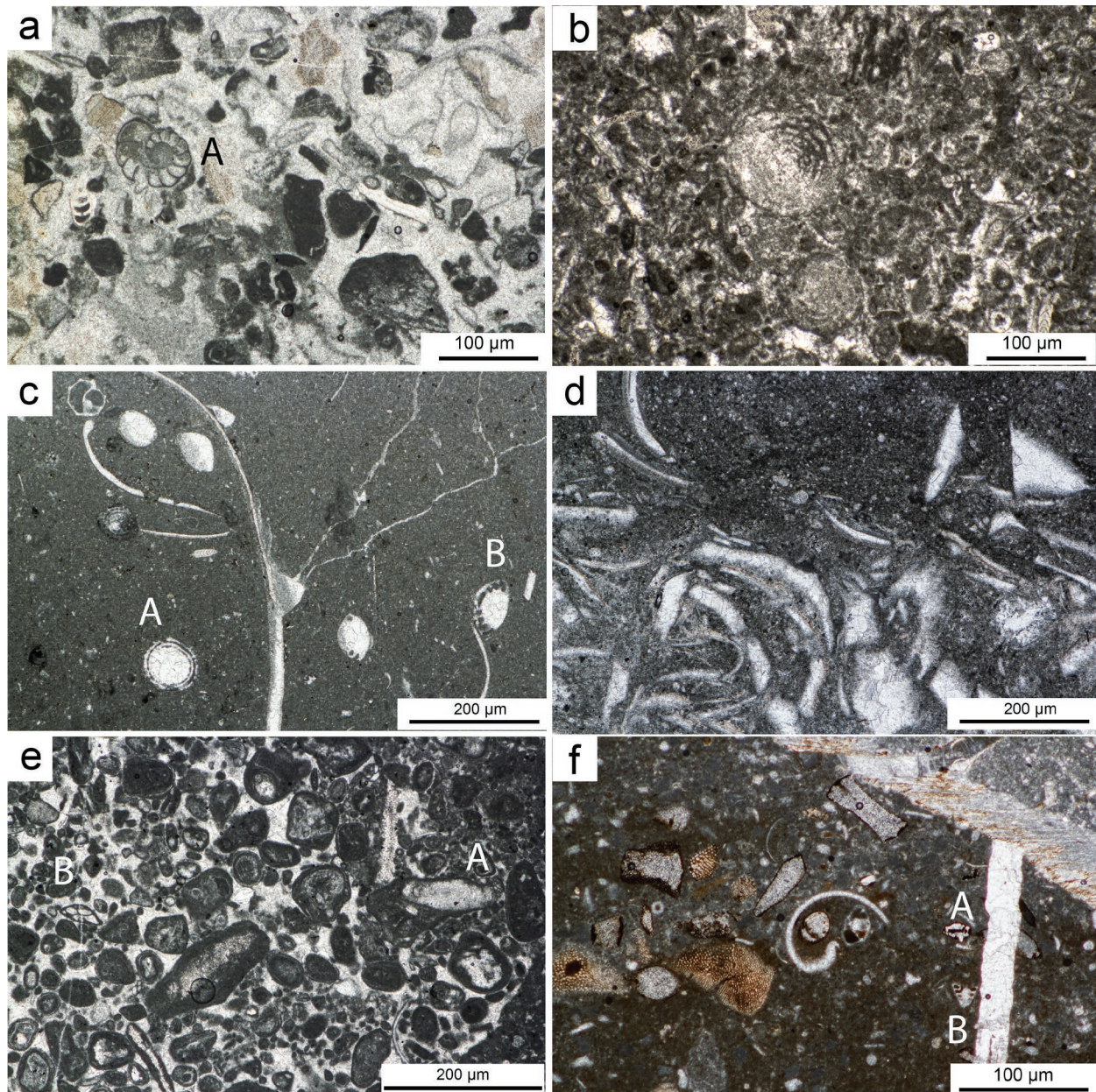
Fig. 5. a — Lithofacies 18 (inferred age: Rhaetian). Grainstone with reef detritus and Duostominidae (*Diplotremina subangulata*; A). SI 371 (thin section). **b** — Lithofacies 18 (inferred age: Rhaetian). Packstone with *Triasina hantkeni* (centre right). SC 174 (thin section). **c** — Lithofacies 18 (inferred age Rhaetian). Wackestone with *Triasina hantkeni* (A) and *Trocholina* (B). SC191 (thin section). **d** — Lithofacies 19 (inferred age: Rhaetian). Layer of coquinoid packstone with thin- and thick-shelled bivalves overlain by a radiolarian biomicrite. Inferred allodapic facies. SC 190 (thin section). **e** — Lithofacies 20 (inferred age: late Rhaetian). Grainstone with ooids and oncoids, *Aulotortus* cf. *tumidus* (A) and "*Tetrataxis*" *humilis* (B). SI 60 (thin section). **f** — Lithofacies 21 (inferred age: Hettangian–Sinemurian). Wackestone with *Involutina liassica* (A), *Trocholina turris* (B), debris of molluscs, crinoid ossicles, Fe-oxide pigment in bioclasts. SC 827 (thin section).

of echinoids, bryozoans, brachiopods, pelagic bivalves, ahermatypic solitary corals, *Boueina*, coralline algae, rare fish teeth, fragments of vertebrate bones. Various extraclasts include dolostone, oomicrite, isolated ooids, wackestone with common *Lenticulina*, and fragments of calcrete crust. Bioclasts and extraclasts show intense microboring and Fe-oxide pigment. Planar to low-angle lamination is present. Extraclasts of calcrete crusts possibly indicate proximity to, or transgression on, an emerged landmass. The characteristics of this lithofacies may suggest deposition above an unconformity.

Possible analogue: We compare this lithofacies with the lowermost part of the upper Aptian–lower Albian shallow-marine Tata Limestone, which is a crinoid-rich, unconformably-based unit of the Transdanubian Range unit (western foreland of the Gerecse to the South Bakony; Haas et al. 2014), commonly containing fragments of Jurassic to Lower

Cretaceous rocks eroded from the deformed substrate (see also Császár et al. 2009). The bulk of Tata Limestone is made up of medium-grained, well-sorted, hummocky-bedded bioclastic grainstone (Császár et al. 2009). These authors report that the hiatus accompanying the unconformity at the base of Tata Limestone may be important, with erosion locally cutting down to Jurassic rocks or even deeper, to the Upper Triassic Dachstein Limestone. A provenance link to the NCA area is unlikely, since deposits of comparable age are generally represented by basinal turbidites (see below).

Inferred age: Early Cretaceous, possibly late Aptian.

Urgonian-type limestone (lithofacies 47 of Table 1)

Characteristics: grainstone–rudstone, sometimes packstone, with common Orbitolinidae (Fig. 8d), among which *Orbitolina*? *(Mesorbitolina) texana*, showing predominantly-agglutinated and rolled tests, *Salpingoporella*, debris of corals, echinoids, bryozoans, brachiopods, thick-shelled bivalves, sometimes bored, among which rudists, and coralline algae. Chert, quartz and carbonate extraclasts range from sparse to up to 20–25 %. Textural and fabric features suggest a depositional setting ranging from high-energy nearshore (predominant) to inner shelf.

Inferred age: Albian.

In the NCA area, layers with Orbitolinidae are generally present as basinal carbonate turbidite (allodapic) deposits derived from nearby Urgonian carbonate platforms that have now been completely lost to erosion (Wagreich & Schlagintweit 1990; Faupl & Wagreich 2000). Beds with Orbitolinidae occur in the upper Barremian to lower Aptian Rossfeld Fm. and Schrambach Fm. (Schlagintweit et al. 2012) and in the Albian Losenstein Fm. (Gaupp 1983), as well as tempestites in the lowermost, transgressive part of the Branderfleck Fm.; they have also been reported from the deep-water succession of the Gerecse basin of the Transdanubian Range unit, e.g., the Aptian to Lower Albian Köszörükőbánya conglomerate (Császár 1995; Faupl et al. 1997).

The deep-water depositional setting of all the units mentioned above contrasts with the inferred shallow-marine to shelf environment of the studied lithofacies. Furthermore, in the studied populations, the pebbles of lithofacies 47 are not associated with clasts of any *Orbitolina*-bearing allodapic facies; this suggests that allodapic units are quite unlikely to be the source of the lithofacies under scrutiny. However, the shallow-water facies with Orbitolinidae occurring in the lowermost Branderfleck Fm., or present as pebbles associated to the NCA allodapic deposits, may be later reworked and incorporated into the gravels of the NCA Gosau Group, from which they may be resedimented in the Southalpine basins.

Possible analogues: Although a provenance from the NCA cannot be excluded, a more probable source of lithofacies 47 is represented in our opinion by the Urgonian carbonate platform deposits of the lower Albian shallow-marine, Urgon-type Környe Limestone of the south-western margin of the Vértes Mts. and North Bakony area (Császár et al. 2012); another possible source is the upper Albian *Orbitolina*-bearing Mesterhajag member of the Zirc Limestone (Northern Bakony) (Császár et al. 2009, 2012), consisting of biointrasparitic grainstone or packstone with benthic foraminifera, algae, and *Orbitolina* becoming particularly abundant in the upper part of the unit (Császár et al. 2012). The quartz and chert grains and sparse carbonate extraclasts present with percentages of up to 20–25 % may denote a link with an emerged land area undergoing erosion. In the inferred source area, shallow marine to shelf sedimentation was influenced by the concomitant upwarping of the central part of the Transdanubian Range during the late Early Cretaceous (Császár et al. 2012).

Upper Albian hybrid quartzarenite (lithofacies 48 of Table 1)

Characteristics: fine- to medium-grained hybrid quartzarenite (Fig. 8e, f) to hybrid calcarenite, sometimes partly silicified, bioturbated (local spreiten), with Nodosariidae, Rotaliidae, *Marssonella*, *Cuneolina*, sparse planktonic foraminifers in finer-grained varieties of the lithofacies (*Pseudothalmanninella ticinensis*, *Hedbergella*, local *Planomalina buxtorfi*), *Glomospira*, sparse agglutinated Orbitolinidae [*Orbitolina* ?*(Conicorbitolina) conica*], Ophthalmidiidae, Textulariidae, debris of echinoids, sponge spicules, sparse bryozoans and corals, brachiopods, serpulids (*Carpathiella triangulata*), coralline algae (*Lithophyllum*), thick- and thin-shelled bivalves, ostracods, sparse radiolarians, peloids. Common extraclasts (up to 70 %) include abundant quartz and radiolarian chert, sparse platform limestone, and dolostone. Local planar/low-angle lamination. This lithofacies contains a significant amount (approximately 25 %) of chrome spinel. The texture and fabric characteristics, as well as bioturbation and the presence of glauconite, suggest a shelf depositional environment.

Inferred age: Late Albian.

The studied lithofacies may be compared compositionally to the NCA Losenstein Fm. of Middle/Late Albian to early Early Cenomanian age (Wagreich 2003) and to the Lower Cenomanian sandstones with orbitolinids of the Branderflek Fm. (Schlagintweit & Wagreich 2005); these formations, however, with the exception of the shallow-water deposits of the lowermost Branderfleck Fm., consist of basinal turbiditic deposits laid down in a deep-water setting (e.g., von Eynatten & Gaupp 1999), which contrasts with the inferred shelf depositional environment of lithofacies 48.

Possible analogue: Lithofacies 48 is thought to display close affinity with the Vraconnian (uppermost Albian) Gajavölgy member of the Zirc Limestone of the Transdanubian Range (e.g., Bodrogi 1991; Császár et al. 2012), which is a greenish-grey, glauconitic, fine-grained, sandy bioturbated limestone embedded in a deep subtidal environment. At its unconformable base, the Gajavölgy member contains extraclasts derived from the uplifted south-eastern limb of the Transdanubian syncline. The presence of abundant extraclasts in this lithofacies is an element of analogy with the above-mentioned unit. In particular, the abundant quartz and chert
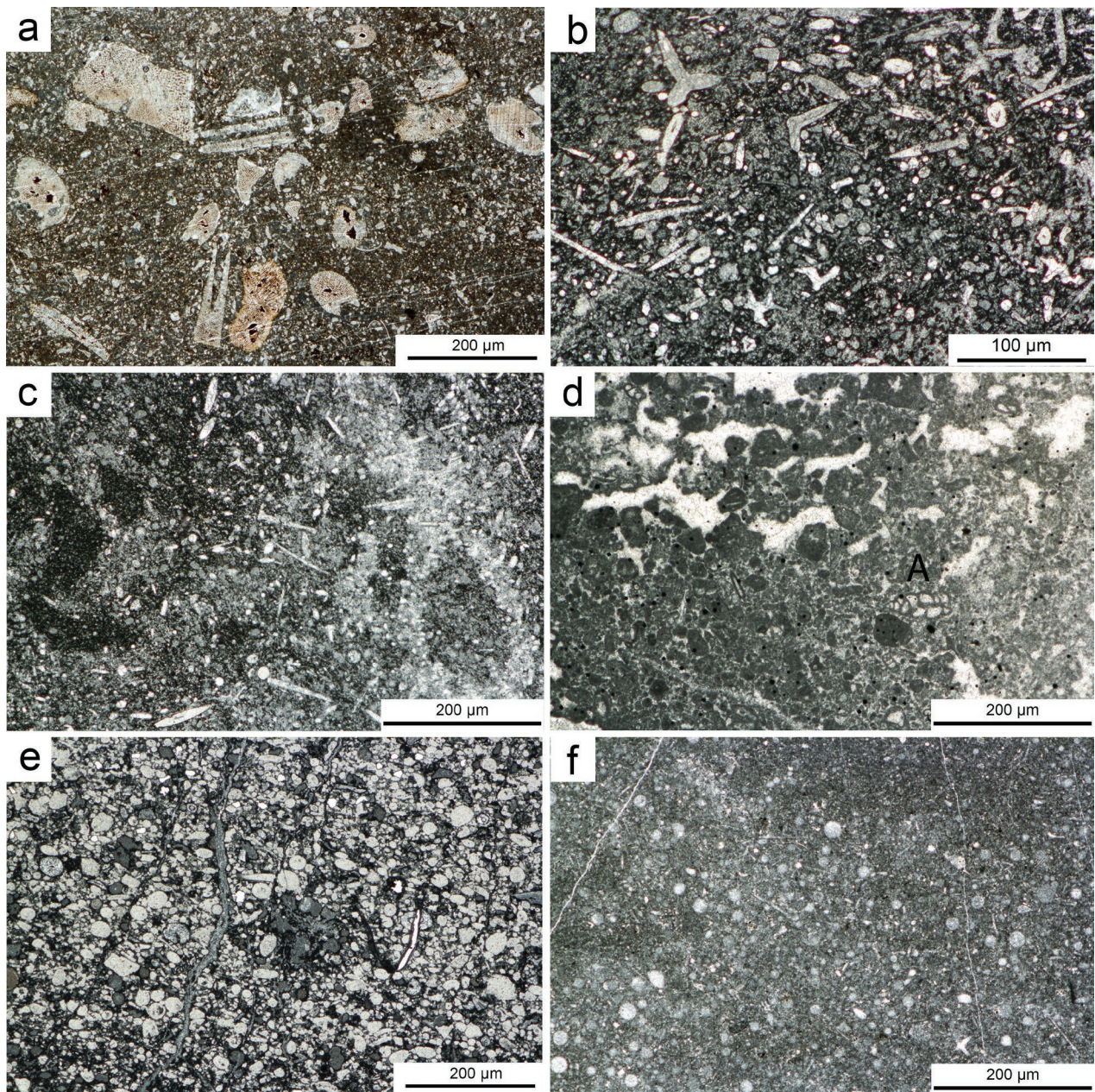
Fig. 6. a — Lithofacies 23 (Inferred age: Sinemurian–Pliensbachian). Hybrid packstone with common crinoid ossicles with Fe-oxide pigment. SI 198 (thin section). **b** — Lithofacies 26 (Inferred age: Liassic). Wackestone/packstone with abundant sponge spicules and radiolarians. SI 384 (dry peel). **c** — Lithofacies 26 (Inferred age: Liassic). Bioturbated wackestone with sponge spicules and radiolarians. SC 432 (dry peel). **d** — Lithofacies 27 (Inferred age: Sinemurian). Peritidal dismicrite with fenestral fabric and *Siphovalvulina colomi* (A). SI 421 (thin section). **e** — Lithofacies 28 (inferred age: Early Jurassic?). Spiculite with predominant sterrasters. SI 328 (dry peel). **f** — Lithofacies 29 (inferred age: late Middle Jurassic). Bioturbated wackestone with radiolarians dominant, sparse sponge spicules. SI 19 (thin section).

clasts are interpreted to represent residual material that survived chemical alteration and was washed out from paleosols evolving in a hot humid climate. This is a feature that corresponds with the intensive weathering that led to the development of the oldest bauxites in the Transdanubian Range, which later formed on emerged areas after the Albian tectonic events (Császár et al. 2009).

Upper Cretaceous sediments of the Gosau-type lithofacies (50–52 of Table 1)

Lithofacies association 50–52 (Fig. 9b–e) are closely similar to the Gosau sediments deposited in continental to shallow-marine environments of the Austroalpine domain of the Eastern Alps and the Transdanubian Range. These usually
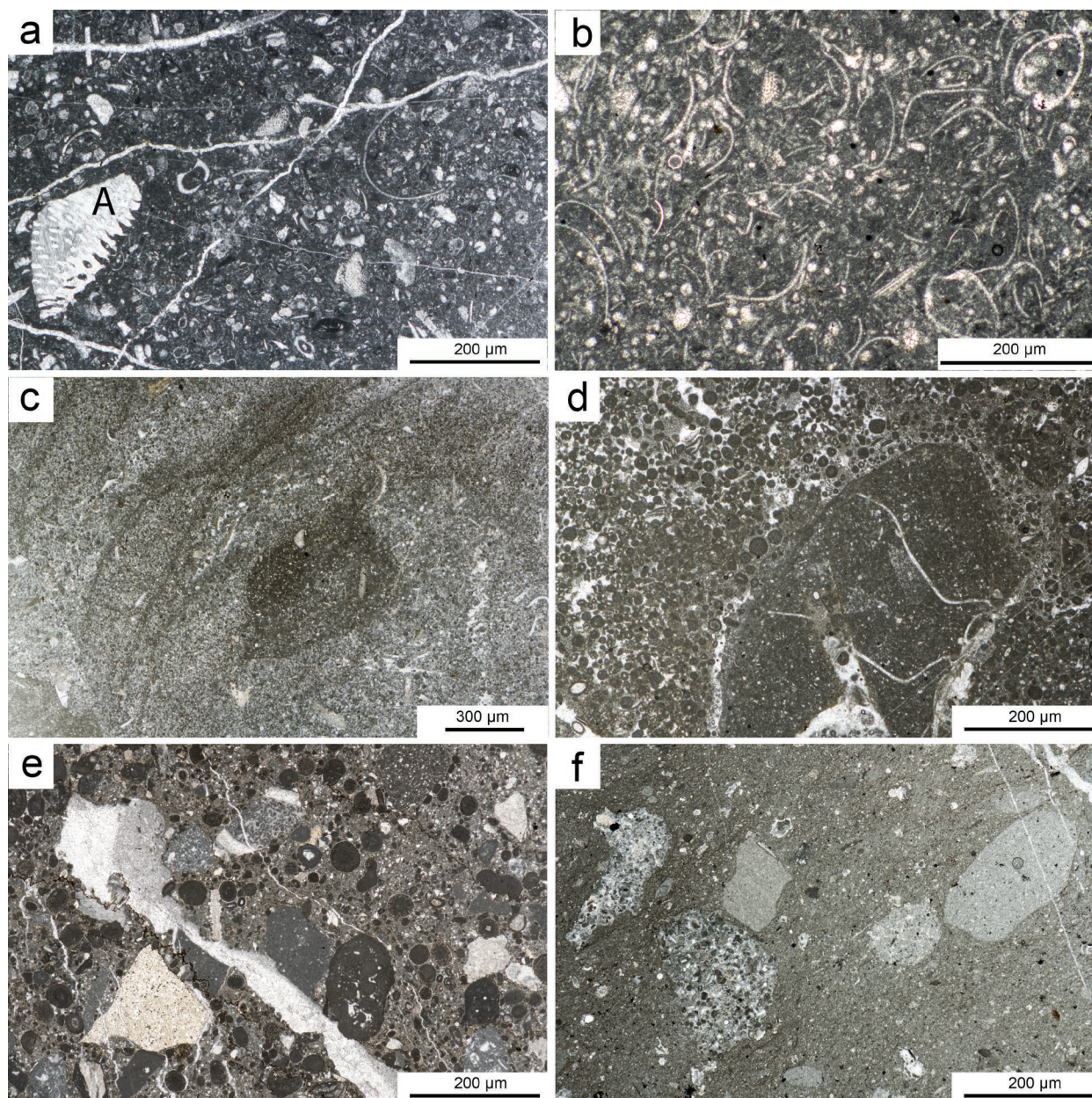
Fig. 7. a — Lithofacies 30 (inferred age: Middle Jurassic). Platform/ramp wackestone with debris of brachiopods (A), crinoids, bivalves, Ophtalmidiidae. SI 62 (thin section). **b** — Lithofacies 31 (inferred age: Middle Jurassic). Bioturbated packstone with *Bositra*-like pelagic bivalves, sparse sponge spicules and radiolarians. SI379 (dry peel). **c** — Lithofacies 33 (inferred age: Bajocian–Callovian). Pelagic bioturbated packstone with stromatolitic laminae, radiolarians, Aptychus, pellets. SI 139 (thin section). **d** — Lithofacies 36 (inferred age: Oxfordian to early Kimmeridgian). Packstone with micritic (pelagic) ooids, ammonoids, Nodosariidae. SI 364 (thin section). **e** — Lithofacies 37 (inferred age: Middle–Late Jurassic). Calclithitic breccia with angular to subrounded extraclasts (among which oolitic packstone, wackestone with radiolarians and spicules, pelsparite, platform limestone, radiolarian chert), reworked ooids and radiolarians in the matrix. SI 146 (thin section). **f** — Lithofacies 37 (inferred age: Middle–Late Jurassic). Calclithitic breccia (debris flow) with extraclasts of platform limestones and fluidal matrix. SC 882 (thin section).

coarse-grained sediments were laid down on a deeply incised surface that formed when the nappe stack of the Eo-Alpine orogen was uplifted, subaerially exposed, eroded, and subjected to the extensional and strike-slip faulting which defined the Gosau basins (Wagreich & Faupl 1994; Sanders 1998; Mandl 1999).

Inferred age: Coniacian–Santonian.

Lithofacies 50

Characteristics: the lithofacies, which is only found in the Sirone Conglomerate, can be defined as hybrid parautochthonous rudist floatstone (Fig. 9b) with *Acteonella*, encrusting, and microencrusting organisms. Two sediment types are commonly associated (Fig. 9b): a biomicritic original matrix,
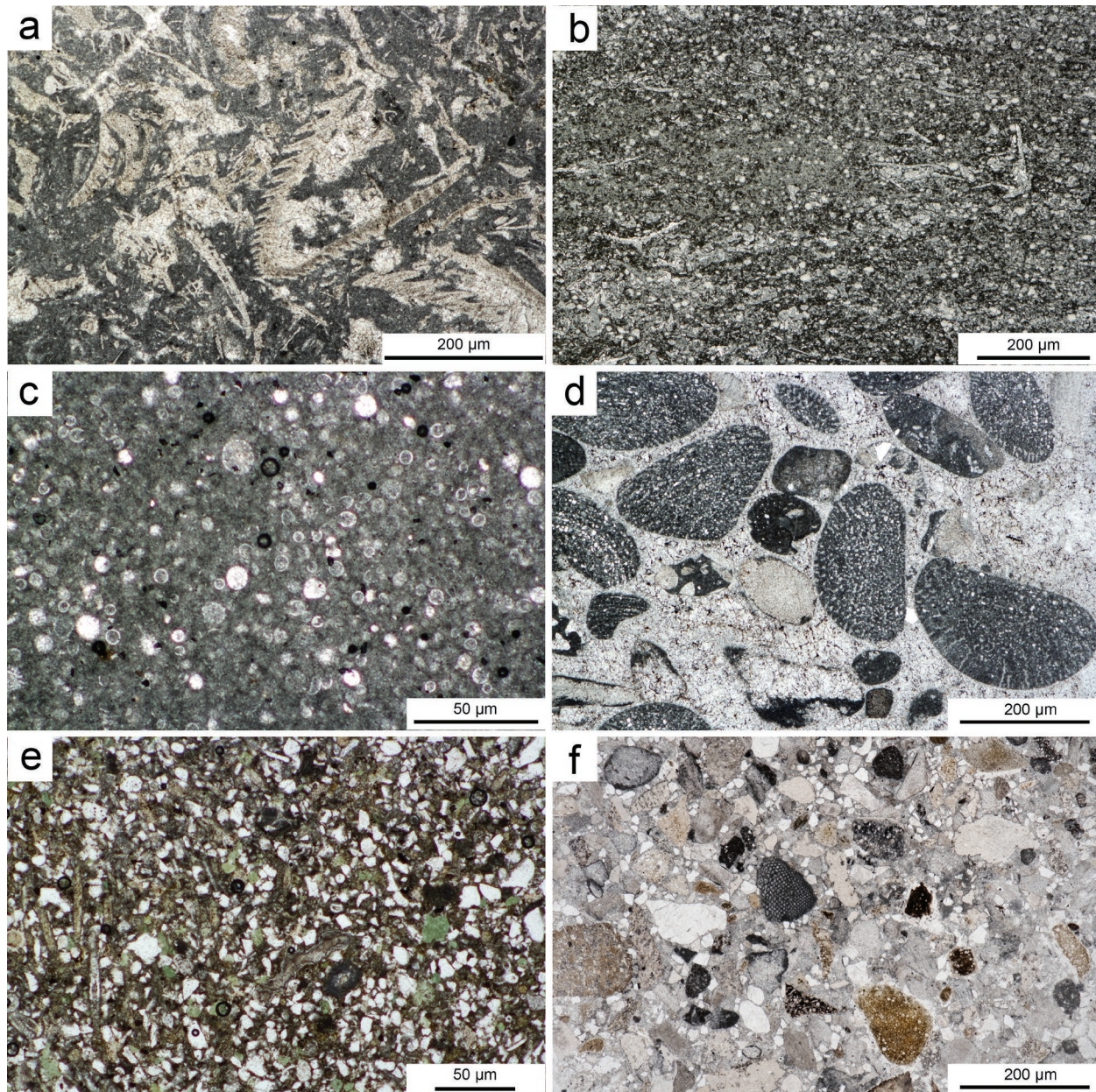
Fig. 8. a — Lithofacies 38 (inferred age: Kimmeridgian–Tithonian). Aptychus packstone. SI 142 (thin section). **b** — Lithofacies 40 (inferred age: Kimmeridgian–early Tithonian). Bioturbated packstone with *Saccocoma*-radiolarian association. SC 258 (dry peel). **c** — Lithofacies 41 (inferred age: Tithonian–Berriasian). Maiolica-type wackestone with *Calpionella alpina* and sparse radiolarians. SC 663 (thin section). **d** — Lithofacies 47 (inferred age: Late Aptian–Albian). Hybrid rudstone with Orbitolinidae showing tests mostly agglutinated and commonly rolled. In association: extraclasts of carbonate rocks and quartz. SI 28 (thin section). **e** — Lithofacies 48 (inferred age: late Albian). Fine-grained hybrid quartzarenite with quartz and glauconite. SC14 (thin section). **f** — Lithofacies 48 (inferred age: late Albian). *Orbitolina*-bearing lithic microrudite with common chert fragments and quartz, associated with clasts of platform limestones. SI 95 (thin section).

either pure or with siliciclastic silt, and a secondary sandy sediment infilling residual, commonly microkarstic voids; the latter was emplaced during resedimentation into the Lombardian flysch basin, as indicated by its analogy with the sand fraction of the Sirone Conglomerate.

This lithofacies is comparable to the rudist formations illustrated by Sanders & Pons (1999) in the Lower Gosau Subgroup of the NCA; these developed in mixed silici-clastic-carbonate, wave-dominated depositional environments, where local rudist communities could survive even in the presence of a moderate siliciclastic input (Sanders & Pons 1999).

The presence of two types of sediments, as well as the local evidence of subaerial exposure and early lithification in the source area, were also described by Gnaccolini (1971) in some isolated ippuritids in the Sirone Conglomerate.

Inferred age: A Santonian age is suggested by penecontemporaneous redeposition of rudist shells in the Lombardian flysch basin, where they were reported in the Sirone Conglomerate (De Alessandri 1899; Venzo 1954).

Lithofacies 51

Characteristics: shallow-marine hybrid floatstone/grainstone/wackestone (Fig. 9c) with *Cuneolina pavonia*, rare *Rotalipora* and *Hedbergella*, *Reophax*, Ophthalmidiidae, rare Miliolidae, *Boueina*, *Bacinella irregularis*, corallines (*Archaeolithotamnium*), Dasycladaceae (*Salpingoporella*, *Triploporella*), '*Rivularia*', *Aeolisaccus dunningtoni*, ?*Carpathiella triangulata*, debris of scleractinians, rudist (Fig. 9c) and non-rudist bivalves, gastropods, sphinctozoan sponges, bryozoans, echinoids, brachiopods, serpulids, ostracods. Among the extraclasts, chert and quartz are predominant, associated with spiculitic and radiolarian wackestone, sparse limestone clasts of carbonate platforms, rare serpentinite.

In the Lower Gosau Subgroup of the NCA (Sanders & Baron-Szabo 1997; Sanders 1998), similar bioclastic limestones are described in the Turonian-Coniacian deposits of the Brandenberg area.

Inferred age: Coniacian–Santonian.

Lithofacies 52

This lithofacies of inferred continental depositional environment is defined as lithic conglomerate and pebbly sandstone with a highly varied spectrum of extraclasts (Fig. 9d, e). Clasts ranging from Paleozoic to Cretaceous in age include: metalitharenite; possibly anchizonal chert with flattened radiolarians and Fe-oxide-pigment; rhyolite; rare mafic effusive rocks; dolostone; platform limestones, such as bioclastic wackestone/packstone/grainstone, pelsparite, pelmicrite, oosparite, biomicrite; lumps of microbial material with "porostromate" tubes; generally azoic silty micrite/microsparite; chert with sponge spicules; radiolarian chert; spongolite; radiolarian and spiculitic biomicrite; biomicrite with pelagic bivalves, radiolarians and small gastropods; biomicrite with pelagic bivalves and debris of echinoids; biomicrite with calpionellids (e.g., *Calpionella elliptica*); fine-grained sandstone; quartzarenite with Rotaliporidae; biomicrite with planktonic foraminifers; quartz (sometimes embayed), isolated laminae of biotite and white mica, rare tourmaline, rare serpentinite.

This lithofacies shows evidence of subaerial exposure, witnessed by several features indicating early cementation. These include: (1) vadose silt, sometimes showing a reddish Fe-oxide pigment, and locally a planar lamination suggesting emplacement as internal sediment; (2) microkarstic vugs (Fig. 9e); (3) calcrete crusts with red-brown and grey zoned bands, sometimes broken and reworked; (4) rootlets; (5) lack of mutual clast interpenetration; (6) weathering rinds and 'hollow pebbles' (Fig. 9d; Kafri & Sass 1996; Sass & Kafri 1998).

According to the model presented by these authors, the formation of rinds (by dedolomitization of the margins in the case of dolomitic pebbles or neomorphic calcitization in the case of limestone pebbles) occurs under subaqueous anaerobic conditions and may be followed (in dolomitic pebbles) by dissolution of the porous cores in an oxidizing vadose microenvironment after emergence. The voiding of the cores of the dolomitic pebbles and the encrusting by calcrete bands are not exclusive to the clasts of this lithofacies, since they are also locally present in isolated pebbles of the studied clast populations (Fig. 9f). Local fill of the cores of 'hollow pebbles' or the microkarstic vugs with pelagic sediment of the Scaglia Rossa (Fig. 9e) or the sandy matrix of the Sirone Conglomerate indicates that core voiding and karstic dissolution occurred in the source area as a result of a peculiar type of weathering before resedimentation in the Southalpine basins.

Concluding remarks on lithofacies association 50–52

The analysis of the lithofacies of the Gosau-type clast group revealed the relatively common incidence of repeated processes of reworking, which lead to polycyclic evolution. Episodes of cannibalization of older deposits and subaerial exposures that interrupt flooding stages are also reported by Sanders (1998) in the Lower Gosau Subgroup. These processes of recycling suggest the incidence of tectonic activity during Gosau sedimentation (Ortner 2001).

When considering the facies characteristics and the inferred depositional environment, lithofacies 50–52 showed an undeniable analogy with the deposits of the Lower Gosau Subgroup of the NCA. On the other hand, if the composition is taken into account, the latter deposits are known to contain abundant ophiolitic detritus yielded by erosion of obducted slices of Penninic oceanic crust (Faupl & Wagreich 1992; von Eynatten & Gaupp 1999). The generally coarse grain size of the examined lithofacies (coarse arenite to fine-grained rudite) prevents a reliable evaluation of the frequency percentages of small mineral grains, such as chromite; however, it should be noted that larger-sized ophiolitic (serpentinite) detritus is very rare within the litharenites/rudites of this group and not found as isolated pebbles. In fact, rarity or lack of serpentinite and chrome spinel in the heavy mineral suite is locally known in the deposits of the Gosau Group of NCA as well (Wagreich, pers. communication). However, when taking into consideration the recognized virtual lack of ophiolitic detritus in the post-Turonian deposits of the Lombardian Flysch (Bernoulli & Winkler 1990), it may be suggested that a source relationship of lithofacies 50–52 association with the Lower Gosau Subgroup of the NCA, despite the facies analogy, is excluded.

A closer affinity is believed to exist with Gosau-type deposits resting unconformably on Austroalpine units located in the structurally-highest position of the Eo-alpine edifice ("Central-Alpine" area of Wagreich & Faupl 1994 and Faupl et al. 1997). It is important to note that these authors describe
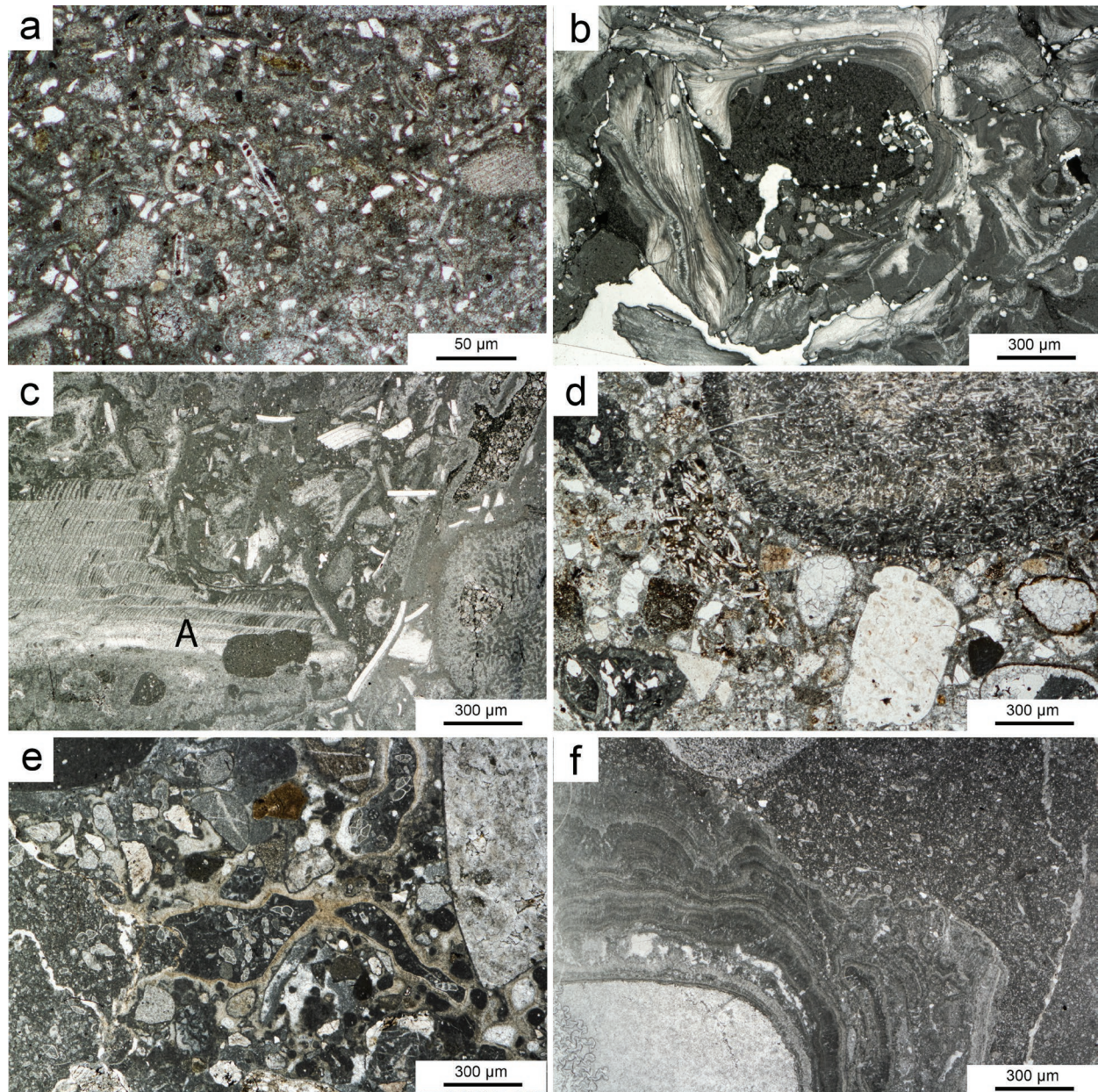
Fig. 9. a — Lithofacies 49 (inferred age: Late Cenomanian–Coniacian). Hybrid packstone with *Vidalina* (?) *hispanica* (centre) and sparse extraclasts. SI 49 (thin section). **b** — Lithofacies 50 (inferred age: Coniacian–Santonian). Hybrid floatstone with rudist shell showing infill partly primary (finer-grained) and partly secondary (coarser-grained) after resedimentation. SI 136 (dry peel). **c** — Lithofacies 51 (inferred age: Coniacian–Santonian). Hybrid floatstone with debris of corals, radiolitids (A) and bivalves. SI 144 (dry peel). **d** — Lithofacies 52 (inferred age: Coniacian–Santonian). Lithic rudite with large spectrum of extraclasts; lack of clast interpenetration suggests early lithification; note the weathering rind in the larger pebble (upper right) and hollow pebble with partial infill of Scaglia Rossa sediment (lower right). SC 167A (thin section). **e** — Lithofacies 52 (inferred age: Coniacian–Santonian). Lithic microrudite with dissolution vugs lined by banded ochraceous crusts and later infilled by Scaglia Rossa pelagic sediment. SC 230A (thin section). **f** — Calcrete crust enveloping a dolomitic pebble in Scaglia Rossa pelagic matrix. SC 102 (thin section).

the Gosau deposits of that area as being either devoid of, or very deficient in ophiolitic detritus (Pober & Faupl 1988 report some chromite in Krappfeld). In the uppermost Austroalpine position, they overlie the Graz Paleozoic and Gurktal nappe system (such as Kainach and Krappfeld and Sankt Paul/Lavanttal respectively), and have an equivalent development in the western part of the Transdanubian Central Range (Bakony Mts.), where alluvial channel conglomerates of the Santonian Csehbánya Formation overlie a bauxite-filled paleokarst surface corresponding to an important regional unconformity, correlated with a major tectonic event of the Alcapa domain (Császár et al. 2009).
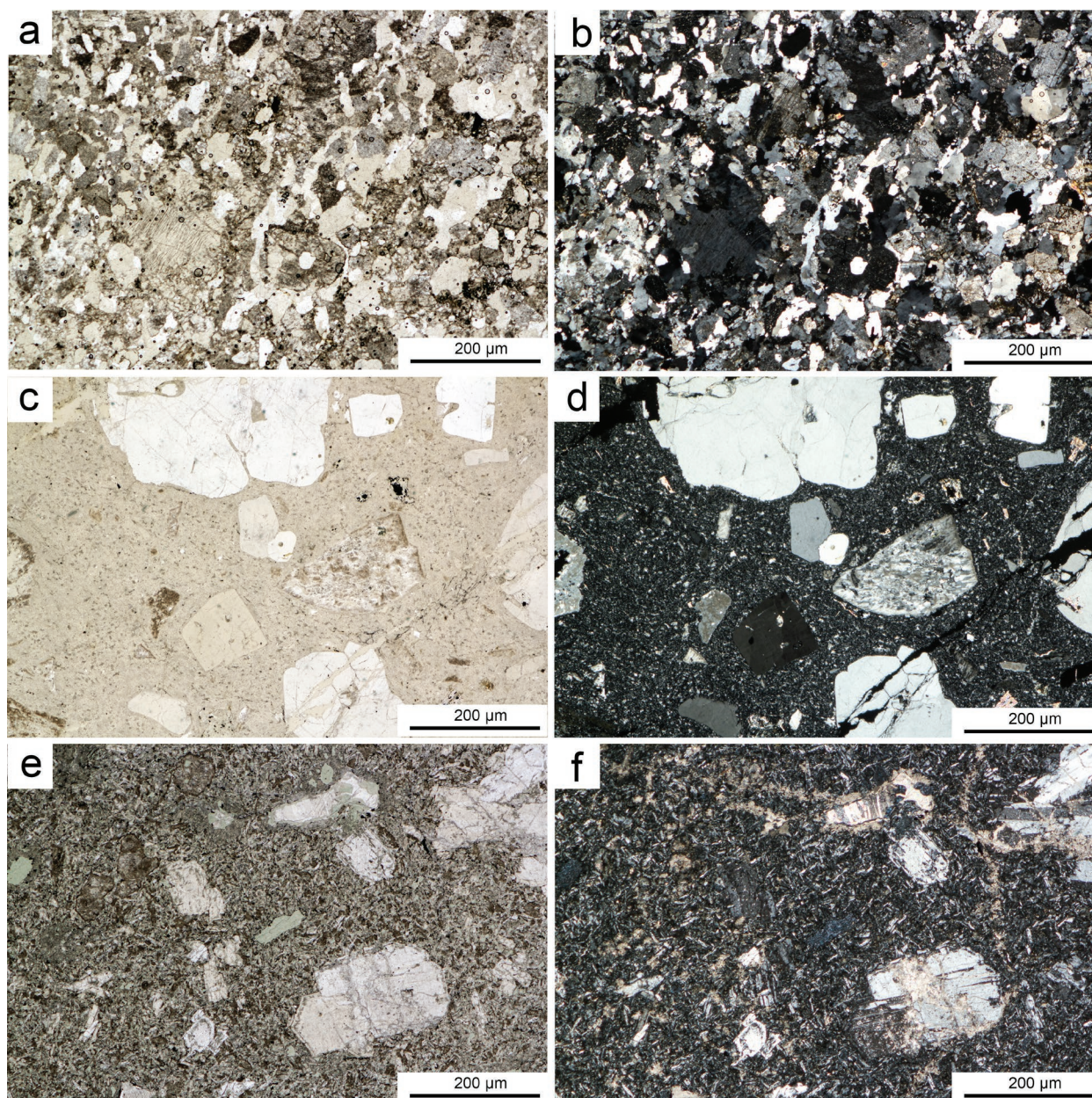
Fig. 10. a — Lithofacies 53 (inferred age: Early Permian). Granitoid rock, parallel nicols. SC 1B (thin section). **b** — The same subject, crossed nicols. **c** — Lithofacies 54 (possible ages: Ordovician, Early Permian, Middle Triassic). Rhyolite, parallel nicols. SI272 (thin section). **d** — The same subject, crossed nicols. **e** — Lithofacies 56 (possible ages: Ordovician, Silurian, Devonian, Carboniferous, Middle Triassic). Mafic effusive rock, parallel nicols. SI 254 (thin section). **f** — The same subject, crossed nicols.

Provenance of clastic sediments and paleotectonic implications

Evidences opposing the hypothesis of a central Southalpine source

Source area reconstructions achieved by Bichsel & Häring (1981) from the analysis of the sedimentary and basement clasts of the Sirone Conglomerate, as well as by Castellarin (1976), from the pebble analysis of the 'Giudicarie Flysch', led the authors to the view that the clasts have an Austroalpine/

Southalpine affinity, and their provenance was from a margin characterized by facies development close to that of the Lombardian Zone of the Southern Alps or that of the Austroalpine nappes.

Doglioni & Bosellini (1987) suggested that the source area of the Lombardian Flysch was an orogenic edifice developed in the Alpine retrobelt as a South-vergent pile of thrust sheets generated in the central Southern Alps by Late Cretaceous tectonics.

Eo-Alpine compressive deformation in the central part of the Southalpine area has indeed been recognized by several

authors (Castellarin 1976; Laubscher 1985; Doglioni & Bosellini 1987; Bersezio & Fornaciari 1988; Bernoulli & Winkler 1990; Schönborn 1992; Bersezio et al. 1993; Castellarin et al. 2006; Berra & Carminati 2010). Doglioni & Bosellini (1987) and Castellarin et al. (2006) noted that this early structural belt built up in Lombardy is unknown in the Dolomites and surrounding areas, east of the northern Giudicarie Lineament, and from this evidence, they argued that a Late Cretaceous left-lateral offset should have occurred along this lineament. However, as noted above (Fig. 2), the sinistral displacement of the Periadriatic Lineament by the strike-slip system of the Giudicarie Line took place during the Neogene, after the Adamello intrusion (e.g., Verwater et al. 2021).

Bersezio et al. (1993) considered that the subsidence in the Lombardian flysch basin was likely induced by the tectonic load of south-vergent thrusts being emplaced in the central Southern Alps, and proposed that the flysch basin represents a flexural basin of the Adriatic plate developed in the Alpine retrobelt area, in front of a Cretaceous 'Orobic' fold and thrust belt (see also Bersezio & Fornaciari 1987, 1988; Doglioni & Bosellini 1987; Bersezio et al. 1993; Wagreich & Faupl 1994; Berra & Carminati 2010; D'Adda et al. 2011; Zanchetta et al. 2011). Instability of the flysch depositional setting is indicated by submarine unconformities and Cenomanian chaotic deposits of the southern Bergamasc Alps, which indicate mass wasting and submarine erosion (possibly linked to submarine canyons – Bernoulli personal communication; Bersezio & Fornaciari 1988; Bernoulli & Winkler 1990).

The ^{40}Ar/^{39}Ar ages of the matrix of pseudotachylite veins along the Orobic and Porcile thrusts (Zanchetta et al. 2011) gave two age clusters of the early tectonic activity in the central Southalpine area: Campanian–Maastrichtian (80–68 Ma) and latest Paleocene to Middle Eocene (55–43 Ma), the younger age seemingly confirming the pre-Adamello deformation of Brack (1981). The data gathered by these authors provide a minimum age for the ductile/brittle transition in the Orobic edifice. Eo-alpine stages of compressive deformation in the Central Southern Alps have also been shown by Carminati et al. (1997) to have occurred as deep-seated changes, with the first pervasive structures affecting the basement and the directly overlying Permian covers, which likely formed under ductile conditions.

ENE-trending compressive structures developed in both basement and sedimentary cover of the central Southern Alps, and are sealed by the oldest (Eocene) parts of the Adamello batholith (Brack 1981, 1984; Laubscher 1985; Schönborn 1992; Callegari & Brack 2002; Mayer et al. 2003; Brack et al. 2008). The emplacement age of ca. 42 Ma for the Presolana dykes and ca. 39 Ma for the Gandino magmatic bodies, both linked to the Adamello intrusion, provide indirect time data on the relative emplacement of Presolana and Gandino imbricates (D'Adda et al. 2011). Zanchetta et al. (2015, and references therein) inferred from fission track ages an intrusion depth of the dykes shallower than 2–3 km, within or below the partial annealing zone (PAZ) of the apatite fission track (AFT) system.

Some evidence exists that erosion occurred in the southern Alps in the Paleogene. The Upper Eocene Ternate Formation yields reworked sediments, most likely of Southalpine origin, such as huge marl clasts, non-lithified and plastically-deformed Scaglia limestones that had probably eroded from submarine canyon walls (Bernoulli et al. 1988). However, the scenario changes entirely in the Late Oligocene with the Gonfolite Group marking an important change to a new depositional system. Thermochronological evidence from the Gonfolite Group synorogenic sediments and the study of the clastic Southalpine foredeep fill indicate a Late Oligocene age for the onset of severe denudation of the Southern Alps. The sediment accumulation rate related to sediment drainage toward the Southalpine foredeep experienced a spectacular increase during the Chattian (Kuhlemann 2000). Between 30 and 21 Ma, the continuous increase of the sediment accumulation rates is interpreted to reflect the build-up of relief in the hinterland and is in line with the onset of coarse clastic sedimentation in the foreland basins at ca. 30 Ma (Spiegel et al. 2004). Exhumation and erosion of the central Alps, as well as basement and cover of the central Southern Alps that was accompanied by south-vergent backfolding, are mainly recorded by the growth and southward progradation of the Upper Chattian to Lower Miocene coarse-clastic Gonfolite Group (Schumacher et al. 1997; Bersezio et al. 1993), a fan delta grading southward to a deep-sea fan (Gunzenhauser 1985; Gelati et al. 1988), and the roughly coeval progradation of the fan-delta complex of the Monte Orfano Conglomerate of latest Oligocene to earliest Miocene age (Sciunnach et al. 2009). Both units contain basement and sedimentary lithoclasts from the Central and Southern Alps. Oligocene uplift of the central Alps, which was accompanied by tectonic denudation (Spiegel et al. 2004) and exhumation of the Bergell intrusion, has since been extremely rapid (Insubric phase of Schumacher et al. 1997).

The bulk of the Gonfolite records mainly the tectonic exhumation and the denudation of the crystalline complexes of the Central Alps (Carrapa & Di Giulio 2001; Garzanti & Malusà 2008), whereas the coeval Monte Orfano Conglomerate consists of detritus derived from the Triassic to Paleogene sedimentary cover of the Southern Alps (with the notable exclusion of older rocks, such as Variscan metamorphites, Collio volcanics, Verrucano Lombardo–Servino clastics; Sciunnach et al. 2009). The latter authors concluded that the Monte Orfano Conglomerate records the postcollisional incipient unroofing of newly uplifted sedimentary formations of the Southern Alps.

In conclusion, what is documented is that, although submarine erosion occurred during the Late Cretaceous to Late Eocene, initial stacking of Triassic units during the Late Cretaceous occurred at depth in the central Southalpine area, and that, even in the Eocene, major structures of this area, although already formed, had not yet been involved in an emerged belt subject to denudation; on the other hand,

there is solid evidence that the onset of active denudation of the Southern Alps is to be referred to the Late Oligocene, in concomitance with the dextral transpressional movements along the Insubric line, accommodating the post-collisional indentation of Adria lithosphere beneath the orogenic wedge (Schmid et al. 1989; Schumacher et al. 1997; Carrapa & Di Giulio 2001; Garzanti & Malusà 2008; Sciunnach et al. 2009). Therefore, in our opinion, the derivation of the clast populations of the Cretaceous Southalpine basins from the erosion of a hypothetical Upper Cretaceous orogenic edifice located in the central Southalpine area can be excluded.

The hypothesis of a major source in the uppermost Austroalpine (Eastalpine and Transdanubian)

Introduction to the geologic evolution of the Austroalpine domain

A brief recall of the geologic evolution of the Austroalpine domain may be useful to support further considerations. The following summary is largely based on Schmid et al. (2004, 2020), Schuster (2004), and Schuster et al. (2013).

In the Triassic, the Meliata–Hallstatt Ocean opened to the southeast of the Austroalpine domain as a part of the western-most Neotethys oceanic realm. The Austroalpine domain then formed a shelf area hosting huge carbonate platforms and facing the ocean to the southeast (Strauss et al. 2023). In the Jurassic, the opening of the Piemont–Ligurian Ocean, which is related to the spreading of the Atlantic Ocean, separated the Apulian microplate (including the Austroalpine domain) from the European continent. Missoni & Gawlick (2011) correlated the Jurassic geodynamic evolution of the NCA with the progressive closure of the western part of the Neotethys Ocean, starting in the late Early Jurassic and leading to the Middle to early Late Jurassic contraction and migration of trench-like basins in front of a propagating thrust belt.

Late Jurassic to Early Cretaceous obduction in front of the Meliata ophiolitic mélanges occurred in the Western Carpathians (Schmid et al. 2008), whereas the scarce traces of Meliata ophiolites in the Eastern Alpine area, and the lack of remnants of ophiolitic slices in the intra-Austroalpine suture, i.e., the Koralpe–Wölz high-pressure belt (Schuster 2004; Schuster et al. 2013), would indicate that the Eo-alpine subduction in Eastern Alps was mostly of intracontinental nature and may have been triggered by a westward transform propagation of the subduction zone in the Meliata ocean (e.g., Janák et al. 2004; Schuster & Stüwe 2008; Handy et al. 2010; Schmid 2020). This is supported by the fact that the obduction front apparently reached only the Juvavic domain in the easternmost part of the Eastern Alps, where ophiolites occur on top of non- or low-grade metamorphic units (Mandl & Ondrejickova 1993; Gawlick et al. 2015; Schmid et al. 2020). However, this reconstruction contrasts with the reported abundant chrome spinel in the heavy mineral assemblages of the deep-water clastics of the Rossfeld Formation (Upper

Valanginian–Aptian) of the Tirolian realm (central NCA), which is regarded as evidence of a derivation from an obducted intra-Austroalpine ophiolite nappe-pile (Meliata suture) (Schlagintweit 1990; Faupl & Wagreich 1992; Wagreich et al. 1995; von Eynatten & Gaupp 1999; Krische et al. 2014). The ophiolitic source is inferred to consist of harzburgite-dominated material containing chrome spinel with relatively high Cr content, comparable in composition to that reported in the Lower to mid-Cretaceous turbidite deposits of the Gerecse Mountains of Northern Hungary (Wagreich et al. 1995 and references therein). Moreover, Krische et al. (2014) claimed that in Late Jurassic to Early Cretaceous times an obducted ophiolite nappe-pile with ophiolitic-radiolaritic mélanges related to the closure of the Meliata ocean was present south of today's NCA.

During the Early and 'middle' Cretaceous orogeny (Eo-Alpine event), the Upper Austroalpine nappes continuously piled up and formed an orogenic wedge in a transpressional top-to-the-W (WNW) tectonic scenario (Eisbacher et al. 1990; Linzer et al. 1995; Schmid et al. 2004; Neubauer & Genser 2018; Héja et al. 2022). More specifically, detached Paleozoic and Mesozoic cover units formed a non- to weakly metamorphic, thin-skinned fold and thrust belt positioned at the northern front of the Austroalpine nappes (Greywacke zone and NCA).

During the Eo-Alpine tectono-metamorphic event, the north-westernmost part of the Adriatic plate, i.e., the majority of the Adria-derived Austroalpine nappes, acted as a lower plate in the sense that it underlies the Eo-Alpine high-pressure belt, while the main part of the Adriatic plate, including the structurally highest Austroalpine nappes and the Southalpine domain, behaved as an upper plate, namely a hanging wall with respect to the Eo-Alpine high-pressure belt (Schmid et al. 2004, 2008, 2020; Schuster 2004; Fig. 11). In the Eo-Alpine orogen, the hanging-wall units located in the highest structural position of the Austroalpine nappe stack are represented by the Drauzug-Gurktal/Ötztal-Bundschuh nappe system in the Eastern Alps (Schmid et al. 2004; Schuster 2004; Schuster et al. 2013), and the corresponding non-metamorphic Trans-danubian Range unit of Inner Western Carpathians (Fodor et al. 2003; Schmid et al. 2008, 2020; Tari & Horváth 2010; Héja et al. 2022; Fig. 11).

The top structural position of these units in the nappe stack is supported by the fact that: (1) some parts (e.g., the Graz Paleozoic and the Gurktal nappe) are unconformably over-lain by the Gosau deposits postdating the Eo-alpine nappe emplacement completed by 84 Ma (Handy et al. 2014, and references therein) and (2) the Mesozoic cover shows only local overprint by a quite low-grade Eo-Alpine metamorphism, and can therefore be equated to the units located south of the Southern Border of Alpine Metamorphism (SAM; Hoinkes et al. 1999). More specifically, the Drauzug–Gurktal nappe system is made up of a Variscan metamorphic basement, anchizonal to greenschist-facies Paleozoic sequences, and non-metamorphic Permian to Triassic sediments (Rantitsch & Russegger 2000; Mandl et al. 2014). The Mesozoic cover of
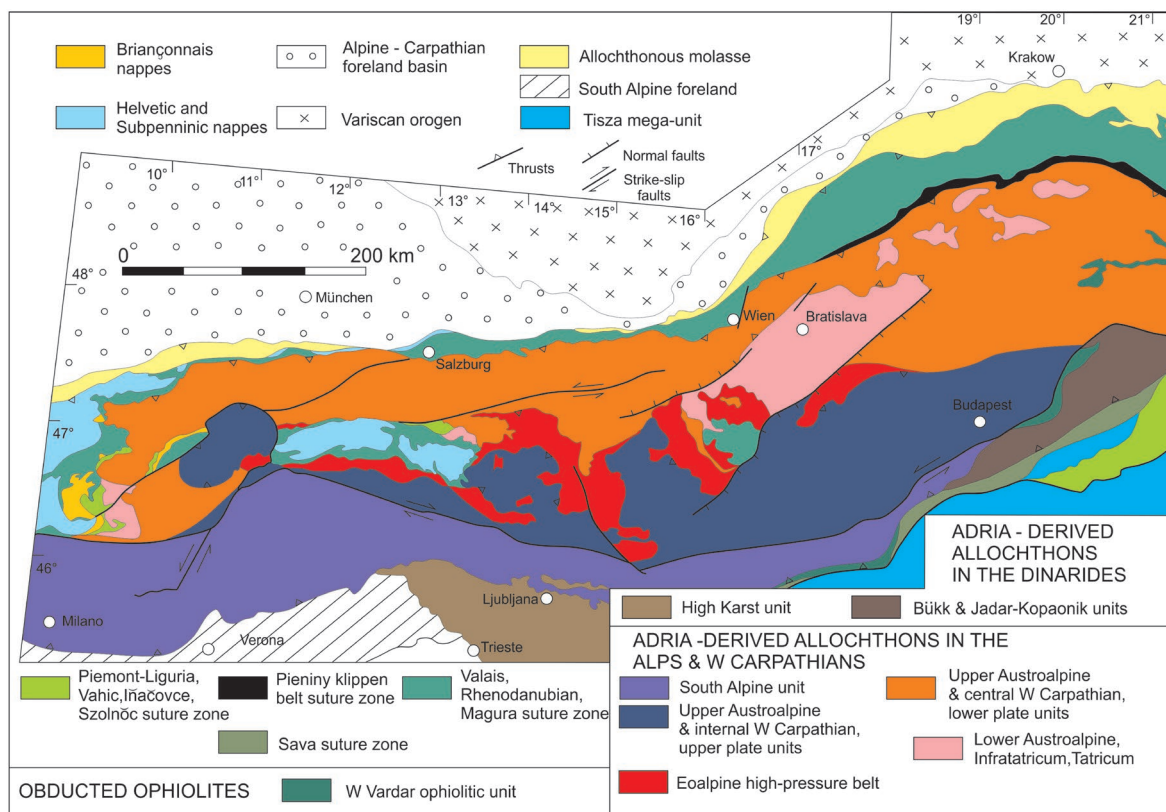
Fig. 11. Excerpt from Schmid et al. (2020) tectonic map of the Eastern Alps and Western Carpathians (slightly simplified). Darkest blue areas represent the uppermost Austroalpine units, including the Ötztal–Bundschuh/Drauzug–Gurktal nappe system of Eastern Alps and the Transdanubian Range unit of the inner Western Carpathians.

this nappe system shows characteristic facies successions which fit into parts of the Southern Alps and the western part of the NCA (Lein et al. 1997).

As noted above, the correlation between the Gurktal–Drauzug/Ötztal–Bundschuh nappe system of the Eastern Alps and the Transdanubian Range unit is based on the consideration that both represent the structural hanging wall with respect to the Eo-Alpine high-pressure belt (Schmid et al. 2008, 2020; Fig. 11). Schmid et al. (2008, 2020) observed that such a correlation is also warranted on structural grounds, since the Transdanubian ranges are located immediately north of the Balaton Line, i.e., the eastern extension of the Periadriatic Line, along which the eastward lateral extrusion of the Alcapa, a megaunit comprising the Austroalpine unit of the Alps and equivalent units of the Western Carpathians (Ratschbacher et al. 1991), took place during the Neogene (and probably earlier), with an estimated dextral offset of 280–350 km (Haas et al. 2014 and references therein). Close affinity of the Transdanubian Range with the Drauzug and the Southern Alps is also shown by the weakly-metamorphosed Variscan basement and nonmetamorphic Permo–Mesozoic cover (e.g., Kázmér & Kovács 1985; Haas et al. 1995; Schmid et al. 2008, 2020).

A high-pressure belt (Fig. 11), represented by the 'Koralpe–Wölz high-P nappe system' (Schuster & Frank 1999; Schuster et al. 2001, 2013; Schmid et al. 2004; Froitzheim & Schuster 2008) and its possible eastern prolongation along a geophysically-defined belt of linear deep-seated faults (Raba and Hurbanovo–Diósjenö faults; Schmid et al. 2020), developed in the Early Cretaceous concurrently with nappe stacking and reached peak conditions in the time span of 95–89 Ma (Thöni 2006). This high-pressure belt subsequently underwent rapid exhumation as an extrusion wedge in the early Late Cretaceous. The exhumation of the continental crust, which had previously subducted and metamorphosed under conditions of UHP/HP, was primarily driven by the buoyancy of the subducted material, as well as the combined detachment-related tectonic unroofing and erosion of the wedge (Neubauer & Genser 2018). Rapid exhumation (5–10 cm yr^{-1}) of the orogenic wedge (Willingshofer et al. 1999; Kurz & Fritz 2003) occurred at 89–84 Ma (Thöni 2006). The uplift of the exhuming UHP/HP wedge marked an important stage of unroofing of the Austroalpine basement complexes to the south of the NCA (Wagreich 1995) and is thought to have resulted in the formation of a true mountain range subject to rapid denudation (Fig. 12).

Neubauer & Genser (2018) noted that since the Turonian, the exhumation of Austroalpine units was accompanied in the Eastern Alps by ESE-directed ductile normal faulting at shallow crustal levels associated with strike-slip faulting (see

also Neubauer et al. 1995; Koroknai et al. 1999 and references therein). This fault system was linked to the collapse of the overthickened orogenic wedge and associated with the formation of the so-called Gosau pull-apart basins. (Neubauer et al. 1995). The post-tectonic Gosau deposits unconformably sealed the earlier structures of the uppermost nappes of the Eastern Alps (Ratschbacher et al. 1989; Neubauer et al. 1995; Wagreich 1995; Willingshofer et al. 1999; Wagreich & Decker 2001) and of the Western Carpathians (Wagreich & Marschalko 1995).

After the main nappe stacking (and in concomitance with the exhumation of the high-P belt), subduction of the South Penninic ocean resulted in the transformation of the Austroalpine northern passive margin towards the Piedmont–Ligurian ocean into an active margin. Slices from this margin were subducted southeastwards under the eo-Alpine nappe pile (Schuster 2004) and partly obducted, thus providing abundant ophiolitic detritus to the Gosau basins of the NCA since the Turonian (von Eynatten & Gaupp 1999). Southern sources continued to be active as well during this time in shedding abundant ophiolitic detritus into the Gosau basins (Stern & Wagreich 2013).

Constrains for uppermost Austraolpine (Eastalpine and Transdanubian) provenance of the Lombardian Flysch

Most of the studied pebble lithofacies provide only general information as it would be expected, because many environments and units were quite widespread and not specific to a single domain; they are, nevertheless, compatible with the units of the Austroalpine *lato sensu* succession (as evidenced by the list of analogues in Table S1 of the Electronic Supplement). However, some lithofacies, as outlined above, provide more specific information. In particular, lithofacies 37 (calclithitic breccia with clasts of Triassic and Jurassic formations) is thought to be indicative of the Middle–Late Jurassic Austroalpine tectonics linked to the progressive closure of the western part of the Neotethys Ocean; the shallow marine to shelf depositional setting of lithofacies 46–48 (?late Aptian to upper Albian) is similar to that of the facies laid down in the Vértes Foreland and Bakony area of the Transdanubian Range unit. In addition, lithofacies 48 shows an abundant extraclastic content suggesting a connection with the regional compressive tectonics that affected the Transdanubian Range area during the Albian. Moreover, the abundant quartz and chert clasts in this lithofacies are interpreted to represent chemical residuals washed out from hot humid paleosols, a feature fitting with the intensive weathering of emerged areas that were accompanied by bauxite formation, which followed the major early Cretaceous tectonic episode in that area (Császár et al. 2009). Finally, lithofacies 50–52 suggest a close analogy to the sediments elaborated in continental to shallow-marine environments and laid down in Gosau basins of the Austroalpine
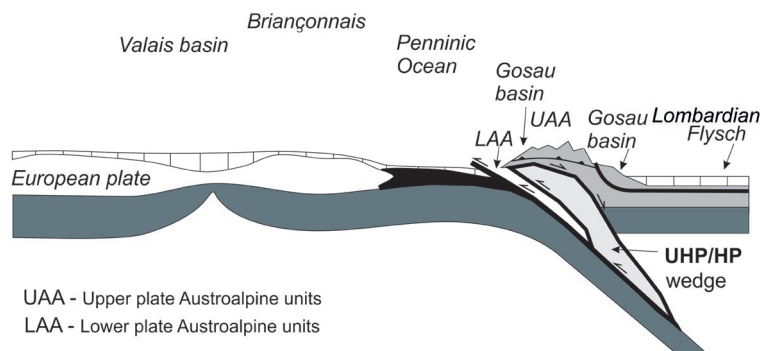

Fig. 12. Schematic tectonic model of the Eastern Alps during the Late Cretaceous exhumation of high-/ultra-high-pressure rocks and formation of Gosau basins. The "upper plate" and "lower plate" Austroalpine units are intended in the sense that they overlie and underlie the Eo-Alpine high-pressure belt respectively (from Neubauer & Genser 2018, modified).

domain after the uplift and denudation of the Eo-Alpine nappe stack.

Dispersal pattern, which is an important tracer for sediment provenance, as well as paleogeography, is represented by ophiolitic detritus. This detritus was abundantly shed into the Lower Cretaceous piggyback basins and the Upper Cretaceous Gosau basins of the NCA area (e.g., von Eynatten & Gaupp 1999), as well as in the tectonically-equivalent basins of the western Carpathians. In contrast, the Lombardian Flysch basin was largely sheltered from the influx of ophiolitic detritus in post-Turonian times (Bernoulli & Winkler 1990). These contrasting situations led Wagreich & Faupl (1994) to the conclusion that there had been no mutual connection between the respective basins, and Bernoulli & Winkler (1990) to the belief of the presence of a barrier between them. Moreover, Wagreich & Faupl (1994) and Faupl et al. (1997) noted that the ophiolitic detritus is missing completely or rare in Upper Cretaceous successions of the 'Central-Alpine' Gosau, i.e., those of Kainach, Krappfeld, and Sankt Paul in Lavanttal, which overlie the uppermost Austroalpine nappes. They therefore suggested that the Lombardian Flysch has a closer relationship with the so-called Central-Alpine Gosau deposits than with those of the NCA, as supported by the presence of pebbles of Southalpine formations in the Kainach Gosau conglomerates as well. They also noted that the Late Cretaceous evolution of the central Transdanubian Range shows closer similarities to the 'Central-Alpine' Gosau than to the NCA.

We propose that the barrier which Bernoulli & Winkler (1990) assume had separated the Lombardian Flysch basin from Austroalpine sources of ophiolitic detritus can be identified with the emerging high-pressure belt and its cover of uppermost Austroalpine (upper plate) units (Fig. 12) that underwent exhumation and uplift at 89–84 Ma (Thöni 2006). The uppermost Austroalpine area, which is thought to extend from the southern part of the Eastern Alps to the inner Carpathians (Transdanubian Range), should correspond to the 'Central Alpine' area of Wagreich & Faupl (1994) and Faupl et al. (1997). In that area, the onset of the Gosau

sedimentation, which comprises a lower part of terrestrial conglomerates to shallow-marine coarse deposits and an upper deep-water marine succession, is attributed to the late Santonian (Faupl & Wagreich 2000). Specifically, the upper parts of the conglomeratic unit (Geistthal Fm.) locally contain snail shells of *Trochactaeon*, which point to a late Santonian to early Campanian age (Gräf 1975). However, it can be postulated that denudation in the 'Central-Alpine' area was already active in pre-Santonian times, as assumed by Wagreich & Faupl (1994; their paleogeographic reconstruction of figure 10), i.e., since the time of rapid exhumation and uplift of the high-pressure belt with its uppermost Austroalpine nappe cover. It may be presumed that clast elaboration occurred there in a variety of high-energy environments comparable to those typical of the Lower Gosau Subgroup of NCA, such as alluvial fans, rivers, fan deltas, and several, generally-mixed siliciclastic carbonate coastal settings. After a possible transitory deposition in the source areas, coarse materials would have been resedimented to the Southalpine basins.

In conclusion, several lines of evidence indicate the highest Austroalpine units of the Eastern Alps and Transdanubian Range as the main source(s) of the Southalpine clast populations.

The Early Cretaceous paleogeography

During the entire Cretaceous, the obducted oceanic slices were an important source of ophiolitic detritus to many Alpine and Carpathian basins. In contrast with the Late Cretaceous situation, 'southward' dispersal of ophiolitic detritus into the Central Alpine and Southalpine areas was active during Early Cretaceous times. This is indicated by the presence of a significant amount of chrome spinel in the Aptian–Albian flysch of the Lienz Dolomites (Drau Range; Lavanter Schichten, Faupl 1976; Faupl & Wagreich 1992), as well as in Lower Cretaceous deposits of the Transdanubian Range unit, such as the Aptian to Lower Albian Köszörüköbánya conglomerates of the Gerecse Basin (Császár et al. 2012) and lithofacies 48 of the studied clast population, which is assumed to be of late Albian age. Furthermore, new analyses highlight that chrome spinel is also an important component of the heavy mineral assemblages of the Aptian-Albian Ra Stua flysch deposits of the northern Dolomites in the Southalpine domain (Table S2 of the Electronic Supplement and Fig. 13; Figs. 1 and 2 for location). These data confirm previous observations that led Scudeller Baccelle & Semenza (1974) to consider the Ra Stua turbidites to be a time-equivalent, distal facies of the Lienz Flysch. Interestingly, the close relationships between the two turbidite systems give support to the hypothesis of the Jurassic–Early Cretaceous age of the eastward strike-slip displacement of the Drau range/Lienz Dolomites (Schuster & Frank 1999).

In conclusion, the inferable paleogeography implies that no major divide separated the above domains during the Early Cretaceous, and heavy mineral assemblages indirectly provide a lower time constraint for the uplift of the Eo-alpine

morpho-structural barrier that later changed regional sediment dispersal patterns.

The hypothesis of a complementary source in a domain with a cover of eastern Southalpine type

In the Sirone Conglomerate, the presence of clasts of typical Paleozoic rocks of the eastern Southern Alps suggests that a complementary source of clastics has been active as a feeder of the Lombardian Flysch. Such clasts include lithofacies 3 (Hochwipfel Flysch), some cherty radiolarites of lithofacies 32, as well as 'quartzites, Devonian Tentaculite limestone, phtanites, phyllites, and the greywackes' reported by Aubouin et al. (1970). We believe that the same source was also involved, along with other northern sources, as a feeder of the Kainach Gosau conglomerates (lying on the Graz Paleozoic), considering that clasts of eastern Southalpine provenance have been repeatedly reported from this Austroalpine unit (Gräf 1972; Flügel 1980, 1983; Gollner et al. 1987; Ebner et al. 1991, 2008; Ebner & Rantitsch 2000; Bojar et al. 2001). More specifically, Hubmann & Gross (2015) reported that, in addition to pebbles indicating a northern Alpine provenance (e.g., Dachstein Limestone, Hierlatz Limestone, Tressenstein/Plassen Limestone, radiolarian cherts), other components of the Kainach conglomerates indicate a Southalpine origin with affinity to the lithofacies of the Carnic succession (Silurian cephalopod limestones, red sandstones of the Gröden Formation, and lower Permian fusulinid limestone). Gollner et al. (1987) emphasized the close relationships between the Kainach Gosau and the Gosau in Bakony (Transdanubian Central Range), as previously noted by Oberhauser (1963) and Woletz (1967). They also observed that marine Permian rocks exist only south of the Periadriatic–Balaton Line and stressed
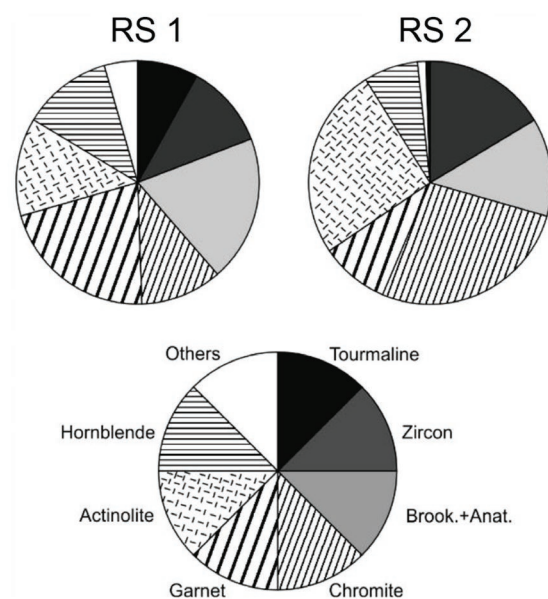

Fig. 13. Heavy mineral association of two Ra Stua samples (63–250 micron fraction).

the compositional difference of the Kainach Gosau, even considering the lack of chrome spinel from the Gosau deposits of the NCA. Together with evidence of short transport from a southern uplifted source, a primary position of parts of the Graz Paleozoic close to domains with a marine Permo–Mesozoic cover of the 'Southalpine/Dinaric type' has also been suggested (Flügel 1980; Gollner et al. 1987; Ebner et al. 1991, 2008; Ebner & Rantitsch 2000). Gollner et al. (1987) proposed that the presumed tectonic contact between them could have been caused by strike-slip faulting or thrusting.

We postulate that the paleogeographic setting implied by the enigmatic composition of the conglomerates of the Kainach Gosau and by the presence of the lithofacies of inferred eastern Southalpine provenance in the Sirone Conglomerate may be linked to syn-Gosau wrench tectonics. Many authors have stressed that since the Turonian, the formation of Gosau basins in the Eastern Alps was associated to wrenching and normal faulting within Austroalpine units (Neubauer et al. 1995; Froitzheim et al. 1996; Willingshofer et al. 1999; Kurz & Fritz 2003; Ortner & Gaupp 2007; Handy et al. 2010). Ortner et al. (2015) documented the presence of repeated unconformities and a growing transpressional fold belt in the Gosau of Muttekopf (western NCA) and suggested that such a tectonic setting may have been an important factor in many other Gosau basins. Linzer et al. (1995) claimed that Gosau sediments were laid down in a continuing NW-directed contractional setting due to oblique convergence, which is associated with WNW-striking dextral transpressional faults and in turn accompanied by a general trend of extension. Neubauer et al. (1995) documented that the subsidence of the Upper Cretaceous Kainach Gosau basin occurred synchronously with uplift of the Gleinalm dome in the context of transpressional wrenching. When considering the importance of wrench tectonics during the Gosau deposition, it may be speculated that a critical role has been played by strike-slip movements along a proto-Periadriatic Lineament, acting as Late Cretaceous precursor of the Cenozoic Periadriatic fault system. This lineament has a long history indeed: inherited from a probable Paleozoic suture (Läufer et al. 2001; Faure & Ferrière 2022), it controlled the location of late Variscan granitoid bodies (Sassi et al. 1994). Moreover, during the Mesozoic, it acted as a large E–W-trending transform fault, which is believed to have connected the spreading of Alpine Tethys with the intra-oceanic subduction of the northern branch of the Neotethys (Meliata–Maliac and Vardar; Handy et al. 2010). Schmid et al. (1989) pointed out that structural features of the Austroalpine nappes (e.g., Ratschbacher 1986) call for a regime of dextral transpression active during the Cretaceous orogeny of the Eastern Alps and concluded that a large portion of the total strike slip motion along the Periadriatic Lineament, which apparently predated its post-late Oligocene movements. Late Cretaceous strike-slip motion along this lineament was also postulated by Handy et al. (2014).

It is suggested conclusively that transpression during Santonian times raised a ridge subject to denudation along the eastern segment of the proto-Periadriatic Lineament which

involved eastern Southalpine successions. This may account for the clastic contribution to the Kainach Gosau from a domain with a marine Permo–Mesozoic cover of eastern Southalpine type and also explains the input of Paleozoic detritus of inferred eastern Southalpine provenance to the Lombardian Flysch basin.

Source to sink distance

Source-to-sink distances must be properly accounted for and may play a role in validating paleogeographic reconstructions. The presence of dropstones in pelagic domains, as in the case of the Scaglia Rossa, does not pose any problems, since driftwood transportation can work over great distances, and only the patterns of oceanic surficial currents determine the areal distribution of drifted material. It is worth mentioning that significant concentrations of pebbles are only known in the Cretaceous deposits of a relatively small area around the village of S. Anna d'Alfaedo. Although the probability of finding drifted pebbles is considerably higher in that area due to the presence of numerous quarries exploiting the Scaglia Rossa, nevertheless, it may be envisaged that the concentration was linked to the presence of a stable mesoscale anticyclonic eddy, where trapped floating trees would have had time to station long enough to decay and release lithic materials and hosted shells.

For the Sirone Conglomerate, different considerations are necessary. Highly-concentrated gravity flows with a massive gravel load may reach considerable distances underwater, but the present-day distance between Lombardy and source areas located in the Transdanubian or even Eastalpine areas would appear excessive. Still, the presence of a set of interconnected Gosau-type basins and an efficient mechanisms of mutual sediment fill-and-spill (or westwards cannibalization of basin fills) may have played a significant role, thus making the problem of distance less puzzling. More importantly, if a palinspastic correction for the Cenozoic right-lateral (eastwards) displacement of the Alcapa along the Periadriatic–Balaton system is applied, Santonian sources, shelf edges (entry points), and sink areas become much closer and transportation distances reasonably possible.

Conclusions

This study aims at the identification of the provenance area(s) of two groups of pebbles/cobbles present in (1) late Turonian to Coniacian pelagic layers of the Scaglia Rossa (dropstones after driftwood transportation) and (2) the Santonian Sirone Conglomerate of the Lombardian Flysch (gravity flow deposits). Rounding and boring, as well as local association with calcrete crusts and evidence of early lithification, suggest that before their transportation into Southalpine basins, the clasts underwent working in a range of high-energy depositional systems, such as alluvial fans, rivers, fan deltas, coastal environments, and, in some instances, episodic

subaerial exposure. Although most of the studied pebble litho-facies show analogy with units which are widespread and not specific of a single paleogeographic domain, they are, never-theless, compatible with the units of the Austroalpine *lato sensu* succession (i.e., typical of both Eastalpine and Trans-danubian areas) and of the Southalpine Lombardian succes-sion (as evidenced by the list of analogue units in Table S1 of the Electronic Supplement). A restricted number of lithofacies provides more focused information, and, in our opinion, are diagnostic of specific domains or parts thereof. Specifically, Late Jurassic lithofacies 37 (Table 1) is indicative of the Upper Austroalpine, because it is inferred to record a tectonic setting peculiar to that area; lithofacies 46–48 are thought to be spe-cific of a Transdanubian area, and the Gosau-type lithofacies 51–53 suggest an uppermost Austroalpine ("Central-Alpine") origin.

Despite the evident affinity of many of the examined clasts with the lithofacies of the Southalpine Lombardian strati-graphic succession, the hypothesis proposed by some authors of a provenance from a proto-Alpine orogenic edifice in the central part of the Southalpine domain can be challenged. Indeed, in the central Southern Alps, initial Late Cretaceous stacking of Mesozoic units occurred essentially at depth (Carminati et al. 1997), and major thrusts of the central Southern Alps were injected in the Eocene by the magma of the Adamello batholith at hypabyssal crustal depth (D'Adda et al. 2011). Finally, several lines of evidence show that the onset of active denudation of the Southern Alps occurred in the Late Oligocene, in concomitance with dextral transpression along the Insubric line, accommodating the post-collisional indenta-tion of Adria lithosphere beneath the orogenic wedge (Schmid et al. 1989; Schumacher et al. 1997; Carrapa & Di Giulio 2001; Garzanti & Malusà 2008; Sciunnach et al. 2009).

Ophiolitic detritus is an important tracer for the provenance, dispersal, and related Alpine paleogeography during the Cre-taceous. This type of detritus, derived from obducted oceanic slices, was abundantly shed into the NCA area from Late Jurassic onwards, particularly into piggy-back basins during the Early Cretaceous, and later into Gosau basins during the Late Cretaceous (e.g., von Eynatten & Gaupp 1999). Analyses of heavy mineral assemblages indicate that, during the Early Cretaceous, this type of detritus was also delivered 'south-wards' to the Central Alpine and Southalpine areas. An inter-ruption of this dispersal path occurred at a later stage, since chromite is absent or extremely scarce in the post-Turonian Lombardian Flysch (Bernoulli & Winkler 1990). This is inter-preted to result from the uplift of a belt separating the northern sources of ophiolitic detritus from the Southalpine retrobelt basins; such a morphostructural barrier is thought to have been created by the exhumation of the "Koralpe–Wölz high-P nappe system" and its cover of uppermost Austroalpine nappes at 89–84 Ma in Turonian to Coniacian times (Thöni 2006). This event marked an important regressional stage (Wagreich 1995) and resulted in the formation of a true mountain range or a vast archipelago. The relevant erosional products, which may be defined as Gosau-type gravels, were essentially produced at

the expense of the top Austroalpine units (upper plate with respect to the Eo-Alpine high-pressure belt) of the Eastalpine and Transdanubian areas (Fig. 12) and were shed "south-wards" into the Southalpine basins after having been elabo-rated in terrestrial to coastal environments.

The existence of a complementary, but highly diagnostic clastic source to the Lombardian Flysch basin during the Santonian is suggested by the presence of Paleozoic clasts of strong eastern Southalpine affinity. A similar, if not the same source was involved as one of the feeders of the conglome-rates of the Kainach Gosau (sealing the Graz Paleozoic), which are known to incorporate clasts from a domain with a marine Upper Paleozoic–Mesozoic cover of eastern South-alpine type, mixed with clasts denoting multiple northern sources (Flügel 1980; Gollner et al. 1987; Ebner et al. 1991, 2008; Ebner & Rantitsch 2000). Considering that the opening of Gosau basins in the Austroalpine domain was characterized by pervasive strike-slip deformation (e.g., Willingshofer et al. 1999), it may be assumed that transpression involved eastern Southalpine units along an eastern segment of the proto-Periadriatic Lineament as well, and that the resulting emerged belt subject to denudation was an important physiographic feature in the Santonian. The Santonian age of this paleogeo-graphic scenario is supported by the fact that the clasts of the Paleozoic lithofacies are present in the Santonian Sirone Conglomerate, but are missing in the clast population of the upper Turonian–Coniacian interval of the Scaglia Rossa. The assumption of Late Cretaceous motion along the proto-Periadriatic Lineament is supported by the reconstruction of Schmid et al. (1989), who argued that a large portion of the total strike slip along the Periadriatic Lineament apparently predates the Neogene movements, considering that structural data from the Austroalpine nappes call for a regime of dextral transpression during the Cretaceous orogeny of the Eastern Alps (see also Polinski & Eisbacher 1992 and Faupl & Wagreich 2000).

In conclusion, our analysis suggests that the main source(s) of exotic clasts were the Eoalpine Uppermost Austroalpine units of the Eastern Alps and Transdanubian Range; in the case of the Sirone Conglomerate, a complementary source is envisaged in a ridge with a sedimentary cover of eastern-Southalpine type, possibly uplifted during Santonian times in response to transpression along the eastern segment of the proto-Periadriatic Lineament.

References

AGIP S.p.A. GESO-SNOR. 1981: Pozzo AGIP Lisanza 1, Scala 1:1000. Permesso Osmate Zona 2, Compilatore G. Scavanino.

Aubouin J., Sigal J., Berland J.-P., Blanchet R., Bonneau M., Cadet J.-P., Guillot P.-L., Lacour A., Piat B. & Vicente J.-C. 1970: Sur un bassin de flysch: stratigraphie et paléogéographie des flyschs crétacés de la Lombardie (versant sud des Alpes orientales, Italie). *Bulletin de la Société géologique de France* (7) XII, 612–658.

Bennett M.R., Doyle P. & Mather A.E. 1996: Dropstones: their origin and significance. *Palaeogeography, Palaeoclimatology, Palaeoecology* 121, 331–339.

Bernoulli D. & Ulmer P. 2016: Dropstones in Rosso Ammoniticofacies pelagic sediments of the Southern Alps (southern Switzerland and northern Italy). *Swiss Journal of Geosciences* 109, 57–67. https://doi.org/10.1007/s00015-015-0205-0

Bernoulli D. & Winkler W. 1990: Heavy mineral assemblages from Upper Cretaceous South- and Austroalpine flysch sequences (Northern Italy and Southern Switzerland): source terranes and paleo-tectonic implications. *Eclogae Geologicae Helvetiae* 83, 287–310.

Bernoulli D., Beckmann J.P., Bolli H.M. & Gunzenhauser B.A. 1987: Upper Cretaceous deep-water sediments near Prella (Southern Alps, Mendrisiotto, Switzerland). *Memorie di Scienze Geologiche* 39, 49–71.

Bernoulli D., Herb R. & Gruenig A. 1988: Ternate Formation, a late Eocene bioclastic submarine fan of the Lombardian basin (southern Alps). In: American Association of Petroleum Geologists, Mediterranean Basins Conference, Abstracts, Nice, 25–28.

Bernoulli D., Ambrosi C., Scapozza C., Stockar R., Schenker F.L., Gaggero L., Antognini M. & Bronzini S. 2018: Foglio 1373 Mendrisio (parte Est) con parte Ovest del foglio Como. Atlante geologico della Svizzera 1: 25 000, Note esplicative 152.

Berra F. & Carminati E. 2010: Subsidence history from a backstripping analysis of the Permo–Mesozoic succession of the Central Southern Alps (Northern Italy). *Basin Research* 22, 952–975. https://doi.org/10.1111/j.1365-2117.2009.00453.x

Bersezio R. & Fornaciari M. 1987: Cretaceous sequences in the Lombardian Basin: stratigraphic outline between the Lakes of Lecco and Iseo. *Memorie della Società Geologica Italiana* 40, 187–197.

Bersezio R. & Fornaciari M. 1988: Tectonic framework of the Lombardy foothills (Southern Alps) between Brianza and Lake Iseo. *Rendiconti della Società Geologica Italiana* 11, 75–78.

Bersezio R., Fornaciari M., Gelati R., Napolitano A. & Valdisturlo A. 1993: The significance of the Upper Cretaceous to Miocene clastic wedges in the deformation history of the Lombardian southern Alps. *Géologie Alpine* 69, 3–20.

Bichsel M. 1980: Zur Sedimentologie des Lombardianischen Oberkreideflyschs zwischen Lecco und Brescia. *Philosophical Doctor Thesis,* Univ. Basel.

Bichsel M. & Häring M. 1981: Facies evolution of Late Cretaceous Flysch in Lombardy (northern Italy). *Eclogae Geologicae Helvetiae* 74, 383–420.

Birkenmayer H., Gastorowski S. & Wieser T. 1960: Fragments of exotic rocks in the pelagic deposits of the Barthonian of the Niedzica Series (Pieniny Klippen-Belt, Carpathians). *Annales Societatis Geologorum Poloniae* 30, 29–58.

Bodrogi I. 1991: A revision of stratotype sections of the Zirc limestone formation with their stratigraphic division on the basis of foraminifers and calcareous algae (upper Albian, N Bakony Mts, Hungary). In: Annual Report of the Hungarian Geological Survey (1993), 217–249.

Bojar A.-V., Ebner F., Fritz H., Hubmann B. & Rantitsch G. 2001: Exkursion am Westrand des Grazer Paläozoikums. In: Hubmann B. (Ed.): Paläozoikumsforschung in Österreich. Workshop. Abstracts und Exkursion. *Berichte des Institutes für Geologie und Paläontologie, Karl-Franzens-Universität Graz*, 3, 59–73.

Bortolotti V. & Malesani P. 1967: Correlazioni tra i flysch cretacei delle Prealpi Lombarde e quelli della coltre alloctona dell' Appennino Settentrionale. *Bollettino della Società Geologica Italiana* 86, 265–267.

Brack P. 1981: Structures in the southwestern border of the Adamello Intrusion (Alpi Bresciane, Italy). *Schweizerische Mineralogische und Petrographische Mitteilungen* 61, 37–50.

Brack P. 1984: Geologie der Intrusiva und Rahmengesteine des Sudwest-Adamello (Nord-Italien). *Mitteilungen der Geologische Institut ETH Universität Zurich* 7612, 1–253.

Brack P., Dal Piaz G.V., Baroni C., Carton A., Nardin M., Pellegrini G.B. & Pennacchioni G. 2008: Carta Geologica d'Italia alla scala 1:50,000. Foglio 058, Monte Adamello.

Cadel G. 1974: Composizione e significato paleogeografico del Conglomerato di Sirone. *Unpublished Degree Thesis*, Padova Geoscience Department, 1–80.

Callegari E. & Brack P. 2002: Geological map of the Tertiary Adamello batolith (northern Italy). Explanatory notes and legend. *Memorie di Scienze Geologiche* 54, 19–49.

Carminati E., Siletto G.B. & Battaglia D. 1997: Thrust kinematics and internal deformation in basement involved foreland fold and thrust belt: the Eastern Orobic Alps case (Central Southern Alps, Northern Italy). *Tectonics* 16, 259–271.

Carrapa B. & Di Giulio A. 2001: The sedimentary record of the exhumation of a granitic intrusion into a collisional setting: the lower Gonfolite Group, Southern Alps, Italy. *Sedimentary Geology* 139, 217–228. https://doi.org/10.1016/S0037-0738(00)00167-6

Castellarin A. 1972: Evoluzione paleotettonica sinsedimentaria del limite tra "piattaforma veneta" e "bacino Lombardo" a nord di Riva del Garda. *Giornale di Geologia* 38, 11–212.

Castellarin A. 1976: Ipotesi paleogeografica sul bacino del Flysch sudalpino cretacico. *Bollettino della Società Geologica Italiana* 95, 501–511.

Castellarin A., Morten L. & Bargossi G.M. 1976: Conglomerati di conoide sottomarina nel Flysch insubrico di Malè e Rumo (Trento). *Bollettino della Società Geologica Italiana* 95, 513–525.

Castellarin A., Vai G.B. & Cantelli L. 2006: The Alpine evolution of the Southern Alps around the Giudicarie faults: a Late Cretaceous to Early Eocene transfer zone. *Tectonophysics* 414, 203–223.

Corradini C., Suttner T.J., Ferretti A., Pohler S.M.L., Pondrelli M., Schönlaub H.-P., Spalletta C. & Venturini C. 2015: The Pre-Variscan sequence of the Carnic Alps – an introduction. *Abhandlungen der Geologische Bundesanstalt* 69, 7–15.

Császár G. 1995: An overview of the Cretaceous research in the Gerecse Mountains and the Vértes Foreland. *General Geology Review* 27, 133–152 (in Hungarian).

Császár G., Haas J., Mindszenty A., Attila Ősi A., Palotai M., Pocsai T., Sasvári Á. & Szives O. 2009: Cretaceous sediments of the Transdanubian Range. Geological Excursion 14–16 May 2009 organized by the Sedimentological Subcommission of the Hun-

garian Academy of Sciences and the Hungarian Geological Society, Field guide, 1–76.

Császár G., Haas J., Sztanó O. & Szinger B. 2012: From Late Triassic passive to Early Cretaceous active continental margin of dominantly carbonate sediments in the Transdanubian Range unit, Western Tethys. 29th IAS Meeting of Sedimentology, Schladming, Austria, Field Trip Guide. *Journal of Alpine Geology* 55, 1–68.

D'Adda P., Zanchi A., Bergomi M.A., Berra F., Malusà M.G., Tunesi A. & Zanchetta S. 2011: Polyphase thrusting and dyke emplacement in the Central Southern Alps (Northern Italy). *International Journal of Earth Sciences (Geologische Rundschau)* 100, 1095–1113. https://doi.org/10.1007/s00531-010-0586-2

de Alessandri G. 1899: Osservazioni geologiche sul Cretacico e sull'Eocene della Lombardia. *Atti della Società Italiana di Scienze naturali e del Museo Civico di Storia Naturale di Milano* 38, 253–320.

Doglioni C. & Bosellini A. 1987: Eoalpine and mesoalpine tectonics in the Southern Alps. *Geologische Rundschau* 76, 735–754.

Ebner F. & Rantitsch G. 2000: Das Gosaubecken von Kainach – ein Überblick. *Mitteilungen der Gesellschaft der Geologie und Bergbaustudenten Österreichs* 44, 157—172.

Ebner F., Kovács S. & Schönlaub H.P. 1991: Das klassische Karbon in Österreich und Ungarn – ein Vergleich der sedimentären fossilführenden Vorkommen. *Jubiläumsschrift 20 Jahre Geologische Zusammenarbeit Österreich–Ungarn* 1, 263–294.

Ebner F., Vozárová A., Kovács S., Kräutner H.G., Krstić B., Szederkenyi T., Jamićić D., Balen D., Belak M. & Trajanova M. 2008: Devonian–Carboniferous pre-flysch and flysch environments in the Circum Pannonian Region. *Geologica Carpathica* 59, 159–195.

Eisbacher G.H., Linzer H.-G., Meier L. & Polinski R. 1990: A depth-extrapolated structural transect across the Northern Calcareous Alps of western Tirol. *Eclogae Geologicae Helvetiae* 83, 711–725.

Emery K. 1955: Transportation of rock by driftwood. *Journal of Sedimentary Petrology* 25, 51–57.

Erba E. & Fornaciari M. 1988: Age of the Cretaceous turbidite systems of the Lombardy basin (Southern Alps). International Geological Correlation Programme, Project 262, Urbino Meeting.

Faupl P. 1976: Sedimentologische Studien im Kreideflysch der Lienzer Dolomiten. *Anzeiger österreichische Akademie der Wissenschaften, Mathematisch-naturwissenschaftliche Klasse* 1976/9, 131–134.

Faupl P. & Wagreich M. 1992: Cretaceous flysch and pelagic sequences of the Eastern Alps: correlations, heavy minerals, and paleogeographic implications. *Cretaceous Research* 13, 387–403.

Faupl P. & Wagreich M. 2000: Late Jurassic to Eocene paleogeography and geodynamic evolution of the Eastern Alps. *Mitteilungen der Österreichischen Geologischen Gesellschaft* 92, 79–94.

Faupl P., Császár G. & Mišík M. 1997: Cretaceous and Palaeogene sedimentary evolution in the Eastern Alps, Western Carapathians and the North Pannonian region: An overview. *Acta Geologica Hungarica* 40, 273–305.

Faure M. & Ferrière J. 2022: Reconstructing the Variscan Terranes in the Alpine Basement: Facts and Arguments for an Alpidic Orocline. *Geosciences* 12, 65. https://doi.org/10.3390/geosciences12020065

Flügel H.W. 1980: Alpines Paläozoikum und alpidische Tektonik. *Mitteilungen der Österreichischen Geologischen Gesellschaft* 71, 72, 25–36.

Flügel H.W. 1983: Problematik und Bedeutung der Herkunft der Gerölle der Mittelsteirischen Gosau. *Hochschulschwerpunkt*, Graz 15 (1982), 109–119.

Fodor L., Koroknai B., Balogh K., Dunkl I. & Horváth P. 2003: A Dunántúli-középhegységi-egység (Bakony) takarós helyzete szlovéniai szerkezeti-geokronológiai adatok alapján. [Nappe position of the Transdanubian Range Unit ('Bakony') based on new structural and geochronological data from NE Slovenia]. *Földtani Közlöny* 133, 535–546 (in Hungarian with English abstract).

Froitzheim N. & Schuster R. 2008: Alpine tectonics of the Alps and Western Carpathians: The Alps. In: McCann T. (Ed.): The Geology of Central Europe 2, Chapter 18. *Geological Society London*, 1141–1181.

Froitzheim N., Schmid S. M. & Frey M. 1996: Mesozoic paleogeography and the timing of eclogite-facies metamorphism in the Alps: A working hypothesis. *Eclogae Geologicae Helvetiae* 89, 81–110.

Gardin S., Marino M., Monechi S. & Principi G. 1994: Biostratigraphy and sedimentology of Cretaceous Ligurid flysch: palaeogeographical implication. *Memorie della Società Geologica Italiana* 48, 219-235.

Garzanti E. & Malusà M.G. 2008: The Oligocene Alps: Domal unroofing and drainage development during early orogenic growth. *Earth and Planetary Science Letters* 268, 487–500.

Gaupp R. 1983: Die paläogeographische Bedeutung der Konglomerate in den Losensteiner Schichten (Alb, Nördliche Kalkalpen). *Zitteliana* 10, 155–171.

Gawlick H.-J., Missoni S., Schlagintweit F., Suzuki H., Frisch W., Krystyn L., Blau J. & Lein R. 2009: Jurassic Tectonostratigraphy of the Austroalpine domain. *Journal of Alpine Geology* 50, 1–152.

Gawlick H.-J, Aubrecht R., Schlagintweit F., Missoni S. & Plašienka D. 2015: Ophiolitic detritus in Kimmeridgian resedimented limestones and its provenance from an eroded obducted ophiolitic nappe stack south of the Northern Calcareous Alps (Austria). *Geologica Carpathica* 66, 473–487. https://doi.org/10.1515/geoca-2015-0039

Gelati R., Cascone A. & Paggi L. 1982: Le unità stratigrafiche aptiano–maastrichtiane delle Prealpi Bergamasche. *Rivista Italiana di Paleontologia e Stratigrafia* 88, 75–112.

Gelati R., Napolitano A. & Valdisturlo A. 1988: La "Gonfolite lombarda": Stratigrafia e significato nell'evoluzione del margine Sudalpino. *Rivista Italiana Paleontologia e Stratigrafia* 94, 285–332.

Germani D. 2007: Formazione del Dimon. Carta Geologica d'Italia 1:50.000 – Catalogo delle formazioni, Fascicolo VII. *Servizio Geologico*, Ispra, 21–25.

Gnaccolini M. 1971: Sedimentologia dei conglomerati di Sirone. *Rivista Italiana di Paleontologia e Stratigrafia* 17, 1–9.

Gollner H., Schirnik D. & Tschelaut W. 1987: The problem of the Southalpine clasts in the "Mittelsteirische Gosau". In: Flügel H. W. & Faupl R. (Eds.): Geodynamics of the Eastern Alps. *Deuticke*, Wien, 156–163.

Gräf W. 1972: Gosau von Kainach. *Mitteilingen der Geologischen Gesellschaft*, Wien 63, 275–278.

Gräf W. 1975: Ablagerungen der Gosau von Kainach. In: Flügel, H.W. (Ed.): Erläuterungen zur Geologischen Wanderkarte des Grazer Berglandes 1:100,000. *Mitteilungen der Abteilung für Geologie, Paläontologie und Bergbau, Landesmuseum Joanneum* 1, 83–102.

Gunzenhauser B.A. 1985: Zur Sedimentologie und Paläogeographie der oligomiocaenen Gonfolite Lombarda zwischen Lago Maggiore und der Brianza (Südtessin, Lombardei). *Beiträge zur geologischen Karte der Schweiz*, 1–114.

Haas J., Kovács S., Krystyn L. & Lein R. 1995: Significance of Late Permian–Triassic facies zones in terrane reconstructions in the Alpine–North Pannonian domain. *Tectonophysics* 242, 19–40.

Haas J., Kovács S., Gawlick H.-J., Grădinaru E., Karamata S., Sudar M., Péró Cs., Mello J., Polák M., Ogorelec B. & Buser S. 2011: Jurassic evolution of the tectonostratigraphic units in the Circum–Pannonian region. *Jahrbuch der Geologischen Bundesanstalt* 151, 281–354.

Haas J., Budai T., Csontos L., Fodor L., Konrád G. & Koroknai B. 2014: Geology of the pre-Cenozoic basement of Hungary. In: Haas J. & Budai T. (Eds.): Explanatory notes for "Pre-Cenozoic geological map of Hungary" (1:500 000). *Geological and Geophysical Institute of Hungary*, Budapest, 1–70.

Handy M.R., Schmid S.M., Bousquet R., Kissling E. & Bernoulli D. 2010: Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps. *Earth-Science Reviews* 102, 121–158. https://doi.org/10.1016/j.earscirev.2010.06.002

Handy M.R. Ustaszewski K. & Kissling E. 2014: Reconstructing the Alps–Carpathians–Dinarides as a key to understanding switches in subduction polarity, slab gaps and surface motion. *International Journal of Earth Sciences (Geologische Rundschau)* 104, 1–26. https://doi.org/10.1007/s00531-014-1060-3

Häring M. O. 1978: The Sirone Conglomerate: a deep-sea fan deposit in the Upper Cretaceous Flysch of Lombardy. *Memorie della Società Geologica Italiana* 18, 57–62.

Héja G., Ortner H., Fodor L., Németh A. & Kövér S. 2022: Modes of Oblique Inversion: A Case Study From the Cretaceous Fold and Thrust Belt of the Western Transdanubian Range (TR), West Hungary. *Tectonics* 41, e2021TC006728. https://doi.org/10.1029/2021TC006728

Hoinkes G., Koller F., Rantitsch G., Dachs E., Höck V., Neubauer F. & Schuster R. 1999: Alpine metamorphism of the Eastern Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen* 79, 155–181.

Hubmann B. & Gross M. 2015: The vicinity of Graz: Upper Silurian to upper Carboniferous of the Graz Palaeozoic, upper Cretaceous of the Kainach Gosau and middle Miocene of Gratkorn. *Berichte der Geologischen Bundesanstalt* 111, 41–74.

Janák M., Froitzheim N., Lupták B., Vrabec M. & Krogh Ravna E.J. 2004: First evidence for ultrahigh-pressure metamorphism in Pohorje, Slovenia: Tracing deep continental subduction in the Eastern Alps. *Tectonics* 23, TC5014.

Kafri U. & Sass E. 1996: Hollow carbonate pebbles: a case study of selective secondary porosity generation, Neogene, Israel. *Sedimentary Geology* 103, 161–174.

Kázmér M. & Kovács S. 1985: Permian–Paleogene Paleogeography along the Eastern part of the Insubric–Peri-Adriatic Lineament system: Evidence for continental escape of the Bakony–Drauzug Unit. *Acta Geologica Hungarica* 28, 71–84.

Koroknai B., Neubauer F., Genser J. & Topa D. 1999: Metamorphic and tectonic evolution of the Austroalpine units at the western margin of the Gurktal nappe complex, Eastern Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen* 79, 277–295.

Krainer K. 1992: Facies, sedimentationprozesse und paläogeography im Karbon der Ost- und Süd Alpen. *Jahrbuch der Geologischen Bundesanstalt* 135, 99–193.

Krische O., Goričan Š. & Gawlick H.-J. 2014: Erosion of a Jurassic ophiolitic nappe-stack as indicated by exotic components in the Lower Cretaceous Rossfeld Formation of the Northern Calcareous Alps (Austria). *Geologica Carpathica* 65, 3–24. https://doi.org/10.2478/geoca-2014-0001

Kuhlemann J. 2000: Postcollisional sediment budget of circum-Alpine basins. *Memorie di Scienze Geologiche* 52, 1–91.

Kurz W. & Fritz H. 2003: Tectonometamorphic Evolution of the Austroalpine nappe complex in the Central Eastern Alps–Consequences for the Eo-Alpine Evolution of the Eastern Alps. *International Geology Review* 45, 1100–1127.

Laubscher H.P. 1985: Large scale, thin-skinned thrusting in the southern Alps: kinematic models. *Geological Society of America Bulletin* 96, 710–718.

Läufer A.L., Loeschke J. & Vianden B. 1993: Die Dimon-Serie der Karnischen Alpen (Italien) – stratigraphie, petrographie und geodynamische interpretation. *Jahrbuch der Geologische Bundesanstalt* 136, 137–162.

Läufer A.L., Hubich D. & Loeschke 2001: Variscan geodynamic evolution of the Carnic Alps (Austria/Italy). *International Journal of Earth Sciences (Geologische Rundschau)* 90, 855–870. https://doi.org/10.1007/s005310100194

Lein R., Gawlick H.-J. & Krystyn L. 1997: Paläogeographie und tektonische Herkunft des Drauzuges – Eine Diskussion auf der Basis von Fazies- und Conodont Colour Alteration Index (CAI)-Untersuchungen. *Zentralblatt für Geologie und Paläontologie* I, 471–483.

Lewis D.W. 1984: Practical sedimentology. *Hutchinson Ross*, Stroudsburg, 1–229.

Linzer H.-G., Ratschbacher L. & Frisch W. 1995: Transpressional collision structures in the upper crust: the fold-thrust belt of the Northern Calcareous Alps. *Tectonophysics* 242, 41–61.

Mandl G.W. 1999: Geology of the central and eastern sector of the Northern Calcareous Alps (NCA). *Berichte der Geologische Bundesanstalt* 49, 36–53.

Mandl G.W. 2000: The Alpine sector of the Tethyan shelf – Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps. *Mitteilungen der Österreichischen Geologischen Gesellshaft* 92, 61–77.

Mandl G. & Ondrejickova A. 1993: Über eine triadische Tiefwasserfazies (Radiolarite, Tonschiefer) in den Nördlichen Kalkalpen – ein Vorbericht. *Jahrbuch der Geologischen Bundesanstalt* 136, 841–871.

Mandl M., Kurz W., Pfingstl S., Schuster R., Hauzenberger C. & Fritz H. 2014: Excursion 1: Geological Evolution of the Austroalpine Seckau Complex (Eastern Alps). PANGEO Austria Graz, 14–19th September 2014. *Berichte des Institutes für Erdwissenschaften der Karl-Franzens-Universität Graz* 20, 4–21.

Massari F. & Medizza F. 1973: Stratigrafia e paleogeografia del Campaniano–Maastrichtiano nelle Alpi Meridionali. *Memorie dell'Istituto di Geologia e Mineralogia*, Padova 28, 1–63.

Massari F. & Savazzi E. 1981: Driftwood transportation of exotic pebbles in the Upper Cretaceous Scaglia Rossa veneta (Mt. Loffa, Southern Alps) suggested by Teredinid tubes. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte* 5, 311–320.

Mayer A., Cortiana G., Dal Piaz G.V., Deloule E., De Pieri R. & Jobstraibizer P. 2003: U/Pb single zircon ages of the Adamello batholith, Southern Alps. *Memorie di Scienze Geologiche*, Padova, 55, 151–167.

Missoni S. & Gawlick H.-J. 2011: Evidence for Jurassic subduction from the Northern Calcareous Alps (Berchtesgaden; Austroalpine, Germany). *International Journal of Earth Sciences (Geologische Rundschau)* 100, 1605–1631.

Neubauer F. & Genser J. 2018: Field Trip Post-EX-1. Transect across the Eastern Alps. *Berichte der Geologischen Bundesanstalt* 126,137–222.

Neubauer F., Dallmeyer R.D., Dunkl I. & Schirnik D. 1995: Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: kinematics, cooling history and sedimentary response in a sinistral wrench corridor. *Tectonophysics* 242, 79–89.

Neubauer F., Liu Y., Dong Y., Chang R., Genser J. & Yuan S. 2022: Pre-Alpine tectonic evolution of the Eastern Alps: From Prototethys to Paleotethys. *Earth-Science Reviews* 226, 103923. https://doi.org/10.1016/j.earscirev.2022.103923

Oberhauser R. 1963: Die Kreide im Ostalpenraum in mikropaläontologische Sucht. *Jahrbuch der Geologische Bundesanstalt* 106, 1–88.

Ortner H. 2001: Growing folds and sedimentation of the Gosau Group, Muttekopf, Northern Calcareous Alps, Austria. *International Journal of Earth Sciences* 90, 727–739.

Ortner H. & Gaupp R. 2007: Synorogenic sediments of the western Northern Calcareous Alps. *Geo.Alp* 4, 133–148.

Ortner H., Ustaszewski M. & Rittner M. 2008: Late Jurassic tectonics and sedimentation: breccias in the Unken syncline, central Northern Calcareous Alps. *Swiss Journal of Geosciences* 101, Suppl. 1, 55–71. https://doi.org/10.1007/s00015-008-1282-0

Ortner H., Kositz A., Willingshofer E. & Sokoutis D. 2015: Geometry of growth strata in a transpressive fold belt in field and analogue model: Gosau Group at Muttekopf, Northern Calcareous Alps, Austria. *Basin Research* 28, 1–21. https://doi.org/10.1111/bre.12129

Pober E. & Faupl P. 1988: The chemistry of detrital chromium spinels and its implications for the geodynamic evolution of the Eastern Alps. *Geologische Rundschau* 11, 641–670.

Polinski R.K. & Eisbacher G.H. 1992: Deformation partitioning during polyphase oblique convergence in the Karawanken Mountains, southeastern Alps. *Journal of Structural Geology* 14, 1203–1213.

Pratt R. 1970: Granitic rocks from the Blake plateau. *Geological Society of America Bulletin* 81, 3117–3122.

Rantitsch G. & Russegger B. 2000: Thrust-related very low grade metamorphism within the Gurktal Nappe Complex (Eastern Alps). *Jahrbuch der Geologischen Bundesanstalt* 142, 219–225.

Ratschbacher L. 1986: Kinematics of Austro-Alpine cover nappes: Changing translation path due to transpression. *Tectonophysics* 125, 335–356.

Ratschbacher L., Frisch W., Neubauer F., Schmid S.M. & Neugebauer J. 1989: Extension in compressional orogenic belts: The Eastern Alps. *Geology* 17, 404–407.

Ratschbacher L., Frisch W., Linzer H.G. & Merle O. 1991: Lateral extrusion in the Eastern Alps; part 2, structural analysis. *Tectonics* 10, 257–271.

Sanders D. 1998: Tectonically controlled Late Cretaceous terrestrial to neritic deposition, Gosau Group, Northern Calcareous Alps (Tyrol, Austria). *Facies* 39, 139–178.

Sanders D. & Baron-Szabo R. 1997: Coral–rudist bioconstructions in the Upper Cretaceous Haidach section (Northern Calcareous Alps, Austria). *Facies* 36, 69–90.

Sanders D. & Pons J.M. 1999: Rudist formations in mixed siliciclastic-carbonate depositional environments, Upper Cretaceous, Austria: stratigraphy, sedimentology, and models of development. *Palaeogeography, Palaeoclimatology, Palaeoecology* 148, 249–284.

Sass E. & Kafri U. 1998: Hollow carbonate pebbles in Neogene conglomerates, central Israel: Paleogeographic and strati graphic implications. *Israel Journal of Earth Sciences* 47, 19–28.

Sassi F.P., Neubauer F., Mazzoli C., Sassi R., Spiess R. & Zirpoli G. 1994: A tentative Comparison of the Paleozoic Evolution of the Austroalpine and Southalpine Quartzphyllites in the Eastern Alps. *Periodico di Mineralogia* 63, 35–52.

Schlagintweit F. 1990: Allochthonous Urgonian limestones of the Northern Calcareous Alps: facies and palaeogeographic framework within the Alpine Orogeny. *Cretaceous Research* 11, 261–272.

Schlagintweit F. & Wagreich M. 2005: Micropaleontology of „Orbitolina Beds" of Lower Austria (Branderfleck Formation, Lower Cenomanian). *Jahrbuch der Geologischen Bundesanstalt* 145, 115–125.

Schlagintweit F., Krische O. & Gawlick H.-J. 2012: First Findings of Orbitolinids (Larger Benthic Foraminifera) from the Early Cretaceous Rossfeld Formation (Northern Calcareous Alps, Austria). *Jahrbuch der Geologischen Bundesanstalt* 15, 145–158.

Schmid S.M., Aebli H.R., Heller F. & Zingg A. 1989: The role of the Periadriatic Line in the tectonic evolution of the Alps. In: Coward M.P., Dietrich D. & Park R.G. (Eds.): Alpine Tectonics, *Geological Society Special Publication* 45, 153–171.

Schmid S.M., Fugenschuh B., Kissling E. & Schuster R. 2004: Tectonic map and overall architecture of the Alpine orogen. *Eclogae Geologicae Helvetiae* 97, 93–117.

Schmid S.M., Bernoulli D., Fügenschuh B., Maţenco L., Schefer S., Schuster R., Tischler M. & Ustaszewski K. 2008: The Alpine–Carpathian–Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss Journal of Geosciences* 101, 139–183. https://doi.org/10.1007/s00015-008-1247-3

Schmid S.M., Fügenschuh B., Kounov A., Maţenco L., Nievergelt P., Oberhänsli R., Pleuger J., Schefer S., Schuster R., Tomljenovi B., Kamil Ustaszewski K. & van Hinsbergen D.J.J. 2020: Tectonic units of the Alpine collision zone between Eastern Alps and western Turkey. *Gondwana Research* 78, 308–374.

Schönborn G. 1992: Alpine tectonics and kinematic models of the central Southern Alps. *Memorie di Scienze Geologiche*, Padova, 44, 229–393.

Schumacher M.E., Schönborn G., Bernoulli D. & Laubscher H.P. 1997: Rifting and collision in the Southern Alps. In: Pfiffner O.A., Lehner P., Heitzmann P., Müller S. & Steck A. (Eds.): Deep structure of the Swiss Alps: Results of the National Research Program 20. *Birkhäuser*, Basel, 186–204.

Schuster R. 2004: The Austroalpine crystalline units in the Eastern Alps. *Berichte des Institutes für Erdwissenschaften der Karl-Franzens-Universität Graz* 9, 30–36.

Schuster R. & Frank W. 1999: Metamorphic evolution of the Austroalpine units east of the Tauern window: indications for Jurassic strike slip tectonics. *Mitteilungen der Gesellschaft der Geologie und Bergbaustudenten Österreichs* 42, 37-58.

Schuster R. & Stüwe K. 2008: Permian metamorphic event in the Alps. *Geology* 36, 603–606.

Schuster R., Scharbert S., Abart R. & Frank W. 2001: Permo–Triassic extension and related HT/LP metamorphism in the Austroalpine–Southalpine realm. *Mitteilungen der Gesellschaft der Geologie und Bergbaustudenten Österreichs* 42, 37–58.

Schuster R., Kurz W., Krenn K. & Fritz H. 2013: Introduction to the Geology of the Eastern Alps. Abstracts and field guides 11th workshop on Alpine geological studies. *Berichte der Geologische Bundesanstalt* 99, 121–133.

Sciunnach D., Scardia G., Tremolada F. & Premoli Silva I. 2009: The Monte Orfano Conglomerate revisited: stratigraphic constraints on Cenozoic tectonic uplift of the Southern Alps (Lombardy, northern Italy). *International Journal of Earth Sciences (Geologische Rundsch)* 99, 1335–1355. https://doi.org/10.1007/s00531-009-0452-2

Scudeller Baccelle L. & Semenza E. 1974: Flysch terrigeno con "strutture contornitiche" nel Cretacico delle Dolomiti ampezzane. Caratteristiche sedimentologiche e significato geodinamico. *Annali dell'Università di Ferrara* 9, 165–179.

Sorbini L. 1968: Prima segnalazione di ciottoli di rocce eruttive e metamorfiche inclusi nella Scaglia Rossa dei Lessini occidentali. *Memorie del Museo Civico di Storia Naturale* 15, 233–235.

Spalletta C. & Venturini C. 1988: Conglomeratic Sequences in the Hochwipfel Formation: A New palaeogeographic hypothesis on the Hercynian Flysch Stage of the Carnic Alps. *Jahrbuch der Geologische Bundesanstalt* 131, 637–647.

Spalletta C., Vai G.B. & Venturini C. 1980: Il flysch ercinico nella geologia dei Monti Paularo e Dimon (Alpi Carniche). *Memorie della Società Geologica Italiana* 20 (1979), 243–265.

Spiegel C., Siebel W., Kuhlemann J. & Frisch W. 2004: Toward a comprehensive provenance analysis: A multi-method approach and its implications for the evolution of the Central Alps. In: Bernet M. & Spiegel C. (Eds.): Detrital thermochronology –

Provenance analysis, exhumation, and landscape evolution of mountain belts. *Geological Society of America Special Paper* 378, 37–50.

Steiner T.M.C., Gawlick H.J., Melcher F. & Schlagintweit F. 2021: Ophiolite derived material as parent rocks for Late Jurassic bauxite: evidence for Tithonian unroofing in the Northern Calcareous Alps (Eastern Alps, Austria). *International Journal of Earth Sciences* 110, 1847–1862. https://doi.org/10.1007/s00531-021-02044-6

Stern G. & Wagreich M. 2013: Provenance of the Upper Cretaceous to Eocene Gosau Group around and beneath the Vienna Basin (Austria and Slovakia). *Swiss Journal of Geosciences* 106, 505–527. https://doi.org/10.1007/s00015-013-0150-8

Strauss P., Granado P., Munoz J.A., Böhm K. & Schuster R. 2023: The Northern Calcareous Alps revisited: Formation of a hyperextended margin and mantle exhumation in the Northern Calcareous Alps sector of the Neo-Tethys (Eastern Alps, Austria). *Earth-Science Reviews* 243, 104488. https://doi.org/10.1016/j.earscirev.2023.104488

Tari G. & Horváth F. 2010: A Dunántúli-középhegység helyzete és eoalpi fejlődéstörténete a Keleti-Alpok takarós rendszerében: egy másfél évtizedes tektonikai modell időszerűsége. [Eo-Alpine evolution of the Transdanubian Range in the nappe system of the Eastern Alps: revival of a 15 years old tectonic model]. *Földtani Közlöny* 140, 463–505 (in Hungarian with English abstract).

Thöni M. 2006: Dating eclogite-facies metamorphism in the Eastern Alps – approaches, results, interpretations: a review. *Mineralogy and Petrology* 88, 123–148. https://doi.org/10.1007/s00710-006-0153-5

Valloni R. & Zuffa G.G. 1984: Provenance changes for arenaceous formations of the Northern Apennines, Italy. *Geological Society of America Bulletin* 95, 1035–1039.

Venturini C. & Spalletta C. 2015: Dimon Formation. *Abhandlungen der Geologischen Bundesanstalt in Wien* 69, 155–158.

Venzo S. 1951: Ammoniti e vegetali albiano-cenomaniani nel Flysch del Bergamasco occidentale. Condizioni stratigrafiche e tettoniche della serie barremiano-turoniana. *Atti della Società Italiana di Scienze Naturali* 40, 175–244.

Venzo S. 1954: Stratigrafia e tettonica del Flysch (Cretacico-Eocene) del Bergamasco e della Brianza orientale. *Memorie descrittive della Carta geologica d'Italia* 31.

Verwater V.F., Le Breton E., Handy M.R., Picotti V., Jozy Najafabadi A. & Haberland C. 2021: Neogene kinematics of the Giudicarie Belt and eastern Southern Alpine orogenic front (northern Italy). *Solid Earth* 12, 1309–1334.

von Eynatten H. & Gaupp R. 1999: Provenance of Cretaceous synorogenic sandstones in the Eastern Alps: constraints from framework petrography, heavy mineral analysis and mineral chemistry. *Sedimentary Geology* 124, 81–11.

Wagreich M. 1995: Subduction tectonic erosion and Late Cretaceous subsidence along the northern Austroalpine margin (Eastern Alps, Austria). *Tectonophysics* 242, 63–78.

Wagreich M. 2003: A slope-apron succession filling a piggyback basin: the Tannheim and Losenstein Formations (Aptian–Cenomanian) of the eastern part of the Northern Calcareous Alps (Austria). *Mitteilungen der österreichischen Geologischen Gesellshaft* 93, 31-54.

Wagreich M. & Decker K. 2001: Sedimentary tectonics and subsidence modelling of the type Upper Cretaceous Gosau basin (Northern Calcareous Alps, Austria). *International Journal of Earth Sciences* 90, 714–726.

Wagreich M. & Faupl P. 1994: Paleogeography and geodynamic evolution of the Gosau Group of the Northern Calcareous Alps (Late Cretaceous, Eastern Alps, Austria). *Palaeogeography, Palaeoclimatology, Palaeoecology* 110, 235–254.

Wagreich M. & Marschalko R. 1995: Late Cretaceous to Early Tertiary palaeogeography of the Western Carpathians (Slovakia) and the Eastern Alps (Austria): implications from heavy mineral data. *Geologische Rundschau* 84, 187–199.

Wagreich M. & Schlagintweit F. 1990: Urgonkalkgerölle aus den Konglomeraten der Lilienfelder Gosau (Oberkreide; NO Kalkvoralpen). *Mitteilungen der Gesellschaft der Geologie und Bergbaustudenten Österreichs* 36, 147–167.

Wagreich M., Faupl P. & Schlagintweit F. 1995: Heavy minerals from Urgonian limestone pebbles of the Northern Calcareous Alps (Austria, Bavaria): further evidence for an intra-Austroalpine suture zone. *Geologica Carpathica* 46, 197–204.

Willingshofer E., Wees J.D. van, Cloetingh S.A.P.L. & Neubauer F. 1999: Thermomechanical consequences of Cretaceous continent-continent collision in the eastern Alps (Austria): Insights from two-dimensional modeling. *Tectonics* 18, 809–826.

Woletz G. 1967: Schwermineralgergesellschaftunngen aus ostalpen Sedimentationsbecken der Kreidezeit. *Geologische Rundschau* 56, 308–320.

Zanchetta S., D'Adda P., Zanchi A., Barberini V. & Villa I.M. 2011: Cretaceous-Eocene compression in the central Southern Alps (N Italy) inferred from $^{40}Ar/^{39}Ar$ dating of pseudotachylytes along regional thrust faults. *Journal of Geodynamics* 51, 245–263.

Zanchetta S., Malusà M.G. & Zanchi A. 2015: Precollisional development and Cenozoic evolution of the Southalpine retrobelt (European Alps). *Lithosphere* 7, 662–681. https://doi.org/10.1130/L466.1

Zuffa G.G. 1980: Hybrid arenites: their composition and classification. *Journal of Sedimentary Petrology* 50, 21–29.

Zuffa G.G. 1985: Provenance of arenites. *D. Reidel Publ.*, Dordrecht, 1–408.

Electronic supplementary material is available online:
Table S1 at http://geologicacarpathica.com/data/files/supplements/GC-75-1-Massari_TableS1.xlsx
Table S2 at http://geologicacarpathica.com/data/files/supplements/GC-75-1-Massari_TableS2.xlsx