

A unique fossil record from neptunian sills: the world's most extreme example of stratigraphic condensation (Jurassic, western Sicily)

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ABSTRACT:

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Neptunian sills at Rocca Busambra, a fragment of the Trapanese/Saccense Domain in western Sicily, host the most abundant ammonite and gastropod fauna which has ever been recorded from the Jurassic of the western Tethys. The fauna is dominated by parautochthonous organisms which were swept into the sills by gentle transport. Ammonites are characterized by perfect preservation and small size, a feature which is due to the predominance of microconchs but also of stunting. The most complete sill is 0.7 m thick and could be separated into 17 levels which range in age from the early Toarcian into the late Kimmeridgian, thus representing the most extreme case of palaeontologically and positionally documented stratigraphic condensation in Earth history. The unique feature of the Rocca Busambra sills is due to the interaction of three processes: extreme stratigraphic condensation on the sea floor, weak tectonic fracturing of the host rock and repeated reopening on top of already existing sills. Contrasting percentages of gastropods in individual levels reflect sea-level oscillations which correspond to long known low- and highstands during the Jurassic of the western Tethys. Comparisons with other ammonite-bearing sill faunas reveal several similarities, but represent only short-timed phases of tectonic pulses and deposition.

Key words: Sicily, Jurassic; Biostratigraphy; Synsedimentary tectonics; Neptunian sills; Condensation; Ammonite fauna; Sea level.

INTRODUCTION

The knowledge of neptunian dykes and sills goes back into the late 19th century. Many examples, the majority from the Mediterranean Jurassic, have been described from the northern and southern Calcareous Alps, the Klippen Belt of Slovakia, the Dinarides, the Iberian chains and elsewhere (references in Flügel 2010: 216–223), a few also from the boreal realm (Jenkyns and Senior 1991; Wall and Jenkyns 2004). But only since the early 1960's has it become evident that some of these unusual depositional environ-

ments are a particular type of "Fossil-Lagerstätten" (Seilacher 1970) which may preserve a unique fossil record which is not found, or only poorly represented, in normal deposits on the sea floor. Generally, dykes were apparently filled by a single rapid sedimentary process that rarely trapped skeletal remains sufficient for an exact dating of the time of infilling. A much more complete biostratigraphic history, however, can be revealed from neptunian sills, which were formed close to the sea floor. In these bedding-parallel voids, shells were not only accumulated but, due to the absence of currents and reworking, are commonly pre-

served in unusual perfection. Neptunian sills may represent a short time-span only but, in the case of condensed or totally missing sedimentation (omission) on the sea floor, they may contain a unique stratigraphic record that has no counterpart in the normal sequence.

Many profound thoughts and careful considerations have been produced about the aspects and processes of stratigraphic condensation (Heim 1934; Jenkyns 1971a; Fürsich 1978; Kidwell 1986; Loutit *et al.* 1988; Martire 1992a; and others; additional references in Flügel 2010: 211–216). The contribution to this subject by Gomez and Fernández-López (1994) appears relatively academic. They distinguish three different processes of condensation (stratigraphic, sedimentary and taphonomic), as if not all of them interact to produce one and the same end-member. The quintessence of all these reflections about stratigraphic condensation is rather simple: Minimum net sedimentation leads to an accumulation of skeletal remains whose different age cannot be distinguished any more in a straightforward vertical sequence. A critical point is reached, when condensation turns into a hiatus (omission) and finally into the negative process of submarine erosion. The latter is an important secondary effect already during the process of condensation proper and is generally accompanied by submarine solution and mineral encrustations. The result of stratigraphic condensation, i.e. the juxtaposition of index-fossils of different age in one and the same level, has a natural lower limit of preservation, because deposition takes place on an open, current-swept sea floor. A random, but nevertheless representative compilation of examples from the Cretaceous, Jurassic, Triassic and Devonian shows that this lower limit is reached at an average sedimentation rate of about 0.1 m/m.y. (Table 1). In neptunian sills, however, this value may be surpassed by one or even two decimal points.

In this study, such an unusual and unique record is presented from Rocca Busambra, a fragment of a drowned and tectonically dismembered pelagic plateau in the Jurassic of western Sicily. Repeated tectonic fracturing created an intricate pattern of neptunian sills and intervening dykes in the topmost levels of the platform. This phenomenon was accompanied by extreme stratigraphic condensation during a long time span (late Early to middle Late Jurassic). By these two processes a unique depositional environment was established in which the most numerous, diverse and exquisite ammonoid and gastropod fauna ever discovered in the Jurassic of the western Tethys is preserved.

PREVIOUS WORK

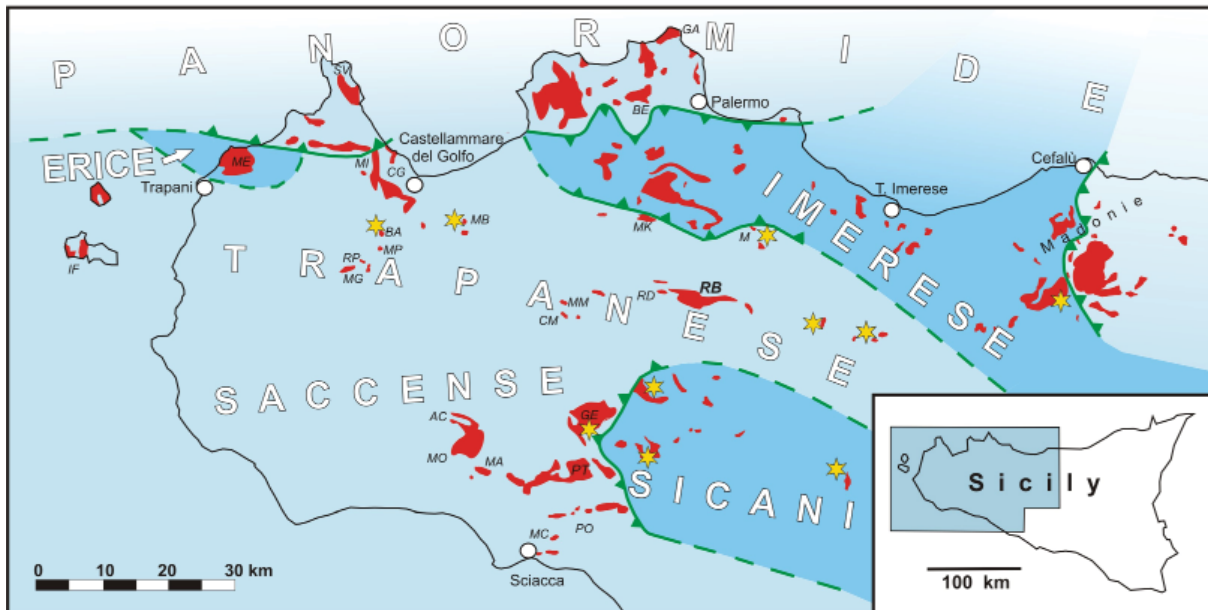
Gemmellaro (1877) was the first to describe and figure a few ammonoids and brachiopods from the so-called “Zona con *Posidonia alpina*” (Dogger) from Rocca Busambra which, distinguished by their small size, excellent preservation and fine-grained red matrix are clearly derived from neptunian sills. A more complete overview of the ammonite fauna from the same area, at that time labelled as Tithonian, was published by De Gregorio (1922), unfortunately illustrated with rather distorted and barely distinguishable figures. Personal efforts to trace the original specimens in the ancient palace of the family in Palermo, now in the possession of Antonio de Gregorio’s grandson, remained unsuccessful, so that this important fauna must be regarded as lost forever. Renz (1924) collected a new ammonite fauna from Rocca Busambra which remained unknown however, until Christ (1958, 1960) incorporated it into his description of Upper Jurassic ammonite faunas from western Sicily. Unfortunately he overlooked the fact that some genera, attributed to the Oxfordian, were in fact Toarcian and Middle Jurassic in age (Wendt 1962). During subsequent years, the exact stratigraphic range of the extremely rich fauna and its long misunderstood provenance from neptunian sills was unraveled by Wendt (1963, 1965, 1969b, 1976, 1971a). The depositional and tectonic evolution of the area was described by Giunta and Liguori (1976), Basilone (2009, 2011), Barraca and Maesano (2012) and Lentini and Carbone (2014, pp. 109–116).

MATERIAL AND METHODS

A total of 56 closely spaced sections through the a few centimetres up to a maximum of about one metre-thick sequence of the sills were measured and sampled in utmost detail. Samples were crushed into 1–5 cm³ big pieces in order to obtain a most complete and representative survey of the entire fauna. By this time-consuming manual work it was guaranteed also that tiny specimens and rare taxa, which are generally overlooked or ignored, were also saved. Unfortunately several boxes with hundreds of perfectly preserved ammonites were stolen during one of my numerous trips to Sicily on the way back to Germany near Catanzarro in Calabria. In spite of meticulous investigations, supported by the local Carabinieri, they have never been recovered and remain probably buried in a nearby road trench or the adjacent macchia.

System/Stage	Zone	Locality	Thickness of condensed sequence (m)	Average sedimentation rate (m/MA)	Sedimentology	Reference
L. Cretaceous Albian	<i>tardefurcata</i> to <i>lautus</i> Zone	Subalpine Chains, S-France	0.25–0.75	0.2–0.4	O, R, phosphorite	Gebhard 1983
L. Cretaceous Albian	<i>tardefurcata</i> to <i>dispar</i> Zone	Vorarlberg, Austria	0.6–0.8	0.15–0.2	O, R, phosphorite	Gebhard 1983
U. Jurassic/ L. Cretaceous	<i>virgatus</i> to <i>subditus</i> Zone	Eastern Russian Platform	1.6–2.4	0.5	?	Zorina <i>et al.</i> 2009
U. Jurassic Kimmeridgian	<i>tenuilobatus</i> to <i>beckeri</i> Zone	Tata Horst, Hungary	2.0	0.4	O, F, nodular limestone	Fülöp 1976
U. Jurassic Kimmeridgian	<i>dentatum</i> to <i>beckeri</i> Zone	Melchtal Alps, Switzerland	0.1–0.5	0.1–0.15	O, R, F	Rod 1946
U. Jurassic Oxfordian/ Kimmeridgian	<i>transversarium</i> to <i>divisum</i> Zone	Cima Campo, Tren- to-Platform, N-Italy	0.9	0.2	O, F	Martire <i>et al.</i> 1991
U. Jurassic Oxfordian	<i>cordatum</i> to <i>transversarium</i> Zone	Kachch Basin, India, Dhosa Conglomerate	0.5	0.35	O, R, S, B	Alberti <i>et al.</i> 2013
M./U. Jurassic Bajocian/ Kimmeridgian	<i>parkinsoni</i> to <i>platynota</i> Zone	Asiago, Trento-Plat- form, N-Italy	15	1.15	O, F, cherts	Martire 1992
M./U. Jurassic I. Bathonian– I. Kimmeridgian	<i>zigzag</i> to <i>acanthicum</i> Zone	Rocca Busambra, Sicily	0.8–1.0	0.07	O, R, F, S	Wendt 1971a
M. Jurassic Bathonian–Callovian	<i>zigzag</i> to <i>calloviense</i> Zone	Monte Inici, W-Sicily	0.2–0.5	0.15	O, R, F, S	Wendt 1964
M./U. Jurassic I. Bathonian/ I. Oxfordian	?	Subbetic Plateau, E-Spain	1.0	0.1	O, R, F	Fels and Sey- fried 1993
M. Jurassic Bajocian	<i>subfurcatum</i> to <i>parkinsoni</i> Zone	Bayeux, France	0.25–0.45	0.3	O, R, F	Fürsich 1971
Aalenian/ I. Bajocian	<i>opalinum</i> to <i>discites</i> Zone	Prérif, N-Morocco	0.1–0.3	0.1	O, phosphorite	Lelièvre 1960
M. Jurassic Aalenian	<i>comptum</i> to <i>concava</i> Zone	S. Vigilio, Trento Platform, N-Italy	0.9	0.6	O, R, F	Callomon <i>et al.</i> 1994
M. Jurassic Aalenian	<i>aalensis</i> to <i>opalinum</i> Zone	Monte Peller, S. Alps, Italy	0.8	0.3	O, R, F	Vialli 1937
Aalenian/ L. Bajocian	<i>aalensis</i> to <i>sauzei</i> Zone	Monte Erice, Sicily	0.15–0.3	0.1	O, R, F	Wendt 1971b
L./U. Jurassic Toarcian/ Kimmeridgian	<i>serpentinum</i> to <i>beckeri</i> Zone	Rocca Busambra, W-Sicily, entire neptunian sill	0.7	0.02	o, r, f, b	this paper
M. Jurassic Aalenian/Bajocian	<i>opalinum</i> to <i>propinquans</i> Zone	Rocca Busambra, W-Sicily, single level in neptunian sill	0.015	0.004	o, r, f	this paper
U. Triassic Carnian	<i>aonoides</i> Zone	Rappoltstein, N-Calcareous Alps	0.6–0.8	0.5	O, R, F	Hornung <i>et al.</i> 2007
M./U. Triassic Anisian/Carnian	<i>smidicus</i> to <i>austriacum</i> Zone	Epidauros, Greece	9.0	0.6	O, R, F	Krystyn 1983
U. Devonian I. Frasnian/ u. Famennian	<i>jamieae</i> to <i>praesulcata</i> Zone	Jebel Amelane, Tafilalt, Morocco	2.0	0.1–0.2	O, R, F	Wendt 1988
U. Devonian u. Frasnian/ I. Famennian	upper <i>gigas</i> to upper <i>crepida</i> Zone	Tafilalt-Platform, Morocco, Kellwasser- Limestone	3.0	0.6	O, R, bituminous limestone	Wendt and Belka 1991

Table 1. Examples of stratigraphic condensation. Average sedimentation rates are calculated from individual biostratigraphic data in relation to the absolute time scale (Gradstein *et al.* 2012). O = omission, R = reworking, F = Fe/Mn-crusts/ooids, D = dissolution, B = bioturbation. Small letters indicate similar, but minor depositional features in the Rocca Busambra sills



Text-fig. 1. Jurassic tectono-palaeogeographic domains in western Sicily. Basins in dark blue, platforms in light blue, thrust sheets (directions generalized) in green, outcrops of Jurassic rocks in red. Yellow asterisks indicate localities of Jurassic submarine volcanism. Boundaries of domains are based on surface data only. Localities: AC = Acque Calde, BA = Monte Barbaro, BE = Bellolampo, CG = Contrada Guidaloca, CM = Contrada Monzealese, GA = Monte Gallo, GE = Monte Genuardo, IF = Isola di Favignana, M = Marineo, MA = Monte Arancio, MB = Monte Bonifato, MC = Monte San Calogero di Sciacca, ME = Monte Erice, MG = Montagna Grande, MI = Monte Inici, MK = Monte Kumeta, MM = Monte Maranfusa, MO = Monte Magaggiaro, PO = Rocca Porcaria, PT = Pizzo Telegrafo, RB = Rocca Busambra, RD = Rocca Drago, RP = Rocca chi Parra, SV = San Vito. Map is based on surface data only and was compiled from numerous publications as well as from the descriptions of the 1:50000 geological maps (Catalano *et al.* 2010, 2011a, b, c) and the 1:250.000 geological map of Sicily (Lentini and Carbone 2014)

A few samples were examined by X-ray and under a scanning electron microscope (SEM). Their elemental composition was measured using an energy-dispersive X-ray analyser (EDX). The figured material is deposited in the collections of the Geological-Palaeontological Institute of the University of Tübingen under the numbers GPIT/CE/9541ff.

JURASSIC TECTONO-DEPOSITIONAL DOMAINS OF WESTERN SICILY

The Jurassic of western Sicily has been the focus of “classic” palaeontological research since the late 19th century and, during the subsequent decades, of biostratigraphic and tectonic studies, making this island a key area of studies of the stratigraphy and palaeogeography of the western Tethys. Rocks of this System are widely exposed as isolated tectonic remnants of a large open-marine carbonate platform and its pelagic cover which is intersected by basins of unknown dimensions. From north to south the following tectono-depositional domains have been distinguished by Catalano and D’Argenio (1982), Catalano

et al. (1996, 2002a, b), Di Stefano (2002), and others (Text-fig. 1):

- Panormide Domain (carbonate platform),
- Imerese Basin,
- Trapanese Domain (carbonate platform to pelagic plateau),
- Sicani Basin,
- Saccense Domain (carbonate platform to pelagic platform).

Due to the isolated and patchy outcrops of Jurassic rocks, the boundaries of these domains can be drawn only approximately. In particular, the position of the southern boundary of the Panormide Domain in the Palermo and Capo San Vito mountains is controversial. Catalano and D’Argenio (1983) have recognized two other domains, the Prepanormide Domain placed internally (i.e. northward) of the Panormide Platform, and the Marineo Basin located somewhere south of the Trapanese Platform. Because Jurassic equivalents of both domains are known only from subsurface data, they have been omitted in Text-figure 1. These units now appear as imbricated thrust sheets, the present boundaries of which are the result of tectonic shortening and clockwise rota-

tion during the Miocene (Avellone *et al.* 2010). The platform domains reappear, buried under a thick pile of nappes emplaced during the Miocene, on the Iblean Plateau in southeastern Sicily. The Panormide, Trapanese, Saccense and Iblean domains are remnants of a huge compound platform (Siculo-Tunesian platform), which became dissected after the Late Triassic (Catalano and D'Argenio 1982; Di Stefano *et al.* 2010). Exact biostratigraphic correlations between platform and basinal deposits are aggravated by the virtual absence of reliable index fossils in the latter.

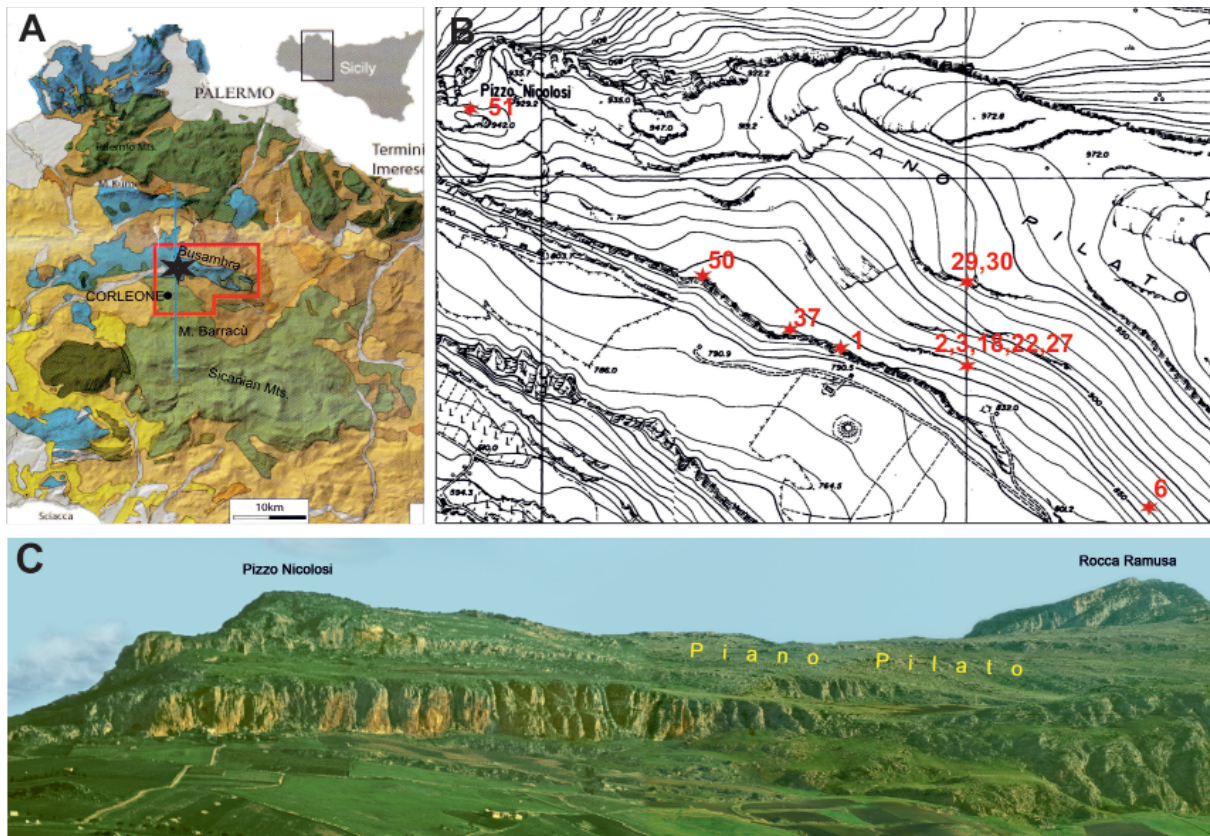
The Trapanese and Saccense Domains display a very similar depositional evolution during the Jurassic and constitute one and the same compound platform, distinguished only by their later tectonic overprint. This is a typical continental margin carbonate platform/pelagic plateau, which is characterized by a sharp boundary between shallow marine limestones in the early Liassic and disconformably overlying pelagic carbonates in the late Liassic to Late Jurassic. Since Jenkyns and Torrens (1971), this environment has often been labelled as "seamounts", not only in Sicily, but also in the Apennines (e.g. Bice and Stewart 1990) and elsewhere in the western Tethys. I avoid this colourful term because it takes attention away from the fact that the present isolated occurrences of condensed pelagic deposits in western Sicily are merely the result of later tectonic fragmentation of a large drowned carbonate platform and not a primary depositional feature.

The western termination of the Trapanese platform in the Middle and Late Jurassic is buried under younger deposits of the Trapanese Domain and a thick pile of Panormide and Prepanormide nappes (Catalano *et al.* 2002b, fig. 3). In westernmost Sicily a remnant of another basin, the Erice Basin (Wendt 1971b; Catalano and D'Argenio 1983) is exposed. Here, the Pliensbachian to Upper Jurassic is represented by about 250 m of thin-bedded pelagic limestones with chert layers (Erice Formation). On Monte Erice the boundary between the Trapanese Platform and the Erice Basin in the lower/middle Liassic is a submarine cliff or stepped margin where upper Pliensbachian cherty limestones overlap peritidal limestones of the Inici Formation (Martire 2002). The prolongation of the Erice Basin towards the north-west is uncertain, because it is probably truncated by the southwards overthrust of the Panormide Domain (Text-fig. 1), of which an upper Cretaceous remnant is still preserved on Monte Erice (Wendt 1971b).

Another platform-basin transition is exposed at Guidaloca north-west of Castellammare del Golfo (Caracuel *et al.* 2002; Catalano *et al.* 2011a, b) where the lower Bathonian to Tithonian is represented by

cherty limestones which differ markedly in lithology and thickness from the typical platform sequence at the adjacent Monte Inici (Christ 1960; Wendt 1963). It is very similar to the nearby Balata di Baida section where Warman and Arkell (1954), Christ (1960) and Catalano *et al.* (2011a) described an unusually thick (>60 metres) sequence of cherty and nodular limestones of Oxfordian (?) to Tithonian age. Also on Monte Kumeta, the intercalation of radiolarites in the Middle/Upper Jurassic Buccheri Formation (Di Stefano *et al.* 2002a) suggests the vicinity of a (tectonically largely suppressed) basinal realm, which may be either the Imerese or the Marineo Basin. A segment of the southern margin of the Trapanese-Saccense Platform is exposed at Pizzo Telegrafo and at Monte Genuardo in the Sicani mountains where some tens of metres of Middle Jurassic pelagic ammonoid wackestones grade into volcanics and Upper Jurassic breccias and radiolarites, thus indicating a slope to basin transition (Di Stefano and Gullo 1986). As a whole, the Trapanese-Saccense Domain can be regarded as a peritidal carbonate platform during the late Triassic/early Liassic which, after subaerial exposure and subsequent drowning developed into a pelagic plateau in the late Liassic. Its sedimentary cover is characterized by a great variety of condensed shallow pelagic wackestones, local crinoid grainstones and pelagic oolites which from place to place exhibit different water depths and depositional environments.

The palaeogeographic and depositional evolution of the Panormide Domain is more complex. Partly it represents a typical shallow-marine carbonate platform with high sedimentation rates from the Late Triassic into the Late Jurassic. This sequence is locally interrupted by uplift and karstification during the Early to early Upper Jurassic, constrained by bauxites (Censi and Ferla 1989; Ferla and Bommarito 1989; Di Stefano *et al.* 2002b; Zarcone and Di Stefano 2010). In contrast, some adjacent areas show close similarities to the Trapanese and Saccense Domains. They are characterized by a break in sedimentation near the Sinemurian/Pliensbachian boundary, followed by condensed upper Liassic/lower Dogger cephalopod limestones and neptunian dykes and sills. This sequence is exposed in several localities: the Capo San Vito Peninsula (Giunta and Liguori 1970; Wendt 1971b) and in the Palermo and Madonie Mountains (Wendt 1969b; Vörös *et al.* 1986; Zarcone *et al.* 2006; Zarcone and Di Stefano 2010). The subsequent transition back into a peritidal environment and a regime of renewed stronger subsidence during the Late Jurassic (Catalano *et al.* 2011a, b) is a rather unusual evolution. The juxtaposition of these contrasting depositional



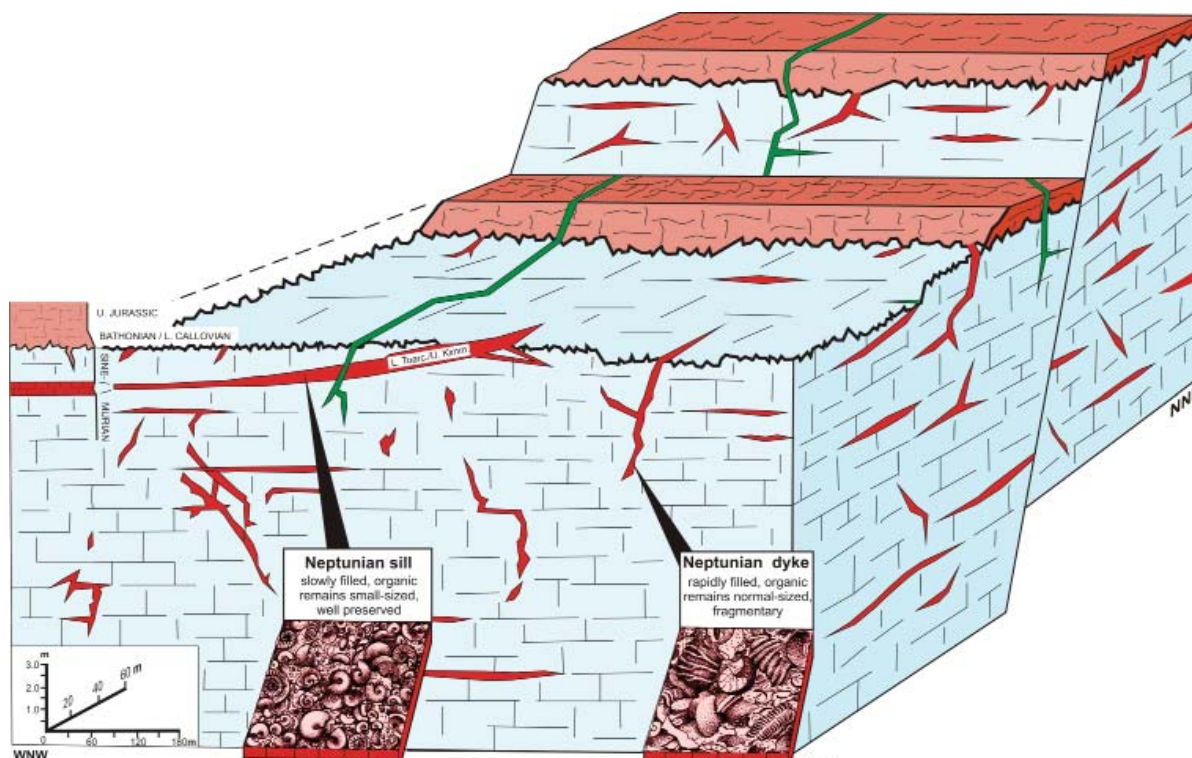
Text-fig. 2. Research area. A. Modified from Basilone (2011). Red asterisk indicates position of Text-fig. 2B. B. Topographic map with location of sections mentioned in the text and on figures 4, 5 and 7 (for exact coordinates see appendix). Distance of grid lines is 1 km. C. Panoramic view from the south on the western part of Rocca Busambra with the research area of Piano Pilato

environments in a small area is difficult to understand and is probably due to tectonic shortening that has eliminated original transitional realms. However, it cannot be excluded that this pattern reflects an original highly dissected fault-bounded submarine topography. The continuation of the Panormide Domain towards east is unknown. Equivalent carbonate-platform deposits reappear in the Madonie Mountains south of Cefalù where they abut, along a north-south trending thrust sheet, against basinal deposits of the Imerese Basin (Text-fig. 1).

GEOLOGICAL SETTING

Rocca Busambra is an approximately west-east trending mountain range about 50 km south of Palermo, 15 km long and up to 2 km wide (Text-fig. 2). It is a fragment of a large shallow-marine carbonate platform of Late Triassic/Early Liassic age (Siculo-Tunesian Platform), which crops out in western Sicily over a total surface area of 5000 km² in a

great number of tectonically isolated remnants, which, in the subsurface, extend over the entire island and the adjacent seas. The sequence consists of several hundred metres thick peritidal platform carbonates of Late Triassic to Early Jurassic (Inici Formation) age which are disconformably overlain by a few metres of reddish, pelagic ammonite-bearing crinoidal limestones of Bathonian to early Tithonian age (Buccheri Formation, Rosso Ammonitico). The latter are covered by upper Tithonian/Neocomian (Lattimusa Formation) and upper Cretaceous (Scaglia) pelagic limestones (Basilone 2009, 2011; Bertok and Martire 2009). As a consequence of various tectonic pulses from the early Toarcian into the Miocene, the upper tens of metres of the lower Liassic platform carbonates are dissected by numerous cracks and veins which run parallel (sills) or oblique to vertical (dykes) to the bedding planes. The former have an observed lateral extent of up to 300 metres, the latter penetrate several tens of metres into the underlying beds. The research area on the western end of Rocca Busambra (Piano Pilato) covers an area of approximately 3 km² (Text-fig. 2B, C).



Text-fig. 3. Idealized image of two tectonic blocks on Piano Pilato near section RB 29/30 displaying the upper part of Inici Formation (blue) and the disconformably overlying Buccheri Formation (red). Jurassic neptunian sills and dykes (width of the latter not to scale) in red, Upper Cretaceous ones in green. Tertiary dykes are omitted. Bedding planes of sills and dykes crowded with ammonites on lower margin are drawn after natural specimens

STRATIGRAPHY OF THE NORMAL SEQUENCE

The depositional sequence of Rocca Busambra embraces the time span from the Upper Triassic (Norian–Rhaetian) into the Miocene (Tortonian), but in the study area only deposits from the Sinemurian to the Upper Cretaceous (Cenomanian–Maastrichtian) crop out (Basilone 2011). It is the typical sequence of the Trapanese Domain that in the Middle/Late Jurassic was characterized by low sedimentation rates, major unconformities and gaps.

Lower Liassic (Inici Formation)

The lithology of this formation is described in detail by Di Stefano *et al.* (2002a), Petti (2005) and Basilone (2012, p. 45). In the study area only the upper part (about 100 m) of the formation is exposed which, due to WNW-ESE trending normal faults crops out repeatedly in several steps (Wendt 1971a, fig. 5; Basilone 2009, figs 5, 10). 3 km farther east, below the summit of Rocca Busambra the thickness of this formation attains at least 400 metres. The Inici Formation consists of a cyclic sequence of sub-

intertidal members, mainly wackestones, frequently with dasycladacean algae, foraminifera and fenestral fabrics. Typical supratidal members (paleosols, speleothems, paleokarst) were described from Monte Maranfusa (Sulli and Interbartolo 2016) 20 km west of Rocca Busambra and were observed also in the study area. Only a few fossils were personally gathered in the lower part of the formation, comprising some gastropod casts, small lycoceratids and a fragment of *Arietites* confirming the Sinemurian age that had been already established by Gemmellaro (1878–82) and Gugenberger (1936). A similar age was reported by Jenkyns (1970b) on the basis of a small ammonite fauna from Rocca Maranfusa that, however, has not been described. The upper tens of metres of white limestones of the Inici Formation are crisscrossed by numerous neptunian dykes (Text-fig. 3; Catalano *et al.* 2010, fig. 29) and sills of Toarcian to Miocene age (see below). On Monte Kumeta, Di Stefano *et al.* (2002a) subdivided the Inici Formation into three members (M1 to M3) to which, on the basis of calcareous algae, a Hettangian to earliest Pliensbachian age was ascribed. An early Pliensbachian age of the upper Inici Formation is in accordance with previous

findings of ammonites on Monte Erice (Di Stefano 1891) and by Gemmellaro (1874) from other localities in western Sicily.

Middle Liassic

This unit is the so-called “zona con *Terebratulina Aspasia*” of Gemmellaro (1874), a term which has long been abandoned. Its attribution to the Middle Liassic is rather imprecise because it is merely based on brachiopods, gastropods and two ammonite species of uncertain provenance. There are only three places in western Sicily where this stage is more precisely dated. Two are in the Panormide Platform where Vörös *et al.* (1986) discovered a neptunian dyke filled with lower Pliensbachian (Carixian) brachiopods at Cozzo di Cugno, and Bellolampo in the same area, where Wendt (1969b) found a neptunian sill with upper Pliensbachian (Domerian) ammonites. These data illustrate the fact that (at least parts of) the Panormide Platform became emergent in the latest Sinemurian or in the earliest Pliensbachian. The third place is Monte Erice near Trapani where a small fauna of silicified ammonites from a white limestone indicates a Domerian age (Wendt 1971b). Unfortunately the latter finding is of only limited biostratigraphic value, because it is derived from a tectonically isolated limestone wedge. Another lithology attributed to the same stage is a reddish crinoidal limestone, interpreted as submarine sand waves by Jenkyns (1971a), which, however, has not yielded any diagnostic fossils. Jenkyns (1971a) and Jenkyns and Torrens (1971) ascribed a Domerian age to this lithology, but Di Stefano *et al.* (2002a) favour a possible lower Pliensbachian (Carixian or early Domerian) age at Monte Kumeta. Analysis of fluid inclusions in banded calcitic overgrowths on crinoid ossicles (Mallarino *et al.* 2002) have yielded a palaeodepth of less than 23 m for the crinoidal limestone from this locality and an enhanced sea level rise towards the early Toarcian.

At Piano Pilato, the crinoidal limestones are only a few decimetres thick or totally absent and have not yielded any diagnostic fossils. Probably they were more widespread originally but were largely removed during the late Domerian erosion. At Pizzo Marabito on the eastern termination of Rocca Buambra, they attain 8 metres and rest directly on Upper Triassic dolomites (Basilone 2011). Where present, the crinoidal limestones are bounded by erosional surfaces and ferromanganese crusts on both bottom and top (Basilone 2009, fig. 6c). These few data indicate that the sudden demise of peritidal platform growth

occurred during the earliest Pliensbachian. If the Domerian age of the crinoidal limestones is correct, this intercalation would indicate a later and local, short drowning and a renewed uplift of the platform during the latest Pliensbachian. Because the earliest post-drowning deposits (Carixian) are known only from the Panormide Domain (Vörös *et al.* 1986) it can be concluded that parts of this platform were tilted northward and thus flooded earlier than the Trapanese and Saccense platforms farther south. These considerations lead to the fundamental question: Was platform growth abruptly terminated by drowning or uplift?

Since the early biostratigraphic research on the Jurassic of western Sicily in the early 1960's, a long and controversial debate arose about the origin of the widespread depositional unconformity on the top of the Inici Formation. It is typical for the Jurassic sequence of the Trapanese and Saccense Domains (e.g. Wendt 1963; Di Stefano *et al.* 2002a) and is also observed in some parts of the Panormide Domain (see above). This very distinct boundary marks a major gap, which at Rocca Busambra embraces the time span from the late Sinemurian (or early Pliensbachian?) to the early Bathonian. In other places, as on the nearby Monte Kumeta, this gap is shorter, but as distinct, and restricted to the late Pliensbachian/early Toarcian (top of the so-called crinoidal limestones (Di Stefano and Mindszenty 2000; Di Stefano *et al.* 2002a; Galácz *et al.* 2007). For a long time the origin of this surface has been attributed to submarine erosion subsequent to the drowning of the carbonate platform. Only hesitantly has the conviction gained ground (included myself) that such a sharp boundary with the pronounced relief can only be the result of subaerial erosion, although this idea had already convincingly been expressed by Jenkyns (1970b, 1971a). Such an interpretation is in agreement with Schlager's (1981) statement that reef and platform growth can always take pace with a rising sea level. Thus, there can be little doubt that the sudden termination of platform growth in western Sicily and similar realms of the Tethyan Jurassic can only be the result of uplift above sea level and subsequent subaerial erosion. Moreover, the difference of estimated water depths between the peritidal environment of the Inici Formation and the disconformably overlying Buccheri Formation (deeper part of photic zone) cannot be explained only by sudden drowning of the platform only. Though the analysis of stable isotopes of the overlying ferromanganese crust does not support the presumed influence of meteoric waters (see below), Di Stefano and Mindszenty (2000) favored a subaerial origin of the

jagged surface (so-called “Kamenitza structures”) of the underlying crinoidal limestones, but they do not strictly exclude possible effects of submarine dissolution. Later, however, Mallarino *et al.* (2002) ascribed this sharp boundary again to “extremely rapid rates of tectonic subsidence” and to an “ecologic perturbation in shallow-water productivity”. In spite of these controversial ideas, the mechanism of uplift above sea level at this boundary became increasingly accepted (Di Stefano *et al.* 2002a; Marino and Santantonio 2010; Sulli and Interbartolo 2016; and others).

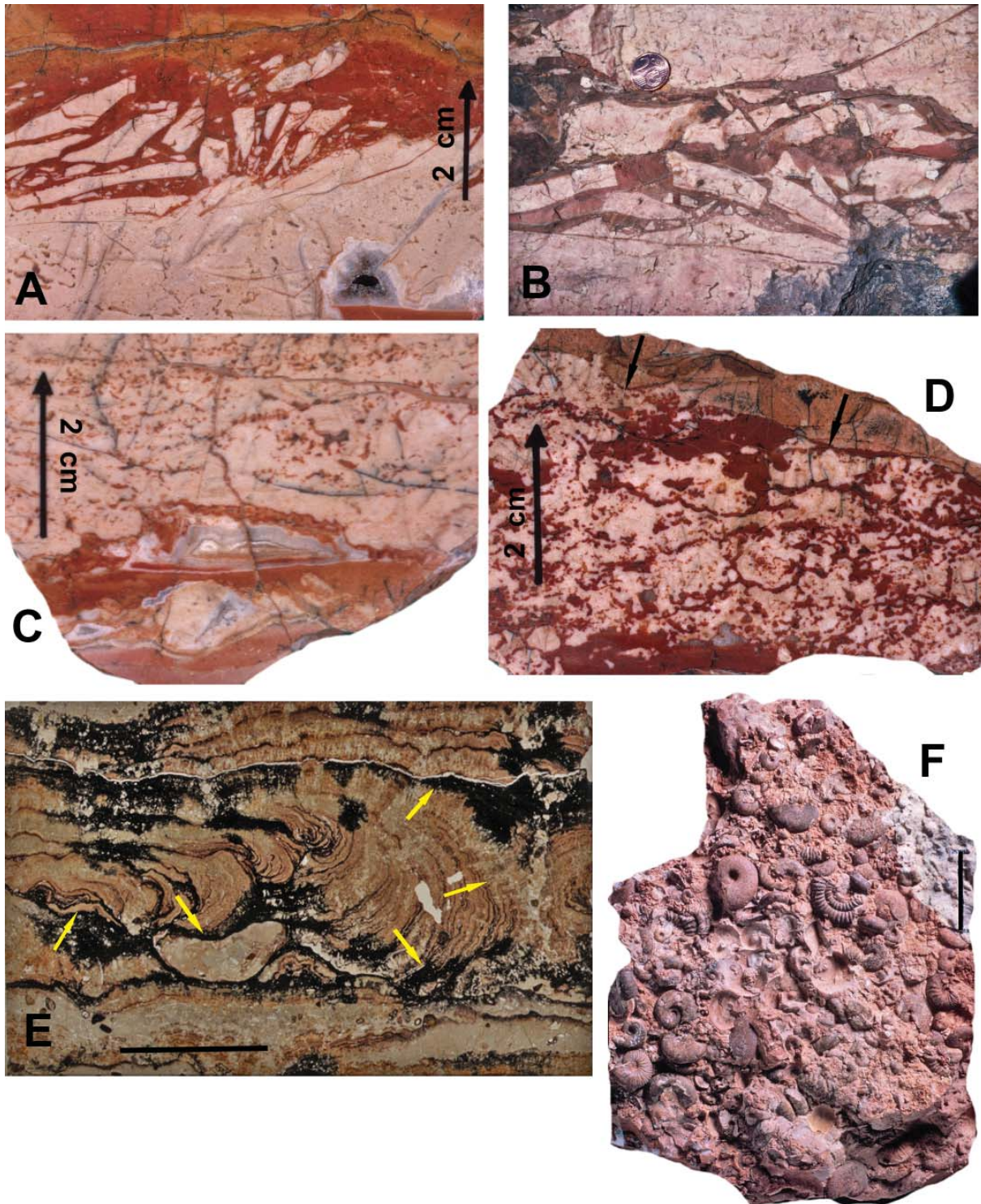
In contrast to the Panormide Domain (Monte Gallo), typical terrestrial deposits such as bauxites have never been found at the top of the Inici Formation in the Trapanese and Saccense Domains. Therefore on Rocca Busambra personal attention was directed to some peculiar cavity fillings in the topmost metre below the eroded surface of this formation. Some are chocolate-brown (Text-fig. 4D) and different from the normal brick-red infillings of other voids. This colour aroused suspicion as to these sediments probably representing a possible bauxitic residue which, however, could not be demonstrated by X-ray diffraction. The same observation was made by Ferla *et al.* (2002) for the bauxites at Monte Gallo which were documented as such only by their isotopic composition. The absence of crystalline bauxite or other Al-minerals in the Rocca Busambra samples, however, does not exclude their presence in an amorphous state, a surmise that is supported by their unusual high Al- and K-peaks in EDX spectra. In this context, attention should also be drawn to the presence of kaolinite in the crinoidal limestones that in some places disconformably overlie the eroded top of the Inici Formation (Jenkyns 1971a), thus clearly showing the existence of emerged areas of the Trapanese Domain.

The ferromanganese oxyhydroxide crust

This is the most conspicuous level in the Jurassic sequence of the Trapanese and Saccense Domain and has often been described and analyzed (e.g. Wendt 1963; Jenkyns 1970c, d; Di Stefano and Mindszenty 2000; Di Stefano *et al.* 2002a; Preat *et al.* 2011). It caps various levels of the Inici Formation or, where present, the overlying crinoidal limestones. Generally this ferromanganese crust caps the underlying strata disconformably but generally bedding-parallel. At Rocca Busambra small pre-Bathonian normal faults are covered by a similar Fe/Mn-crust (Text-fig. 5A, E). An angular unconformity of up to 30° at this boundary is visible on Monte Erice (Wendt 1971b, fig. 2). Minor angular unconformities are also ob-

served on the island of Favignana, Rocca chi Parra (Wendt 1963; Martire and Pavia 2004) and on Rocca Busambra (Bertok and Martire 2009).

Detailed field observations of this level and the associated ferromanganese nodules were performed in several localities in western Sicily by Jenkyns (1970c, d), Mascle (1974) and Di Stefano and Mindszenty (2000) at Monte Kumeta and in other places of the Trapanese and Saccense Domains. Chemical analyses show variable high amounts of poorly crystalline Fe₂O₃ and MnO₂ (iron-manganese oxyhydroxides). These investigations agree in the conclusion that the source of the mineral concentrations is probably related to the contemporaneous submarine volcanism that has long been known from various localities in western Sicily (Text-fig. 1, references in Basilone *et al.* 2014). Fragments of volcanic rocks have also been discovered in several places in the Ferrich red limestones of the basal Buccheri Formation (Jenkyns 1970c). At Monte Pispisa, the ferromanganese crusts are directly connected to hydrothermal dykes (Wendt 1963). The crust has been named “the main hardground” by Di Stefano *et al.* (2002a) though attached organisms settling on it are much less common than expected. They are restricted to some sessile foraminifera (Wendt 1970; Di Stefano and Mindszenty 2000, fig. 13b) and various types of boring microorganisms attributed to iron-bacteria, lichens (!), fungi or boring sponges (Preat *et al.* 2011). The latter authors were probably not aware, that the presence of “lichens” would imply a subaerial environment, which can definitely be excluded. Apart from these undeterminable microorganisms, larger shell-bearing remains, however, have never been recorded. Also Seyfried (1978) observed that the common Fe/Mn-crusts in the Jurassic of south-east Spain contain, apart from “boring algae”, only sessile foraminifera and serpulids (which are difficult to distinguish from one another, particularly in a juvenile state of the latter). At Rocca Busambra, the thickness of the crust ranges from a few to about 60 cm (Text-fig. 5). It consists of wavy brownish to blackish laminae with intercalated iron-stained mudstones that document repeated interruptions of the mineral concentrations, small-scale unconformities, omission and reworking, showing that growth of the crust was a rather complex and intermittent process. Growth of the mineral laminae is directed not only upwards but also laterally and downwards, showing that the crust locally had a “spongy” structure with open spaces that were later filled with fine-grained sediment (Text-fig. 4E). This texture may be the cause for the surprising fact that the ferruginous



Text-fig. 4. A. *In-situ*-breccia of limestone clasts (Inici Formation) on base of fossiliferous neptunian sill (lower Toarcian). Section RB 3. B. *In-situ*-breccia along bedding plane of peritidal limestone filled with unfossiliferous red mudstone. Lower level of neptunian sill, about 10 m below top of Inici Formation. 2-cents-coin for scale. Section RB 1. C. "Roof" of uppermost neptunian sill. Remaining cavity filled by several generations of spar. Section RB 29/30. D. Top of Inici Formation. Solution cavities filled with dark-red Al- and K-rich mudstone and capped (arrowed) by disconformably overlying pelagic cephalopod limestones of Buccheri Formation (Bathonian). Scale bar 2 cm. Section RB 27. E. Ferromanganese crust in section RB 37. Yellow arrows indicate divergent growth directions. Scale bar = 1 cm. F. Surface of bedding plane in section 29, unit 15, crowded with small ammonites (upper Oxfordian, *bimammatum* Zone). Scale bar = 2 cm

Stage	Zone	Locality	Reference
l. Toarcian	<i>bifrons</i> to <i>variabilis</i>	Monte Kumeta (T) Monte Magaggiaro (S) Bellolampo (P)	Galacz <i>et al.</i> 2007 Di Stefano <i>et al.</i> 2002c; Pallini <i>et al.</i> 2004 Gemmellaro 1886; Wendt 1969b; Vörös <i>et al.</i> 1986
u. Toarcian/u. Aalenian	<i>meneghinii</i> to <i>concovum</i>	Contrada Monzalese (S)	Di Stefano <i>et al.</i> 2002c
u. Aalenian/l. Bajocian	<i>aalensis</i> to <i>concovum</i>	Monte Erice (T), Monte Bonifato (T)	Wendt 1963
Aalenian/m. Bajocian	<i>opalinum</i> to <i>sauzei</i>	San Vito Penisola (P)	Wendt 1971b, Zarccone <i>et al.</i> 2006
u. Bajocian/l. Bathonian	<i>parkinsoni</i> to <i>zigzag</i>	Rocca chi parra (T) Monte Maranfusa (T) Monte Kumeta (T)	Pavia <i>et al.</i> 2002; Martire and Pavia 2004 Jenkyns 1970 Galacz 2008
l. Bathonian/l. Callovian	<i>zigzag</i> to <i>anceps</i>	numerous localities in the Trapanese and Saccense domains	Wendt 1963, 1965; Jenkyns 1971; Martire and Pavia 2002; Santantonio 2002; and others
u. Bathonian		Montagna Grande (T)	Martire and Pavia 2004

Table 2. Diachronous age of the base of the Buccheri Formation (and equivalents) in the Panormide (P), Trapanese (T) and Saccense (S) Domains

crusts (also termed *Frutexitis*, colloform structures or deep-water stromatolites) were not a suitable substrate for higher organisms such as sponges, worm tubes, bryozoans, ahermatypic scleractinian corals or mollusks. In other words, the ferruginous crusts may locally have been a kind of a firm- rather than a real hardground. The age of the crust can only relatively be determined by the base of the overlying Buccheri Formation, which significantly differs in age, thus clearly indicating that the crust proper is diachronous (Table 2). In this context it should be noted that the crust is not present everywhere at this boundary. For example it is lacking locally at Rocca Busambra (Text-fig. 4D) and at Rocca Porcaria, in spite of an enormous stratigraphic gap between the Inici and the Buccheri Formation in both localities.

Faced with these contrasting ages of the top of the ferromanganese crust two questions arise: (1) Have the underlying peritidal limestones of the Inici Formation been flooded at different times? And (2) which time span is represented by the crust proper? The first question can rather easily be answered: Flooding of the Trapanese/Saccense platform should have occurred more or less contemporaneously during the early Toarcian (*serpentinum* Zone), even if this stage is constrained by equivalent deposits only in a few places, either at the sea floor (see above) or in neptunian dykes (Monte Kumeta) or sills (Rocca Busambra). But it would be contradictory to assume that in the rather restricted area of these domains the transgression occurred over enormous time intervals. Certainly, the base of the Buccheri Formation shows different ages from place to place. However, this fact can be explained by the assumption that missing time equivalents are the result of non-deposition, rather than of different periods of flooding. Drowning and flooding of the Panormide

Platform farther north, however, occurred somewhat earlier as was emphasized above. A similar case of stepwise flooding of a carbonate platform (from the early Sinemurian into early Pliensbachian) has been reported from the central Apennines by Marino and Santantonio (2010).

Heim (1924) compared fossil ferromanganese crusts and nodules to recent oceanic ones, not only with regard to their composition, but also to their growth rates, which range from 1 to 15 mm/10⁶ years (Ku 1977). If, based on these data, we assume an average growth rate of 10 mm/10⁶ years for the fossil crusts, in the time elapsed from the early Toarcian (begin of flooding) to the base of the Bathonian (latest documented record of the beginning of normal deposition on the sea floor), i.e. within approximately 13 m.y., a crust of 13 cm could have grown. This estimate would be in good agreement with the observation that the fossil Fe/Mn crusts are a few up to several tens of centimetres thick. However, this calculation is based on the untenable assumption, that the fossil nodules and crusts were formed in a similar environment as their recent oceanic counterparts. Moreover, if we admit such a long growth rate, one should occasionally find erosional remnants of the crust embedded in coeval deposits of neptunian sills, but this is never the case. Therefore a much more realistic comparison should be made with recent shallow water ferromanganese nodules for which growth rates from 0.01 to 1 mm/year have been obtained (Manheim 1965; Ku and Glasby 1972; Calvert and Price 1977; Hlawatsch *et al.* 2002). These data are more compatible with the actually observed thickness of the Jurassic crusts and their formation at different intervals after the beginning of drowning. Another indication of a relatively rapid growth of fossil crusts and nodules is the rather common pres-

ence of encrusting sessile foraminifera (see above). It can be concluded that the ferromanganese crusts on the drowned carbonate platforms were formed at shallow depths within the photic zone (Jenkyns 1970c, d) during the time span of approximately one ammonite zone.

Middle–Upper Jurassic

This unit is generally called Rosso Ammonitico in spite of its rather different appearance compared to coeval deposits in the type areas on the Trento Platform, in Liguria, Toscana, Lazio, Umbria, Marche and Molise. Therefore preference is given to the neutral term Buccheri Formation (references in Basilone 2012), which was originally established for the deeply buried Iblean Plateau in southeastern Sicily (Patacca *et al.* 1979). At Rocca Busambra, after the gap during the Pliensbachian–late Bajocian, sedimentation on the eroded sea floor started again at the base of the Bathonian. Strongly condensed deposits of early Bathonian to middle Callovian age are widespread in western Sicily, and their rich ammonite faunas have been intensely studied since the late 19th century. Surprisingly, ammonites from this interval at Rocca Busambra (faunal list in Wendt 1971a) are much rarer compared to other condensed sections of the same age. Faunas collected from different levels in the lowermost 80 cm of the Buccheri Formation overlying the ferromanganese crust document at least three intervals: early Bathonian/middle Callovian, late Oxfordian and early Kimmeridgian. All specimens are normal-sized and attain diameters of up to 40 cm. Many are primary fragments, which are generally leached and Fe/Mn-coated on their upper surfaces.

The youngest ammonite (*Nebroditis peltoideus* Gemmellaro) indicating the middle Kimmeridgian (*acanthicum* Zone) was collected 1.8 m above the base of the Buccheri Formation. These findings show that the stratigraphic condensation at Rocca Busambra was still more extreme than in coeval neighboring sites (Table 1). The occurrence of *Calpionella alpina* Lorenz, indicating an early Tithonian age, 7.5 m above the base of the Buccheri Formation (Bertok and Martire 2009, fig. 4) shows that the sedimentation rate had slightly increased since the late Kimmeridgian.

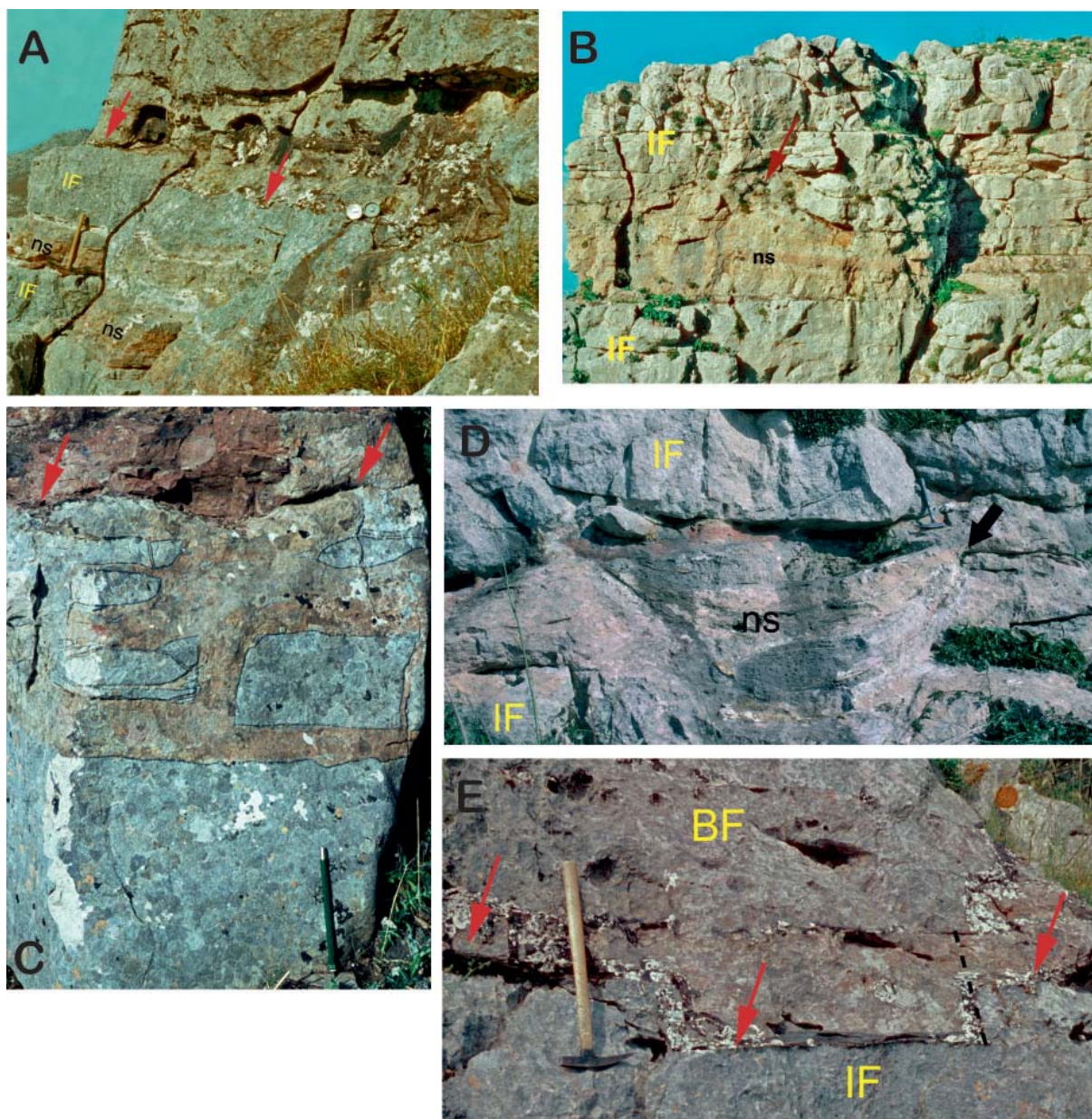
The Buccheri Formation consists of up to 10 m of thick-bedded red wacke- and packstones, generally with a high amount of crinoid debris. Biogenic remains are often reworked, micro-bored and iron-stained and may attain up to 40% of the rock volume.

Most common are ammonites, pelagic pelecypods (*Bositra*), planktonic foraminifera (Tamajo 1960, figs 4, 8), rare benthic foraminifera and ostracods. Other grains comprise small ferromanganese oncolites (Mn-nodules), intraclasts, lithoclasts, peloids and rare concentrically laminated micritic ooids. The latter are interpreted by Jenkyns (1972) as a pelagic counterpart of shallow-water ooids. In the examined sections they are less common than in neighboring areas where they may attain diameters of up to 25 mm.

In their meticulous studies in the same area as the present research (Piano Pilato), Martire and Bertok (2002) and Bertok and Martire (2009) distinguished two different lithologies and depositional geometries: the “normal” and the “anomalous” Rosso Ammonitico. The former was deposited conformably, i.e. bedding-parallel to the underlying peritidal limestones of the Inici Formation, while the latter was deposited unconformably (i.e. onlapping and partly angular) on an inclined stepped surface of the same formation. The authors distinguish seven microfacies types and additional subtypes, among which are massive, (pseudo)nodular, intraclast and megabreccia facies which were assigned to different depositional environments.

It is sometimes difficult to follow the lengthy arguments of the two authors regarding microfacies and depositional geometries, which appear partly contradictory. Thus, some figured specimens of the so-called megabreccia facies (Bertok and Martire 2009, fig. 6G, H) clearly display a strongly condensed lithology, emphasized by the wavy iron-stained bedding planes and lithoclasts, rather than representing a typical breccia. Their figures 3D and 6A show bored and iron-stained clasts, but this is not what is commonly understood as a nodular limestone. Essentially all these various facies types characterize one depositional type only: extreme condensation by minimum sediment input, submarine erosion and reworking.

In particular, I disagree with the authors' interpretation of significant depositional geometries as the result of gravitational sliding and collapse. Such a process would necessarily imply the presence of semilithified sediments capable of sliding. But such a premise is excluded by the extreme condensation, accompanied by rapid cementation. Both aspects are also accepted by the authors, but curiously enough the existence of later faults seems to be ignored by them. Thus, none of the numerous WNW-ESE trending faults is shown, though they are clearly visible in the field. Some of them are dated from dykes with vertical offsets as Late Cretaceous (Cenomanian to Maastrichtian) which were reactivated during the



Text-fig. 5. A. Section RB 30. Neptunian sill (ns) in uppermost metre of Inici Formation (IF), off-set by pre-Bathonian normal fault. Base of disconformably overlying Buccheri Formation marked by Fe/Mn-crust (arrowed). Length of hammer handle is 50 cm. B. Roof-like opening (arrowed) of neptunian sill (ns) into overlying thick-bedded limestone of Inici Formation (IF). Section RB 51. C. Intricate system of neptunian sills and dykes (boundaries marked by black lines). Main fossiliferous sill on top (arrowed). Length of green pencil is 15 cm. Section RB 22. D. Steep-angle lateral onlap (arrowed) of main sedimentary sill (ns) in section RB 3, IF = Inici Formation. Hammer (left of black arrow) is 30 cm long. E. Depositional disconformity between Lower Liassic Inici Formation (IF) and Bathonian/Upper Jurassic Buccheri Formation (BF) with ferromanganese crust at the base (arrowed). Hatched lines mark small pre-Bathonian normal faults. Hammer handle is 50 cm long. Section RB 2

Miocene. In contrast to the cross-sections by Wendt (1971a, fig. 4), Basilone (2009, figs 5 and 10) and in the geological map of Rocca Busambra (Basilone 2011), the repeated stepwise outcrop of the Buccheri rocks (Text-fig. 3) is explained by Bertok and Martire (2009) as the result of gravitational sliding.

The red thick-bedded limestones of the Buccheri Formation are disconformably overlain by one metre of white marly limestones (Lattimusa Formation) that is, however, preserved only in a few patches. Their Tithonian age is documented by rare ammonites (*Simoceras admirandum* Zittel), the brachiopod

Pygope diphya (Columna) and common calpionellids. Younger deposits of Late Cretaceous (Scaglia) and Eocene age (Amerillo Formation) are not preserved in the normal sequence of the Piano Pilato area and are considered here only as far as they occur in neptunian dykes or sills.

The depositional history of the Jurassic in the Panormide, Trapanese and Saccense Domains is clearly triggered by syn-sedimentary tensional movements and can be summarized as follows:

Early Jurassic:

- Hettangian–Sinemurian: rapid carbonate-platform growth of the Inici-Formation,
- Earliest Pliensbachian: demise of platform growth, uplift above sea level and formation of an irregular surface by minor block faulting and karstification,
- Carixian: drowning of (parts of?) the Panormide platform indicated by the formation of neptunian dykes and sills,
- Domerian: local submersion and deposition of shallow-marine crinoidal sand-waves in the Trapanese and Saccense Domains. Continuing emergence in most other areas of the same domains,
- Early Toarcian: total submergence (drowning) of the entire platform areas; very restricted deposition of condensed pelagic cephalopod limestones on the sea floor and in neptunian dykes and sills; widespread non-deposition and submarine erosion in most areas.

Middle Jurassic:

- Aalenian to Bajocian: Continuous omission or reduced sedimentation on the sea floor, minimum deposition of pelagic carbonate ooze in dykes and sills,
- Latest Bajocian/early Bathonian–Callovian: Widespread sedimentation of condensed pelagic limestones on the sea floor.

Late Jurassic:

- Continuous pelagic condensed deposition on the drowned platforms showing a deepening-upwards trend,
- Local uplift of the Panormide Domain and formation of bauxites (late Early to early Late Jurassic, but not well dated).

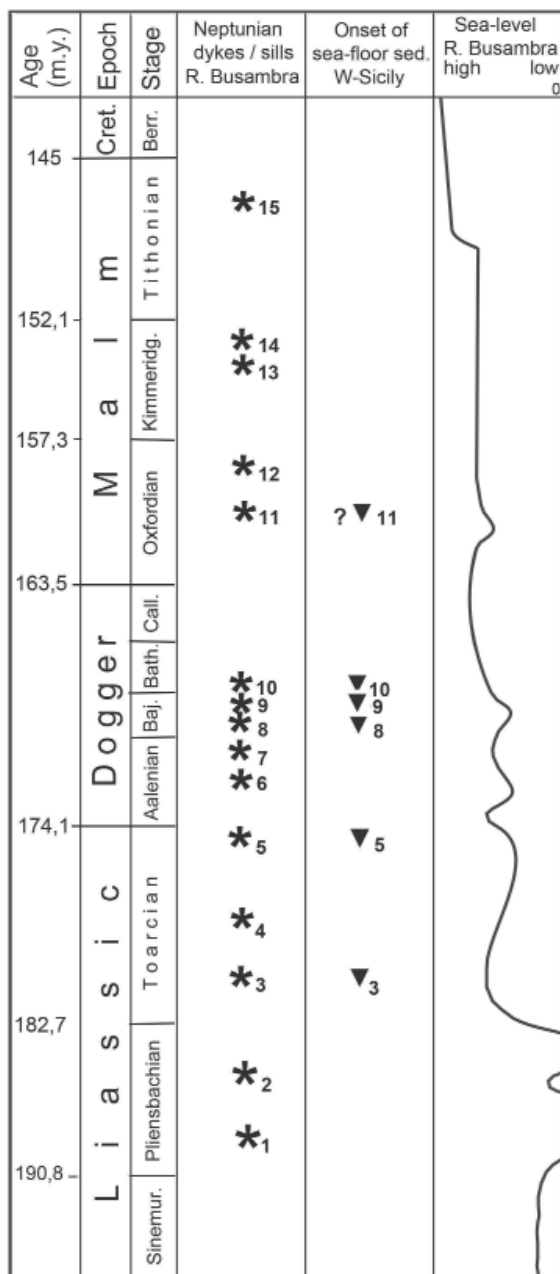
SYNSEDIMENTARY TECTONICS

The most spectacular evidence of syn-sedimentary extensional tectonics is given by the neptunian dykes and sills that are widespread and well documented in the geological record, particularly in Mesozoic sequences (references in Flügel 2010, pp.

217–223). Neptunian dykes are very common in the Jurassic of western Sicily and have been studied in great detail in the past. Warman and Arkell (1954) were the first to mention tectonic fissure fillings in the Jurassic of Rocca chi Parra (Trapanese Domain), but at that time a discussion of their more than local importance was beyond the scope of a mere biostratigraphic examination of the sections which soon became keystones for the depositional history of the Jurassic. The most impressive examples of neptunian dykes can be observed at Rocca chi Parra, Monte Kumeta and Rocca Busambra where the age of formation and infilling has been precisely dated (Wendt 1963, 1971a; Mallarino 2002; Di Stefano *et al.* 2002a; Pavia *et al.* 2002; and others). The compilation of data on the formation of neptunian dykes and sills (Text-fig. 6) shows that the tectonic activity in western Sicily started in the early Pliensbachian and continued discontinuously throughout the entire Jurassic. Still earlier movements are reported from the Iblean Plateau, where Ronchi *et al.* (2000) ascribed a Sinemurian age to neptunian dykes on top of the Inici Formation. If this dating, based on nannofossils, is correct, the Iblean Plateau would have been tilted even earlier. Subsurface data from this plateau indicate a pronounced block faulting and basin formation (Streppenosa Basin) already by the Rhaetian/Hettangian boundary time (Catalano and D'Argenio 1983) but the biostratigraphic evidence for this tectonic phase is poor.

The first comprehensive study of Jurassic neptunian dykes and sills and their formation was presented by Wendt (1965), followed by numerous local studies (references in Basilone *et al.* 2010 and Sulli and Interbartolo 2016). There is a common agreement that these phenomena are related to continental rifting during the breakup of Pangea and the early evolution of the Tethys (Jenkyns 1970b; Bernoulli and Jenkyns 1974; Zempolich 1993; and others). Both vertical and horizontal fissures reflect a slight upwarping and vertical dilation of the uppermost 10–30 m of the lithified host rock, thereby opening small cracks and voids that were subsequently filled by calcareous ooze.

A different interpretation of the formation of neptunian sills was proposed by Winterer *et al.* (1991), Winterer and Sarti (1994) and Sarti *et al.* (2000) who invoke lateral movements (listric faults) on a paleoslope creating major slide blocks and crevices within the host rock, an idea which had already been rejected by Łuczyński (2001). Thus, the invoked listric faults which should have created the bedding-parallel voids in the Liassic of Capo S. Andrea near Taormina



Text-fig. 6. Timing of formation of Jurassic neptunian dykes and sills correlated with onset of sea floor sedimentation, and sea level changes. 1–2 Bellolampo (Panormide Domain), 3–15 Rocca Busambra. Note that onset of sea floor sedimentation is always coeval with tectonic pulses. 1 = Carixian, 2 = Domerian, 3 = lower Toarcian (*serpentinum/bifrons* Zone), 4 = upper Toarcian (*variabilis* Zone), 5 = uppermost Toarcian (*aalenis* Zone), 6 = lower Aalenian (*murchisonae* Zone), 7 = lower Aalenian (*sowerbyi/propinquans* Zone), 8 = middle Bajocian (*humphresianun* Zone), 9 = upper Bajocian (*niortense* or *parkinsoni* Zone), 10 = lower Bathonian (*zigzag* Zone), 11 = middle Oxfordian (*transversarium* Zone), 12 = upper Oxfordian (*bimammatum* Zone), 13 = upper Kimmeridgian (*eudoxa* Zone), 14 = upper Kimmeridgian (*beckeri* Zone), 15 = upper Tithonian. Oscillations of sea level interpreted from faunal distribution patterns of Text-fig. 9

(Sicily) “need not to have been great: less than a meter” (Sarti *et al.* 2000, p. 259). Similar minimal amounts of slips are imagined for neptunian sills in the Betic Cordillera of southern Spain (Winterer and Sarti 1994, p. 1118). Such imperceptible movements can be ignored without hesitation. Among many hundreds of examined neptunian sills, the present author has never observed any bedding-parallel displacements at the boundaries between the infilling and the host rock. Everywhere, roof and floor of the sills fit together well showing that these phenomena were not accompanied by listric faults. Because the opening of these voids was a repeated and discontinuous process, presumed lateral movements should also have disturbed previous infillings of individual sill layers, producing slumps and slides, but this never the case. Detailed analysis of sill sequences, not only on Rocca Busambra but also elsewhere in the Mediterranean Jurassic, have revealed that within these deposits only slight vertical, but never horizontal movements can be observed. Moreover, neptunian sills and dykes were predominantly created on internal platforms and not on platform margins, not only in Sicily but also on the Trento Platform (see below).

From the different age of dykes and sills on Rocca Busambra, the timing of syn-depositional tectonic fracturing events can be precisely deciphered. These data show that the onset of deposition on the drowned platform was always coeval with some of these tectonic pulses during the Jurassic (Text-fig. 6). Subsequent to these intra-Jurassic movements, at least four other tectonic phases have been dated during the Late Cretaceous (late Cenomanian, Coniacian, Campanian, Maastrichtian), followed by less common ones during the middle Eocene and the late Miocene. The formation and infilling of neptunian dykes and sills depends on three main conditions: (1) The host rock was completely lithified as can be deduced from its sharp boundary with the dykes and associated *in-situ* breccias (Text-fig. 4A, B). (2) Deposition on the sea floor was zero (omission) or negative (submarine erosion). (3) Minimum gravitational input of pelagic calcareous ooze. An occasionally invoked “injection” for the infilling of the sills (Winterer *et al.* 1991; Łuczyński 2001) is very far-fetched and would imply a very rapid sucking of pre-existing unlithified sediment into the voids, a process which is in absolute contradiction to the overall extreme low depositional rate in both depositional environments, sea floor and neptunian sills. In some places the direction of the dykes follow later major tectonic lineaments. Thus, on Rocca Argenteria, the western prolongation of Rocca Busambra, their direc-

tion (WNW-ESE) corresponds to that of later faults (Longhitano *et al.* 1995). At Monte Kumeta, Avellone *et al.* (2010) found a similar directional coincidence of neptunian dykes with later transpressional faults. On Rocca Busambra, it is difficult to measure the direction of the dykes because they are generally visible only on vertical rock surfaces that do not allow an insight into the third dimension. Basilone *et al.* (2010, 2014) found clear relationships between the directions of dykes and later fault systems.

A less eye-catching piece of evidence for synsedimentary tectonics is the presence of small intra-Jurassic normal faults that are locally observed at the conspicuous gap in the normal sequence between the Inici and Buccheri Formations (Text-fig. 5A, E).

THE NEPTUNIAN SILLS AT ROCCA BUSAMBRA

Geometry

The cm- to dm-thick layers are intercalated at various levels of the approximately upper tens of metres of the white, thick-bedded limestones of the Inici Formation (Text-figs 3, 5A–D). But only the uppermost level, a few cm to about 1 m below the top, is locally very fossiliferous, whereas the fossil content decreases significantly in deeper levels where only rare or no skeletal remains could be found. Occasionally the “roof” of the topmost sill is partially or totally eroded so that in some places a seemingly “normal” sequence is present (e.g. RB 6, RB 51). Post-Bathonian sills are rare and have been found either on top of the main sill or intercalated in the lower levels of the Buccheri Formation. Only 6 openings (entrances), each several metres wide, could be detected in the entire research area (Text-fig. 5B, exaggerated on Text-fig. 3). Due to the stepwise tectonic repetition of the sequence in up to 7 steps, the sills can laterally be followed over a total distance of 2.5 kilometres. The lateral extension of the uppermost sill ranges from 60 m (RB 6) to about 300 m (RB 29/30) in outcrop, suggesting a (rather speculative) two-dimensional space of up to several 10000s of square metres for individual sills. Generally, sills pinch out gradually between the over- and underlying beds of the Inici Formation. However, some sills onlap at angles of up to 60° on the encasing rock (Text-fig. 5D). The following sedimentological and palaeontological results were obtained from 56 closely spaced sections, which reveal a highly com-

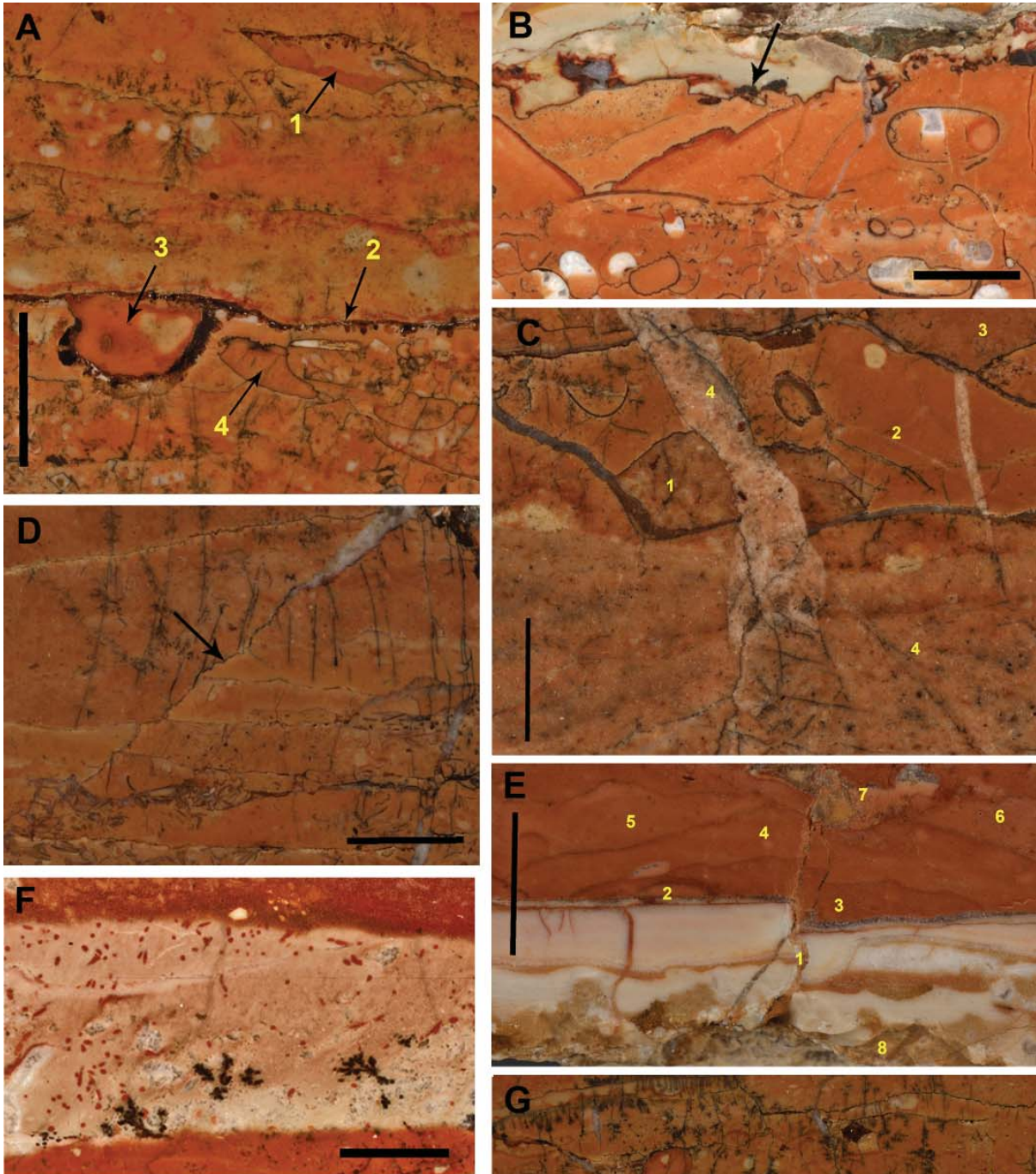
plex biostratigraphic record over a time-span of about 30 million years.

Microfacies

The lithology of the neptunian sills consists of brick-red, rarely pink or yellowish mud-, wacke- or packstones with variable amounts of skeletal debris. SEM-micrographs show that the matrix is heavily recrystallized so that no remains of suspected, carbonate-producing pelagic algae (coccoliths) could be traced. Among the larger organisms one can distinguish allochthonous (i.e. reworked) from parautochthonous biogenic material. Allochthonous shells are always fragmented, Fe/Mn-encrusted and commonly bored by tiny undeterminable microorganisms. Parautochthonous shells are much less fragmented, typically complete and enveloped by a thin black-brownish veneer that facilitates the separation of the shells from the surrounding matrix. This coating is a post-depositional feature and must not be confused with the Fe/Mn-crusts of allochthonous shells, as is constrained by the fact that the coating surrounds the entire shell, not only the upper side, i.e. after its complete embedding. Most common are ammonoids and gastropods, followed by pelecypods, ostracods (commonly double-valved), foraminifera (mainly globigerinids that may attain up to 40% of the rock volume), crinoid ossicles, rare *Saccocoma* and minor groups (see below). Much rarer are grainstones, composed of either *Bositra* shells or crinoid ossicles (e.g. upper part of level 14). In contrast to the mud-supported lithologies listed above, the grainstones document rapid infillings of cavities. A unique, rather puzzling type of microfacies is a fenestral fabric found in one section only (Text-fig. 4C) where it overlies the level with the youngest fauna (lower Kimmeridgian, *beckeri* Zone). Flügel (2010, p. 193) discusses several modes of formation of this fabric, but it is difficult to decide which of these may be applied to this apparently rather dark depositional environment.

Non-biogenic components are lithoclasts of the encasing Inici Limestone, in particular near the base (Text-fig. 4A, B), as well as reworked fragments of older sill deposits, rare calcareous ooids, limonitic detritus and quartz grains. The latter, though extremely rare, may be related to the middle Jurassic submarine volcanism (Jenkyns 1970c; Basilone *et al.* 2010) or, eventually, to the more distant emerged basement rocks of the Calabro-Peloritan massif farther east.

At a first glance, the texture of the neptunian sills appears simply as well-bedded with some interca-



Text-fig. 7. Close-ups of polished vertical sections of neptunian sills. A–D, F–G from RB 18. A. Boundary between units 6 and 7. 1 = reworked clast from lower level, 2 = Fe/Mn-stained boundary, 3 = erosional remnant, 4 = reworked ammonite. B. Boundary between units 15 and 16 marking major gap with erosional surface (arrowed). C. Top of unit 13 showing subsequent depositional stages (1–3), separated by high-angle unconformities, cross-cut by sedimentary dyke (4). D. Oblique, erosionally overprinted normal fault (arrowed) in unit 9. E. Base of main neptunian dyke in section RB 50 (lower Toarcian), fragmented by minor fault (1) and small fissures, overlain by unconformable layers of mudstone (2–7) and underlain by later (probably Oxfordian) neptunian sill (8). F. Fucoid burrowings in topmost level of unit 17. G. Small normal fault (arrowed) off-setting erosional surface in unit 9. All scale bars = 1 cm

Class/Order	Species	Specimens	Remarks
Ammonoidea	> 400	~ 5000	pa
Aptychi	11	60	al
Nautiloidea	?	few fragments	al
Rhyncholites	?	26	al
Coleoidea			
Belemnoidea	10	38	al
<i>Atractites</i>	?	28	al
Gastropoda	236	~ 2800	pa
Lamellibranchiata	36	~ 200	a, pa or al
Scaphopoda	2	19	a
Brachiopoda	19	172	al
Echinoidea	10	26	a, pa, al
Crinoidea	10	15	pa, partly al
Scleractinia	?	80	pa, partly al
Crustacea	?	7	pa?
Fish teeth	?	8	al

Table 3. Numerical composition of the faunas from the neptunian sills at Rocca Busambra. a = autochthonous, al = allochthonous, pa = parautochthonous

lated ferromanganese veneers and calcitic veins. A closer view, however, reveals that the depositional record is much more complicated and shows the following special microtextures: (1) Microlayers pinch out laterally at a cm-scale, or are erosionally capped and may display lateral onlaps at steep angles (Text-fig. 7C). (2) The surface of individual layers is commonly slightly iron-stained indicating minor omission and/or reworking (Text-fig. 6A, B). (3) Mm-sized neptunian dykes cut older underlying beds (Text-fig. 7C). They can be dated only relatively by their upper boundaries, which are related to a younger sill level. (4) Micro-faults with mm-offsets indicate continuing synsedimentary extensional tectonic movements (Text-fig. 7B, D, E, G), that are thus much more common than the major ones which have been dated biostratigraphically by individual sill- or dyke-generations (Text-fig. 6). Similar phenomena have also been observed by Di Stefano *et al.* (2002a, pl. 49, fig. 4) in the normal, strongly condensed sequence of Monte Kumeta. (5) Bedding-parallel calcitic veins have the same origin as (4), but can be followed over much longer distances. These cracks, due to their greater distance from the “entrances” of the sills, have often not been reached by calcareous ooze and were therefore closed by cement growing from both the floor and top. Occasionally it can be observed that the top of the calcite crystals is capped by solution rims. (6) *Frutexitis* “bushes” grew from the top of open spaces downward showing that these structures may form even under reduced light conditions. (7) Open spaces, generally at the top the entire infilling, were concentrically closed by banded calcite (Text-fig. 4C).

Fauna

Provenance and habitat: The bulk of the fauna was collected close to the few entrances into the sill system, particularly in the sections RB 2, 3, 6 and 18. Though comparable data on numbers of species and specimens are not available from other contemporaneous collections, it appears that the fauna of the neptunian sills at Rocca Busambra is the richest ever collected in the Jurassic of the western Tethys. The provenance and the numerical composition of the sill fauna are listed on Tables 3 and 4. According to the distance from their presumed habitat, three groups can be distinguished: (1) autochthonous, (2) allochthonous and (3) parautochthonous.

(1) It is not surprising that autochthonous organisms are extremely rare in these dark, narrow (few centimetres wide) submarine cavities in which every kind of organic matter was rapidly oxidized thus offering only a very limited nutrient source. Some trace fossils of uncertain affinity and very rare sessile foraminifera were figured by Wendt (1971a, pl. 17, 18). The few endobiotic organisms in faunas 1–5, 7, 8 and 10, such as scaphopods, irregular echinoids and some pelecypods (nuculoids), indicating temporary soft grounds, must also be attributed to the autochthonous fauna because these organisms could not have existed on the current-swept rocky sea floor. The probable autochthonous origin of some Scleractinia is discussed below.

(2) Clearly allochthonous elements (fragments of larger shells) are locally accumulated in neptunian dykes (Text-fig. 3 lower right; Wendt 1971a, pl. 15, fig. 5) but very rare in the sills. An occasionally observed chaotic accumulation of both undamaged and fragmented shells reflects rapid deposition and is probably due to the activity of storms. Some shells are perforated by different kinds of microborings (not listed in Tables 3 and 4) which do not allow any speculations about the original environment, but are certainly post-depositional, i.e. allochthonous (Wendt 1971a, pl. 18, figs 1–4). The virtual absence of large shells in the sills cannot be an effect of “sieving” through the openings on the current-exposed sea floor, because these are wide enough for an easy access into the sills.

(3) The principal group is the: parautochthonous fauna, i.e. those skeletal remains which, over a short distance from their habitat, were swept into these open spaces by gentle transport. The parautochthonous fauna is extremely rich, diverse and generally well preserved. Its depositional environment can be visualized as a rocky shoal covered by sea grass or green algae which served as a suitable substrate for

Unit (fauna)	Thickness (cm)	No. of levels	Fauna						Age	
			Ammonites			Gastropods (%)	Other organisms (%)	Endobenthos	Stage	Zone
			No. of species	No. of specimens	%					
1	0.5–1.5	4	32	424	37.8	56.5	5.7	P, S	L. Toarcian	<i>serpentinum</i> to <i>bifrons</i>
2	1.2–2.2	3	36	56	33	58.3	8.7	P	L./U. Toarcian	<i>bifrons</i> to <i>variabilis</i>
3	4.5	3	37	588	43.5	49.1	7.4	P	U. Toarcian	<i>variabilis</i> to <i>dispansum</i>
4	1.0–1.5	2	28	487	87.2	5.4	7.4	E, P, T	U. Toarcian	<i>aalensis</i>
5	2.0	5	37	372	4.7	90.5	4.8	P	L. Bajocian	<i>opalinum</i> to <i>propinquans</i>
6	1.5	2–3	30	74	56	38	6		L. Bajocian	<i>sowerbyi</i> to <i>propinquans</i>
7	3–4	4	17	51	83	6.8	10.2	S	L. Bajocian	<i>propinquans</i> to <i>humphresianum</i>
8	1	3	7	42	22.5	60.5	17	P, S, T	L. Bajocian	<i>humphresianum</i>
9	7	8	20	36	28.2	55.7	16.1	T	U. Bajocian	<i>humphresianum</i> to <i>niortense</i>
10	3	5	21	107	15	60	25	P, S	U. Bajocian	<i>niortense</i> to <i>parkinsoni</i>
11	2	1	5	179	84	4.6	11.4		L. Callovian	<i>macrocephalus</i>
12	2	1	13	164	87	5.2	7.8	P	L. Callovian	<i>macrocephalus</i>
13	10	6	11	60	67.5	14.5	18	E	L./U. Oxfordian	<i>mariae</i> to <i>transversarium</i>
14	5	3	22	232	80.4	4.3	15.3		U. Oxfordian	<i>transversarium</i>
15	10	2	32	215	93.2	2.4	4.4		U. Oxfordian/ L. Kimmeridgian	<i>bimammatum</i> to <i>planula</i>
16	11	9	40	700	84	5.4	10.6		M./U. Kimmeridgian	<i>planula</i> to <i>eudoxa</i>
17	5–6	4	14	90	86.5	6.5	7	T	U. Kimmeridgian	<i>beckeri</i>

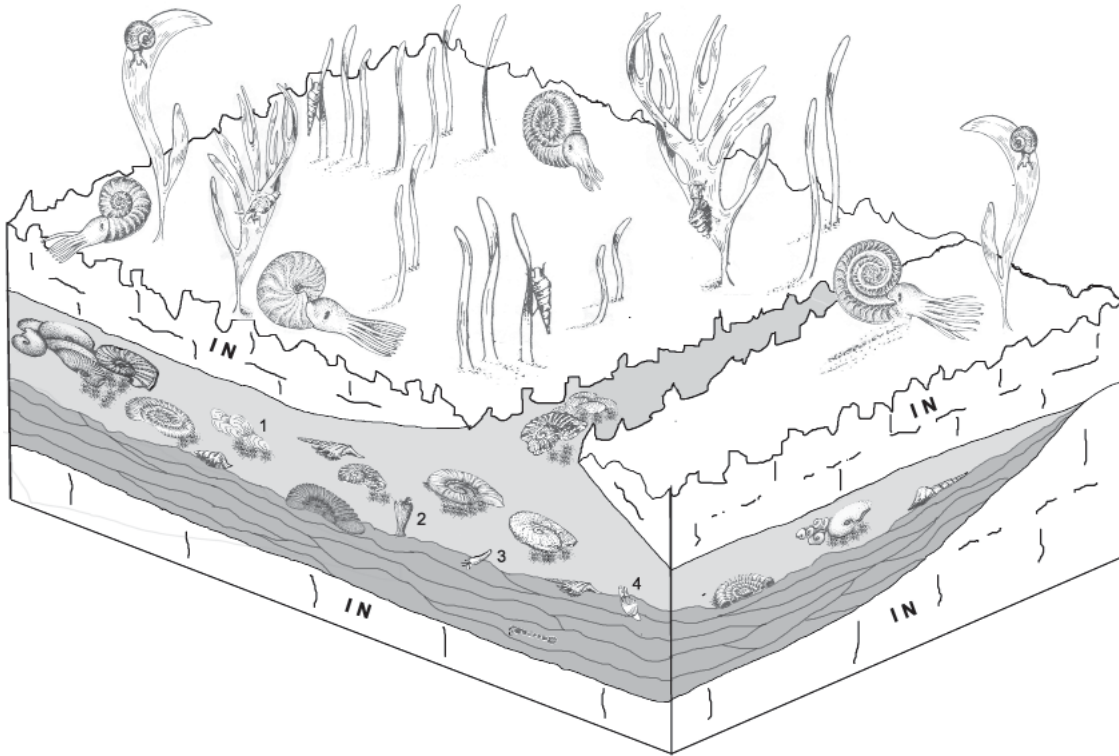
Table 4. Numerical composition of faunas 1–17 at Rocca Busambra based on 3877 generically and/or specifically determined ammonite and 2724 gastropod specimens. E = irregular echinoderms, P = pelecypods (nuculids only), S = scaphopods, T = trace fossils

herbivorous gastropods and a shelter for microconch ammonites. This bottom-dwelling fauna was swept into the nearby crevices and accumulated predominantly near the entrances of the sill system. A small portion was transported into more distant voids in which the percentage of shells diminishes increasingly. Local soft grounds of the sill sediment were settled by a sparse endobiotic fauna such as irregular echinoids, dentaliids, nuculids and burrowers. Hard- or firmgrounds served as a substrate for still rarer fixosessile organisms such as scleractinian corals (Text-fig. 8).

The clear relationships and the contemporaneity of the sill fauna with that of the normal sequence, however, remain rather enigmatic. It must be admitted that the normal fauna was not collected with the same meticulousness as the sill fauna. But it is obvious that, apart from ammonites, other invertebrate groups are largely underrepresented or lacking in the normal fauna. This observation is particularly striking for the gastropods which, next to ammonites, are the most diverse and numerous group in the sills but very rare in the normal fauna. Though comparisons between both faunas are possible only in the interval from the early Callovian to the late Kimmeridgian, the contrast of faunal compositions in these stages is evident. From this observation arises the question: whether or not one and the same

ammonite zone, represented in both faunas is, in a strict biostratigraphic sense, exactly coeval. The time resolution of the ammonite zonation, adopted in this paper, is about 1 m.y. per zone, time enough within such a long interval for repeated, but not precisely contemporaneous re-establishments of small-scale biotic environments. For example, the *bimammatum* Zone of the normal sequence must not be strictly contemporaneous to the same zone in the sills. This contradiction may be explained by a mere depositional difficulty: During times of highly condensed deposition on the sea floor, the entrances to the sills and dykes were probably completely sealed. When they were reopened and sill sedimentation continued, there should have been a hiatus in the normal sequence which, however, is impossible to detect. These repetitions have been demonstrated by the coincidence of tectonic pulses and onsets of new depositional phases on the sea floor (Text-fig. 6), but some of them must have occurred at time intervals that are too short to be distinguished biostratigraphically.

Systematic composition of the sill fauna: Details as to the abundance, preservation, composition, and palaeoecological significance of the sill fauna have been treated in Wendt (1971a, pp. 167–183). Here, only the most significant features are summarized.



Text-fig. 8. Palaeoecological reconstruction of entrance to neptunian sill at top of Inici Formation (IN). Most details of living and fossil organisms adopted and modified from McKerrow (1974). 1 = *Bositra*, 2 = scleractinian coral, 3 = *Dentalium*, 4 = nuculid pelecypod. Not to scale

Ammonoidea: This is the most common group (Tables 3, 4) of which the most typical representatives are shown on Plates 1–5. Much rarer than ammonoids are aptychi, which often do not correspond in size to the presumed equivalent ammonoid genera and thus are partly allochthonous. The most striking feature of the ammonite specimens is their small size (generally not exceeding 3 cm in diameter) and their excellent preservation. They have been analyzed in detail by Wendt (1971a) who, in comparison with conspecific/congeneric taxa, could demonstrate that a significant part, if not the majority, are microconchs. This interpretation is emphasized by the fact that about 15% of the shells are preserved complete with body chamber, i.e. they are certainly adult. But also those shells with only partially preserved body chamber (up to 60% within individual faunas) are probably microconchs as well. The excellent preservation of the shells is certainly the result of deposition in completely sheltered areas that were not affected by bottom currents and show almost no reworking. Moreover, a hitherto poorly known percentage of the ammonoids is stunted. This fact is rather difficult to verify and has been documented for three species only (*Hildoceras bifrons* Bruguière, *Calliphylloceras nilssoni* (Hébert)

and *Sutneria cyclodorsata* (Moesch)) by comparison of specimens from the sill fauna with conspecific microconchs from the central Apennines and the Swabian Jurassic. Some adult microconchs of *Sphaeroceras* in fauna 8 attain only 3 mm of end-diameter (Pl. 2/8B). Conspecific examples from the Trento Platform (Southern Alps, Italy) are three times larger (Sturani 1971, pl. 10, fig. 9) emphasizing that this genus from the neptunian sills is also stunted. I avoid further lengthy discussions about the causes of dwarfism, because it would imply endless and unproductive speculations. It should be noted, however, that some specimens of the sill faunas attain a more or less normal size (e.g. Pl. 4/14A, 15A; Pl. 5/16A, 16H) for which an allochthonous origin cannot be excluded.

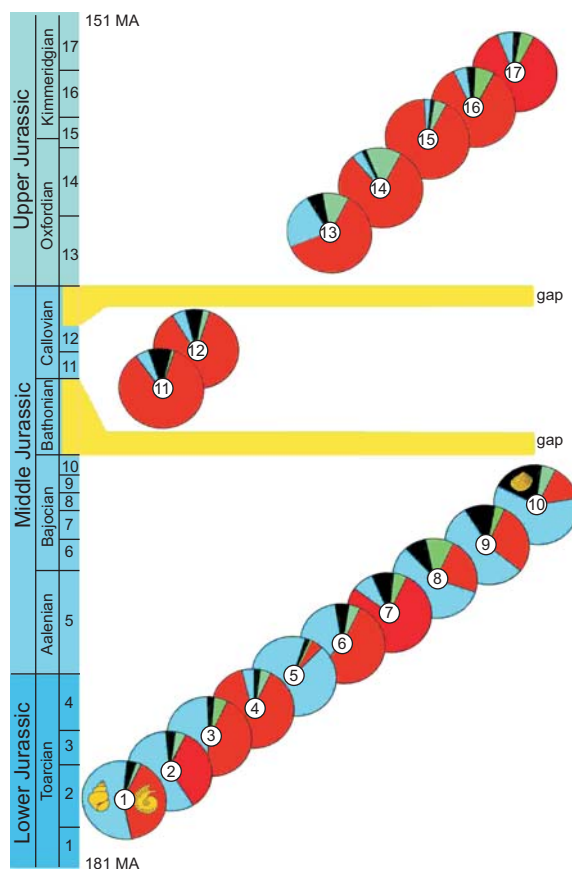
Nautiloidea: The few specimens are fragments of larger shells which are locally accumulated in one and the same place indicating an *in-situ* decay. Rhyncholites were only found in Oxfordian and Kimmeridgian faunas. Both groups seem normal-sized and are therefore considered as allochthonous.

Coleoidea: Belemnnoidea are a typical boreal faunal element, but rare in the Mediterranean Jurassic. Only 35 rostra and 3 epirostra were found, and surprisingly none in the Toarcian where there is a max-

imum of evolution in the boreal realm. In the sill faunas, belemnites made their first appearance in fauna 5 (Aalenian/lower Bajocian) from where one species of the rare genus *Rhabdobelus* was described by Weis *et al.* (2014). Faunas 6–8, 10, 14 and 16 have yielded only 14 fragments with distal parts of phragmocones of up 15 mm in diameter, suggesting that they were normal-sized and probably allochthonous. This interpretation is supported by the fact that in some levels of the normal sequence belemnites are rather common. *Atractites* is a survivor from the Triassic but still present in the Mediterranean Lower Jurassic. 28 phragmocones were found in faunas 1–3, 5, 15 and 16, among which the latter two occurrences are remarkable because they extend the hitherto known stratigraphic record of the genus into the late Kimmeridgian.

Gastropoda: Next to Ammonoidea, gastropods are the most common group, but the number of species and specimens varies considerably in individual faunas (Text-fig. 9, Table 4). A high percentage of the species is endemic (Conti *et al.* 2004). Apart from a short evolutionary study of some Trochoidea and Turbinoidea (Szabó *et al.* 1993), only one genus (*Discohelix*) among the Archaeogastropoda has been systematically described so far (Wendt 1968). The remaining material (about 2500 specimens) was entrusted in 1989 to A. Conti (Rome), S. Monari (Padova) and J. Szabó (Budapest) for a monographic study which in 2005 was almost completed (pers. comm.) but, regrettably enough, will probably never be published. These authors emphasized that this fauna is the richest ever recorded from the Jurassic of the western Tethys. The number of gastropod taxa tentatively determined by the present author up to 1971 is considerably enlarged by the still unfinished revision of S. Conti and collaborators and comprises 224 species among which 137 are new (Conti *et al.* 2004).

Pelecypoda: Their abundance ranges from 2.5 to about 10% of the total fauna. The unusual high percentage of 20% in fauna 10 can be explained by a significant sea level lowstand in the late Bajocian that is also emphasized by the contemporaneous increase in gastropod abundance (Text-fig. 9). The most frequent genus is *Bositra* (*Posidonia* auct.), which accumulated in some grainstone layers and on bedding planes. This pelagic pelecypod is also common in the normal sequence and therefore certainly allochthonous. Other genera are very rare and include either attached as well as burrowing forms. Together with Scaphopoda the latter indicate the presence of soft bottoms. Byssate genera (*Parallelodon*, *Modiolus*, *Inoceramus*, *Chlamys*, *Plagiostoma*) require the ex-



Text-fig. 9. Evolution of faunal composition in neptunian sills at Rocca Busambra from the lower Toarcian into the upper Kimmeridgian. Red = ammonites, blue = gastropods, black = pelecypods, green = remaining invertebrates. Note the two major gaps in the Bathonian/lower Callovian and in the uppermost Callovian

istence of firm- to hardgrounds and probably settled on the rocky sea floor near the entrances to the sills. With some reservation they are attributed to the parautochthonous fauna.

Brachiopoda: Compared to the normal fauna, brachiopods are underrepresented (up to 4%) or even lacking in the sill faunas. The observation that a high percentage of the specimens are univalved, indicates that they were transported over larger distances, i.e. they are an allochthonous faunal element. Complete specimens of *Pygope* are common to both normal and sill faunas in the Kimmeridgian, showing that also this genus is allochthonous.

Crinoidea: They constitute only a subordinate element of the sill fauna. Among isolated specimens only 5 fragments of thecae and 8 compound columnalia were found and generically determined. Their minute size (2–6 mm across) suggests that they are probably derived from a special habitat near the en-

trances to the sills, but it is uncertain whether they are juvenile or stunted. The more common crinoid debris found in some levels (attaining 5–10% of the skeletal grains) has probably been swept-in from more distant habitats.

Echinoidea: Compared to other occurrences in the Mediterranean Jurassic, the small size of complete coronae of both regular and irregular echinoids (up to 2 cm) in the sill faunas suggests a particular environment, i.e. they may largely be attributed to the parautochthonous fauna. In contrast, irregular echinoids (*Galeropygus*, *Collyrites*) are certainly autochthonous and indicate the occasional presence of softgrounds that did not exist on the open sea floor.

An exception is the occurrence of up to 5 cm long spines of cidarids, which are certainly derived from an extraneous (allochthonous) source.

Scleractinia: The origin and habitat of the 80 coral specimens found in almost all faunas is more difficult to interpret. The majority of them are ahermatypic, i.e. they must not have required clear photic conditions. Several specimens of *Caryophyllia* were autochthonous because two holdfasts were found attached to ammonite shells (i.e. *post-mortem*) and another to a thin Fe/Mn-encrusted hardground. Other ahermatypic corals are attached to conspecific skeletons, an observation which suggests a parautochthonous origin as well (Wendt 1971a, pl. 15, fig. 4). The few hermatypic genera (*Chomatoseris*, *Cladophyllia*, *Epistreptophylum*), all from the Upper Jurassic, have counterparts in the normal sequence and must have lived on the open sea floor. Features common to both groups are their small size and their generally perfect preservation, often with complete holdfasts. The sparse occurrence of hermatypic corals until the early Kimmeridgian must not necessarily indicate the permanence of photic conditions (Gill *et al.* 2004), particularly because the obvious decrease of herbivorous gastropods in the Late Jurassic emphasizes the deepening of the depositional environment.

Stratigraphy

The ammonite fauna of the Sicilian Jurassic has been described in the monumental work of Giorgio Gaetano Gemmellaro (1832–1904), which was carefully revised by Pavia and Cresta (2002). Although Gemmellaro's followers have largely built on this fundamental work by detailed biostratigraphic research with the exact attribution of genera and species to individual levels and ages, up to the present time it has not significantly been enlarged by new monographic palaeontological studies. The reason for this short-

coming is well known and unfortunately valid worldwide: Palaeontologists are a dying-out breed. Among others, this regrettable observation has also been realized and corroborated with numbers by Macleod (2014). Thus this paper can only give a brief overview of a unique fauna which was already known to Gemmellaro and De Gregorio but later fell into oblivion. Plates 1–5 illustrate this ammonite fauna and its unusual preservation and diversity.

The faunal composition of units 1–17 is summarized in Table 4. This biostratigraphic subdivision of the most complete, 70 cm thick sill (combined from sections RB 2, 3 and 18) is merely accidental and depends mainly on natural surfaces along which the massive rock could be split into bedding-parallel slices. The detailed composition of the invertebrate faunas of the sills is listed in Wendt (1971a, pp. 153–163). Additional material has been collected during later years. The individual ages of the units are indicated on Plates 1–5.

Base: The base of the sills is more or less planar, i.e. parallel to the bedding planes of the underlying white peritidal limestones (Inici Formation), but locally undulated at a cm-scale. Rare brecciation at the base exhibits “frozen” tectonic movements, as is displayed by the good fitting together of the clasts (so-called *in-situ*-breccias, Text-fig. 4A, B).

Unit 1: Individual levels wedge out laterally after a few centimetres, an observation which is valid also for the overlying units. They show oblique, intermitted bedding, sub-parallel to the morphology of the base. The top layer is an iron-stained erosional surface indicating a break in sedimentation. The ammonite fauna is dominated by Phylloceratida and Hildoceratidae (subfamilies Harpoceratinae and Hildoceratinae) and, to a lesser degree, by Lytoceratida. The finding of *Onychoceras multicoatum* Renz is surprising because this species has been known only from the upper Toarcian.

Unit 2: Only in one section could this unit be separated from the underlying one. Semi-lithified and iron-stained pebbles in the lowermost layer indicate slight water movement. The composition of the ammonite fauna is similar to and only a little younger than fauna 1.

Unit 3: The middle one of the three levels is thickest and appears to have been deposited rather rapidly. In contrast to the under- and overlying beds it contains some crinoid debris. The ammonite fauna is almost contemporaneous with fauna 2. Common to faunas 1–3 is the very low number of Dactylioceratinae. The archaeogastropod genus *Discohelix* displays the highest number of species and specimens in faunas 1–3.

Unit 4: The two levels are separated by a knobby surface indicating a minor stratigraphic gap. With only 28 ammonite species, fauna 4 is one of the poorest ones with respect to the number of specimens. Phylloceratida are relatively rare, but Lytoceratida are more common than previously. *Pleydellia aalensis* (Reinecke) and *Pseudolioceras wunstorfi* (Monestier) account for over 50 % of the ammonite fauna. The remarkable find of a small (1.5 cm across) irregular echinoid (*Galeropygus priscus* Cotteau) indicates the presence of temporary soft grounds in the sill.

Unit 5: Comprising 7 ammonite zones (*opalinum* to *propinquans* Zone) in 2 cm of thickness, this is the most condensed unit of the entire section. This is not as surprising as it appears, because also in other "normal" sequences of pelagic plateau areas in Sicily and elsewhere in the Tethyan Jurassic (e.g. Southern Alps, northern Morocco) the lower Bajocian is also extremely condensed (compare Table 1). Up to 5 levels can be vaguely recognized in this unit that, as with the previous and subsequent ones, can be laterally followed over short distances only.

Unit 6: The topmost level is a faint iron-stained omission surface. The ammonite fauna is relatively poor and can be attributed to the *sowerbyi* to *propinquans* Zone, i.e. it is partly coeval with the preceding unit from which it can barely be separated.

Unit 7: The 4 levels are separated by faint intervening omission surfaces in between. Only the lower one has yielded a sufficient number of ammonite species that still belong to the *propinquans* Zone. One centimetre higher up, three species of *Chondroceras* document the *humphresianum* Zone.

Unit 8: The few ammonites gathered from this unit are remarkably small and can hardly be determined specifically. They can be attributed to the *humphresianum* Zone and show strong affinities to the partly contemporaneous fauna described by Sturani (1971) from the Trento Plateau in northern Italy (see below). The top of this unit is an irregular iron-stained omission surface.

Unit 9: The weak intermittent syn-sedimentary tectonics is evidenced by an oblique normal fault (Text-fig. 7D). The bulk of the sparse ammonite fauna is concentrated in a 1-cm-thick level at the top containing many uncoiled specimens of *Spiroceras* and *Apsorroceras*, which probably mark the boundary between the *humphresianum* and the *niortense* Zone. The very peculiar microconch of *Dimorphinites* (*Vigoriceras*) *centriglobus* Rioult with a gastropod-like siphon (Pl. 3/9B) indicates the *parkinsoni* Zone, showing that faunas 9 and 10 overlap.

Unit 10: Less complete equivalents of this fauna

have been found in only 2 other sections. The base is a minor gap illustrated by a slight change in colour and the corroded top of unit 9. The basal and upper levels are most fossiliferous and represent the *niortense* and *parkinsoni* Zone of the middle and upper Bajocian, but the *garantiana* Zone has not been clearly documented. The top of the unit is the most significant hiatus in the entire sequence, which is marked by a 1 mm thick ferromanganese crust and the total absence of Bathonian deposits. Equivalents of this stage have only been found in the normal sequence and in dykes but nowhere in the sills. Therefore, this gap in the sill sequence must be interpreted that during or at the end of the *parkinsoni* Zone the sill was completely filled up to the roof. At that time the ferromanganese crust and the subsequent onset of normal sedimentation on the sea floor had completely sealed all the entrances into the neptunian sill system.

Unit 11: Because this unit consists of one level only it appears to have been deposited rather rapidly. The ammonite fauna is represented by very small juvenile specimens that rarely can be determined specifically. Their attribution to the lower Callovian is in accordance with fauna 12, which has the same age. At this time, the sills were reopened raising the question, however, why this movement affected only the top, thus continuing the seemingly concordant deposition in the sills, and not somewhere deeper. One can only speculate that this was the weakest (less lithified) level, which was most susceptible for a renewed reopening of the sills. Although the *macrocephalus* Zone of the lower Callovian is documented not only in the sills but also in the normal sequence, both faunas do not appear exactly time-equivalent. This fact leads to the assumption that sill-fauna 11 corresponds to a gap in the normal sequence that cannot exactly be encompassed biostratigraphically.

Unit 12: As with the preceding case, this unit also consists of only one level. The sparse ammonite fauna is dominated by spiroceratids that document the *macrocephalus* Zone of the lower Callovian. The top is another important hiatus marked by a 1–2 mm-thick calcitic vein and the total lack of middle to upper Callovian deposits. It must be concluded that at this time the sill was again completely filled up to the top and that the openings to the sea floor were closed, so that no calcareous mud could infiltrate the sill.

Unit 13: The upper 3 levels exhibit several discontinuity phenomena such as lateral onlap, ferromanganese staining and reworking. The relatively poor ammonite fauna was collected in the lowermost 1–2 cm thick level, which can be attributed to the *cordatum* Zone of the lower Oxfordian. A finding of

Creniceras dentatum (Oppel non Bruguière) in the uppermost level indicates that this unit comprises also the upper Oxfordian (*transversarium* Zone). A subsequent 0.5 cm thick, composite sediment-calcite sill (S in Pl. 4) of unknown age marks the boundary with unit 14. It cuts a sedimentary dyke that penetrates some centimetres into the underlying level, showing that the boundary between units 13 and 14 is a hiatus of unknown duration.

Unit 14: The rich ammonite fauna collected in the lower, 2-cm-thick level (Pl. 4) is essentially the same as that described by Christ (1960), which herewith can be attributed to its exact stratigraphic horizon. Its age is not much different from that of fauna 13 (*transversarium* Zone), but should represent the upper part of the zone. It is overlain by a 3-cm-thick level of *Bositra*/crinoid grainstone that has not yielded any ammonites. This lithology is rare in the fossiliferous neptunian sills, but has been observed also in lower sill stockworks that do not contain any ammonites. It documents a rapid deposition of skeletal debris probably derived from temporary crinoid meadows on the sea floor. In this context, it should be borne in mind that since unit 11, deposition took place in both environments, i.e. on the open marine sea floor and in the poorly accessible neptunian sills. This fact gives rise to a question that is difficult to answer: Why the sills were not rapidly filled with sediment that was now available at the sea floor? As mentioned above, one can only speculate that deposition within the sills corresponds to equivalent gaps in the normal sequence and that the sills were repeatedly reopened on the top of the last layer. This intermittent sedimentation and the coeval tectonic pulses must have occurred during time spans that were too short to be detected biostratigraphically. In this context, it is noteworthy that the top of unit 14 is a sharp boundary indicating another gap of uncertain duration.

Unit 15: The lower level is a grain- to wackestone with fine-grained shell and Mn/Fe-stained debris that appears to have been deposited rather rapidly. It contains only few biostratigraphically diagnostic remains among which *Amoebopeltoceras berrense* (Favre) is most common (Pl. 4/15C). The upper level is very rich in ammonites (Text-fig. 4F) of which some (e.g. *Sutneria cyclo dorsata* (Moesch), Pl. 4/15G) reveal that this level is extremely condensed and probably comprises also the middle Kimmeridgian. The top shows a ragged microrelief of mm-scale indicating another hiatus.

Unit 16: This unit has yielded the most abundant and diverse ammonite fauna of the entire section (Pl. 5/16). Unfortunately it could not be split manu-

ally into individual levels, of which up to 9 can be distinguished in polished slabs. Its age ranges from the *acanthicum*- into the lower *beckeri* Zone of the middle to late Kimmeridgian. A remarkable finding is a specimen of *Cymaceras gümbeli* (Oppel), a genus that is not known from other places in the Mediterranean Jurassic (Pl. 5/16J).

Unit 17: The lower part can be easily distinguished by its pink to pale-grey colour and the presence of numerous furoid burrows (Text-fig. 7F) that do not occur in the underlying units. It contains numerous small-sized, mostly fragmentary ammonites with yellow-stained shells that represent the youngest sill fauna. The overlying levels are dark pink or yellowish in colour and did not yield any shell remains. The top is generally marked by a thin calcitic crust that fills the remaining space beneath the enclosing Sinemurian/lowermost Pliensbachian peritidal limestone of the Inici Formation (Pl. 5).

Faunal assemblage trends and environment

The proportional composition of the individual faunas, based on the number of specimens, and their variation from the early Toarcian into the late Kimmeridgian is illustrated in Text-figure 9. The 17 faunas are clearly dominated by ammonoids and gastropods, but their individual composition does not show an unequivocal trend. Faunas 1–3 are rather similar with a slight dominance of gastropods over ammonoids. However, this pattern is completely reversed in fauna 4, which is distinguished by a 95% dominance of ammonoids. The boundary between the two levels (Pl. 1) is an undulating brown iron-stained surface with microborings and thus represents a gap that cannot be more precisely calibrated biostratigraphically. Still more surprising is another total reversal of the percentage of both groups in the subsequent fauna 5. And in this case there is no sharp boundary between the two fossiliferous levels. Faunas 6 and 7 show again an increasing percentage of ammonoids (Text-fig. 9), but this trend is once more reversed in faunas 8–10. Indeed, equivalent boundaries in the rock column show minor depositional gaps (Pl. 3). With faunas 11 and 12 the predominance of ammonoids over gastropods and other benthic organisms becomes more and more evident (Text-fig. 9).

What is the reason for these contrasting patterns of the faunal composition? The most plausible explanation is related to oscillations of sea level. Most of the gastropods were herbivorous and thus depended on the existence of sea grass meadows on the sea floor, even if these did not leave any fossil record.

The total absence of calcareous algae in the entire sequence is not an argument against a luxuriant vegetation on a rocky, current-swept sea floor. One could even apply this speculation to the unusual ammonite faunas: Did these microconchs find a suitable shelter in these rampant sea grass meadows? A similar model was favored by Sturani (1971, p. 46) for the Bajocian microconch ammonoid faunas near Asiago (Trento Platform, northern Italy). However, I cannot go so far in my speculations about the palaeoenvironment of the Sicilian sill faunas as Aubrecht and Schlögl (2011), who concluded that a similar fauna collected from neptunian dykes and sills in the western Carpathians was “troglobite”, i.e. that these organisms essentially lived in these narrow and dark habitats. For me it is difficult to imagine that small-sized ammonites swam in narrow fissures that were barely wider than the animals themselves (if not horizontally – but this is not a serious alternative model). Moreover, the two authors contradict themselves writing that “the empty shells were most probably swept by bottom currents”, and a few lines below that the dykes contain an “autochthonous cave fauna” of “small ammonites” (and others). Recent submarine caves have been extensively studied by Riedl (1966) who reported a highly diverse fauna from these environments. But it consists essentially of attached organisms, and these are virtually lacking in neptunian dykes and sills, not only at Rocca Busambra but also in comparable occurrences.

The depositional environment of the sills is a closely spaced sequence of hardgrounds that offered only very scarce habitats for some microborers and burrowers. But local temporary soft grounds must have existed, otherwise the rare records of small scaphopods, burrowing pelecypods (e.g. *Nucula*, *Cuspidaria*, *Pleuromya*) and irregular echinoids (*Galeropygus*, *Collyrites*) cannot be explained. The sparse, also small-sized hard- or firm-ground fauna (byssate pelecypods, regular echinoids, crinoids) probably settled on the rocky crevices near the sea floor and, from the Callovian onwards, also on the current-swept sea floor. In this context, it is surprising that crinoid remains are only a minor constituent of the sill fauna. In the normal sequence of the Upper Jurassic, however, crinoids flourished, as can be deduced from the common crinoid wacke- and packstones.

Sea level changes

I am not aware of any published sea level curve for the Jurassic of Sicily. Di Stefano and Mindszenty

(2000, fig. 16) have sketched major sea level changes in a series of cartoons from Monte Kumeta, which are deduced from significant depositional features. A critical point in this paleobathymetric sequence is the still uncertain biostratigraphic position of the so-called crinoidal limestones, capping the Inici Formation in some places, which may be late Pliensbachian (Domerian) in age (see above). Probably they represent a local and short marine incursion whose deposits were subsequently again uplifted and eroded. This is perfectly shown at Monte Kumeta (Di Stefano and Mindszenty 2000) and at Rocca Busambra (Basilone 2009). The overall abrupt termination of the Inici carbonate platform was caused by uplift above sea level and widespread karstification during the early Pliensbachian. This fall of sea level corresponds well to the curves of Hallam (1988) and Haq *et al.* (1988). The transgression (highstand) during the early Toarcian (*serpentinum* Zone) is a global phenomenon, partly associated with an oceanic anoxic event (Jenkyns 1988; Hallam 1988, 2001; Elmi 1990; Woodfine *et al.* 2008; Sabatino *et al.* 2009). Even if deposits of this age are rare in western Sicily, either on the sea floor or in neptunian sills, it is evident that drowning was contemporaneous in the Trapanese and Saccense Domains, though the gap between the termination of shallow platform growth and the latest onset of pelagic sedimentation in the early Bathonian is generally much larger (Table 2). In some parts of the Trapanese and Saccense Domain it comprises the entire Liassic and the uppermost Triassic (Wendt 1963; Basilone 2011). The contrasting patterns in the ammonoid/gastropod distribution since the early Toarcian, documented in the sill-sequence of Rocca Busambra (Text-fig. 9), are probably also related sea level oscillations. They exhibit three lowstands: late Toarcian, early Aalenian and Bajocian (Text-fig. 6), which are well expressed in Hallam's (1988) curve and have also been documented in the Subalpine Basin in southern France (Elmi 1990), but appear less distinct in Haq's *et al.* (1988) curve. After the late Bajocian/early Bathonian transgression sea level remained virtually constant. It is only interrupted by a short shallowing interval during the middle Oxfordian, as can be deduced from a slight increase of gastropod abundance (Text-fig. 9). The latter may be coeval to a similar one in Hallam's (1988) curve. Another rise of sea level is evident all over the western Mediterranean in the middle Tithonian, marked by a rather sudden onset of fine-grained mudstones (Lattimusa, Biancone, Maiolica) with a pelagic microfauna dominated by calpionellids (Basilone 2012, p. 60). Apart from the lower Toarcian, a correlation between major tectonic

pulses and sea level highstands, however, is not clearly expressed.

These coincidences of sea level oscillations between Rocca Busambra and the global curves of Haq *et al.* (1988) and Hallam (1988) suggest that the Sicilian example is more than a local (tectonic) phenomenon, even if comparable data from other places in Sicily are not available so far. In this respect it should be noted that the drowning succession (Zempolich 1993) and the “local” sea level curve from the Trento Platform (Southern Alps, Italy, Cobianchi and Picotti 2001) display a similar pattern.

COMPARISONS

Fossiliferous neptunian sills rare in the geological record and none can compete with those from Rocca Busambra regarding the wealth of palaeontological and depositional information. But there are some comparable occurrences worth mentioning that shed additional light on this unique type of “Fossilagerstätten”.

Palaeozoic

Kurdistan (Iraq): Vašiček (1988) described a fauna of small ammonites from the upper Permian of Kurdistan, which in size and preservation resemble very much the Rocca Busambra sill faunas. Though stratigraphic and sedimentologic data from this area are not available, the lithology (brownish mudstone) and the presence of blocky calcite surrounding the shells in the upper part of the fossiliferous level clearly show that they had been entombed in a sheltered environment, i.e. in neptunian sills or dykes.

Neptunian sills have also been mentioned from the Devonian of the Canning Basin in Western Australia (Playford 1984), but they do not contain any shell remains and therefore cannot be dated.

Triassic

Bosnia: The Middle/Late Triassic tectono-sedimentary evolution of the external Dinarids bears striking resemblances to the Jurassic of western Sicily. It reflects a similar breakup and subsequent drowning of a large carbonate platform or ramp accompanied by intense submarine volcanism, in this case due to the opening of the Neotethys Ocean (Gawlik *et al.* 2012). The upper metres of the lower Anisian platform carbonates are crisscrossed by numerous neptunian dykes, which are filled with red fossiliferous

(mainly brachiopods and ammonites) mudstones. The platform carbonates are disconformably overlain by pelagic red, condensed cephalopod limestones (Bulog Formation, Hallstatt facies) and radiolarites of late Anisian to late Carnian age. In the vicinity of Sarajewo several very fossiliferous neptunian sills have been discovered (Wendt 1973), which occur either near the top of the platform carbonates (Haliluci near the type locality of Han Bulog) or are intercalated in the upper Carnian (Julian) Bulog limestones (Mount Trebevic). In the latter locality, the most complete sill is 2–5 cm thick and consists of 5 levels that pinch out laterally over short distances. The uppermost level contains numerous tiny ammonites, some with partly preserved body chambers (microconchs or stunted?) that are cemented by clear calcite. In contrast to the lower levels, deposition was rapid in the top level and the shells were obviously swept in by storms. Such a process is inferred from the chaotic, often imbricated orientation of the shells and the absence of calcareous ooze (Text-fig. 10A–C). Later tectonic fragmentation in this locality has precluded a more precise observation of the lateral extent of the sill. The minimal size of the ammonites cannot be a sieving effect because the opening of the sill is rather large (Text-fig. 10A). Its precise age could not be determined, but it must be younger than late Carnian. The neptunian sills near Haliluci a few centimetres below the top of the platform carbonates are probably older. These discoveries reveal the activity of previously unknown syndimentary extensional tectonic driving forces whose influence on the condensed deposition of the Hallstatt facies remains to be elucidated.

Greece: On the island of Hydra a similar palaeogeographic and stratigraphic situation as in Bosnia is exposed in several thrust sheets. Upper Scythian/lower Anisian peritidal platform carbonates of the Eros Limestone are unconformably overlain (often angular) by a few metres of condensed upper Anisian (Illyrian) cephalopod limestones which are also named Bulog Limestone. The upper tens of metres of the Eros Limestone are crisscrossed by numerous neptunian dykes filled with red mudstones, in particular in the tectonic unit of the Marina zone (Wendt 1973). Some of them run parallel to the bedding of the encasing platform limestones and generally do not contain any shell remains, but some are laminated and crowded with tiny gastropods. Future research will probably discover also ammonite bearing sills.

Northern Calcareous Alps: It has long been known that the highly fossiliferous Middle/Upper Triassic



Text-fig. 10. A. Neptunian sill in the upper Carnian Bulog Limestone of Mount Trebevic (Sarajewo, Bosnia) with preserved remnants of floor and roof (arrowed), opened along a hardground. Entrance to sill is visible in upper left. Scale bar = 2 cm. B. Polished bedding-parallel slab of C, crowded with tiny ammonites. Scale bar = 2 cm. C. Close-up of uppermost level of A. Note imbricated shells typical for storm deposits. Scale bar = 1 cm

Hallstatt limestones of the Salzkammergut and Styria in Austria were not only deposited as condensed levels on the sea floor but also in neptunian dykes and sills (Schlager 1969; Krystyn *et al.* 1971; and others). The submarine fissures were created by syndimentary tectonics, but the accumulation of shells in these voids, unlike as on Rocca Busambra, appears as a rather rapid and not recurrent process. On the other side the occasionally mentioned predominance of gastropods and small ammonites in the Hallstatt examples bears strong resemblance to the fossiliferous sills described in the present paper.

From Rappoltstein near Berchtesgaden (S-Germany) Hornung *et al.* (2007) described lower Carnian ammonites which, at a very low sedimentation rate (about 0.7 m.y., Table 1), were accumulated by currents in neptunian sills. In contrast to the above-mentioned examples, the fauna appears normal-sized and of a low diversity.

Jurassic

Western Sicily: Rocca Drago: Cecca and Pochettino (2000) and Martire *et al.* (2002) have listed a rich fauna of well-preserved ammonites from a 20 cm thick neptunian sill. Microfacies, small size of the specimens, interpreted as a predominance of microconchs, excellent preservation and the accompanying gastropods show surprising similarities to the sill fauna of the nearby Rocca Busambra. In contrast, deposition within the sills at Rocca Drago appears to have been a relatively short process, which represents an interval of only one or two zones of the lower Kimmeridgian.

Monte Maranfusa: Sulli and Interbartolo (2016) found two neptunian sills in this locality 10 km west of Rocca Drago. They are 10–15 thick and occur 7 m and 13 m below the top of the Inici Formation. Due to their considerable depth below the sea floor their

fossil content is poor (*Bositra*, foraminifera, crinoids, tiny ammonites) allowing only a vague dating as late Lias/Dogger.

Montagna Grande (Sicily): Several generations of neptunian sills were described by Martire and Pavia (2004) at Poggio Roccione (part of Montagna Grande). They are mostly filled with calcite, but some could be dated by ammonites as middle Oxfordian and by calpionellids as late Tithonian/early Berriasian, thus indicating short-timed tectonic pulses as on Rocca Busambra.

Monte Barbaro near Segesta (Sicily): Christ (1960) listed a fauna of ammonoids of Oxfordian age that closely matches those from the Rocca Busambra sills. The description of the outcrop is somewhat obscure and does not allow any information about their provenance. But the good preservation, the small size of the specimens and the brownish coating indicate that they were accumulated in neptunian dykes (Jenkyns 1970a and own observations). This must have been a very rapid process representing a short interval within one ammonoid zone. The fauna had not been collected by the author himself but was purchased from the late Giuseppe Bonafede (pers. comm. 1959) who at that time was the retired housekeeper of the Geological Institute of Palermo and who, as a boy, had still accompanied Giorgio Gaetano Gemmellaro into the field.

Bellolampo near Palermo (Sicily): Wendt (1971a, p. 186) listed a Domerian ammonite fauna from a grey laminated neptunian sill 2 m below the top of the Lower Liassic peritidal limestones. Because it consists essentially of 2 or 3 species of *Juraphyllites* only, the stratigraphic message is poor, but it supports the interpretation of an uplift of parts of the Panormide platform in the early Pliensbachian and the subsequent drowning.

Eastern Sicily: Taormina: The complicated stratigraphic and tectonic structure of the Longi-Gallodoro unit, to which the small promontory of Capo S. Andrea near Taormina belongs, was deciphered by Truillet (1969–70), Schmidt (1980), Lentini and Carbone (2014, pp. 228–230) and others. The presence of 3–15 cm thick neptunian sills, intercalated in thick-bedded lower Liassic peritidal limestones, was first recognized by Sigal and Truillet (1966). On the basis of foraminifera (protoglobigerinids), these authors could attribute their age only roughly to the Dogger-Malm. Their record of “embryos of ammonites and gastropods”, however, arouses suspicion that this is the place from which G. Seguenza (1887a, b) had listed a rich ammonite fauna (37 species) of Bajocian age. Sturani (1967)

assigned it to the *subfurcatum* Zone and emphasized the small size of the ammonites, among which common spiroceratids are an unusual faunal element. These fragile, open-coiled shells could only be well preserved in sheltered areas such as neptunian sills. To one’s surprise, this important fauna collected by Giuseppe Seguenza was never studied in detail later, which suggests that it was destroyed by the terrible earthquake of Messina in 1908. Additional remarks regarding the fauna were made by Luigi Seguenza (1900), the son of Giuseppe Seguenza, who tragically died, only 31 years old, in the same earthquake. Truillet (1970) dated 10 generations of dykes from the Early Liassic into the Palaeocene, among which are four Late Cretaceous sills, but Sarti *et al.* (2000) could distinguish only four generations of late Liassic to Late Cretaceous age.

Trento Platform (northern Italy): Sturani (1971) published an important work on Bajocian ammonites from the Trento Plateau which in composition, preservation and size match the Busambra fauna so closely that one would automatically attribute them to neptunian sills. However, according to the author these shells were accumulated in small crevices in the host rock, which were created by karstification and subaerial brecciation. He also outlined a convincingly new idea of the palaeoenvironment which he visualized as a rocky sea floor covered by algal meadows. In each of the localities studied by Sturani, the biostratigraphic range of the individual faunas comprises only one zone each of the Bajocian (*humphresianum*, *subfurcatum* and *garantiana* Zone) showing that the accumulation of shells was a repeated, but more or less rapid depositional process. The different ages of ammonite faunas accumulated in the crevices must preclude at least three phases of uplift and karstification during the Bajocian, a conclusion that had not been treated sufficiently by Sturani. A personal visit of the outcrops has fully confirmed Sturani’s meticulous work and interpretations. A summary of Sturani’s (1971) work can be found in Clari and Pavia (2002).

All the more surprising is a different explanation for the formation of the crevices proposed by Winterer *et al.* (1991). These authors attribute the minute fissures, dykes and sills to “gravity-driven slides and slumps of semi-brittle platform strata commonly along décollement contacts between layers of different competence”. This interpretation can hardly be reconciled with Sturani’s detailed observations and for several reasons is contradictory in itself: (1) It is difficult to imagine, how semi-lithified lay-

ers of limestone, capable of slumping and sliding, were able to retain open spaces after their gravitational displacement, in particular within the upper 1–2 metres which should be the most plastic levels. (2) The subaerial karstification and weathering of the surface of the underlying Domerian/Toarcian limestones was convincingly demonstrated by Sturani. Thus, the marginal minute prism cracks of the breccia clasts figured by Sturani (1971, figs 6, 7, 12, 14) can only be a result of the action of meteoric waters (Schöll and Wendt 1971, fig. 3). Their subsequent filling by clear calcite is, of course, a submarine process. (3) Between the top of the underlying host rock (Domerian or Toarcian) and the infilling of the fissures is a hiatus that lasted at least 5 m.y., sufficient time for a total lithification of the former. (4) The accumulation of small (microconch) ammonites is not the result of mechanical sorting, but reflects a particular environment. By the way, Sturani would never have formulated the idea that the “filling of the cavities took place in subaerial conditions” (Winterer *et al.* 1991, p. 390). To conclude, it is reassuring to confirm that in his epochal work Sturani, one of Italy’s most talented geologists in the second half of the 20th century, left an unequivocal memory of his restless activity that tragically ended at the age of 37 during field work on the Messinian. Neptunian dykes and laminated sills in the vicinity of Sturani’s famous localities were later described by Martire (1996), but apparently they do not contain any ammonites.

In the western Lessini Mountains N of Verona (southern Trento Plateau) Benetti *et al.* (1990) found a remarkable, condensed ammonite fauna of early to middle Kimmeridgian age in a 0.2 to 0.8 m thick neptunian sill which is overlain by Bajocian Rosso Ammonitico nodular limestones. Most of the specimens are small-sized (probably microconchs) and well preserved. In composition and age this fauna resembles fauna 16 of Rocca Busambra.

Northern Calcareous Alps: In the Sonnwendgebirge east of Innsbruck (Austria) a great variety of neptunian sills, intercalated in the upper metres of Upper Triassic peritidal platform carbonates, was discovered by Wendt (1969a). They are generally finely laminated and, apart from fragmentary large ammonites, contain mostly small-sized and well-preserved specimens and many gastropods. The sills were rather rapidly filled as can be concluded from their individual age that comprises only short time spans each, ranging from the Sinemurian into the late Toarcian. Moreover, they document a repeated tectonic activity during the Liassic which was pre-

viously unknown. Similar phenomena have been reported from other places in the Northern Calcareous Alps (e.g. Schöll and Wendt 1971).

Western Carpathians (Slovakia): Schlögl *et al.* (2009) and Aubrecht and Schlögl (2011) described neptunian dykes and sills (unfortunately not clearly distinguished from one another) of late Bathonian to Tithonian age, which are characterized by highly diverse invertebrate faunas. Their typical feature is the predominance of microconch ammonoids, which are interpreted as cave dwellers. Without sharing this opinion (see above) it is evident that some of them are derived from neptunian sills, whereas the accompanying fixosessile fauna (scleroforaminifera corals, serpulids, sponges, crinoids, sessile foraminifera) probably settled in near-surface crevices.

Southern Spain: A great variety of fossiliferous neptunian sills were observed in the Jurassic of the Subbetic Zone (references in Vera *et al.* 1988) ranging in age from the early Domerian into the Oxfordian. Without adding new biostratigraphic data, the formation of the sills and dykes was comprehensively discussed by Winterer *et al.* (1994). Their different opinion on the palaeotectonic occurrence and the formation of these features was already rejected above.

England: From South England (Dorset and Wessex Basin in Somerset) Jenkyns and Senior (1991) and Wall and Jenkyns (2004) described two of the few occurrences of fossiliferous neptunian sills known from the boreal realm. Both are related to coeval condensed deposits on the sea floor and document various phases of synsedimentary faulting during the Early and Middle Jurassic. Individual sills, close to palaeo-faults, were dated by ammonites as Toarcian (*bifrons* to *thouarsense* Zone) and Bajocian (*garantiana* Zone). The fine-grained sill sediment, being graded and cross-bedded, was apparently sucked into older, lithified deposits by injection during submarine faulting, thus indicating that the filling of the voids was a very rapid process.

Cretaceous

Spain: Fossiliferous neptunian dykes and sills, clearly connected with reduced sedimentation on the sea floor, are common in the Lower Cretaceous of SE-Spain, but apparently they have not yet awakened more than local interest. Seyfried (1978, pp. 39, 117) mentioned upper Berriasian/Barremian ammonites from neptunian sills

in the Betic Cordillera, but details about the preservation, composition and environment of the faunas and the geometry of the voids are lacking.

Sicily: A totally different type of neptunian sills of Late Cretaceous age was observed at Capo S. Andrea near Taormina (NE-Sicily; Sigal and Truillet 1966) and at Rocca Busambra. They are only a few centimetres thick, finely laminated and, apart from numerous benthonic and planktonic foraminifera, do not contain any other skeletal remains. At Capo San Andrea, these sills are intercalated in thick-bedded Middle/Upper Jurassic *Bositra* limestones (Rosso Ammonitico), and were interpreted by Sarti *et al.* (2000) as microturbidites. Because the corresponding normal deposits (pelagic mudstones of the so-called Scaglia or Amerillo Formation) are not condensed, the infilling of the sills must have been a very rapid process representing only a short interval of one foraminiferal zone. Therefore a more feasible depositional interpretation of the obvious graded bedding is that the laminae are the result of frequent storms that repeatedly swept the foraminifera into the small openings of a previously formed tectonic fissure system. Thus, the fissure fillings can be considered as distal graded rhythmites or tempestites rather than as microturbidites (pers. comm. T. Aigner, Tübingen). The same interpretation must be applied to the very similar sills at Rocca Busambra that are intercalated in the peritidal limestones of the uppermost Inici Formation.

This short review of comparable occurrences is far from being complete, but it shows that neptunian sills are an underestimated source of immense palaeontological and tectonic information. They allow a much more precise dating of synsedimentary movements than can be achieved by tectonic and depositional criteria only. Though the above-mentioned examples are essentially known from the Mesozoic, fossiliferous neptunian sills should also be found in similar palaeogeographic settings in the Palaeozoic.

CONCLUSIONS

(1) Stratigraphic condensation is the result of extremely reduced sedimentation on the sea floor interacting with current-induced reworking and chemical solution. The preservation lower limit of these processes is about 0.1 m/m.y., but this value can be surpassed by one or two orders of magnitude in neptunian sills.

(2) The normal sequence of the Jurassic in western Sicily is typical for drowned platforms. It starts with

rapidly deposited peritidal platform carbonates in the early Liassic (Hettangian to earliest Pliensbachian), which are capped by a characteristic erosional unconformity. The latter shows evidence of uplift above sea level and subaerial karstification. This erosional surface is disconformably covered by a diachronous ferromanganese crust and overlain by pelagic condensed Toarcian to Upper Jurassic bioclastic wacke- or packstones which show a deepening-upwards trend. Available data indicate that the flooding of the platform occurred earlier in some parts of the Panormide than in Trapanese-Saccense Domain, thus indicating a northward tilting of the former.

(3) On the western termination of Rocca Busambra an intricate network of Jurassic neptunian dykes and sills is exposed. The most fossiliferous sills are intercalated in the uppermost 1–2 metres of the lower Liassic peritidal limestones of the Inici Formation and host the most abundant and diverse ammonoid and gastropod fauna which has ever been recorded from a single place in the Jurassic of the western Tethys.

(4) Formation of the neptunian sills and dykes was caused by tensional movements as an effect of the early breakup of Gondwana. Among these well-known tectonic movements during the Jurassic, 15 pulses could be biostratigraphically dated, ranging in age from the early Pliensbachian into the Tithonian. The earliest movements are recorded only on the Panormide platform. Additional minor movements during the Jurassic are documented within the sills by depositional features such as erosional surfaces, discontinuities and reworking. Later tectonic pulses occurred from the Late Cretaceous into the Miocene.

(5) The neptunian sills at Rocca Busambra are the result of an interaction of three concomitant processes: (a) extreme biostratigraphic condensation or omission on the sea floor, (b) opening of near-surface bedding-parallel cracks in the underlying peritidal platform carbonates and (c) continuing synsedimentary tectonics causing repeated openings on top of the sedimentary infillings.

(6) The stratigraphic record of the most complete sill encompasses the interval from the early Toarcian to the late Kimmeridgian (30 m.y.) in up to one metre in thickness. This strongly condensed sequence is not complete and encloses at least two major gaps, one in the Bathonian/lowermost Callovian, the other in the upper Callovian. Numerous minor stratigraphic gaps can be recognized by depositional features only such as omission, erosional surfaces and abrupt lateral discontinuities.

(7) The fauna of the sills is dominated by ammonoids and gastropods, but includes all other groups of invertebrates, however, in much smaller numbers. As an effect of deposition in absolutely sheltered areas, ammonoids are exceptionally well preserved, commonly with complete body chambers. Their small size is due to the predominance of microconchs that probably lived in sea grass meadows on the sea floor, in the neighborhood of herbivorous gastropods. A secondary reason for the reduced size is stunting, which has been proved for some species.

(8) Individual percentages of herbivorous gastropods in the sill faunas have allowed calibration of oscillations of relative sea level. After two emergence intervals in the early Pliensbachian and around the Pliensbachian/Toarcian boundary, the sea level curve shows lowstands in the late Toarcian, early Aalenian, middle Bajocian and middle Oxfordian and a subsequent deepening-up trend in the Tithonian.

(9) Comparisons with other fossiliferous neptunian sills in the Alpine/Mediterranean Jurassic and Triassic show several similarities to the present study regarding depositional environments and ammonite faunas, but they represent only short intervals of condensation and relative sparse accumulations of well-preserved shells.

(10) The faunas of the neptunian sills at Rocca Busambra and comparable occurrences offer new insights into a particular type of “Fossil-Lagerstätten” whose study and exploitation could be a biostratigraphic and palaeontologic challenge for future research.

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APPENDIX

Coordinates of sections mentioned in the text and on Text-figures 2, 4, 5, and 6. Letters A–H refer to facies profiles with the same letters in Wendt (1971a, figs 1–3).

RB 1 (A): N 37° 51,645'; E 13° 20,121'

RB 2–3 (C): N 37° 51,637'; E 13° 20,436' (= section 4 in Wendt 1971a, fig. 10)

RB 6 (H): N 37° 51,373'; E 13° 20,661'

RB 18 (C): N 37° 51,637'; E 13° 20,399' (= section 5 in Wendt 1971a, fig. 10)

RB 22 (C): N 37° 51,637'; E 13° 20,429'

RB 27 (C): 5 m W of RB 3.

RB 29 (E): N 37° 51,753'; E 13° 20,508'

RB 30 (E): N 37° 51,754'; E 13° 20,506'

RB 37 (A): 100 m WNW of RB 1

RB 50 (A): close to RB 1

RB 51 (G): N 37° 51,778'; E 13° 19,286'

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PLATES 1-5



Box 1: A. *Arietites* sp. (9541), B. *Hildoceras bifrons* Brugüiere (9542), C. *Mercaticeras mercati* (Hauer) (9543), D. *Hildoceras bifrons* n. subsp. (9544), E. *Harpoceras subexaratum* Bonarelli (9545), F. *Polyplectus discoides* (Zieten) (9546), G. *Lytoceras spirorbis* Meneghini (9547), H. *Frechiella achillei* Renz (9548).

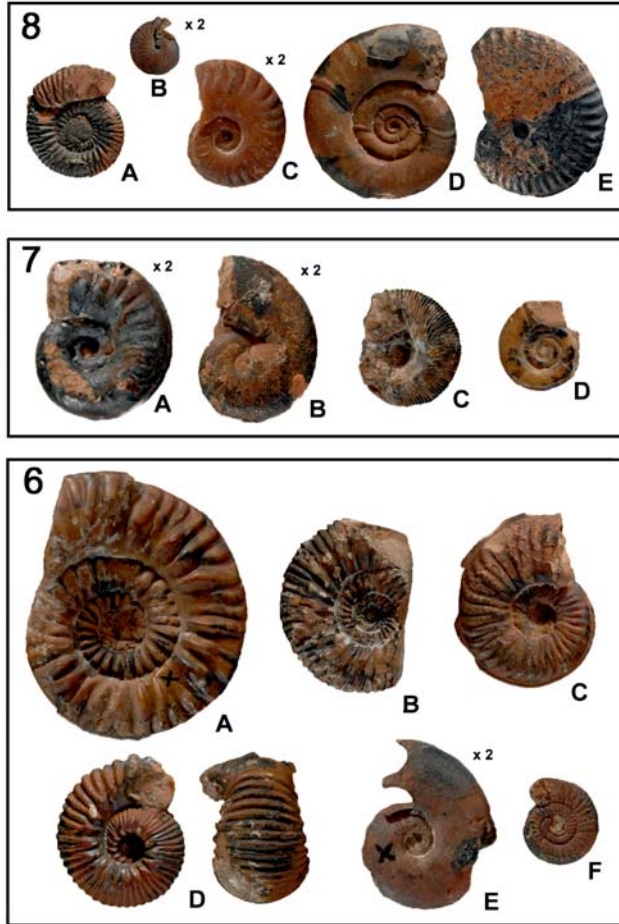
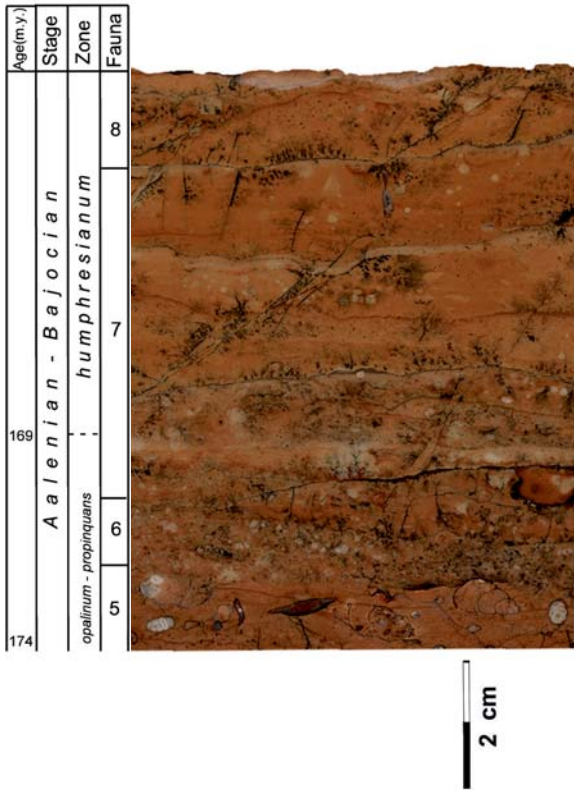
Box 2: A. *Phymatoceras erbaense* (Hauer) (9549), B. *Harpoceras subtile* Schirardin (9550), C. *Hildoceras bifrons* n. subsp. (9551), D. *Paroniceras sternale* (Orbigny) (9552), E. *Transicoeloceras viallii* (Pinna) (9553), F. *Leukadiella helenae* Renz (9554), G. *Crassiceras latum* Merla (9555).

Box 3: A. *Brodieia bayani* (Dumortier) (9556), B. *Pseudolioceras* aff. *lectum* (Simpson) (9557), C. *Phymatoceras robustum* Hyatt (9558), D. *Collina aegocerooides* Ramaccioni (9559), E. *Hildoceras semipolitum* Buckman (9560), F. *Onychoceras vaceki* Schweigert (9561), G. *Onychoceras* n. sp. (9562).

Box 4: A. *Pseudolioceras wunstorfi* (Monestier) (9563), B. *Pleydellia aalensis* (Reinecke) (9564), C. *Dumortieria* sp. (9565), D. *Onychoceras* n. sp. (9566), E. *Catullocceras* sp. (*forma aegra*) (9567).

Box 5: A. *Ludwigia umbilicata* Buckman (9568), B. *Docidoceras* sp. (9569), C. *Docidoceras modestum* (Vacek) (9570), D. *Zurcheria pugnax* (Vacek) (9571), E. *Leioceras opalinum* (Reinecke) (9572), F. *Tmetoceras scissum* (Benecke) (9573), G. *Docidoceras* sp. (9574), H. *Otoites* (*Trilobiticeras*) *platygaster* Buckman (9575).

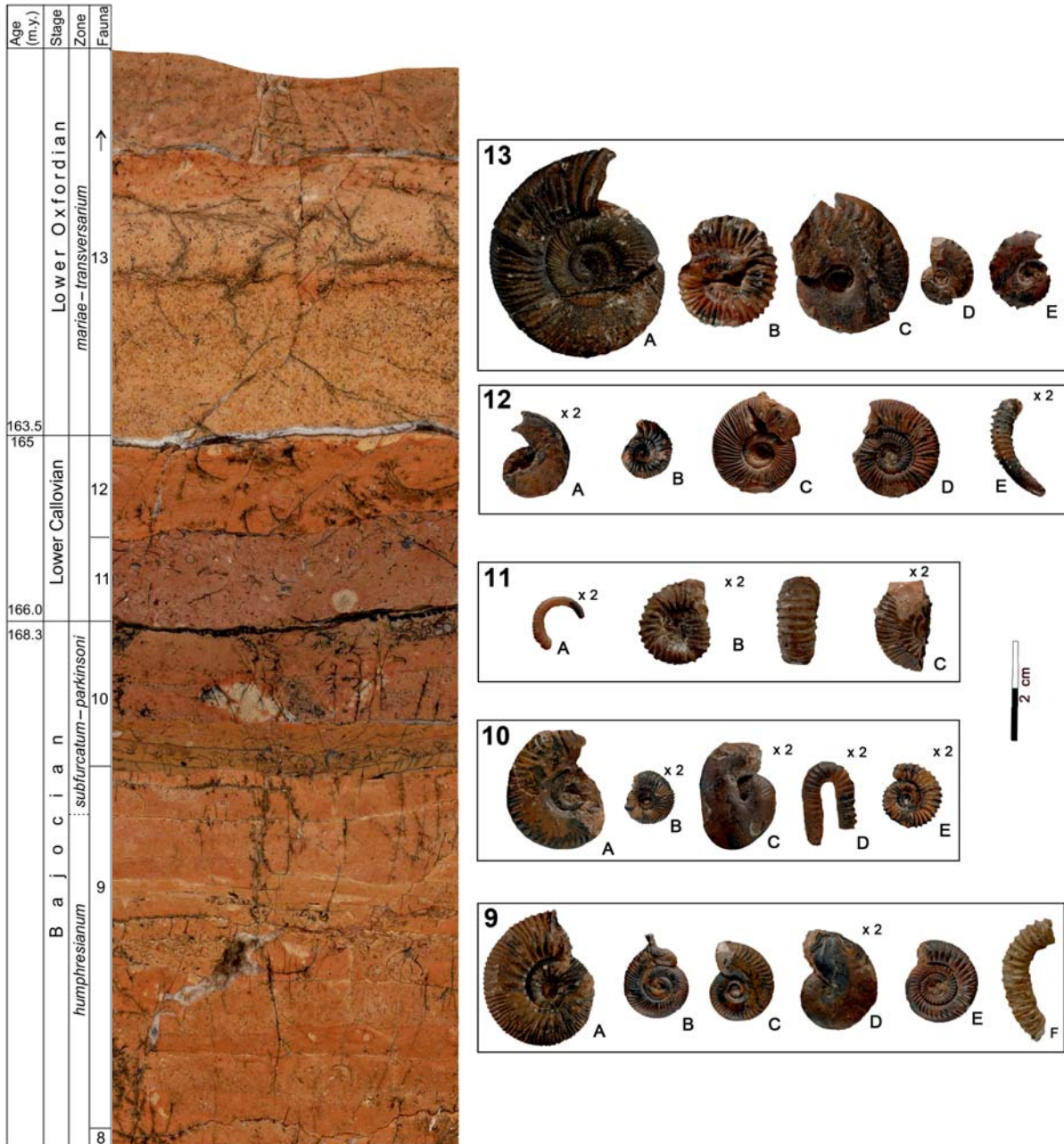
Note that all sections and ammonites in Plates 1–5 are natural size (if not enlarged). Box numbers correspond to equivalent faunas on left margin of sections. Absolute ages after Gradstein *et al.* 2012.



Box 6: A. *Eudmetoceras prosphues* Buckman (9576), B. *Normannites braikenridgii* (Sowerby) (9577), C. *Sonninia pinguis hannoverana* (Hiltermann) (9578), D. *Otoites (Trilobiticeras) platygaster* Buckman (9579), E. *Cadomoceras cf. carinatum* Buckman (9580), F. *Bigotites* sp. (9581).

Box 7: A. *Sonninia* sp. (9582), B. *Cadomoceras carinatum* Buckman (9583), C. *Chondroceras gervillii* (Sowerby) (9584), D. *Nannolytoceras nicolisi* (Parona) (9585).

Box 8: A. *Stephanoceras* sp. (9586), B. *Sphaeroceras brongniarti* (Sowerby) (9587), C. *Strigoceras symplectum* (Buckman) (9588), D. *Nannolytoceras polyhelictum* (Böckh) (9589), E. *Strigoceras pseudostrigifer* (Maubeuge) (9590).



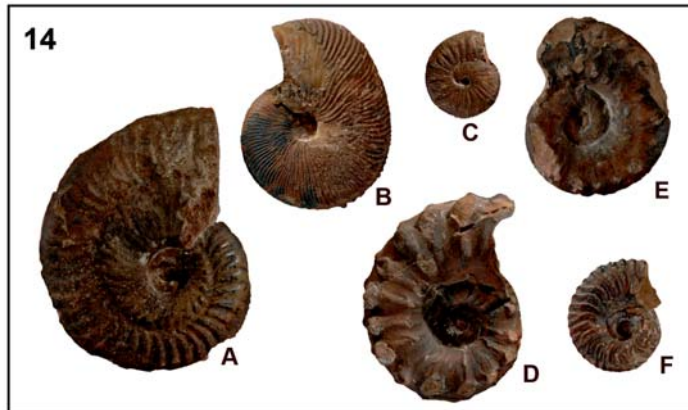
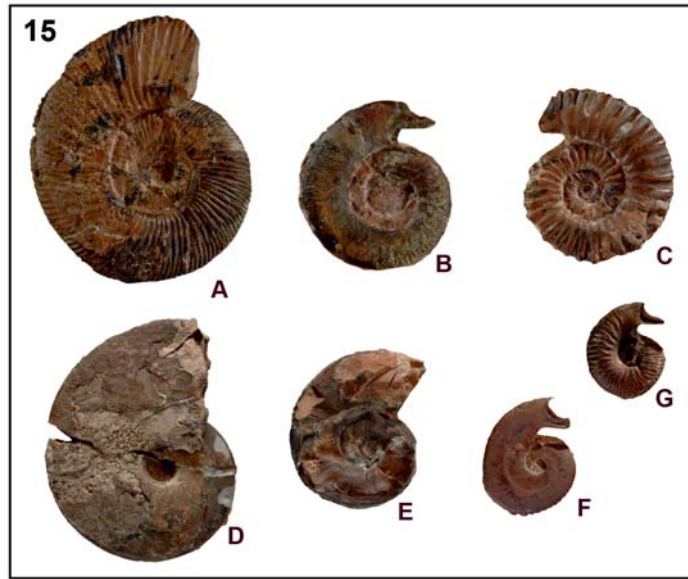
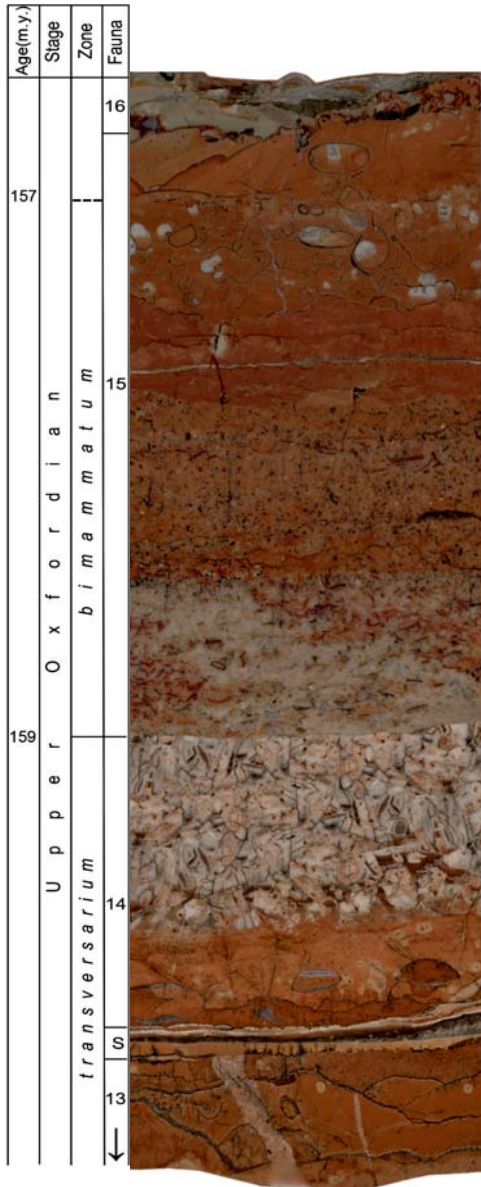
Box 9: A. *Stephanoceras umbilicum* (Quenstedt) (9591), B. *Dimorphinites (Vigoriceras) centriglobus* Rioult (9592), C. *Oppelia* cf. *subradiata* (Sowerby) (9593), D. *Strigoceras symplectum* (Buckman) (9594), E. *Cleistosphinctes* sp. (9595), F. *Spiroceras annulatum* (Deshayes) (9596).

Box 10: A. *Oecotraustes* cf. *genicularis* Waagen (9597), B. *Garantiana (Orthogarantiana) conjugata* Bentz (9598), C. *Oecoptychoceras grossouvrei* (Brasil) (9599), D. *Spiroceras (Plagiamites) cyphus* Buckman (9600), E. *Strenoceras* cf. *bajocense* (Defrance) (9601).

Box 11: A. *Parapatoceras calloviense* (Morris) (9602), B. *Peltoceratoides* sp. (9603), C. *Cadomites* sp. (9604).

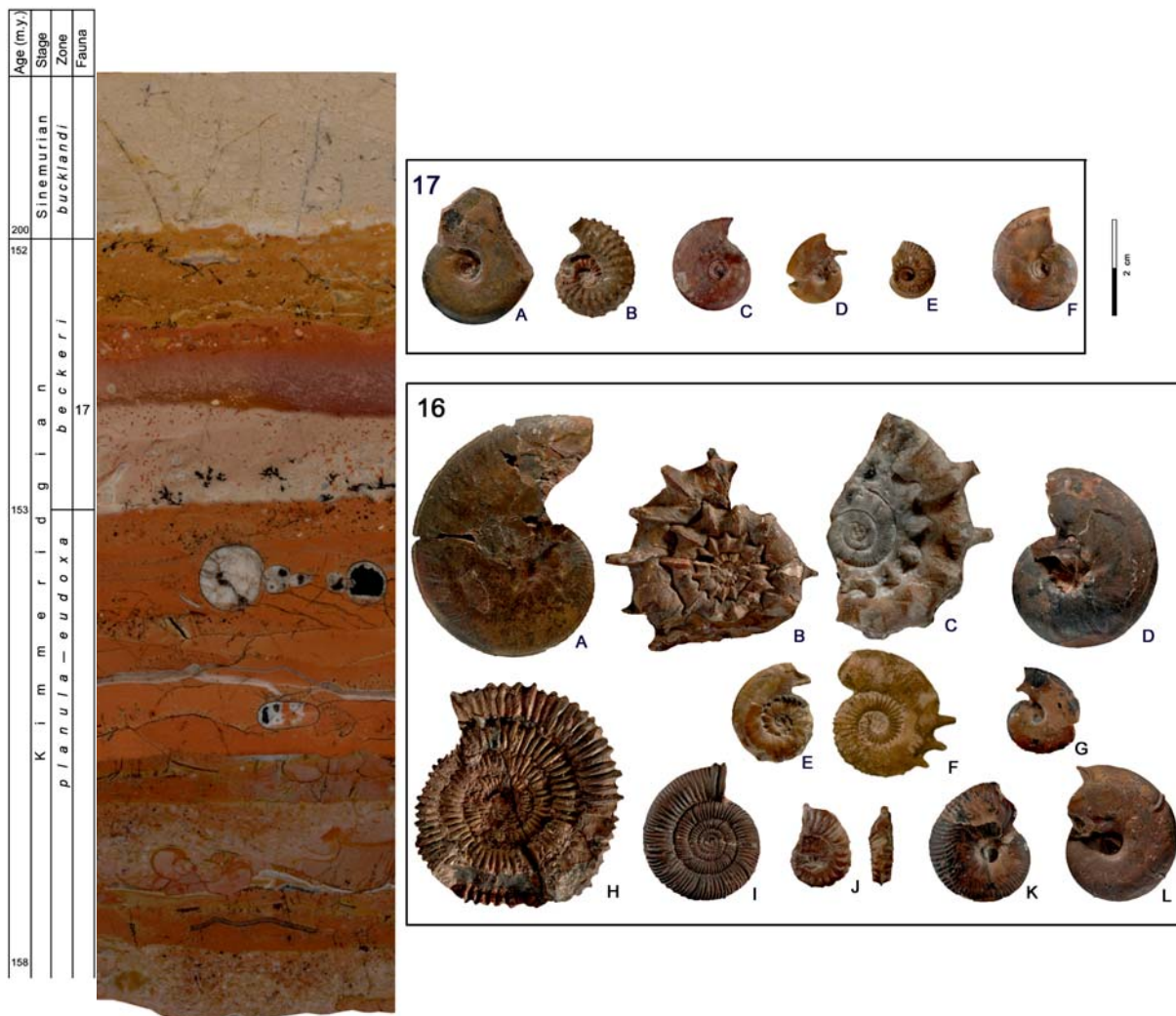
Box 12: A. *Oecotraustes thrax* Stephanov (9605), B. *Reineckeia* sp. (9606), C. *Dichotomosphinctes* sp. (960), D. *Choffatia* (?) sp. (9608), E. *Parapatoeras tuberculatum* (Baugier and Sauzé) (9609).

Box 13: A. “*Perisphinctes*” *noetlingi* Loriol (9610), B. *Peltoceratoides* sp. (9611), C. *Campylites helveticus* Jeannet (9612), D. *Distichoceras bicostatum* (Stahl) (9613), E. *Creniceras crenatum* (Orbigny) (9614).



Box 14: A. *Ochetoceras canaliculatum* (Buch) (9615), B. *Taramelliceras anar* (Oppel) (9616), C. *Neomorphoceras chapuisi* (Oppel) (9617), D. *Clambites (Struebinia) simplex simplex* Zeiss (9618), E. *Clambites (Euaspidoceras) oegir* (Oppel) (9619), F. *Gregoryceras toucasianum* (Orbigny) (9620).

Box 15: A. *Discosphinctes virgulatus* (Quenstedt) (9621), B. *Microsphinctes stockari* (Moesch) (9622), C. *Amoebopeltoceras berrense* (Favre) (9623), D. *Trimarginites arolicus* (Oppel) (9624), E. *Clambites aff. merianii* (Quenstedt) (9625), F. *Creniceras* n. sp. (9626), G. *Sutneria cyclodorsata* (Moesch) (9627).



Box 16: A. *Streblites laevipictus* (Fontannes) (9628), B. *Ceratophinctes rachistrophus* (Gemmellaro) (9629), C. *Ceratosphinctes septenarius* (Quenstedt) (9630), D. *Aspidoceras altenense* (Orbigny) (9631), E. *Hybonoticerias mundulum attenuatum* Berkhemer and Hölder (9632), F. *Hybonoticerias* sp. (9633), G. *Creniceras dentatum* (Reinecke) (9634), H. *Nebroditis (Mesosimoceras) cavourii* (Gemmellaro) (9635), I. *Nebroditis* aff. *hospes* (Neumayr) (9636), J. *Cymaceras gümbeli* (Oppel) (9637), K. *Eurynoticerias paparellii* Canavari (9638), L. *Sowerbyceras torticulcatum* (Orbigny) (9639).

Box 17: A. *Haploceras elimatum* (Oppel) (9640), B. *Simocosmoceras* n. sp. (9641), C. *Calliphylloceras benacense* (Catullo) (9642), D. *Glochiceras* cf. *solenoides* (Quenstedt) (9643), E. *Sutneria* cf. *eumela* (Orbigny) (9644), F. *Sowerbyceras loryi* (Meunier-Chalmas) (9645).