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Artikel: Jurassic pelagic deposits from Southeast Tuscany : aspects of sedimentation and new biostratigraphic data
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In the *Monti di Poggiano*, situated about 2 km west of Montepulciano, an almost complete Middle Liassic to Lower Cretaceous sequence is exposed in several adjacent quarries. The geological situation and the local stratigraphy have been described already by LOTTI (1910), LOSACCO & DEL GIUDICE (1958), FAZZINI et al. (1968) and PAREA (1970). The measured section begins somewhere in the Calcare Selcifero, which is conformably overlain by the Marne a Posidonia, the Diaspri, a few metres of Rosso ad Aptici and, finally, by about 15 m of Maiolica limestone. Both, the upper part of the Marne a Posidonia and the Rosso ad Aptici provided determinable aptychi (see below).

In the *Rapolano area*, previously studied by DE ANGELIS D'OSSAT (1879), LOSACCO (1951), LOSACCO & DEL GIUDICE (1958) and CANUTI & MARCUCCI (1967), no continuous section is exposed, but part of the Jurassic sequence could be reconstructed from different outcrops. Our data are mainly drawn from two localities: 1. Near Podere Monte Camerini, about 1 km southeast of Rapolano, we surveyed the upper part of the Marne a Posidonia. A conglomeratic layer found at about 3 m below the top of the formation yielded abundant aptychi. The Diaspri, though outcropping in a number of abandoned quarries in the same area, generally appeared too weathered to allow a detailed investigation. 2. Relatively fresh exposures of radiolarites, aptychus beds and Maiolica limestone occur along the state road No. 326, immediately east of Rapolano. The continuity of the section is repeatedly interrupted by faults, but nevertheless an almost complete Upper Jurassic sequence could be compiled. From these outcrops the major part of the Tithonian aptychus assemblage described below was collected.

In the *Chianti region*, northeast of Siena, Jurassic sediments appear only in few, small outcrops near Cintoia and further south, near Lucolena. Accounts dealing with their stratigraphy have been published by VALDUGA (1948), BORTOLOTTI & PASSERINI (1965) and CANUTI et al. (1965). We attempted no detailed study of this area, but a cursory reexamination of the localities referred to by these authors revealed that the mainly Upper Jurassic deposits exposed compare well lithologically with those in the above areas. At Borro di Cafaggio, southwest of Cintoia, we found some aptychi both in a slide conglomerate underlying the Diaspri and near the top of the Rosso ad Aptici.

LITHOLOGY

Calcare Selcifero

The lowest lithologic unit considered in this study consists of well-bedded, slightly siliceous grey calcilutites with intercalated resediments. Limestone beds are separated by thin, dark-grey marly or greenish clayey interlayers. Towards the top of the formation somewhat thicker, reddish marl interbeds occur and in general the limestone/marl transitions become more gradual. However, locally the limestones display somewhat nodular surfaces. In this upper part of the Calcare Selcifero, replacement chert tends to be more frequent. The sediment generally appears thoroughly mottled; bioturbation has led to a complete destruction of primary sedimentary structures. Particles of coarse silt and sand grade, which are mainly biogenic, are unevenly distributed and may be concentrated in streaks with blurred outlines.

The microfauna is dominated by radiolarians and sponge spicules; most of them, however, are preserved merely as spar-filled moulds, occasionally with geopetally lodged framboidal pyrite or infilled sediment. Minor components are benthonic foraminiferas, ostracodes and problematic microfossils, such as *Stomiosphaera* and *Globochaete*.

SEM-investigation has shown that a considerable percentage of the mud fraction of the sediment is represented by valves and valve fragments of calcareous nanno-organisms (Fig. 3*a*). On account of their morphology and valve ultrastructure, even though the latter has undergone strong alteration by diagenetic overgrowth, these nannofossils can be assigned reliably to the still enigmatic group of the schizosphaerellids (AUBRY & DÉPÊCHE 1974 and references therein). In places, *Schizosphaerella* valves are rather tightly packed, but commonly they occur scattered through a neomorphic mosaic of blocky micrite and microspar, which yields no direct information on the nature of the other original constituents of the fine-grained sediment. However, it seems unlikely that neomorphic calcite and calcite cement are derived primarily from skeletons of planktonic organisms, as is the case in lithified true pelagic carbonate oozes. Rather, we think that the original sediment was heterogeneous mineralogically, with significant admixtures of metastable aragonite and high-magnesian calcite supplied from contemporaneous shallow-water areas. Such a contribution indeed appears feasible, as demonstrable neritic material occurs in the sand fraction of associated sediment gravity flow deposits (see below). Contrasting with the episodical supply of the coarser material, we envisage a rather

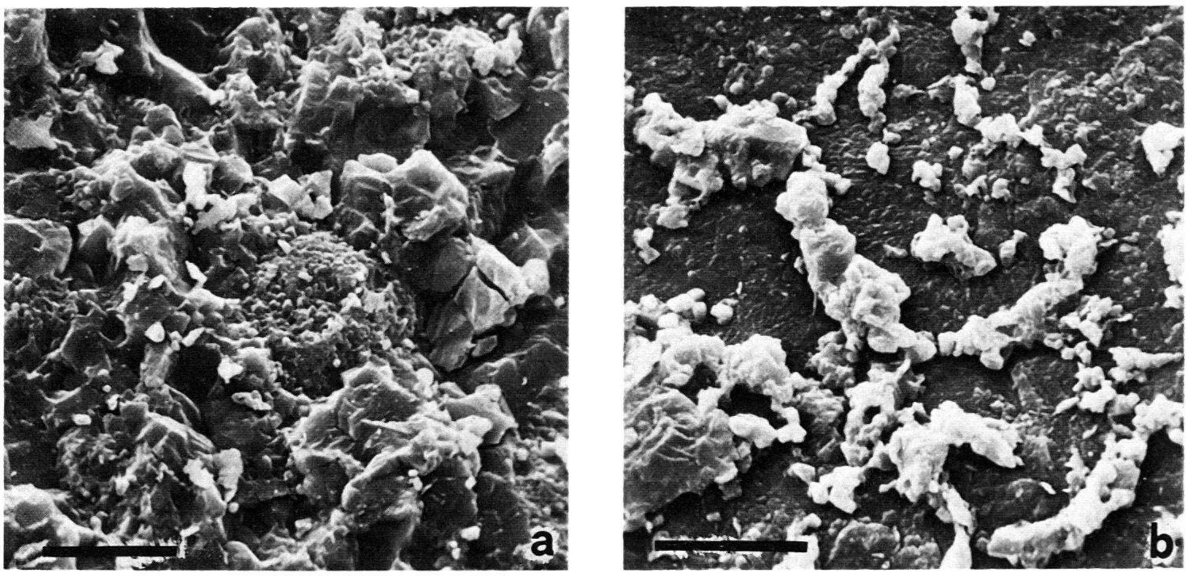

Fig. 3. Groundmass of slightly siliceous hemipelagic microbioclast lime wackestone in the Calcare Selcifero: badly preserved (diagenetically altered) *Schizosphaerella* valves and valve fragments scattered throughout a mosaic of blocky micrite and microspar (in part neomorphic, in part void-filling cement) (*a*), some of which is replaced by granular microquartz (*b*).

Calcare Selcifero; Middle Liassic; Monti di Poggiano. SE-micrographs of fresh broken surface (*a*) and polished and etched surface (*b*) of the same sample; scale bars 10 μ.

constant, possibly tide-induced, transfer of carbonate lutum from shallow-water to adjacent deeper areas, with dispersal and deposition then being largely the same as for the fine-grained truly pelagic components of the sediment.

Thin-sections and SE-micrographs of polished and etched sediment surfaces reveal microquartz and fibrous chalcedony locally replacing carbonate (Fig. 3*b*) and filling moulds and interparticle voids. Calcite-cemented moulds and calcitic replacement fabrics in turn suggest that radiolarians and originally opaline sponge spicules, disseminated throughout the sediment, constitute the source of silica.

In the Calcare Selcifero, *subaqueous gravity movement* is documented by various types of deposits, ranging from slides of virtually coherent stacks of beds to thin turbiditic layers: slides and slump-sheets may reach thicknesses of 6 or 7 m. They consist exclusively of remobilized intrabasinal hemipelagic sediment. Although such intercalations are sometimes masked by Tertiary tectonics, their non-tectonic origin is clearly demonstrated by the occurrence of plastic deformation within these complexes. Deformed beds may disintegrate laterally into slide-conglomerates wherein pebbles are supported by a slightly more marly, fluidally structured matrix. Phacoidal deformation ("lenticular flow", cf. VOIGT 1962) preferentially occurs along shear planes between almost undisturbed portions of slide complexes. Along such zones the lens-shaped, partially or completely retextured phacoids are usually closely packed and separated only by thin marly or argillaceous streaks.

Occasionally, in the normally deposited calcilutite intercalated between remobilized sediment masses, somewhat lenticular bedding has been observed. In thin-section, these beds typically reveal a faintly laminated structure similar to that of the early-diagenetic phacoids. Such a modification of primary bedding and depositional textures is known to occur just up-slope of slump scars, i.e. in zones subjected to tensional stresses prior to release of the slump-sheets. However, motion and emplacement of large remobilized sediment masses is likely to cause virtually the same features in underlying slightly consolidated strata.

In addition, the Calcare Selcifero contains conglomeratic layers up to metre-thick, usually featuring sharp planar contacts with the underlying beds. Structural and textural characteristics point to deposits of highly concentrated gravity flows (probably with combined characteristics of grain flow and debris flow; MIDDLETON & HAMPTON 1976). The beds generally start with a relatively thin inversely graded interval. Vertically this is followed by a poorly sorted pebbly interval, which displays no more than a crude normal coarse-tail-grading and usually occupies 60 to 80% of the bed thickness. Slightly rounded to subangular limestone pebbles make up a supporting frame, with interstices filled by a slightly marly lime mud plus granule- and sand-sized material. Near the top of this division, packing of the pebbles suddenly becomes looser and, at the same time, a clear gradation develops among the finer constituents. The gradation finally passes up into a distinct parallel-lamination indicating traction-current deposition. Consequently, we suspect that this thin, fine-grained upper layer represents the deposit of dilute suspension entrained above the mass flow (cf. HAMPTON 1972, MIDDLETON & HAMPTON 1976). The ruditic components of these conglomerates are invariably derived from intrabasinal sources. In contrast, their arenitic fraction is dominated by penecontemporaneously displaced shallow-water material, such as fragments of calcareous algae, oncoids, ooids, peloids and neritic lithoclasts. Variable amounts of pelagic biodetritus may be admixed. The depositional fabric of these conglomerates has been modified by pressure solution: a network of mainly horizontal stylolites suggests a considerable reduction of the initial bed thickness.

Turbidites, usually *AE* beds, may reach thicknesses of up to 20 cm; more complete Bouma sequences have rarely been observed. As in the conglomerates described above, the sand fraction in the turbiditic layers is mainly shallow-water derived. Up-section, however, neritic material is gradually replaced by pelagic components (e.g. fragments of thin-shelled pelecypods).

From the sedimentary features observed, we conclude that the Calcare Selcifero was deposited in a morphological basin. More specifically, from both the type and the volumetric importance of the redeposited beds, a gently inclined depositional slope environment can be inferred for the sequence exposed in the Monti di Poggiano. The composition of the resediments reflects supply from two different sources, one located in shallow water further away and a second, apparently more important, higher up on the basin slope itself. We suppose that in the upper reaches of the slope, sediment gravity movements have been induced by episodic oversteepening due to an increased influx of platform-derived material and/or slight flexural deformation related to continuing differential subsidence of the basin. Breaks in slope or merely a gradual decrease of the slope angle basinwards might then account for the emplacement of slumps and slides, and for the "freezing" of mass flows.

Marne a Posidonia

In Tuscany the Calcare Selcifero is normally overlain by a predominantly marly unit called "Marne a Posidonia". South of the Arno river, its thickness varies from only a few metres to about 60 m, according to the palaeotectonic setting. In the Monti di Poggiano we have measured about 40 m.

As implied by its name, small thin-shelled posidoniids constitute an important faunal element of this unit. Other macrofossils are virtually absent and the chronostratigraphic extent of the Tuscan Marne a Posidonia is therefore controversial. Early regional geologists (FUCINI 1905, ZACCAGNA 1932) assigned them to the Late Liassic. MERLA (1951) then considered them Middle Jurassic, most probably Bathonian/Callovian in age, based on the pelecypods which he invariably referred to *Posidonia alpina* GRAS. This age assignment was largely approved by subsequent students of Tuscan geology, although *Bositra buchi* (RÖMER)[5]) (= *Posidonia alpina* GRAS) meanwhile proved not to be determinative for the respective time-strati-

[5]) We usually found the preservation of the delicate shells to be insufficient for a specific determination. However, exceptional, well-preserved specimens compare well with the presumably nekto-planktonic *Bositra buchi*, studied by JEFFERIES & MINTON (1965). Valve lengths measured range from 4 to 8 mm; thicknesses vary between 45 and 60 μ. The valves, slightly ovate in outline and without ears, display pronounced concentric corrugations which can be seen in thin-section (Fig. 4*b*) to affect the full thickness of the shell.

graphic interval, but to range from Toarcian to Oxfordian (JEFFERIES & MINTON 1965). MERLA's view was questioned first by FEDERICI (1967), who argued for an early Aalenian age for the base of the Marne a Posidonia. After this, in a study on the Tuscan Mesozoic south of the Arno River, FAZZINI et al. (1968) confirmed FUCINI's discovery of a Late Liassic ammonite fauna in the lowest part of the Marne a Posidonia at Monte Cetona (cf. Fig. 1 for location). The ammonite specimens listed by these authors, as well as the ammonite assemblage collected by ourselves in the same outcrop of red nodular marls a few metres above the top of the Calcare Selcifero, indicate Middle Toarcian (Mercati and Erbaense Zones). On account of sporadic (indeterminable) ammonite remains found in a similar stratigraphic position at some additional localities throughout Southern Tuscany, FAZZINI et al. (1968) suspected that the Marne a Posidonia in general comprise not only the Middle Jurassic but also part of the Upper Liassic. A roughly isochronous passage from the grey hemipelagic limestones of the Calcare Selcifero to marly and commonly red deposits over the whole Tuscan zone in Late Liassic time appears feasible indeed, particularly as a corresponding changeover is a common feature in basinal successions deposited along the periadriatic segment of the southern Tethyan margin (Umbria, Lombardy, Western Greece; ZACCAGNA 1932, BERNOULLI & RENZ 1970, JENKYNS 1974, BERNOULLI et al. 1979).

For the top of the Marne a Posidonia a Callovian age is indicated by an aptychus assemblage collected during this survey and described below.

Much of the unit is dominated by red foliate clayey marls and marls displaying a faint lenticularity due to bioturbation. Their carbonate content is 35 to 40% on average. Main carbonatic constituents are shell debris of posidoniids, preferentially oriented parallel to bedding, *Schizosphaerella* valves with their voids frequently cemented by blocky microspar, and lutitic calcite grains of unknown origin. Silt-sized detrital quartz and feldspar occur very rarely and siliceous biodetritus is sparse. *X*-ray diffraction traces show the clay component of the sediment to be mainly illite and illite/montmorillonite mixed-layer minerals, with a trace of chlorite. Haematite accounts for the red staining. SE-micrographs of polished and slightly etched surfaces reveal a pronounced parallel orientation of the clay particles. Compaction caused the clay flakes to become concentrated into minute seams. Where these seams were draped over carbonatic grains, a mesh-like microstructure resulted.

The red marls, which probably accumulated slowly by pelagic settling, are interbedded at irregular intervals with thin, calcareous shell beds, standing out in weathering profile. More careful inspection reveals structurally and texturally differing types of such skeletal limestones. Some of them bear features generally thought to be distinctive of rapid deposition by turibidity currents, others compare with beds known as "Posidonia"-lumachelles (cf. STURANI 1967):

Turbiditic layers typically maintain the same thickness throughout the outcrop. They have sharp bases with occasional shallow scours. Most of the beds are visibly graded, some with a lamination superimposed, and are overlain by massive red marly mudstones, which would appear to consist of the fine-grained material deposited from the diluted tails of the turbidity currents (*E* Bouma division). The upper boundary of such turbiditic mudstones is ill-defined due to bioturbation. However, the thickness of a complete cycle commonly might not exceed some 5 to 10 cm.

Apart from shells of posidoniids, in the lower part of these turbidites only coarse to medium sand-sized intraclasts of pelagic biomicrite and unidentified calcite particles of fine sand to silt grade (possibly skeletal debris), may be of importance. The fine-grained matrix, as well as the fine sediment constituting the turbiditic mudstones, is a red, haematite-stained, clay-rich mud with a seemingly "pelletted" texture, which on SE-micrographs turns out to be due to numerous scattered *Schizosphaerella* valves.

Distinct gradations, occasionally with traces of an impersistent and ill-defined lamination, but no sedimentary structures pointing to an extended phase of tractional deposition are found in beds containing abundant lithoclastic material. Over a major part of the graded divisions intraclasts, decreasing upward in mean size, form a supporting framework. Clast interstices are filled mainly with skeletal material, compactionally crushed and distorted around lithoclasts; only minor amounts of lutite are usually present. As the overall proportion of lithoclastic material diminishes near the top of the graded division, skeletal components tend to be aligned along the bedding as a consequence of postdepositional compaction. The graded beds finally pass up into marly turbiditic mudstone. The transition is either still gradational, by progressive dilution of skeletal debris, or abrupt across a rather distinct textural boundary.

Some beds in which the coarser components are almost exclusively bioclastic and with a comparatively high lutum content throughout, exhibit a more complex internal organization (e.g. Fig. 4*c*). Although not fully discernible macroscopically, again a progressive gradation from the base of the bed up into the turbiditic mudstone is present; but superimposed on the grading, which is expressed by an upward decrease in size and abundance of shells and shell debris of posidoniids, are plane laminations and, sometimes, additional faint cross laminations. These laminations, with laminae alternately rich and poor in bioclastic material, are irregularly spaced and commonly rather diffuse. However, well-sorted, sharp-based laminae of either shell fragments or silt-sized, equant calcite grains of questionable origin and, likewise, nearly pure mud strips also occur. The structural and textural properties of this lithotype recall some types of "graded laminated silt and mud beds" analyzed by PIPER (1972), in that even the coarser components may behave hydraulically in a way similar to silt due to their high surface/volume ratio. The depositional mechanism PIPER envisages to account for this particular type of fine-grained resediment includes alternating phases of cohesive (mud deposition by adhesion) and granular (tractional deposition of silt) bed conditions in a turbidity current with gradually waning competency.

Size-sorted shell debris, particularly common in this second type of turbiditic layers, implies that valve fragmentation occurred prior to deposition, either in the source area or during an early stage of mass flow. As is found in the intraclast-bearing beds, there is, however, also evidence for further skeletal breakage due to compaction, after final deposition. We thus may infer that turbiditic layers were virtually uncemented at the time of major compactional deformation.

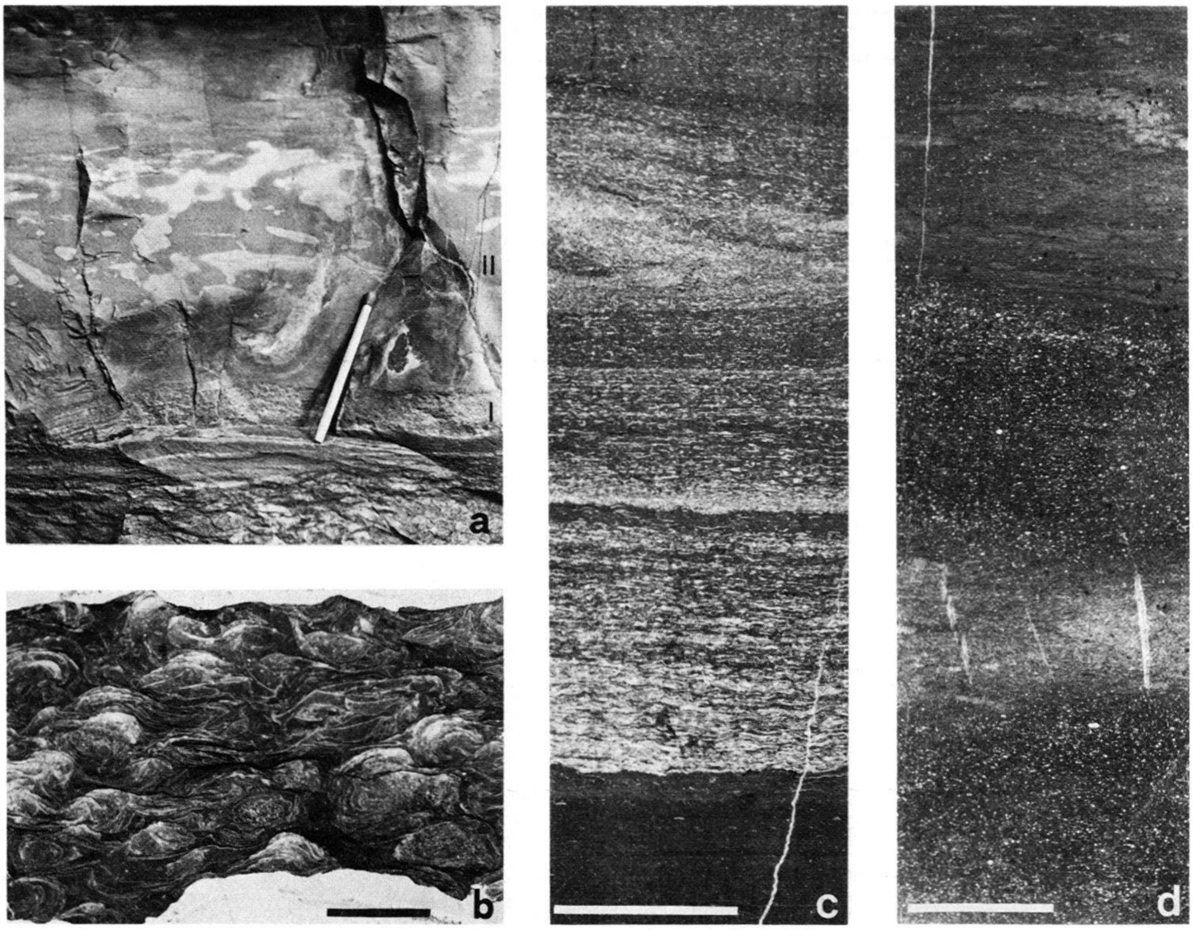

Fig. 4a. Turbidite consisting exclusively of redeposited pelagic sediment ("pelagic turbidite"). Graded and laminated bioclastic (pelagic bivalves) calcarenite to calcisiltite (I) passing upward into a disproportionally thick, reddish, turbiditic marlstone (*E* Bouma division) with light-coloured speckles, which in part are halos around burrows (II). The turbidite rests with a sharp, erosional contact on dark red clay-rich marl, interlaminated with very thin and laterally discontinuous bioclastic layers (possibly winnowed deposits of bottom currents active during interturbiditic periods.)

Marne a Posidonia (upper part); Middle Jurassic; Rapolano, near Podere Monte Camerini.

Fig. 4b. *Bositra* lumachella; lag deposit of winnowing bottom currents. Minor compactional breakage of the delicate fossils and, in particular, the spar-filled cavities beneath convex-side-up oriented valves suggest early diagenetic cementation.

Marne a Posidonia (lower part); ? uppermost Liassic / early Middle Jurassic; Monti di Poggiano. Thin-section; scale bar 0.5 cm.

Fig. 4c. Turbiditic layer overlying marly mudstone. The sand and silt fractions are constituted mainly by debris of pelagic bivalves. Gradation is superimposed with an irregularly spaced lamination. Skeletal material in the basal part of the gradation has been crushed after emplacement of the layer by compaction.

Marne a Posidonia; Middle Jurassic; Rapolano, near Podere M. Camerini. Thin-section; scale bar 0.5 cm.

Fig. 4d. Two successive couplets, each consisting of a radiolarian-rich (radiolarian packstone to wackestone) and an overlying mottled pelite layer. Throughout the latter, much of the original calcilutite has been replaced by silica (the lower, light-coloured pelite layer macroscopically appears as vitreous chert with diffuse boundaries). Within the bioclastic layers, instead, the bulk of the Radiolaria is preserved only as calcite-cemented moulds set in a clay-rich matrix. The inferred depositional process is low-density turbidity flow.

Diaspri (facies *A*); uppermost Middle Jurassic; Monti di Poggiano. Thin-section; scale bar 0.5 cm.

Compared with the evenly bedded turbiditic layers, the bedding of the *lumachelles* is quite irregular, and laterally discontinuous. Lumachelles commonly wedge out over a distance of only a few metres, and sometimes even less. They are sharply bounded both at the base and at the top, and reach a maximum thickness of about 2 cm. Generally, the lower bed surfaces exhibit an irregular relief, whereas upper surfaces are merely gently undulating and often formed by a tight pavement of well-preserved *Bositra* valves primarily oriented convex side up. Inside the beds there is no preferred orientation of valves, but typically they occur in glomerate clusters with fine-grained sediment trapped amongst them (Fig. 4*b*). In contrast with the formerly described turbiditic layers, the lumachelles lack evidence of an extensive compaction. The majority of the valves were left uncrushed and, moreover, spar-filled open-space structures beneath valves in convex-up position are common in this lithology. Obviously, lithification of these beds commenced early, possibly close to the sediment/water interface, and with increased burial cementation was already sufficient to prevent compactional breakage of the valves.

Based on the features outlined, we conceive of this type of shell beds as a kind of lag deposit generated by periodically active bottom currents. In fact, the shell pavements with shells preferentially in the hydrodynamically stable convex-up position are reliable indicators of current activity. In particular, we suppose that these pavements occasionally found at the top of lumachelles record non-depositional intervals due to temporarily enhanced current velocities. There is, however, no unequivocal explanation for the glomerate arrangement of valves inside the beds. Glomeration could be caused by bioturbation, as suggested by Kuhry et al. (1976); but more likely it is related to primary sedimentary processes. Similar dispositions of valves of larger benthonic pelecypods have been reported by Reineck & Singh (1975, Fig. 210). The examples cited by these authors formed either by swash and backwash or by tidal currents on Recent beaches or tidal flats. But, in view of the small dimensions and light weight of *Bositra* valves, it seems plausible that an unsteady bottom circulation could effect closely similar features in a deeper-marine low-energy environment.

In the area studied, the uppermost quarter of the Marne a Posidonia reveals a different bedding pattern and, on the whole, a markedly more calcareous development:

In the Monti di Poggiano, a rather distinct and regular alternation of clayey marls and pink to cream-coloured, marly lime mudstones to wackestones (50 to 70% $CaCO_3$) appears some 10 m beneath the top of the unit. Initially, bed thicknesses of both lithologies range from 3 to 5 cm; but up-section clay-rich interbeds progressively thin to only fine, greenish-grey shaly partings. Aptychi and belemnites are sparsely scattered through these shales. Components of the marly limestones include debris of posidoniids, rare small sponge spicules and radiolarians. An upward increase in radiolarians is accompanied by an increase of silica-replaced micrite in the matrix. Many of the marly limestone beds are current-laminated internally. Up to within 4 or 5 m of the contact with the overlying Diaspri, thin turbiditic shell layers, which develop into marly lime mudstone by gradation, occasionally interfere in the sequence. Along such bioclastic layers bands or lenses of reddish, vitreous replacement chert are found quite frequently.

In contrast, in the Rapolano area bedding is highly irregular in the corresponding stratigraphic interval, with bed thicknesses ranging from a few centimetres to about 1 m (Fig. 5*a*). The predominant lithology is again a slightly siliceous, lime-rich (50 to 65% $CaCO_3$) marlstone with variable amounts of microbioclastic hash (mudstone to wackestone). The SEM shows that the chief constituents of the carbonate lutite are blocky calcite (in part neomorphic, in part clearly cement), schizosphaerellids and, for the first time, small coccoliths (Fig. 6*b*). In contrast to their usual preservation throughout the sequence, *Schizosphaerella* valves typically are rimmed by radially arranged bladed calcite crystals (Fig. 6*a*), formed by

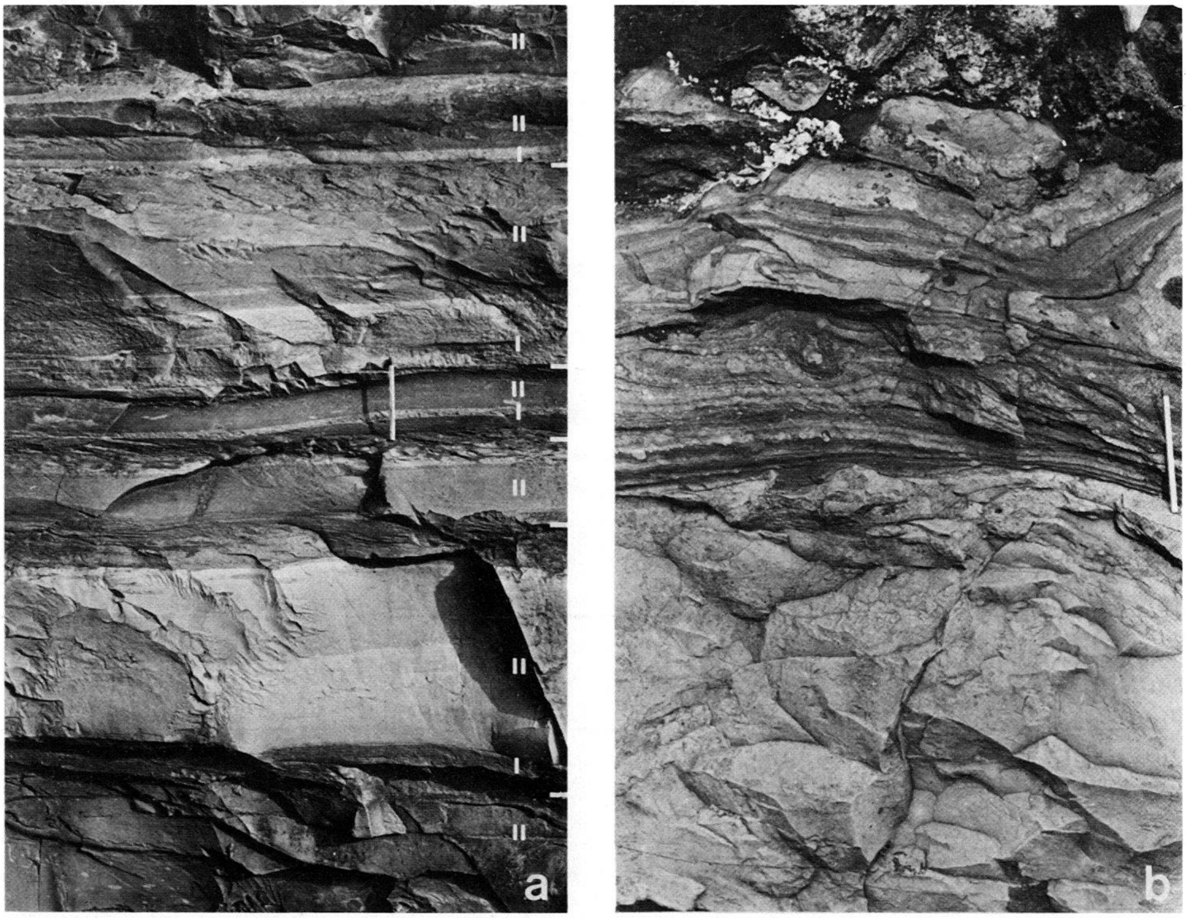

Fig. 5a. Sequence of "pelagic turbidites". The prevailing lithology is mainly dull red, slightly siliceous turbiditic marlstone (II). The marlstone may form individual beds or develop from a graded and/or laminated bioclastic layer (I; cf. Fig. 4*a*). The turbidites commonly are thinly interlayered with fissile shale (interturbiditic sediment; marked by horizontal dashes). Note dark burrow infills near top of the light-coloured massive marlstone.

Marne a Posidonia (upper part); Middle Jurassic; Rapolano, near Podere Monte Camerini.

Fig. 5b. Laminate structure in red, marly matrix of a mass-flow deposit. Lighter-coloured laminae resulted from deformation of incipiently consolidated pebbles and granules and their merging into the embedding marl-matrix. The large boulder of marly limestone (massive turbiditic mudstone) in the lower half of the photograph was deformed peripherally but has otherwise retained its primary depositional texture.

Marne a Posidonia (top); late Middle Jurassic; Rapolano, near Podere Monte Camerini.

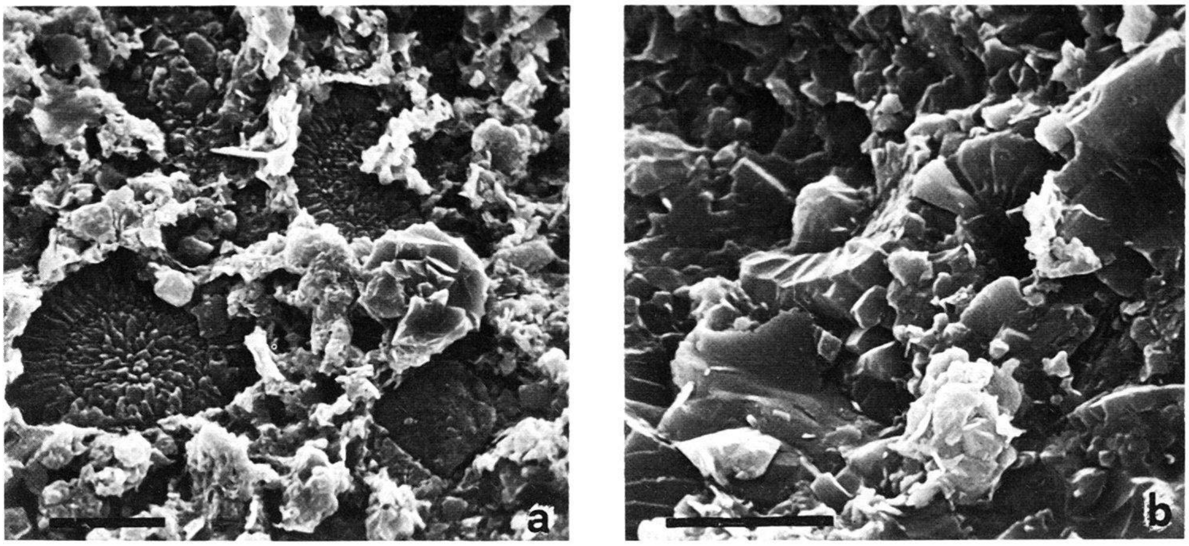

Fig. 6. Groundmass of slightly siliceous reddish turbiditic marlstone (cf. Fig. 4*a* and 5*a*). Calcitic constituents include *Schizosphaerella* valves, typically with a diagenetic rim of radially oriented, bladed, calcite crystals *(a)*, overgrown coccoliths *(b)*, blocky neomorphic calcite and calcite cement. Main non-carbonate components are granular microquartz replacing calcite and clay minerals.

Marne a Posidonia (upper part); Middle Jurassic; Rapolano, near Podere Monte Camerini. SE-micrographs of polished and etched surface *(a)* and fresh broken surface *(b)*; scale bars 10 μ *(a)* and 5 μ *(b)*.

displacive precipitation and/or replacement of surrounding micrite during burial diagenesis. Likewise, coccolith plates usually show conspicuous diagenetic overgrowth. Main non-carbonate components are clay minerals and granular microquartz. Apart from occasional burrow structures in the upper part of the beds, the marlstones have a massive appearence. Their colour is mainly dull red, but in places grey or pale green. Common are variegated layers with light-coloured speckles (Fig. 4*a*) which in some cases can be seen to be developed as halos around burrows. The marlstones may form individual beds, parted by thin layers of fissile clayey marl. Frequently, however, marlstone beds evolve gradually from current-laid biocalcarenite layers, less than one to several centimetres thick, which either reveal the lower flow regime *C* and *D* Bouma divisions or graded bedding with an indistinct lamination superimposed (Fig. 4*a*). Such association, together with the restricted occurrence of bioturbation structures, suggests that the massive marlstone layers are allochthonous throughout and were emplaced rapidly, as *E* Bouma divisions (theoretical aspects concerning feasibility of deposition of unusually thick layers of fine-grained sediment by turbidity currents are discussed by HESSE 1975). According to this view, the intervening thin, carbonate-poor, fissile marl layers would reflect disproportionally longer periods of normal (hemi)pelagic sedimentation.

Sedimentological evidence implies that the increased overall carbonate content in the upper part of the Marne a Posidonia is mainly due to a high proportion of relatively carbonate-rich, fine-grained resediment. As the source areas of the resediments in the Marne a Posidonia were located exclusively in deeper-marine realms, fine-grained redeposited sediment and "autochthonous", (hemi)pelagic sediment should not differ markedly in composition. Substantially lower carbonate contents in the presumed (hemi)pelagic deposits are thus not likely to be a primary characteristic of sedimentation, but rather an effect of carbonate dissolution on the sea-floor. Low accumulation rates conceivably allowed extensive dissolution in the "autochthonous", (hemi)pelagic mud, whereas rapidly emplaced gravity-flow depo-

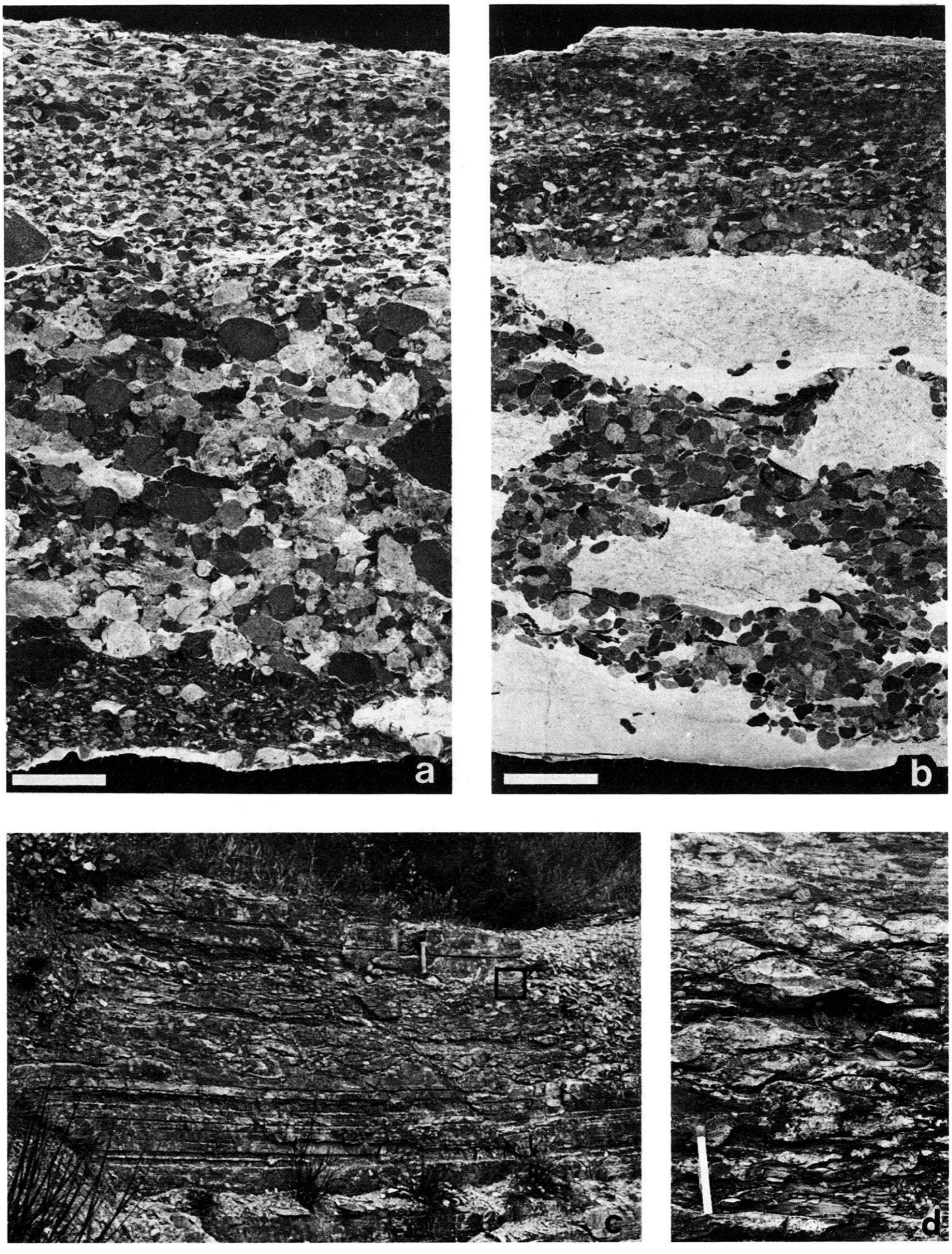

Fig. 7. (Explanations see opposite page.)

sits were only superficially affected. This implies, of course, that dissolution of carbonate in the source areas of the resediments was less effective than in the basin. If we suppose that there was no significant areal variation in the rate of carbonate supply from surface and intermediate waters, we then may infer either that the source areas themselves were preferred sites of deposition of current-reworked sediment and hence of fast accumulation and less effective carbonate solution, or that simply their shallower bathymetric position was the cause of a smaller rate of carbonate dissolution.

In comparison with the Calcare Selcifero, *slumped beds* and *coarse clastic deposits* are much less important in the Marne a Posidonia. In the Poggiano section, minor slumps occur near the base of the formation (Fig. 7*c*) and in its more calcareous upper part. The bases of slump-sheets are always parallel with bedding surfaces of the underlying undisturbed sediment. Within the slump deposits plastic deformation evidently prevailed throughout. Constituent beds typically exhibit an irregular pinch-and-swelling and often they are disrupted into elongate lenticular bodies, which in turn may be imbricated or dragged into tight recumbent folds. In places, sedimentary layering was obliterated completely and the sediment remobilized into a mud pebble conglomerate, with ellipsoidal or spindle-shaped, internally deformed pebbles (phacoids) set in a fluidally structured shaly matrix (Fig. 7*d*). The lumpy upper surface of the slump-sheets is usually levelled out by an overlying graded shell bed or an evenly laminated marlstone.

Near Podere Monte Camerini, southeast of Rapolano, at the very top of the formation there is an intercalation of conglomeratic mudstones, which might have progressively evolved from slumping: The lowest bed, 30 to 40 cm thick, rests with a sharp, but irregularly undulating contact (possibly load-deformed slide marks) on a

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Fig. 7a. Clast-supported small pebble/granule conglomerate with a basal layer mainly composed of pelagic bilvalves. Lithic components include various pelagic and hemipelagic lithologies but none of shallow-water origin. Obviously, the texture of the bed has been modified considerably by postdepositional pressure-solution (note tight interlocking of clasts in the coarse central layer). The internal structure suggests that the bed was emplaced by debris flow.

Marne a Posidonia (lower part); lower Middle Jurassic; Rapolano, near Podere Monte Camerini. Negative print from acetate peel; scale bar 1 cm.

Fig. 7b. Clast-supported granule conglomerate containing large lumps of slightly siliceous pelagic lime wackestone and numerous aptychi; irregularly-based upper layer of an otherwise matrix-rich debris flow deposit. The granules are invariably intraformational. Tight packing of granules is due to postdepositional compactional deformation and intergranular pressure-solution. The ragged outline of the lumps indicates that they were still soft when incorporated into the layer.

Marne a Posidonia (top); late Middle Jurassic (Callovian); Rapolano, near Podere Monte Camerini. Negative print from acetate peel; scale bar 1 cm.

Fig. 7c/d. *c:* two minor slump-sheets (each of them 50-60 cm thick) overlying thin-bedded, mainly turbiditic, red marlstones. The style of deformation in the slump-sheets suggests that the beds involved were virtually unconsolidated at the moment of slumping. *d* detail of *c:* mud pebble conglomerate resulting from thorough (phacoidal) deformation of unconsolidated sedimentary layers. The conglomerate is overlain by a plane-laminated marlstone.

Marne a Posidonia (base); Upper Liassic; Monti di Poggiano.

massive turbiditic mudstone. Based on fabric and internal structures, the deposit can be divided into two subunits, with an irregular and in places rather diffuse interface. Throughout the lower, thicker part rounded to subangular small pebbles and granules of radiolarian / pelagic bivalve mudstone to wackestone, of skeletal calcarenite (reworked current-deposited shell beds) and of silica-replaced radiolarian wackestone are "floating", dispersed or in clusters, in a commonly structureless, but sometimes fluidally structured lime-rich marl matrix. The long axes of the clasts tend to be aligned parallel to the bedding. Where the clasts are more densely packed, features are observed which indicate mutual plastic deformation during motion of the slurry and/or during compaction, and exceptionally, clasts are imbricated. In contrast, over the upper 5 to 8 cm thick part of the bed granules and sand grains make up a supporting frame that postdepositionally has been tightened further by compactional deformation and interparticle pressure-solution (Fig. 7*b*). The layer also contains abundant aptychi (Fig. 8, 11) and large mud lumps, which

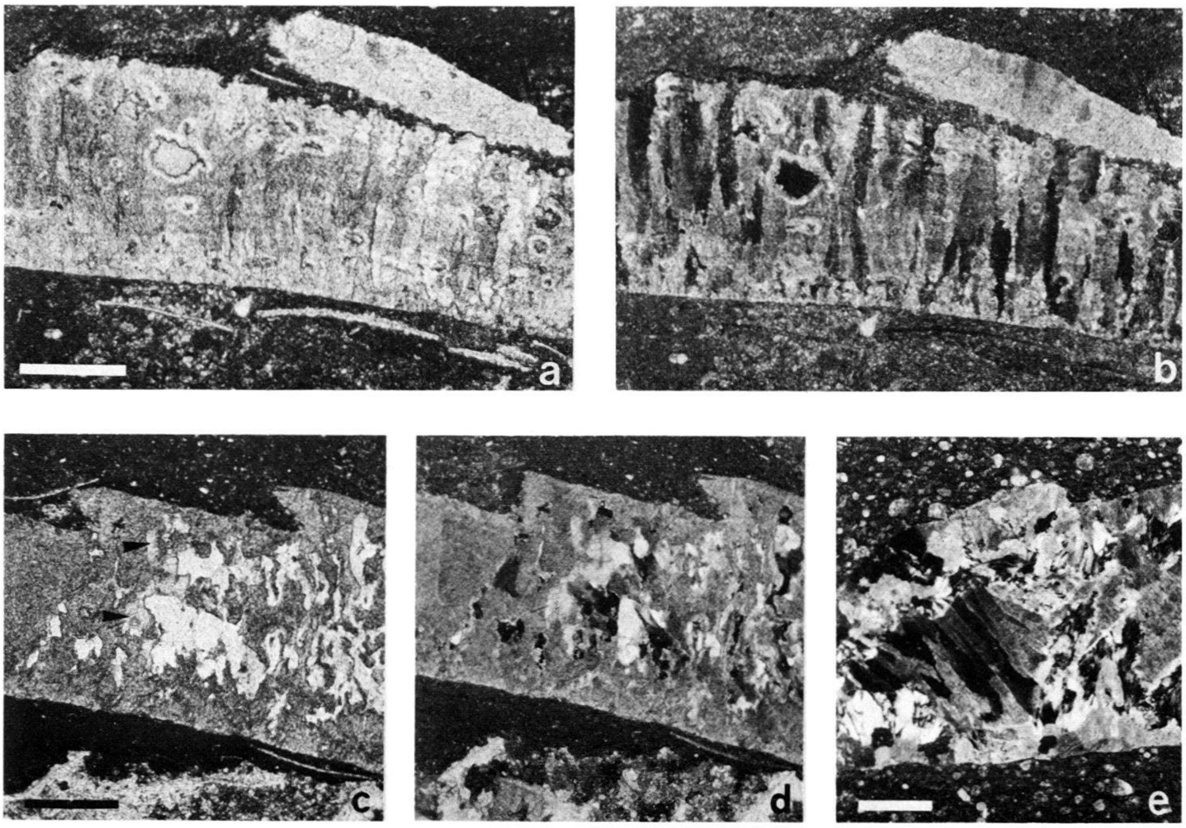

Fig. 8. Preservation of Middle Jurassic Cornaptychi.

a (normal light) and *b* (crossed nicols): bored and surficially severely corroded valve (about longitudinal section). Organic corrosion might have been aided by inorganic calcite dissolution. Irregularly bounded, fibrous calcite crystals arranged perpendicularly to the valve surface represent a recrystallization fabric, with mere relics of the original valve microstructure preserved.

c (normal light) and *d*/*e* (crossed nicols): partial silification of valves (subradial sections). The coarse calcitic recrystallization fabric is partially replaced *(c, d)* by irregularly shaped megaquartz with undulose extinction and microcrystalline quartz (arrows point to calcite crystals incipiently replaced by microquartz), or *(e)* by length-slow chalcedony.

Marne a Posidonia (top); late Middle Jurassic (Callovian); Rapolano, near Podere Monte Camerini. Thin-sections; scale bars 0.5 mm.

obviously were not lithified at all when incorporated into the clast fabric. Clast size does not vary gradationally up through this layer, but the whole size distribution, although with the coarsest percentiles prevailing, occurs over about 80% of the layer thickness and fining above is due to a rather abrupt disappearance of the granule fraction. Following this clast-supported layer, there is a sharply bounded bed, 90 cm thick, of massive red marlstone with interspersed granule- and coarse sand-sized calcilutite clasts and small, dark red shale chips, strictly aligned parallel to bedding (planar fabric). The next higher depositional unit, about 1.3 m thick, in turn, contains light-coloured marly limestone clasts varying in size from less than 1 cm to 1 m across. The embedding red marl-matrix typically exhibits a laminate structure (secondary lamination due to sediment gravity flow, "Lamellierung"; VOIGT 1962). This lamination is often picked out by thin layers with lighter shades, which in places can be seen to develop laterally from a thoroughly deformed mud pebble or stringed mud granules (Fig. 5*b*). The inference is that even the more calcareous redeposited material was only slightly consolidated prior to remobilization and that therefore small clasts tended to be sheared and to merge with the matrix during mass flow. By contrast, boulders usually have retained the primary depositional texture, except along their periphery. Lithologically they appear to compare most nearly with the massive turbiditic mudstones which are the prevailing lithology in the upper part of the Marne a Posidonia in the area.

The overall structure of these beds implies that deposition occurred through "freezing" and that transport, at least in the last stages of movement, was by debris flow (HAMPTON 1975). In this interpretation, only the occurrence of the clast-supported upper layer in the bed first described seems strange. An explanation of its origin, however, is suggested by the fact that in experiments on subaqueous debris flows sediment can be seen to be continually torn away from the frontal region ("snout") of the high-concentration wedge and thrown into a dilute suspension trailing behind the "snout" (cf. HAMPTON 1972). Presumably the competence of this suspension is not sufficient to carry the whole range of particle sizes supplied and only the finer fractions are maintained in the turbulent cloud, which finally bypasses the debris flow as a a turbidity current. Coarser particles may settle out rapidly and accumulate along the upper surface of the moving debris sheet, as competence of the flow prevents them from sinking downward.

Still in the Rapolano area, another clastic facies - namely thin-bedded (10 cm at maximum), clast-supported conglomerates - occurs sporadically in the prevalently marly, lower part of the formation. The size range of the constituent lithic components is from small pebbles (approximately 1 cm, but sometimes up to 2.5 cm in longest dimension) to coarse sand. Coarser clasts tend to have their long axes aligned parallel to the bedding. Apart from a generally higher carbonate content, the lithic material compares in large part with the formational lithologies. In addition, the detrital fraction includes rock fragments derived from the underlying Calcare Selcifero as well as clasts of a red biomicrite containing fragments of small ammonites (with the shell moulds cemented by blocky calcite), which has not been encountered elsewhere in the Marne a Posidonia of the area studied. Clast interstices in places can be seen to be filled with a clay-rich mud interspersed with shell debris of pelagic bivalves, but frequently lithoclasts are tightly interlocked due to postdepositional pressure-solution. Typically, these conglomeratic beds reveal a rather distinct internal tripartition with a poorly sorted middle layer, comprising the coarsest clasts, sandwiched between two, usually thinner and finer-grained layers (Fig. 7*a*). As in the case of the bed illustrated, the basal layer may consist essentially of bioclastic material (pelagic bivalves and, subordinately, tiny aptychi). The lower bed surface may exhibit an irregular undulate relief which is neither reflected at the top of the bed, nor at the interfaces between the different subunits, but it is levelled out in the basal layer. The upper boundary of the beds is mainly distinct, though there is commonly no parting plane, but a direct passage into a thin layer of massive marly mudstone, as it is the case in the associated thin turbidites (see above).

Because of their low matrix content and their apparently sheet-like extension we infer that these conglomerates are the products of deposition from heavily loaded basal layers of sporadic larger turbidity currents. Concentration of the coarse freight near the base of the flows and its final separation from the main current are likely to have been induced by a flattening of the slope towards the basin floor and concomitant spreading out of the turbidity current (dissipation of current energy). Tendency towards a planar clast fabric together with the internal structure of the deposits suggest that the lagging basal layers did not come to rest immediately after separation, but continued to move, at least for some short distance, by laminar mass flow - we suspect by debris flow (cf. HAMPTON 1975, p. 842). In regards to the feasibility of this transport mechanism, despite the scarcity of matrix, we consider the following two points of primary importance: 1. The generally significantly reduced specific gravity of the lithic components, due to incomplete lithification. 2. The relatively wide size distribution of the clastic material (for a discussion about the effects of sorting on competence and mobility of flowing debris see RODINE & JOHNSON 1976).

Diaspri

In the area studied, the Diaspri can be subdivided into several facies. In the following paragraphs we shall outline their distinctive features and briefly discuss the depositional processes that appear to have been involved in their formation.

Most recently, FOLK & MCBRIDE (1978) have dealt in considerable detail with the sedimentology of Ligurian radiolarites. Based on evidence gathered from numerous sections, they have concluded that deposition of the monotonous chert/shale alternations ("ribbon-bedded" radiolarite) in the Ligurian realm was largely by turbidity currents. Although the Tuscan radiolarites (Diaspri) in the sections studied by us comprise a broader spectrum of depositional facies, sediment dispersal likewise turned out to have been current-controlled over much of the sequence. Many of the inferences drawn in the following account, which was drafted before publication of FOLK & MCBRIDE's study, thus receive considerable support.

Facies A

The transition between the Marne a Posidonia and the overlying Diaspri is best exposed in the Monti di Poggiano. There is a rather gradual change in lithology and we placed the formational boundary at the base of an interval of about 6 m of thin-bedded (average 5–6 cm), variegated, highly siliceous limestones interbedded with shaly layers up to 1 cm thick. The former contain flat lenses and thin layers of vitreous chert with diffuse boundaries. Commonly in one bed several chert bands are found. Thicker interbeds, up to 15 cm, occur occasionally. In these, however, both slightly undulose bed surfaces and the irregular shape of the cherts suggest an origin by soft sediment slumping.

In thin-section, undisturbed strata appear layered internally: they consist of an alternation of centimetre-thick radiolarian-rich layers with radiolarians occasionally graded in abundance (radiolarian packstone to wackestone), and of strongly bioturbated, nearly sterile pelite divisions (Fig. 4*d*). Under the SEM the pelite is seen to be a spongy aggregate of granular microquartz enveloping calcilutite, rare fragments of thin-shelled bivalves, clay minerals and subordinate iron-bearing minerals. The vitreous chert observed macroscopically corresponds to zones in which virtually all of the original fine-grained carbonate has been replaced by silica. In contrast, the layers packed with Radiolaria are markedly depleted in silica. Radiolarian moulds are almost invariably filled by microspar or drusy sparite. The radiolarian outlines are generally badly preserved; conspicuous flattening is common and minute clay seams wrapping round the calcite-cemented moulds account for a somewhat mesh-like fabric.

As can be inferred from well preserved bioturbation structures in the silica-replaced pelite portions, diagenetic processes, such as the implied redistribution of biogenic opal, obviously did not significantly alter sedimentary features. Thus, the alternating thin layering observed is likely to be primary. Relics of a current lamination, preserved in unburrowed portions of the sediment, suggest that textural and compositional variations are due to a current-controlled sediment dispersal, rather than to cyclic changes in plankton productivity. By comparison with the genetic interpretation of the Neraida Chert in Eastern Greece by Nisbet & Price (1974), slowly moving, dilute turbidity flows, derived from intrabasinal sources, are considered as the depositional agent. Accordingly, a couplet (termed "set" by Nisbet & Price) composed of a radiolarian-rich layer and an overlying, mostly mottled pelite division (or part of it) can be interpreted as representing the basic depositional unit. A bed, defined by two shale partings, is usually composed of two to four amalgamated sets. Set thicknesses may vary considerably within one and the same bed. Variations in thickness of individual sets were found to depend chiefly upon varying thicknesses of their pelite intervals. This might imply partial reworking of already deposited cycles by subsequent flows or by a normal bottom circulation (e.g. Huang & Stanley 1972). The virtual lack of obvious erosional features between individual sets is likely to be due to obliteration by burrowing organisms, particularly as there was probably some time interval between individual flows. By contrast to the composite beds, the intervening shales are supposed to have accumulated predominantly as pelagics during long-lasting interturbiditic periods.

Facies B

The virtually carbonate-free Diaspri begin with a few metres of greenish to pale, irregularly stratified cherts interlayered with prominent turquoise to light-green shales. Bed thicknesses vary considerably, both vertically and horizontally: beds

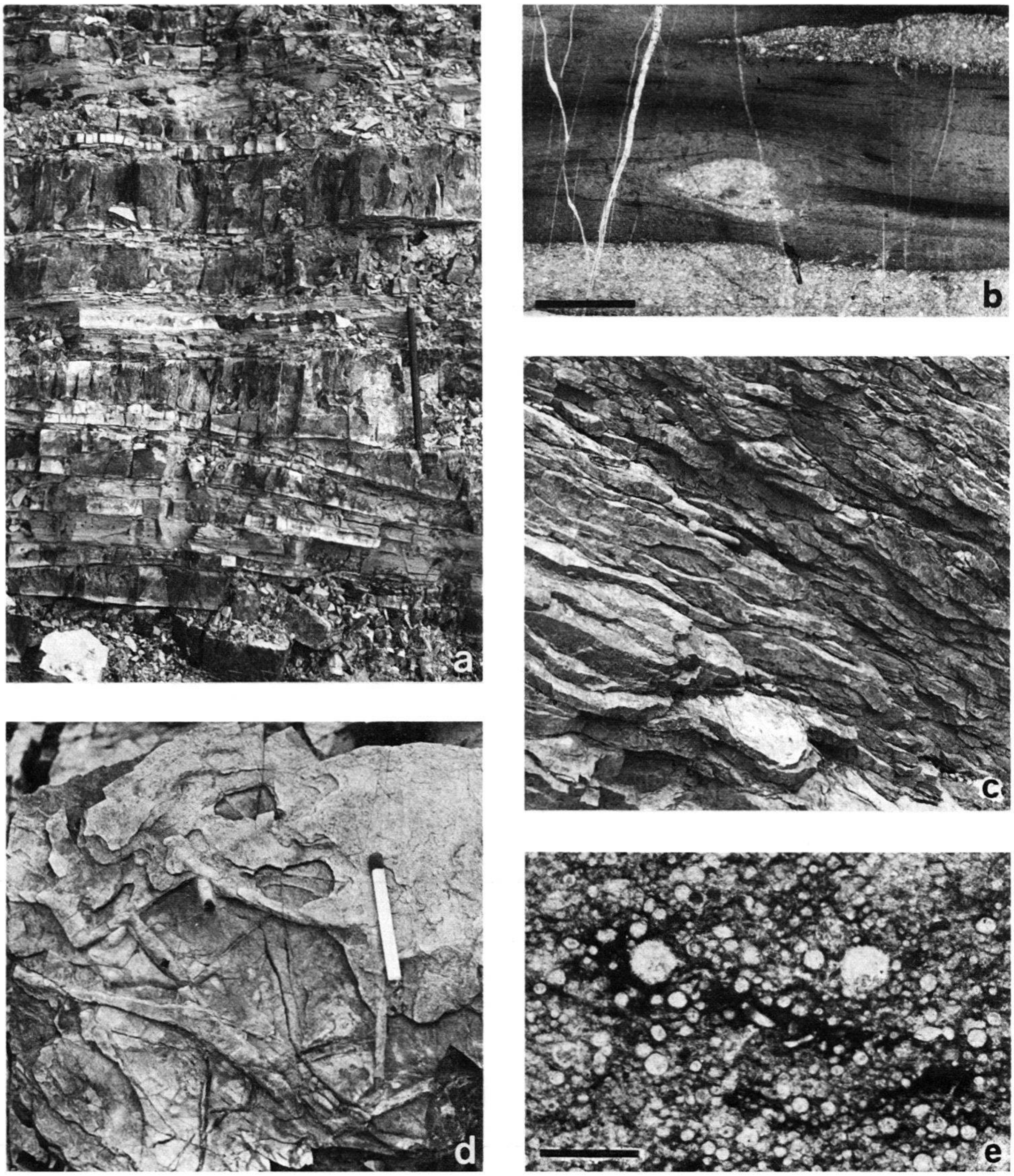

Fig. 9a. Bedding pattern characteristic of Diaspri-facies *B*. Irregular alternation of lenticular and wedge-shaped, brownish to pale green cherts and turquoise siliceous argillite. Some of the chert beds are pure, vitreous, radiolarian chert (radiolarian packstone to grainstone) with a massive appearence in thin-section; others include instead a number of alternating thin bioclastic and silicified mud laminae, poor in or free of radiolarians (cf. Fig. 9*b*). Deposition presumably has been ruled by fluctuating bottom currents.

Diaspri (facies *B*); early Upper Jurassic; Monti di Poggiano. Pencil for scale.

Fig. 9b. Internal structure of thin chert layer. Sharply bounded laminae and isolated lens-shaped concentrations of Radiolaria (mainly microquartz- or chalcedony-filled moulds) embedded in silicified clayey mud.

Diaspri (facies *B*); early Upper Jurassic; Monti di Poggiano. Thin-section; scale bar 0.5 cm.

may thicken laterally or pinch out over only a few metres or split into thinner beds (Fig. 9*a*). Close examination of some apparently continuous chert layers shows them to consist of a number of elongated lenses that replace each other laterally.

Thicker cherts usually have a massive appearance, because the internal sedimentary structures have presumably been obliterated during diagensis. Thinner strata, on the other hand, bear unequivocal evidence of current activity. They consist of irregularly alternating, light-coloured 0.5–5 mm thick laminae tightly packed with Radiolaria and brown or greenish silicified mud streaks containing little or no bioclastic material. Their colour depends on abundant inclusions of clay minerals, some questionable carbonaceous matter and authigenic iron-bearing minerals (especially pyrite). Lamination generally is well-defined, but diffuse contacts between intervals of differing composition may also occur. Such gradual boundaries are more usually found at the base of bioclastic laminae. In contrast to facies *A*, individual laminae are laterally discontinuous: they generally exhibit wedge-shaped or lenticular outlines. In short, their shape and arrangement closely resemble – on a smaller scale – the macroscopic bedding pattern illustrated by Figure 9*a*. Within the bioclastic laminae, internal depositional structures are often preserved. The most frequent one is current cross-lamination, indicating that laminae have resulted from migration of small current ripples. Traces of cross-laminae, made evident by subtle differences in sorting (e.g. size-sorted Radiolaria) are commonly slightly concave and tangential to the substratum. Cross-laminated units are either bounded by erosional surfaces and overlain by another current-laminated bioclastic layer or, more often, followed by a mud interval. Additionally, sharply defined lens-shaped concentrations of Radiolaria occur in the mud intervals between more continuous bioclastic layers (Fig. 9*b*). These most likely represent remnants of isolated (starved) current ripples formed on a cohesive mud substratum. Both the common wedging of laminae and the presence of isolated ripples suggest that current energy repeatedly slackened off during accretion; hence tractional motion and, consequently, lateral supply of bioclastic material stopped and incipient laminae became blanketed by a mud layer.

Fig. 9c. Bedding pattern of Diaspri-facies *C*. Dark-coloured (manganese oxide-stained), nodose radiolarian cherts with intervening thin argillaceous shales. Extreme irregularity of bedding is considered to be due to both strong biogenic reworking of sediment near the depositional surface and differential compaction during subsequent chertification.

Diaspri (facies *C*); Upper Jurassic; Monti di Poggiano. Hammer (centre of the photograph) for scale.

Fig. 9d. *Planolites*-burrows on the surface of a chert lens (to the right above masked by foliate, siliceous argillite).

Diaspri (facies *C*); Upper Jurassic; Monti di Poggiano.

Fig. 9e. Radiolarian chert consisting essentially of ill-defined microquartz-filled radiolarian (mainly spumellarian) moulds. Some moulds, commonly the larger and better preserved, are cemented by fibrous chalcedony. Only rarely radiolarian tests (with the original opal replaced by microcrystalline quartz) or parts of them are preserved. Dark-stained matrix is mainly haematite and clay, which occasionally fill central capsules of radiolarian tests.

Diaspri (facies *C*); Upper Jurassic; Monti di Poggiano. Thin-section; scale bar 0.5 mm.

In a study on Tertiary deep-water sediments cored during DSDP Leg 28 (Antarctica) PIPER & BRISCO (1975) list a number of arguments for the deposition of abundant silt laminae at Site 268 by bottom rather than by turbidity currents. Textural and structural properties of our examples match well the criteria established by these authors. Consequently, we interpret laminar concentrations of radiolarian skeletons as being due to winnowing bottom currents and suppose sediment distribution and deposition, in this facies, to be controlled largely by a fluctuating bottom circulation. This, in turn, suggests that the markedly irregular bedding pattern seen in outcrop (Fig. 9*a*) still reflects primary, depositional features and is not merely the product of diagenetic processes.

Facies C

Up-section, facies *B* passes gradually into about 10 m of nodose red or dark-coloured radiolarian chert. Single strata are bounded by irregularly undulating surfaces, which laterally merge over, at most, a few metres (Fig. 9*c*). These undulations show varying wavelengths and their amplitudes range from only some millimetres to several centimetres; they form either broad, smooth ridges or prominent rounded domes and knobs. The cherts are interbedded with argillaceous shales, but in this case the interbeds are usually thin and may even be reduced to paper-thin partings.

Besides this particular type of stratification, deformative as well as figurative bioturbation structures are another striking feature of this facies. The cherts generally display a bioturbate texture with no relics of any diagnostic physical sedimentary structure. Radiolarian tests in largely varying states of preservation are unevenly distributed through the sediment (Fig. 9*e*). Typically they are concentrated in randomly scattered nests defined by weakly translucent, silicified, ferruginous mud stringers. Occasionally the boundaries between compositionally differing zones seem to have been accentuated during diagenesis, most likely by recrystallization processes related to chertification (e.g. LANCELOT 1973). Pervasive burrowing, as inferred from the recorded textural inhomogeneity, points to a slow accumulation in an environment devoid of substantial current reworking.

By contrast, structured burrows and trails are restricted to the bed surfaces, where they occur both as epichnial and hypichnial ridges. Irregularly branching burrows with a subcircular section of a few millimetres diameter are dominant; they are referable to *Planolites* (Fig. 9*d*). In addition, tunnels of up to 3 cm diameter have been found; these typically show *Y*-shaped (Thalassinoides-type) branching. A biogenic origin is also assumed for isolated circular mounds occasionally present on the upper surfaces of chert layers. Larger mounds, up to 10 cm in diameter, contain a central pit. Morphologically similar structures have been reported from other ancient siliceous deposits (e.g. MCBRIDE & THOMSON 1970, p. 69 and Plate 18, Fig. B) and are also known to be a rather common feature of biogenically reworked present day sea-floors (e.g. HOLLISTER et al. 1975, Fig. 21/17; HUANG & STANLEY 1972, Fig. 6, p. 532). The Recent examples are generally referred to a still unknown bottom-dwelling organism.

The occurrence of figurative bioturbation structures along the chert/shale interfaces suggests that such interfaces record primary compositional discontinuities. Accordingly, the nodose bedding pattern of this facies is likely to reflect neither a purely diagenetic segregation of an originally homogeneous deposit, nor a penecontemporaneous deformation structure related to gravity sliding or slumping (cf. p. 724), but to be based upon a primary stratification. There is, however, evidence for considerable postdepositional alteration of the original bed geometry. Such evidence includes minor tensional cracks which occasionally were found to incise dome-shaped bed surface irregularities. Contrary to septarian cracks, which typically are widest in the center of a concretion and die out towards its periphery, these fractures invariably widen towards the bed surface. On larger bulges, they occasionally form a spider's web-like pattern cutting through epichnial burrow systems. Narrow veins are completely filled by length-fast chalcedony (cf. Fig. 9*b* in WISE & WEAVER 1974). Broader cracks, on the other hand, may display complex fillings: they often are merely lined by fibrous chalcedony, whilst the central space is filled by silicified argillite (Fig. 10*a*). The inference is that soft mud from the overlying argillaceous interbed entered open cracks. This implies that fracturing occurred prior to final consolidation of the rock and we agree with WISE & WEAVER (1974) and E.F. McBride (1977, pers. comm.) who relate it to differential compaction during burial diagenesis[6]). Accordingly, one is led to conclude that, in a given horizon, chertification of the initial siliceous ooze did not proceed uniformly, but occurred through accretion around some scattered, early formed nodule nuclei, in analogy with current models of chert-nodule formation in carbonate rocks (e.g. WISE & WEAVER 1974, HSÜ 1976).

The stages of development of nodose radiolarites could then be as follows:

1. Under conditions of very slow and discontinuous accretion of sediment in a well oxygenated environment, intensive biogenic reworking results in both an inhomogeneous texture and an uneven spatial distribution of the sediment in each respective surface layer. The latter is suggested by the irregularly moulded depositional surfaces seen on bottom photographs from pervasively burrowed, slowly accreting present day sea-floors.
2. After some burial, increasing concentration of dissolved biogenic silica in the pore fluid leads to the formation of sporadic chert-nodule nuclei by precipitation of a diagenetic silica phase (most probably disordered cristobalite) within preserved opaline microfossil tests and interstices. Nuclei probably develop selectively at sites differing from the surrounding sediment either by their higher initial porosity and permeability (e.g. VON RAD & RÖSCH 1974, LANCELOT 1973) and/or by the presence of residual organic matter (e.g. BERGER 1974). Creation of such local differences in texture and/or composition conceivably could be related to bioturbation.

[6]) This observation differs from LANCELOT's findings (1973, p. 398) in Cretaceous and Lower Tertiary brecciated cherts from the Central Pacific: LANCELOT never found sediment-filled veins and thus timed such fracturing later in diagenesis.

3. Chert nodules and lenses develop by accretion around nuclei, with dissolved silica being supplied across a concentration gradient in the interstitial fluid (cf. Hsü 1976). Contemporaneously, load compaction starts to affect differentially the already cemented nodules together with the residual soft or merely slightly lithified sediment, and as a consequence "diagenetic cracks" (e.g. Fig. 10*a*) may form locally. (On the other hand, in carbonate rocks differential compaction usually does not significantly influence the final bed geometry since, concomitant with chert-nodule growth, calcite cementation proceeds within the host rock, with part of the cement being represented by calcium carbonate expelled in the course of chert growth; e.g. Wise & Weaver 1974.)
4. Chertification is completed by lateral coalescence of nodules and lenticular chert bodies to form more continuous layers. Finally, lithification of the argillaceous partings takes place.

In conclusion, we envisage differential compaction, due to contrasts in competency originating within the sediment during chertification, as accounting primarily for the nodose bedding observed in this facies. Such development, however, has very likely been assisted by the presence of a primary irregularity of the bedding resulting from strong biogenic reworking. Moreover, we suspect that, at least locally, diagenetic processes have merely accentuated a primary microtopography of the sea-floor.

Facies D

The nodose radiolarites are overlain by markedly even-bedded, locally slightly calcareous, varicoloured or dark cherts rhythmically interlayered with turquoise to pale green, fissile siliceous argillite (cf. facies *B*). Up-section, this facies grades into the increasingly more calcareous lithologies of the Rosso ad Aptici (see below).

In the Rapolano area where facies *D* is most typically developed (Fig. 10*d*), the chert/shale ratio lies between 3:1 and 4:1. The thicknesses of the chert beds range from 5 to 10 cm, but they group mainly round the lower value. The chert beds are inhomogeneous; they consist of laterally continuous bands of reddish to grey-green, calcareous granular chert and more intensely coloured, dark-red to brown-grey vitreous chert. Vitreous chert commonly is confined to one or exceptionally two bands in the central part of a bed (dark strips in outcrop photograph Fig. 10*d*). Boundaries between vitreous and granular layers are usually vague and irregular. Many cherts are found to contain minor sedimentary structures suggesting current activity and, moreover, the suite of internal structures observed in some thicker beds strongly infers deposition from turbidity currents.

On a microscopic scale, Radiolaria appear as the main constituent of these rocks. They are poorly preserved and with few exceptions they lack original wall structures. Moulds which are filled either by microcrystalline or fibrous chalcedonic quartz or, in some cases, by a calcitic cement, show various degrees of flattening, obviously depending on the extent of compactional deformation before cementation. At the base of some thicker beds, Radiolaria are mixed with coarser, partly silicified, calcareous skeletal debris (pelagic bivalves and/or *Saccocoma*). The fine-grained portion of the sediment is composed mainly of microquartz (replacing carbonate), calcilutite and clay minerals. Tiny dolomite rhombs occur scattered through the vitreous chert and small amounts of finely dispersed, minute particles of iron and/or manganese oxides and hydroxides, or pyrite and some possible remains of organic material account for staining.

Vitreous chert bands presumably developed preferentially along layers originally composed essentially of radiolarian tests. However, depositional textures (varying from radiolarian packstone to wackestone) usually are preserved only in a few patches scattered through large areas where most radiolarian moulds lack well-defined outlines or even have melted into light-coloured stringers of microquartz, with complete loss of the original grain fabric. In stained zones, the original presence of a matrix is suggested by the distribution of pigments.

In contrast, dull granular chert tends to mark mud-supported textures as well as intervals with an admixture of coarser, originally calcareous skeletal debris. The granular chert contains virtually all the carbonate, which accounts for an average carbonate content of up to 20% in certain beds. Under the SEM and in thin-section the granular chert appears to consist of a framework of aggregated, locally tightly intergrown quartz microgranules (cf. facies *A*) which encloses calcite-cemented radiolarian moulds, residual calcipelite, clay flakes and iron-bearing minerals.

X-ray diffractometer analysis shows the clay component of the interlayered shales to consist entirely of illite (muscovite), possibly with traces of chlorite. The quartz recorded on diffractometer traces seems to be finely dispersed throughout the shale. No unbroken radiolarian skeletons and only negligible amounts of skeletal debris have been found in sieved samples.

As mentioned above, there is striking evidence, mainly in the thicker beds, that these have been deposited by turbidity currents: the suite of their internal structures conforms perfectly to the Bouma sequence. Besides radiolarians, the bottom division of such beds commonly contains ghosts of coarser calcareous skeletal fragments and questionable sponge spicules. No bottom marks have been noted. Alignment of coarser skeletal grains may result in a few faint horizontal laminae in the basal few millimetres of a bed. A rapid upward decrease in size and abundance of the coarser bioclasts suggests some sort of grading. The main portion of the *A* division, however, is usually represented by a dark-stained, poorly resolvable mass of fused Radiolaria (vitreous chert), passing up into a distinctly parallel-laminated interval (*B* division) of alternating dark and light laminae (Fig. 10*b*). Individual laminae are a few radiolarian diameters thick. Colour mottling observed in the succeeding division (*C*) can be shown by *x*-ray radiography to be due to convolution, with single deformed low-angle cross-laminae being locally discernible. Across this interval finer particles, chiefly silica-replaced calcipelite and some questionable radiolarian debris, substitute gradually for Radiolaria. Correspondingly there is a transition from vitreous into granular chert. Furthermore *x*-ray radiographs reveal a delicate, irregularly spaced plane parallel-lamination (*D* division) in the topmost part of such chert beds. The finest fractions laid down by the turbidity currents (*E* division) consequently have to be contained in the accompanying siliceous shales.

By contrast, none of the thinner chert layers investigated exhibits the complete Bouma cycle, nor can the majority of them be simply labelled as base-cut-out Bouma sequences, although faint cross-laminations, including occasional minor

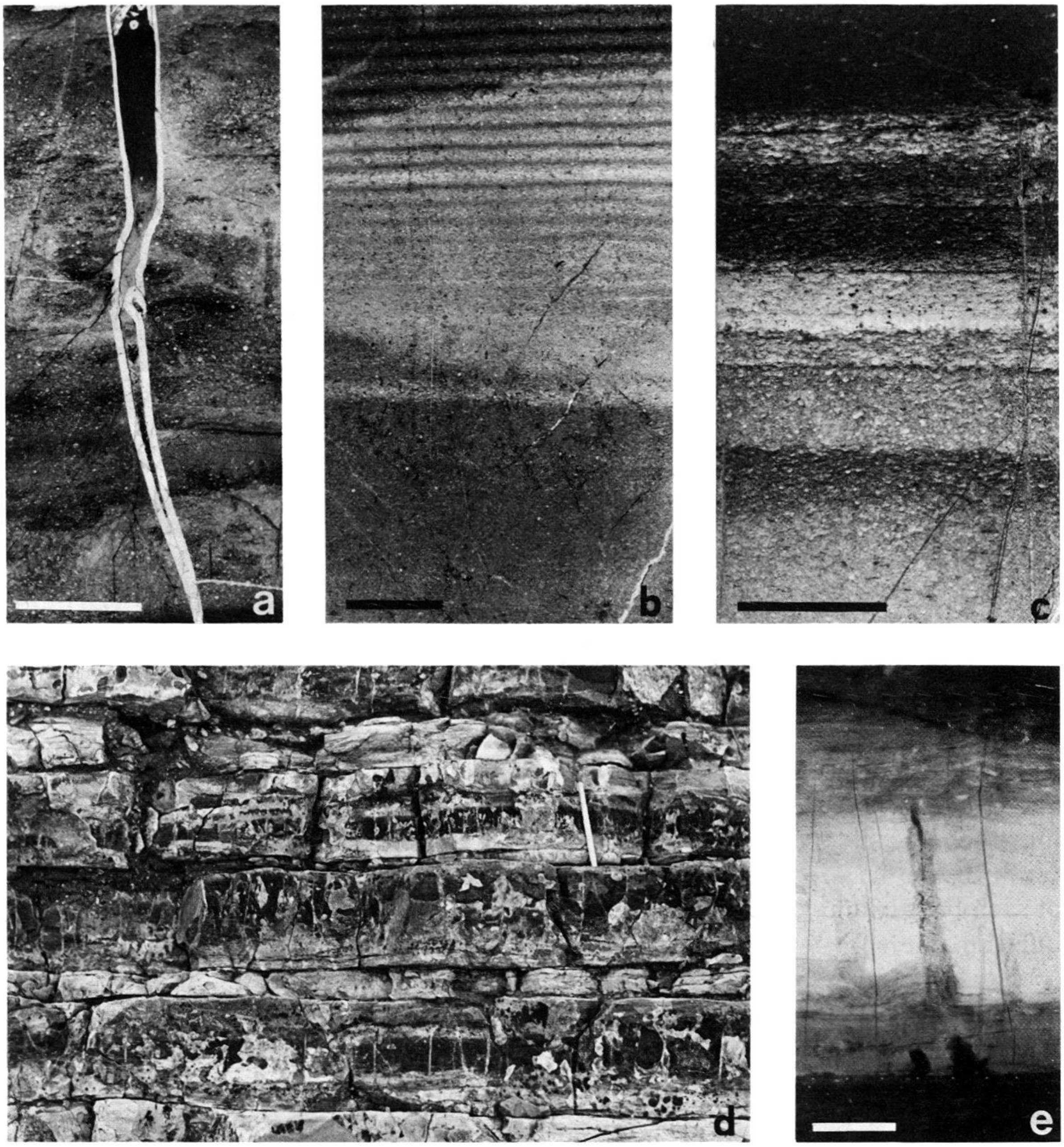

Fig. 10a. Sediment-filled, diagenetic, tensional crack incising a dome-shaped bulge at the upper surface of a radiolarian chert bed. Crack development may be reconstructed as follows: 1. Formation of a tensional fracture due to inhomogeneous compactional deformation of an unevenly consolidated sedimentary layer. 2. Incipient parting of fracture walls and simultaneous cementation of the arising fissure by length-fast chalcedony, with single incremental stages (thin seams of fibres oriented perpendicularly to the fracture) defined by sutures of included iron-bearing minerals, which are roughly parallel to the fracture walls (not discernible at the scale of the photograph). Within the seam contiguous to the fracture walls chalcedony fibres occasionally are found to be in optical continuity with components of the wall rock, such as radiolarian mould fillings (syntaxial overgrowth). 3. Progressive divergence of fracture walls; cementation (fibre growth) cannot keep up with divergence and, hence, overlying soft or merely slightly consolidated argillaceous mud can enter the crack. A continuous downward-increase of the overall thickness of the chalcedony rim suggests, that the crack did not open (and fill) along its full length all at once, but gradually from top to bottom (larger, light-coloured particles at the very top of the crack-

convolutions, and horizontal laminations (Fig. 10*c*) appear to be quite common. Rather, different structural units tend to be repeated irregularly, thereby composing various types of beds, most of which are, in detail, difficult to interpret. However, some beds turn out to be made up of the load deposited by several intermittent small-scale suspension flows, on account of obvious internal amalgamation features. In other cases the structural sequence observed is more likely to reflect an oscillatory decline of energy in a single depositing current (cf. HESSE, VON RAD & FABRICIUS 1971). Still other types could possibly have resulted from partial reworking of a turbiditic layer by normal bottom currents (cf. HUANG & STANLEY 1972).

Further evidence that even thinner chert beds consist predominantly of rapidly deposited, most likely turbiditic units is provided by the spatial distribution of organic sedimentary structures. In the studied samples, strong, destructive bioturbation, indicated by a mottled structure with burrows flattened during early compaction, appears to be confined to rather discrete horizons. Generally, the upper 1 or 2 cm of a chert bed are strongly affected by burrowing, whereas in the lower parts even delicate primary bedding features are preserved. However, additional mottled horizons may occur in certain beds. For instance, beds with a strikingly symmetrical aspect in outcrop, appear to owe their symmetry to the presence of a mottled layer both at the top and the bottom with an intervening, virtually undisturbed, current-laminated unit between. From thin-sections and radiographs (Fig. 10*e*) it can be seen that the lower reworked horizon has a truncated top, which, as a textural

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filling are chalcedony; presumably fragments of the cement lining the fracture walls, split off and squeezed into the sediment-filled crack during continued compactional deformation of the rock).

Diaspri (facies *C*); Upper Jurassic; Monti di Poggiano. Thin-section; scale bar 0.5 cm.

Fig. 10b. Upper part of *A* division and distinctly plane-laminated *B* division of a complete Bouma cycle, 9 cm thick. Vitreous chert, composed essentially of microcrystalline quartz, with a relict texture suggesting that radiolarian tests did originally represent the main constituent of the sediment. Dark tinge is due to included clay, pyrite and possible remains of organic material. Light-grey patch is red-stained by finely dispersed haematite.

Diaspri (facies *D*); Upper Jurassic; Rapolano, along state road. Thin-section; scale bar 0.5 cm.

Fig. 10c. Irregularly spaced plane lamination in vitreous radiolarian chert passing upwards into massive, sligthly calcareous radiolarian mudstone (granular chert). Vitreous chert reveals relict textures of radiolarian packstone to wackestone. Gradational colour change in the lowermost lamina is probably due to radiolarians originally graded in abundance.

Diaspri (facies *D*); Upper Jurassic; Rapolano, along state road. Thin-section; scale bar 0.25 cm.

Fig. 10d. Bedding pattern of Diaspri-facies *D*. Alternate thin bedding of slightly calcareous grey-green granular chert with bands of vitreous chert (dark-coloured) and turquoise siliceous argillite. The prime depositional mechanism inferred from minor sedimentary structures and relict textures is turbidity flow.

Diaspri (facies *D*); Upper Jurassic; Rapolano, along state road. Match for scale.

Fig. 10e. Animal traces (escape-traces) piercing a fastly emplaced, most probably turbiditic unit (note sharp lower contact and traces of faint current lamination preserved in its lower part) between two mottled layers. Mottled layers (radiolarian wackestone) are slightly calcareous, dull granular chert, whereas the current-laid unit in between is a band of vitreous radiolarian chert (sharply defined, vertical dark lines cutting the vitreous chert are tectonic fractures).

Diaspri (facies *D*); Upper Jurassic; Rapolano, along state road. Negative print from *x*-ray radiograph of very thin slab; scale bar 1 cm.

boundary, also coincides with a change from granular chert below to vitreous chert above. In the laminated unit above this contact, bioturbation is restricted to isolated, distinct traces. Both scattered, elliptical burrow cross-sections and occasional upward-piercing, nearly vertical traces - possibly escape-traces - are usually visible. In the upper part of such a current-laminated, central unit primary sedimentary features disappear gradually as a result of increasing burrow density.

The nature and importance of the "autochthonous", (hemi)pelagic sediment presents an intriguing question. Sedimentological evidence yields no conclusive clues. Interturbiditic mud might be comprised in the top most part of the argillitic interlayers which, however, for their greater part are the fines (*E* Bouma division) deposited from the low-density tail of the foregoing turbidity current. Or, the (hemi)pelagic interval might be represented by the above-mentioned, erosionally cut mottled layers occasionally recognized at the base of chert beds. Even a combination of the two foregoing possibilities is conceivable. Then, the lower surface of probably many beds would represent a mere diagenetic boundary, developed somewhere within the (hemi)pelagic division beneath a current-laid unit. In any case, the chert/shale repartition actually observed (Fig. 10*d*), neither reflects directly the original proportion of redeposited and "autochthonous" (hemi)pelagic sediment, nor is it an accurate indication of individual depositional events. Nevertheless, the supposed prime depositional process of this facies - that is turbidity currents - can be inferred in outcrop from the markedly smooth and regular stratification.

Rosso ad Aptici

As pointed out in the introductory remarks to this study, in Southern Tuscany there is usually an intervening unit of aptychus-bearing siliceous limestones and marls between the carbonate-poor radiolaritic deposits and the light-coloured nannofossil limestones of the Maiolica, as is the case in the Lombardian zone of the Southern Alps. The term "Rosso ad Aptici" applied in the Southern Alps, is thus used here for these transitional beds, which traditionally have been included in the Diaspri.

The Rosso ad Aptici is well-developed both in the Monti del Chianti (Cintoia) and in the Rapolano area (10 to 12 m and about 15 m respectively), but is reduced to 5 m approximately in the Monti di Poggiano. Aptychi recovered from various horizons within the Rosso ad Aptici support a Tithonian age (see below).

In the Poggiano section the Rosso ad Aptici is represented by a sequence of thin-bedded yellowish siliceous limestones with layered chert and interbedded purple shales. Radiolarians, generally appearing as microquartz- or chalcedony-filled moulds embedded in a matrix of calcilutite and clay, still are the dominant faunal element; only in the upper part of the sequence do numerous *Stomiosphaera, Globochaete, Saccocoma* ossicles, some aptychi and rare calpionellids associate with them. Relict textures suggest that cherts have developed along layers or laminae originally enriched with radiolarians by some method of sedimentary sorting (cf. Diaspri facies *B, D*).

The Rosso ad Aptici exposed along the road section east of Rapolano is more heterogeneous lithologically: Above the well-bedded upper part of the Diaspri there are about 4 m of seemingly poorly bedded purple siliceous marls. Looked at more closely, these marls reveal a thin, yet irregularly spaced layering with layers rich and poor in radiolarians which, in turn, yields evidence for a spasmodic accretion through turbidity currents (cf. Diaspri facies *A*). Radiolarian-rich layers, ranging in thickness from a few millimetres to several centimetres typically are graded by an upward decrease in abundance of radiolarians. In addition, radiolarians often decrease perceptibly in mean size up through a layer, and sometimes gradations are superimposed with a faint and laterally impersistent lamination. Radiolarians are almost invariably replaced and/or cemented by calcite. Mudstone layers, composed of haematitic clay, micrite, microcrystalline quartz and only a few scattered radiolarians, in large part develop gradationally from a bioclastic layer, and become increasingly bioturbated upward. Frequently, even the lower boundary of a successive graded bioclastic layer is blurred as a result of burrowing, but only rarely are traces found to extend further into or even across graded divisions (escape traces, cf. Diaspri facies *D*).

The sequence continues over a few metres with light grey, slightly siliceous, marly lime wackestones and intercalated thin red marl-layers. Stratification (5–10 cm) is indistinct, as the two lithologies commonly merge gradually into each other. Silt- and sand-sized components of the marly limestone include radiolarians (mainly calcite-filled moulds), *Stomiosphaera*, fragments of small aptychi and microbioclastic hash, presumably derived in large part from the planktonic crinoid *Saccocoma;* coccoliths are common in the groundmass. By contrast, in the red marly intervals Radiolaria clearly prevail. A strong bioturbation, having obliterated primary depositional structures and textures throughout, impedes genetic interferences to be drawn about alternate bedding. The lithological differentiation might either reflect variations in the accumulation rate and the consequent differential effect of carbonate dissolution (cf. p. 732), or an essentially diagenetic segregation.

The main distinctive features of the upper half of the Rosso ad Aptici in the Rapolano section are the presence of layered and nodular red cherts, and a more regular and quite distinct bedding. Constituent lithologies comprise pink to light-coloured more or less marly limestones (microbioclast mudstones to wackestones), usually with a mottled structure, and dark-red clayey marls. Macrofossils are restricted to aptychi and rare belemnites. In this upper part of the Rosso ad Aptici, Radiolaria markedly decrease in abundance; conspicuous concentrations merely occur in the lower structural divisions of occasional intervening turbiditic layers.

In the sections studied, the Rosso ad Aptici / Maiolica transition is never gradational, but always the aptychus beds are overlain by a sheet of slumped Maiolica limestone (cf. Fig. 2). Based on the calpionellid associations in the uppermost part of the Rosso ad Aptici [*Crassicollaria parvula* REMANE, *Crassicollaria massutiniana* (COLOM) and in the slumped beds in the basal part of the Maiolica respectively [*Calpionella alpina* LORENZ, *Calpionella elliptica* CADISCH, *Calpionellopsis oblonga* (CADISCH), *Tintinnopsella carpathica* (MURG. & FILIP.) and very rare, obviously reworked, specimens of *Crassicollaria*] the unconformable formational contact appears to include the Jurassic/Cretaceous boundary, with a possible minor stratigraphic gap.

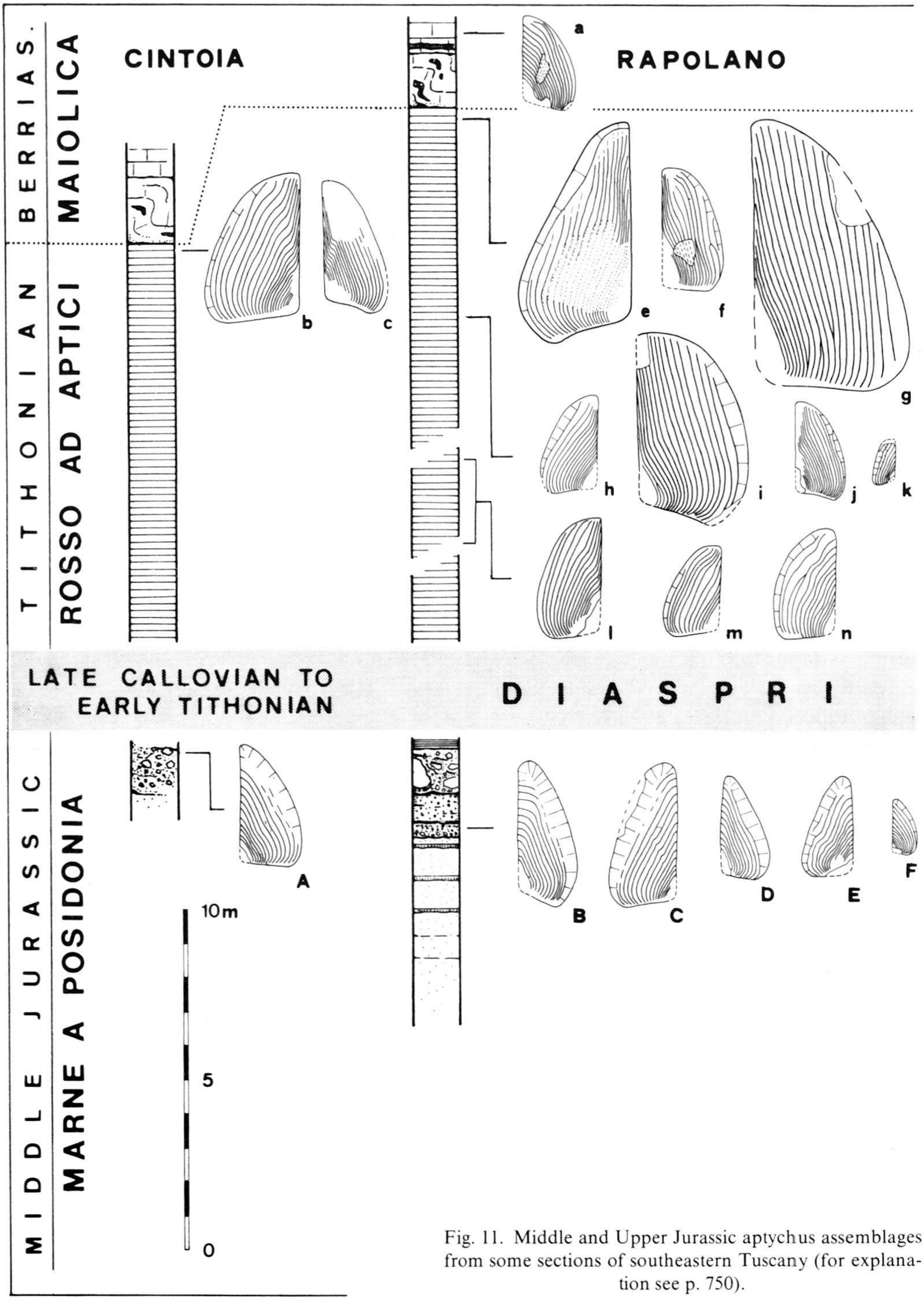
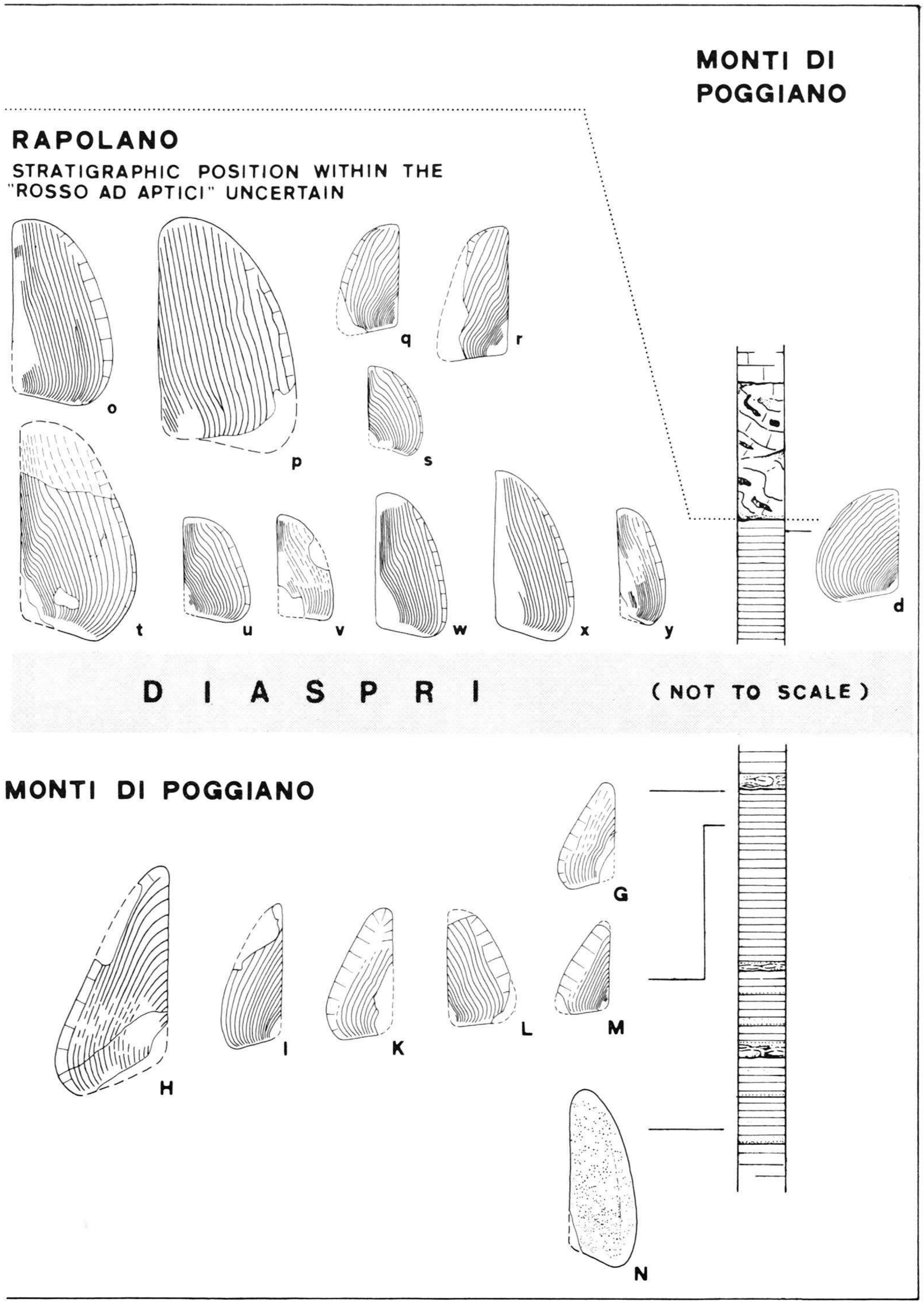


Fig. 11. Middle and Upper Jurassic aptychus assemblages from some sections of southeastern Tuscany (for explanation see p. 750).


MONTI DI POGGIANO
RAPOLANO
STRATIGRAPHIC POSITION WITHIN THE "ROSSO AD APTICI" UNCERTAIN
o
p
q
r
s
t
u
v
w
x
y
d
D I A S P R I
(NOT TO SCALE)
MONTI DI POGGIANO
G
H
I
K
L
M
N

Explanations to Figure 11

Middle Jurassic (Callovian)

A *Cornaptychus* cf. *rapolanus* n.sp., J28388; Cintoia; 1×.

B *Cornaptychus* cf. *rapolanus* n.sp., J28360 (see Fig. 12*d*); Rapolano; 1×.

C *Cornaptychus rapolanus* n.sp., J28359; holotype (see Fig. 12*a, b*), Rapolano, 1×.

D *Cornaptychus rapolanus* n.sp., J28383 (see Fig. 12*e, o*); Rapolano; 1×.

E *Cornaptychus* cf. *rapolanus* n.sp., J28382 (see Fig. 12*f*); Rapolano; 1×.

F *Cornaptychus rapolanus* n.sp., J28387; juvenile; Rapolano; 1×.

G *Cornaptychus* cf. *hectici* (QUENSTEDT), J28358 (see Fig. 12*i*); Monti di Poggiano; 1×.

H *Cornaptychus hęctici* (QUENSTET), J28384; compare TRAUTH (1930, Pl. 3, Fig. 8); Monti di Poggiano; 1×.

I *Cornaptychus hectici* (QUENSTEDT), J28381; Monti di Poggiano; 1×.

K *Cornaptychus* cf. *hectici* (QUENSTEDT), J28357 (see Fig. 12*g*); Monti di Poggiano; 1×.

L *Cornaptychus hectici brevis* TRAUTH, J28355; Monti di Poggiano; 1×.

M *Cornaptychus* cf. *hectici* (QUENSTEDT), J28356 (see Fig. 12*h, p*); Monti di Poggiano; 1×.

N *Cornaptychus toscanensis* n.sp., J28386; holotype (see Fig. 12*k, l*); Monti di Poggiano; 1×.

Tithonian

b *Lamellaptychus beyrichi subalpinus* (SCHAFHÄUTL), J28338; Cintoia; 1×.

c *Lamellaptychus beyrichi fractocostatus* TRAUTH (1938, Pl. 10, Fig. 10), J28396; Cintoia; 1×.

d *Lamellaptychus* sp., J28397; presumably related to *Lamellaptychus inflexicostatus latus* TRAUTH (1938, Pl. 12, Fig. 6); Monti di Poggiano; 1½×.

e *Punctaptychus triangularis* n.sp., J28351; holotype (see Fig. 12*m, n*); Rapolano; 1×.

f *Lamellaptychus* cf. *submortilleti* TRAUTH, J28342; Rapolano; 1½×.

g *Lamellaptychus rectecostatus* (PETERS), J28350; compare QUENSTEDT (1846-9, Pl. 22, Fig. 26*a*); Rapolano; 1×.

h *Lamellaptychus* cf. *submortilleti* TRAUTH (1938, Pl. 10, Fig. 25), J28343; Rapolano; 1½×.

i *Lamellaptychus* cf. *rectecostatus* (PETERS), J28346; transition to *Lamellaptychus beyrichi;* Rapolano; 1×.

j *Lamellaptychus beyrichi* (OPPEL), J28344; Rapolano; 1½×.

k *Lamellaptychus* ? *lamellosus* (PARKINSON), J28345; juvenile, compare TRAUTH (1938, Pl. 11, Fig. 3); Rapolano; 1½×.

l *Lamellaptychus* cf. *submortilleti* TRAUTH, J28333; Rapolano; 1×.

m *Lamellaptychus* cf. *submortilleti* TRAUTH, J28339; juvenile; Rapolano; 1½×.

n *Lamellaptychus* sp., J28340; Rapolano; 1×.

o *Lamellaptychus* cf. *rectecostatus* (PETERS), J28341; ? transition to *Lamellaptychus beyrichi;* Rapolano; 1½×.

p *Lamellaptychus rectecostatus* (PETERS), J28334; Rapolano; 1×.

q *Lamellaptychus* cf. *submortilleti* TRAUTH, J28349; Rapolano; 1½×.

r *Lamellaptychus* cf. *submortilleti* TRAUTH, J28336; Rapolano; 1½×.

s *Lamellaptychus* cf. *submortilleti* TRAUTH, J28347; Rapolano; 1½×.

t *Lamellaptychus beyrichi* (OPPEL), J28394; Rapolano; 1×.

u *Lamellaptychus beyrichi* (OPPEL), J28348; Rapolano; 1½×.

v *Lamellaptychus* cf. *beyrichi* (OPPEL), J28352; Rapolano; 1×.

w *Lamellaptychus* cf. *beyrichi* (OPPEL), J28331; Rapolano; 1×.

x *Lamellaptychus beyrichi* (OPPEL), J28332; Rapolano; 1×.

y *Lamellaptychus beyrichi longus* TRAUTH (1938, Pl. 10, Fig. 14), J28354; Rapolano; 1×.

Berriasian

a *Lamellaptychus* cf. *aplanatus* (GILLIÉRON), J28335; Rapolano; 1½×.