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## Depositional model for calcilutites: Scaglia Rossa limestones, Umbro-Marchean Apennines

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**SUMMARY:** The calcilutites of the mid-Cretaceous to uppermost Eocene Scaglia Rossa Formation in Italy have previously been interpreted as a continuous sequence of slowly deposited pelagic limestones. However, regional considerations of thickness, sedimentation rates and facies distribution, together with detailed analysis of composition, texture and sedimentary structures suggest that turbidity currents have played an important part in the deposition of, at least, the middle (Maastrichtian) member. Turbiditic calcilutites are very fine-grained and massive, whereas the pelagites are coarser-grained, mottled and bioturbated. There is, however, a continuous gradation of facies and processes between these two end-members, that we believe is applicable to many other modern and ancient deep-water carbonate systems. The common overlap of turbiditic and pelagic processes in fine-grained 'pure' carbonates arises partly from their relative lack of flocculation compared with muddier sediments.

The Umbro-Marchean Apennines of central Italy comprise Mesozoic and Cenozoic sediments that have been crumpled into large open folds and broken by normal faults. The anticlines raise topographically more resistant Mesozoic limestones above easily eroded Tertiary clastics in the flanking synclines (Fig. 1). This has resulted in long NW-SE trending mountain ridges through which antecedent rivers flowing to the Adriatic have cut deep gorges and exposed good sections.

In common with other Tethyan areas, the region evolved from a carbonate shelf in the early Mesozoic, to a series of carbonate basins and platforms active from the Jurassic to Palaeogene, that were finally levelled and filled by Miocene clastics. The whole area is probably parautochthonous (Bortolotti *et al.* 1970).

We have concentrated in this paper on part of the basin-platform system of late Cretaceous-Palaeogene age, the Scaglia Rossa Formation. This is between 200 and 400 m thick and comprises dominantly limestones, with interbedded marlstones, shales and cherts. A small part of the Scaglia Rossa at Gubbio (Fig. 1) has recently been the subject of detailed lithostratigraphic, biostratigraphic and magneto-stratigraphic studies and has been designated as the type section for the late Cretaceous-Palaeocene geomagnetic reversal time-scale (Alvarez *et al.* 1977). This area is also well known for the controversy surrounding a supposed high-iridium anomaly at the Cretaceous-Tertiary boundary and its implication for asteroid impact and Mesozoic extinctions (e.g. Alvarez *et al.* 1980; Wezel *et al.* 1981).

There has been a further controversy in previous papers over the age and depositional processes of the Scaglia Rossa limestones (e.g.

Alvarez & Lowrie 1981; Wezel 1981). In particular, studies of the section near Gubbio have emphasized the pelagic nature of the limestones (Arthur 1976; Arthur & Fischer 1977), whereas more extensive studies throughout the Umbria-Marchean Apennines have pointed to the turbiditic character of much of the Scaglia Rossa (Wezel 1979).

We have therefore examined in greater detail the sedimentology of the fine-grained facies throughout the area of outcrop of the Scaglia Rossa, with a view to evaluating the conflicting evidence on the processes by which the sediments were deposited. Careful field observation, measurement and sampling has been followed-up by thin section petrography, X-ray diffraction and X-radiography of thin rock slices.

### Stratigraphy

The mainly rose-coloured limestones and associated sediments of the Scaglia Rossa formation straddle the Cretaceous-Tertiary boundary from the mid-Turonian to uppermost Eocene (Fig. 2; Renz 1936; Luterbacher & Premoli Silva 1964; Premoli Silva *et al.* 1976). In most parts of Umbria, the dark organic-rich fissile shales and lighter-coloured marls of the Aptian-Albian Marne a Fucoidi Formation pass conformably up into grey, greenish and whitish limestones and dark cherty black shales of the Scaglia Bianca Formation. These extend into the early Turonian and appear to be conformably overlain by the Scaglia Rossa. However, on the east coast at Mount Conero the upper part of the Marne a

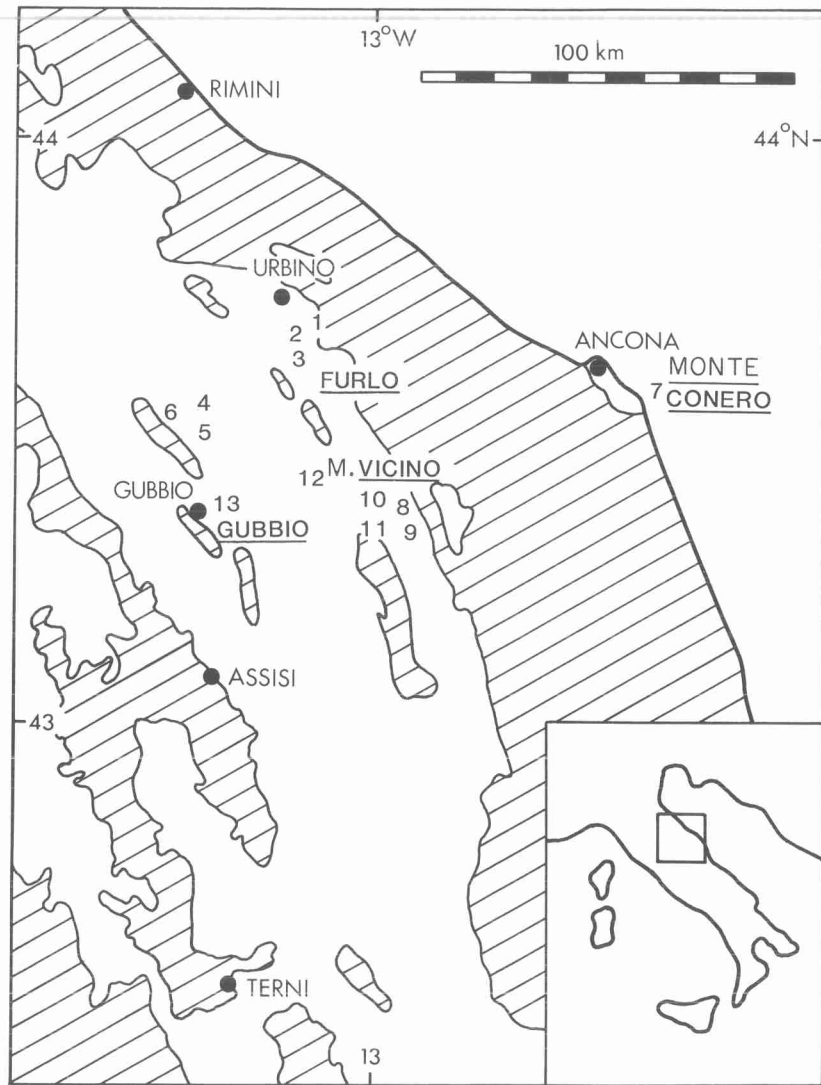


FIG. 1. Geological map of part of central Italy showing study area. Oblique hachure = upper Tertiary—Quaternary; blank = Mesozoic—lower Tertiary (including Scaglia Rossa Formation). Numbers refer to measured sections of Fig. 3 (cf. Wezel 1979). Regional names underlined are those areas referred to most frequently in the text.

Fucoidi and the entire Scaglia Bianca are missing and there is a marked discontinuity near the base of the Scaglia Rossa (Wezel 1979). At the end of the Eocene, the Scaglia Rossa in most places passes conformably into Oligocene varicoloured marls and limestones of the Scaglia Variegata Formation, although locally there are disconformable contacts, and thence into Oligo-Miocene volcanoclastic and clastic turbidite basin-fill of the Scaglia Cinerea Bisciario and Marnosa Arenacea Formations. The Scaglia Rossa itself has been subdivided into five members (Fig. 2;

Wezel 1979) that are broadly correlatable over the whole of the Umbria-Marche area (Fig. 3). From base to top these are as follows: The *Lower Cherty Member* (LCM) comprises thin- to medium-bedded limestones interbedded with thin, irregular chert layers throughout and rare marlstone-shale partings in the lowermost 15–20 m. It ranges from 20 m to 160 m in thickness, being between 80 and 120 m in most sections and having an average sedimentation rate of 6–10 mm/1000 yrs. The *Lower Marly Member* (LMM) is a relatively

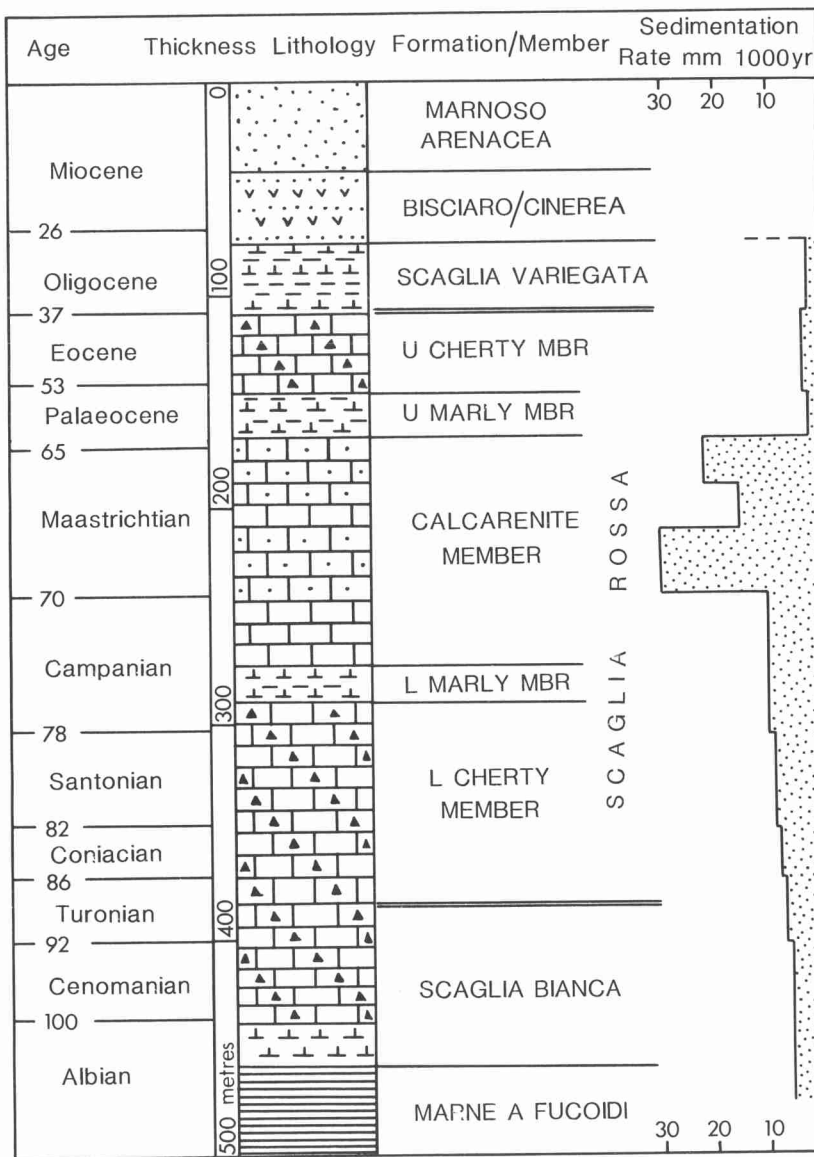


FIG. 2. Stratigraphy, average thickness lithology and average compacted sedimentation rates of the mid-Cretaceous to Miocene succession in central Italy. Solid lines = shale; stipples = sandstone; v = volcanogenic sandstones; see Fig. 3 for other ornamentation.

thin horizon from 0–10 m thick. It comprises interbedded marlstones and shales and is commonly slumped and faulted. This deformation appears to be of both syn-sedimentary and probable tectonic origin related to the relative plasticity of the interval.

The *Calcarenite Member* (CAM) comprises thin-to thick-bedded limestones with thin (average 2–3 mm, rarely > 1 cm) marlstone or shale partings;

in parts the limestones are calcarenites and calcirudites. It ranges from 40 m to 160 m in thickness, averaging about 80–100 m, and accumulated at a rate of 5–20 mm/1000 yrs, or locally over 30 mm/1000 yrs.

The *Upper Marly Member* (UMM) is lithologically similar to the LMM, commonly slumped and faulted in a similar way especially at its relatively abrupt contact with the underlying

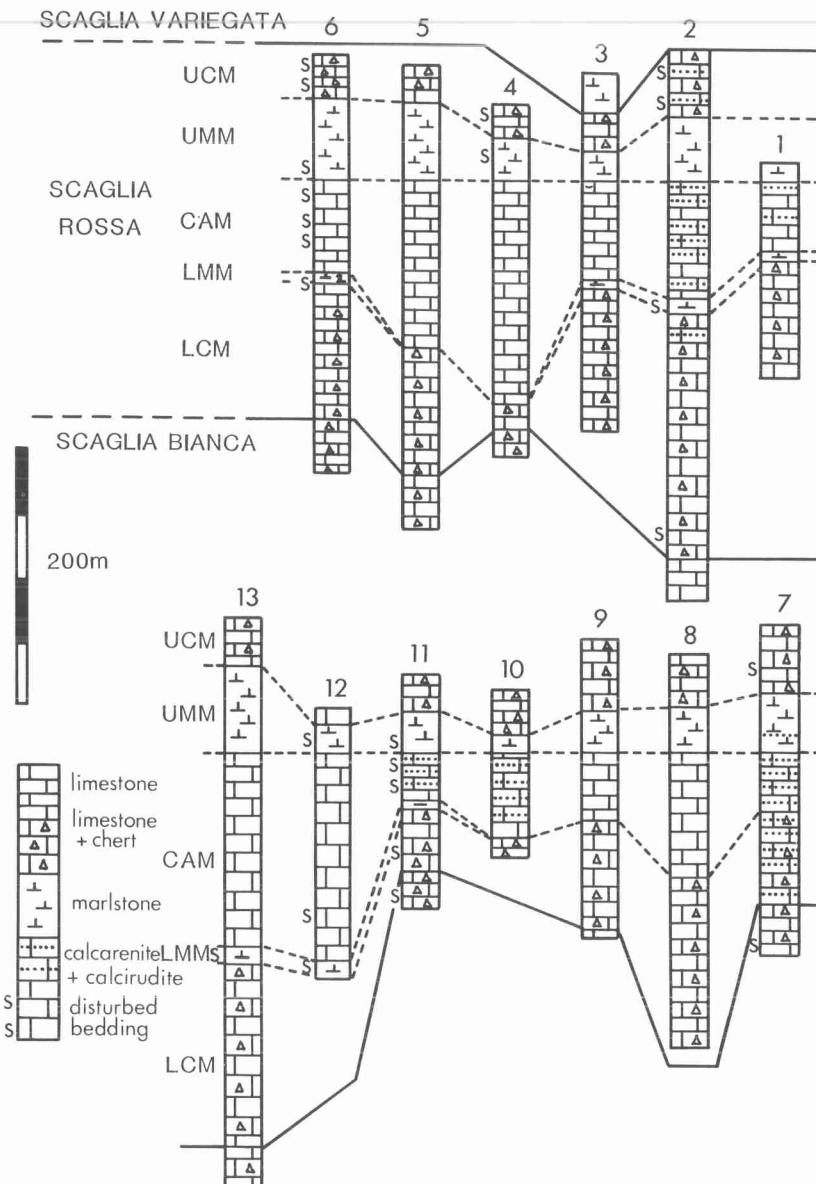


FIG. 3. Measured sections of Scaglia Rossa Formation in various parts of Umbria-Marche regions of central Italy, based on Wezel (1979). 1. Fossombrone, 2. Pietralata (Furlo), 3. Acqualagna, 4. Bacciardi, 5. Moria, 6. Fosso del Mulino, 7. Monte Conero, 8. Apiro, 9. Frontale, 10. Monte Vicino, 11. Vittore di Genga, 12. Morello, 13. Gubbio. See Fig. 1 for locations. Scaglia Rossa Formation is divided into five members: LCM, Lower Cherty Member; LMM, Lower Marly Member; CAM, Calcarenite Member; UMM, Upper Marly Member; UCM, Upper Cherty Member.

CAM, and is mainly thicker ranging from 10 m to 30 m (rarely more) with an average sedimentation rate of 1–5 mm/1000 yrs.

The *Upper Cherty Member* (UCM) is lithologically similar to the LCM, but is thinner (up to 60 m) and has a somewhat lower sedimentation rate.

Chert is absent and marlstone-shale partings are rare in the lower part of interval, both becoming more frequent and thicker upwards. The shaley 'partings' are commonly over 2 cm in thickness and rarely over 10–15 cm, and the whole interval appears more varicoloured.

Detailed biostratigraphic zonation of the Scaglia Rossa has been worked out by Renz (1936, 1951), Luterbacher & Premoli Silva (1962, 1964), Premoli Silva (1977) and Premoli Silva *et al.* (1976). Although Coccioni (1978) found some rather puzzling Miocene forams in certain shale interbeds, it now seems most likely that these were the result of some natural, perhaps tectonic, contamination process (Alvarez & Lowrie 1981; Wezel 1981, Coccioni 1983). Magnetostratigraphy of the Scaglia Rossa is summarized by Alvarez *et al.* (1977) and Lowrie & Alvarez (1977).

### Sediment facies

Five main facies can be recognized within the Scaglia Rossa formation: calcirudites, calcarenites, calcilutites/fine-grained limestones, marlstones/shales, and cherts. These are described briefly below (Fig. 4) before we examine in more detail the characteristics of the dominant facies, the calcilutites or fine-grained limestones.

The *calcirudites* are mainly medium to very thick-bedded (up to 3 m) detrital limestones made up of bioclasts and rare mudstone lithoclasts up to several centimetres in diameter. They also

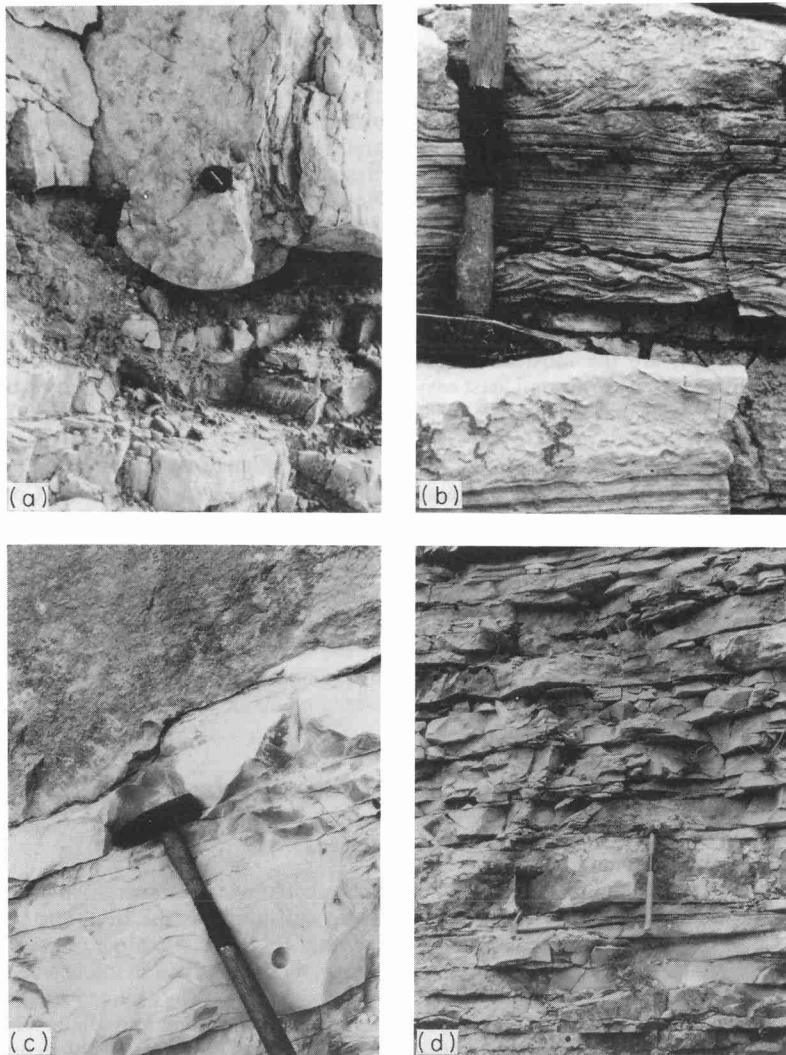


FIG. 4. Photographs of main Scaglia Rossa facies. (a) Calcirudite with large flute cast cutting into marlstone and calcilutite (b) Parts of two graded calcarenite—calcilutite turbidite beds (c) Calcirudite/coarse-grained calcarenite erosive into calcilutites; note *Zoophycos* trace fossil to left of hammer handle. (d) Interbedded calcilutite and calcarenite (whiter) beds with very thin shale partings.

occur as thin (0–10 cm), discontinuous, commonly negatively-graded layers. The bioclasts include molluscs, echinoids, bryozoans, corals and rudists, commonly fragmented and associated with sand-sized foraminiferal debris. The beds are commonly massive to graded with a scoured, erosive base (flutes up to 30 cm deep) and more gradational top. They are clearly the result of sediment gravity-flow (?turbidity currents) derived from a shallow-water carbonate platform to the east.

The *calcarenites* are also often medium to very thick-bedded (up to 3 m) detrital limestones, occurring either separately or as part of a graded calcirudite-calcilutite bed. The most obvious sand-sized components are foraminiferal fragments with some probable molluscan debris, but recrystallization has obscured much of the original character. The beds are normally flat-bottomed and more or less distinctly graded with a range of internal structures including horizontal, cross and convolute lamination, water-escape structures and, near the top, bioturbation. Partial and complete Bouma sequences are common, and the beds clearly result from turbidity current or related sediment gravity transport.

The *calcilutites* or, to use a less genetic term, *fine-grained limestones*, are the most abundant facies but more difficult to describe and least easy to interpret. It is these beds that are interpreted as pelagites, especially in the west near Gubbio, and as fine-grained calciturbidites near Monte Conero on the east coast. They are discussed in detail in the following section.

The *marlstones* and shales form a continuum from beds with up to 50% CaCO<sub>3</sub> especially in the LMM and UMM, to thin beds and partings of shale with less than 5% CaCO<sub>3</sub>. They occur throughout the Scaglia Rossa, interbedded with the harder prominent limestones with more or less regularity. Their crumbly and fissile nature obscure any primary internal sedimentary features. They appear to result partly from variation in the biogenic-terrigenous input and partly from diagenetic dissolution of carbonate. This facies is also discussed below.

The *cherts* are thin, irregularly-bedded and nodular layers mainly confined to the LCM and UCM. They are mostly reddish in colour, but greyish cherts also occur towards the basal contact with the Scaglia Bianca, intermittently through the UCM, and at Monte Conero. The cherts are commonly very hard, intensely-fractured and recrystallized rocks, that probably derive originally from siliceous pelagic microfauna and flora.

The regional and stratigraphic distribution of these five facies is notable (Fig. 3). Calcirudites

and calcarenites are dominant near Monte Conero in the east and also form a significant part of the succession in parts of the Furlo-Monte Vicino area. Further west, near Gubbio, they are completely absent and calcilutites are dominant. Stratigraphically, they mainly occur in the CAM although locally form part of the LCM, UCM and UMM. The other facies show less clear regional partition, apart from that associated with the thickness variation of the separate members. Stratigraphically, the marlstones and shales are more common and thicker-bedded in the early members and the cherts are confined to the cherty members.

Each of the facies may be variously disturbed or contorted. In particular, the LMM and UMM and, less commonly, the UCM show highly chaotic bedding. To some extent this disturbance of the more shaly horizons may be a result of preferred tectonic slip along the more plastic intervals as the whole sequence was folded. However, some of the tightly-folded beds of the CAM (Figs. 3 and 4) enclosed in completely undisturbed flat-lying strata and showing a range of deformed structures in a single slump, appear to be the result of slumping of soft and semiconsolidated sediments that had accumulated on a depositional slope. Preferential dissolution along folded bedding planes has in some cases produced a 'fish-bone' pattern that obscures the true nature of the folds. There is also evidence of relatively small-scale channelling, both in the coarser-grained facies at Monte Conero and in the mostly fine-grained calcilutites and calcarenites of the Furlo-Monte Vicino area. In the former area, the channels are best developed in the CAM, being several metres deep and several tens of metres wide, whereas in the latter they are mostly shallower and less broad, confined to the UMM and filled with lenticular calcarenite beds averaging 20–50 cm in thickness.

## Calcilutite characteristics

### Bedding

The most obvious characteristic of the Scaglia Rossa calcilutites is the rhythmic nature of the bedding (Fig. 5). Throughout the region the harder, more massive and thicker-bedded calcilutites are separated by thinner beds or very thin partings of marlstone and shale. The calcilutite bed thicknesses are very variable from less than 5 cm to as much as 120 cm, although within any one part of the section they tend to be more uniform, whereas the intercalated marlstone-shale layers are about an order of magnitude thinner, from

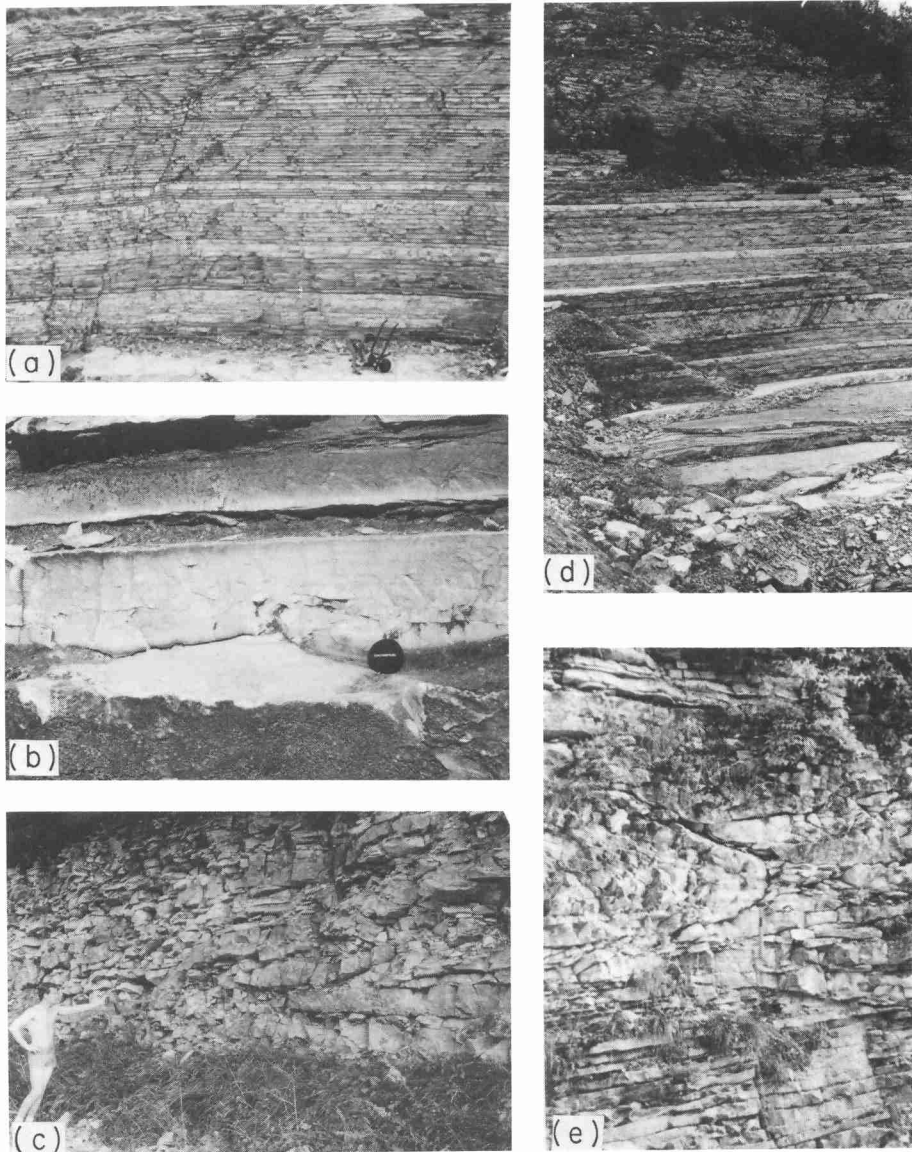


FIG. 5. Photographs of typical features in Scaglia Rossa calcilutites. (a) Thinning-upwards sequence of calcilutite and calcarenite (white) beds over about 15 m section (cf. Fig. 6(a)). (b) Detail of calcilutite and thin shale beds; lower calcilutite has 'over-run' a *Zoophycos* mound on underlying bedding surface and re-established a planar surface. (c) Lensing, channelling and slump features in calcilutites, near centre of photograph. (d) Irregular variation in calcilutite and calcarenite bed thickness over about a 16 m section (cf. Fig. 6(b)). (e) Slumped horizon overlain and underlain by horizontally-bedded calcilutites.

5 mm to 100 mm, or in some cases are completely absent. Mostly, the beds are very even and flat-bedded, locally with abundant stylolites that may obscure the true nature and thickness of the bedding. More rarely there is some minor swelling and pinching.

The thickest beds tend to occur in the CAM,

particularly towards the top and in the middle parts. The upper part of the LCM may also be thicker-bedded than other parts of the succession. These thick beds are not strikingly different in appearance, although at Monte Conero and in parts of the Furlo-Monte Vicino area they are commonly associated with thick-bedded

calcarenites and calcirudites. However, where calcarenites are not present, as at Gubbio, the two stratigraphically equivalent intervals in the CAM comprise thick-bedded calcilutites.

The change in bed thickness is commonly

gradational over 5–40 m of section producing both thinning and thickening-upward sequences (Figs 5 and 6). In other cases, the thicker beds occur together in isolated packets, of 5–15 m in thickness, or more or less randomly through the succession.

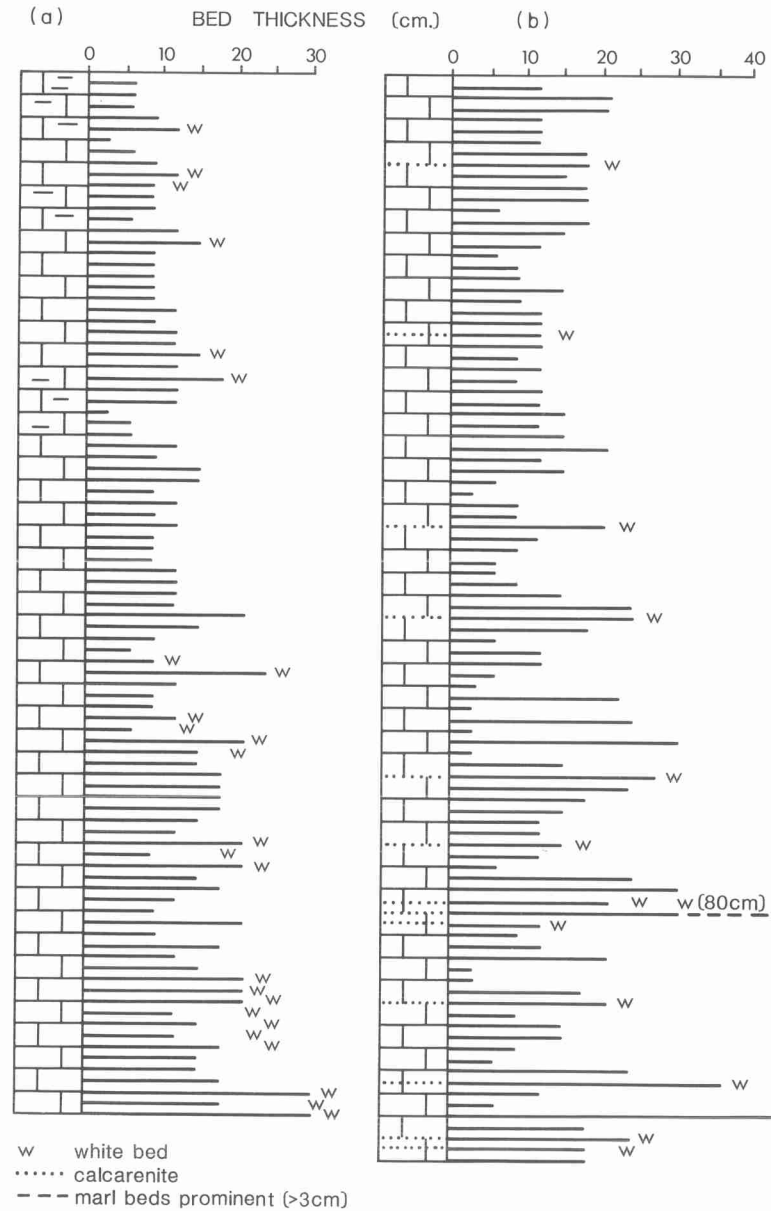


FIG. 6. Measured sections and bed thicknesses in the Furlo region: (a) Monte Cesana, Lower Cherty Member, thinning-upwards sequence over 15 m section (cf. Fig. 5(a)); (b) Monte Pietralata, Calcarenite Member, more irregular variation in bed thickness over 16 m section (cf. Fig. 5(b)). Only limestone beds measured (calcilutites and calcarenites): interbedded marls-shales mostly very thin (< 5 mm) except as indicated towards top of Section (a).

### Composition

The calcilutites are composed dominantly of  $\text{CaCO}_3$ , with scattered pelagic foraminifera in a nannofossil or indeterminate micritic matrix. Re-crystallized silica occurs in minor amounts as sand-sized spheroidal blebs, probably after pelagic siliceous microfossils. Other minor non-carbonate components include feldspars, clay minerals, and rare magnetite, haematite and other heavy minerals, all of which are more abundant in the marlstones and shales than in the calcilutites. The organic-carbon content is very low, ranging from 0.07% in the calcilutites to 0.17% in some shales (Arthur & Fischer, 1977). X-ray diffraction analysis of some 60 samples of the fine ( $<4 \mu\text{m}$ ) residues from crushed and acidified calcilutites shows the minor but significant presence of smectite (including expandable mixed-layer clays), illite, kaolinite, chlorite, quartz (probably biogenic silica), orthoclase and plagioclase. Non-acidified samples were also processed for the relative proportion of calcite to non-carbonates. The regional, stratigraphic and facies distribution of these components is illustrated in Figs 7 and 8 with respect to three geographical areas (Monte Conero, Furlo-Monte Vicino, Gubbio), four stratigraphic intervals (UCM, CAM and LCM of the Scaglia Rossa and the Scaglia Bianca), and red versus white calcilutites.

In the east, Monte Conero is characterized by high or very high kaolinite/chlorite, orthoclase/plagioclase and calcite/silica ratios, and by a relatively low silica/feldspar ratio. The central Furlo-Monte Vicino belt has a high kaolinite/chlorite and more intermediate orthoclase/plagioclase, calcite/silica and silica/feldspar ratios. And, furthest west near Gubbio, we find the lowest kaolinite/chlorite, orthoclase/plagioclase and calcite/silica ratios, but somewhat higher silica/feldspar ratio. The smectite/illite ratio also shows a slight decrease from east to west. A certain amount of local variability is noted within the Furlo-Monte Vicino belt but it is difficult to separate this clearly from the stratigraphic signature.

The stratigraphic differences within the Scaglia Rossa formation are equally pronounced. The LCM and UCM (base and top) have relatively low kaolinite/chlorite, orthoclase/plagioclase and calcite/silica ratios but a higher silica/feldspar ratio. The intermediate CAM, by contrast, has higher kaolinite/chlorite, orthoclase/plagioclase and calcite/silica and lower silica/feldspar ratios. Smectite/illite appears to decrease slightly up-section. There were insufficient samples from the UMM and LMM to make an adequate compar-

ison of mineral ratios, although they both appear to be somewhere in between the CAM and the cherty members. The Scaglia Bianca Formation is markedly different from the Scaglia Rossa, with a very much higher silica/feldspar ratio and low smectite/illite, kaolinite/chlorite and orthoclase/plagioclase ratios.

The different facies show rather less clear mineralogical variation, though this may in part be due to an overprint of the regional and stratigraphic signatures. The few coarse-grained calcirudites and calcarenites analysed have very

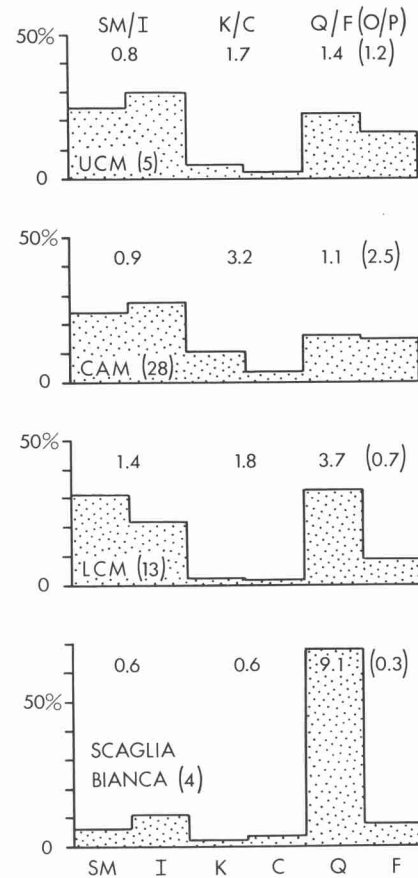


FIG. 7. Calcilutite composition (X-ray diffraction results) and mineral ratios for four litho-stratigraphic intervals throughout the Umbria-Marche region. UCM (5 samples) Upper Cherty Member, CAM (28 samples) Calcarenite Member, LCM (13 samples) Lower Cherty Member, Scaglia Bianca (4 samples). SM = smectite + expanding mixed-layer clays, I = illite, K = kaolinite, C = chlorite, Q = quartz, F = feldspar, O = orthoclase, P = plagioclase. Numbers indicate mineral ratios as shown. Percentages are based on weighted peak heights and are not considered absolute.

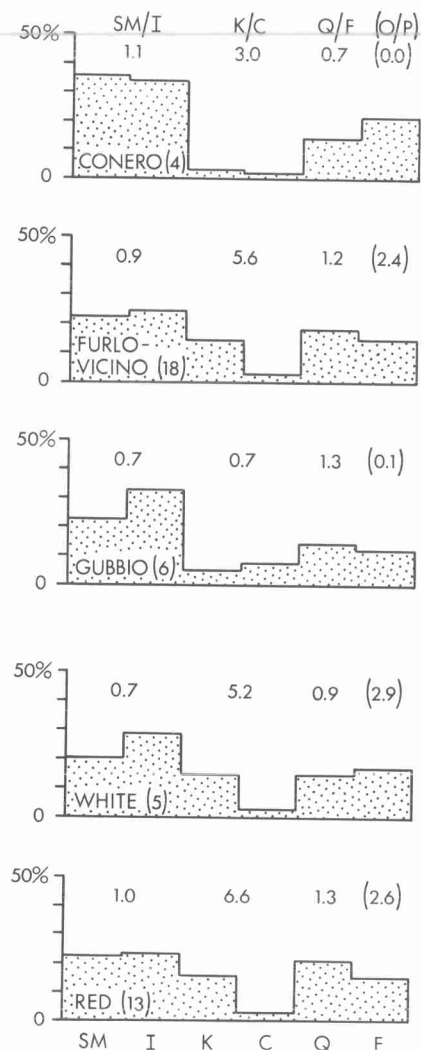


FIG. 8. Calcilutite composition and mineral ratios for Calcarenite Member only of three separate regions, Monte Conero, Furlo-Monte Vicino and Gubbio, and for white and red lithologies of the Furlo-Monte Vicino area. See Fig. 7 caption for further explanation.

high calcite/silica ratios with little or no fine terrigenous fraction; the little there is shows high kaolinite/chlorite and orthoclase/plagioclase and low silica/feldspar ratios. The cherts, of course, are also distinctive; but the main difference between the calcilutites, marlstones and shales is simply one of  $\text{CaCO}_3$  content so that the calcite/silica and  $\text{CaCO}_3$ /terrigenous fraction ratios are highest in the calcilutites and lowest in the shales. The only consistent difference between the whi-

fish and reddish lithologies is that the former have more carbonate and the latter more terrigenous fine fraction. The mineral ratios show subtle and variable differences; for example, in the CAM the calcite/silica ratio is higher in the white than red facies, whereas the opposite is true in the LCM.

Relatively few geochemical data are available for the Scaglia Rossa formation as a whole (Vannucci *et al.* 1979), although more attention has been paid to the section near Gubbio (Arthur 1976; Arthur & Fischer 1977) and to the Cretaceous-Tertiary boundary in particular (Alvarez *et al.* 1980; Wezel *et al.* 1981). Arthur (1976) has shown that geochemical profiles of metal contents (Fe, Ti, Ni, Mn), alumina and silica across limestone-shale couplets show maxima in the shales and minima in the middle of the limestone beds. Although the concentration in the shales is by a factor of 20 to 50, the total metal content in a given shale is about the same as that in the adjacent limestones, and concentration was probably the result of diagenetic dissolution of carbonate from the shales and its transfer to the adjacent limestones. There may have been some initial sea floor dissolution as well.

Wezel *et al.* (1981) suggest that the enrichment of iridium in the shale interbed at the Cretaceous-Tertiary boundary as well as at several other horizons within the Scaglia Rossa, is due to a combination of diagenetic concentration, very slow sedimentation rates and, possibly, volcanic contributions, rather than to extraterrestrial sources (Alvarez *et al.* 1980).

### Colour

At the two ends of the colour spectrum of the Scaglia Rossa facies are the dark-brownish red shales and the white calcirudites and calcarenites. The calcilutites ranged through this spectrum from darker red to pale red or rose and pinkish white to white. Most of the sequence at Monte Conero is white, including the calcilutites, whereas most of the Gubbio section is various shades of red and pink. In the central Furlo-Monte Vicino belt all the colours are represented and, most commonly, the white beds (coarse or fine-grained) are clearly distinct from the red. However, either white to red or red to white upward gradations can occur in the same bed and, in some cases, a mottled relationship is observed.

As noted above, the compositional differences between red and white beds are gradational and slight. White contains more carbonate and red more terrigenous material as well as slightly more iron.

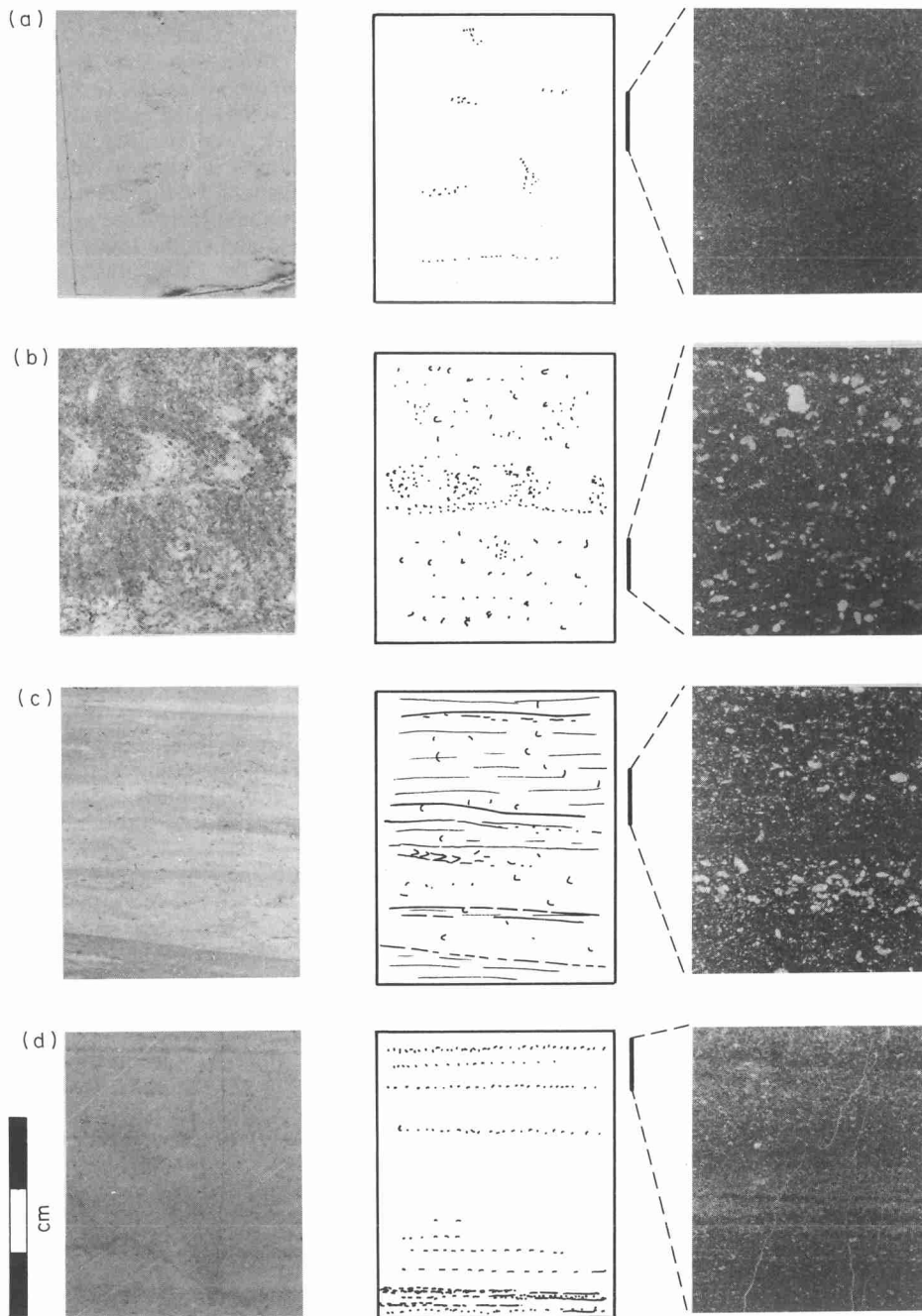


FIG. 9. Structural detail for calcilutites, shown by photograph of polished surface (left column), thin-section photograph of detail (right column) and sketch (centre column) for each of three Scaglia Rossa types. (a) massive, structureless, slightly mottled, very fine-grained; (b) burrowed, bioturbated, poorly-sorted, coarser-grained; and (c) indistinct or irregular lamination. Shown for comparison is the more clearly laminated calcilutite of the Scaglia Bianca (d).

### Structure and texture

After careful observations in the field, and of numerous polished slabs, X-radiographs and thin sections we can confidently say that the calcilutites are remarkably free from primary sedimentary structures. Apart from widespread bioturbation and burrowing (described below), there are three main structural types (Fig. 9). One is very fine-grained, massive and structureless, the second is more poorly-sorted, slightly coarser-grained, mottled and bioturbated, but otherwise structureless. The former rarely has indistinct banding or thin fine-grained foraminiferal lamination and more commonly some bioturbation, and the latter may show irregular patches and discontinuous lenses of coarser-grained foraminifera and wispy shale laminae. The third type shows very indistinct layering or lamination, picked out by foraminiferal concentrations, slight colour changes, shale wisps, grain alignment or an alternation of the other two structural types.

All three types can occur in either reddish or whitish calcilutites throughout the Scaglia Rossa, and all gradations between the three are observed. A more systematic study than the present one might show a preferential regional or stratigraphic distribution of these three types. Our limited data suggest that the mottled, coarser-grained type is dominant overall, the massive, fine-grained type occurs preferentially in the CAM and in the Monte Conero area, and the indistinctly laminated type is most prevalent in the lower part of the LCM.

At Monte Conero and in the Furlo-Monte Vicino area many of the clear turbiditic calcarenite and calcirudite beds pass upwards into the fine-grained massive calcilutite, and then this grades upwards into the coarser-grained mottled and bioturbated calcilutite (Fig. 10). These two structural types always occur in this same order and, in some cases, the lower one is white and the upper is red. The transition from calcarenite to calcilutite tends to be relatively abrupt, commonly disturbed by load-like and water-escape structures, and yet shows both compositional and positive textural grading. The transition from massive to mottled (white to red) calcilutites is completely gradational, with slight compositional and negative (reverse) textural grading (Fig. 10).

### Bioturbation and burrowing

A wide range of burrows is found in Scaglia Rossa calcilutites, both on bedding surfaces and randomly throughout even the thickest beds (Figs 5 and 10). Most beds in fact are burrowed or, at

least, bioturbated to differing degrees. Where recognizable traces occur these include *Zoophycos*, *Planolites*, *Chondrites*, *Helminthoida*, *Palaeodictyon*, *Granularia* and *Thalassinoides*, several of which are systematic surface-combers that require relatively long intervals of time to thoroughly work over an area for food. No systematic variation of burrow types has been observed, but general bioturbation of the sediments appears to be slightly more pronounced in the Gubbio area and in the lower parts of the Scaglia Rossa (in the LCM, LMM and lowest part of the CAM).

## Discussion

### Facies interpretation

Most previous workers on the Scaglia Rossa have emphasized its pelagic character (e.g. Arthur 1976; Arthur & Fischer 1977) whereas Wezel (1979) argues that the formation is mostly turbiditic. Other studies have also pointed out the existence of calcarenite turbidites within a mainly pelagic sequence (Crescenti 1969; Crescenti *et al.* 1969). While there is little doubt that these coarser-grained lithologies were deposited by turbidity currents or related mass gravity-flow processes, our detailed investigations suggest that the more dominant fine-grained lithology (calcilutite or fine-grained limestone) cannot be explained simply as entirely turbiditic or entirely pelagic.

We agree with previous arguments (Arthur & Fischer 1977) that the calcilutite-shale rhythmic bedding is due to a combination of episodic sedimentation and diagenetic dissolution of carbonate. There is certainly evidence of shale-filled burrows in the calcilutites indicating primary alternation of carbonate-rich and carbonate-poor episodes, whereas the compositional profile across a calcilutite-shale couplet, stylolites in the calcilutites and dissolution features in the shale (Wezel *et al.* 1981) all indicate that CaCO<sub>3</sub> has been dissolved from the shales and partly transferred to the calcilutites. The rocks of the Scaglia Rossa formation and their mode of origin are undoubtedly very similar to many other limestone-shale sequences throughout the world (e.g. Hallam 1964; Fischer & Arthur 1977; Einsele 1982; Einsele & Seilacher 1982).

However, our interpretation of the Scaglia Rossa departs from most earlier studies in suggesting, (1) that the input of *both* carbonate and of terrigenous material has fluctuated through different parts of the sequence; and (2) that the episodic increase in carbonate was influenced, not

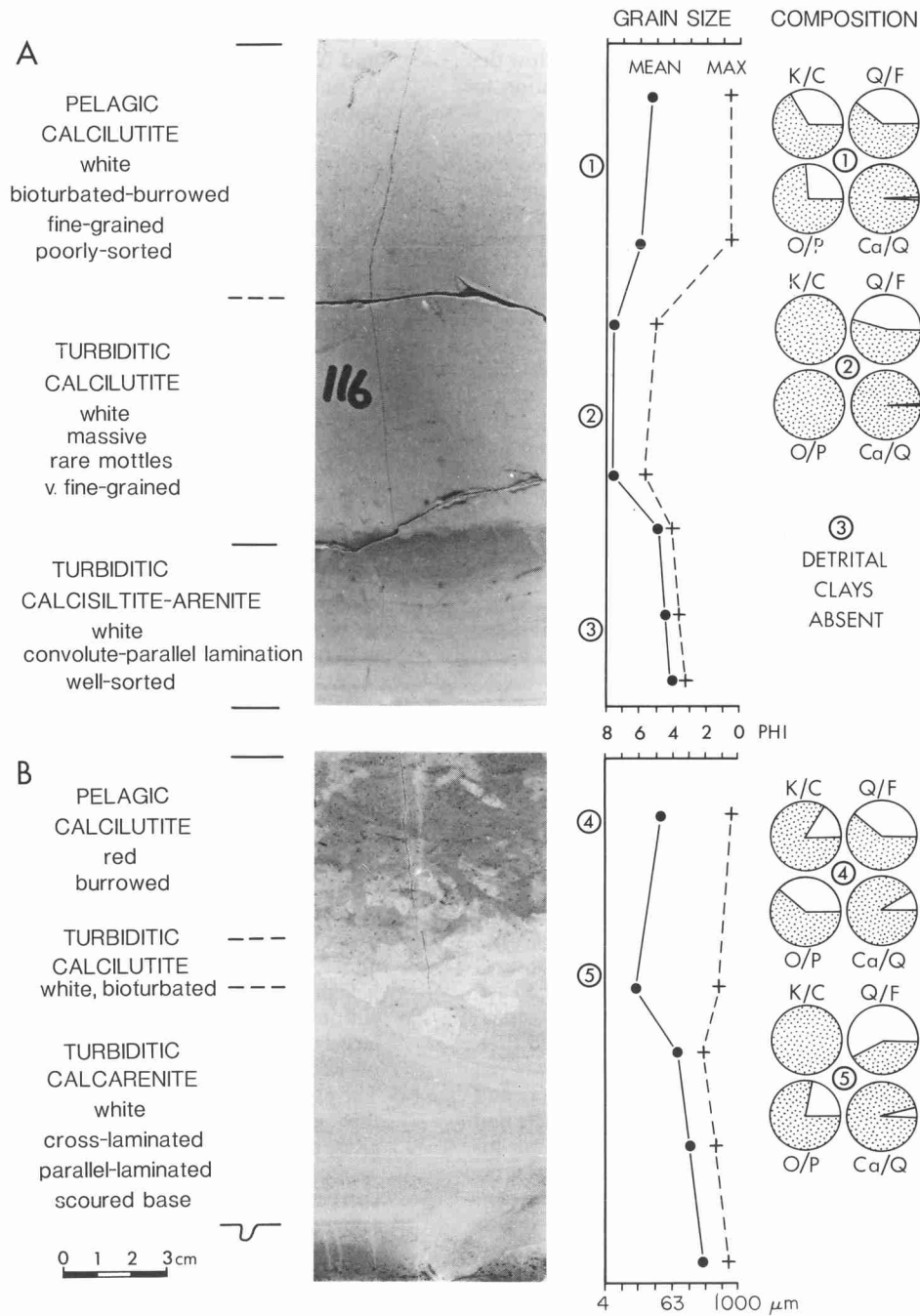


FIG. 10. Structural, textural and compositional detail for two calcarenite-calcilutite turbidites, (a) from Monte Conero and (b) from Furlo. Composition of the five numbered levels shown in terms of mineral ratios: K = kaolinite, C = chlorite, Q = quartz (silica), F = feldspar, O = orthoclase, P = plagioclase, Ca = calcite. In each case, the shaded area refers to the first-mentioned mineral.

only by variation in biogenic productivity at the surface and by carbonate dissolution on the sea floor, but also by carbonate input into the system from turbidity currents. We summarize below the evidence for a turbidity current contribution to the Scaglia Rossa calcilutites.

- (1) Major variations in thickness (by a factor of 2 or 3) of different members and hence of sedimentation rates over a few kilometres in the Furlo-Monte Vicino area, particularly of the CAM and UMM. This seems difficult to explain by such extreme variation in pelagic sedimentation over such short distances. The succession at Monte Conero is thinner than those further west, which is in part due to internal erosion or non-deposition.
- (2) Coarse-grained calciturbidites (calcarenities and calcirudites) are common, particularly at Monte Conero and Furlo-Monte Vicino and in the CAM. It seems unlikely that these would be so prevalent and widespread and yet that fine-grained distal calciturbidites would be completely absent.
- (3) Locally there are clear slump and channel features, commonly involving calcilutites. This suggests local slopes, instability and downslope resedimentation.
- (4) The thickest calcilutite beds, presumably indicative of increased carbonate input, occur most commonly in the CAM member in association with coarser-grained calciturbidites.
- (5) The thinning-upward and thickening-upward sequences as well as the less regular variations in bedding thickness are strikingly analogous to those of clastic turbidite successions.
- (6) Many of the calcirudites contain shallow-water shelly debris, derived from the east, whereas the calcarenites contain much resedimented pelagic material in addition. A certain amount of terrigenous material was also being supplied to the basin(s), and we interpret the high kaolinite/chlorite and high orthoclase/plagioclase ratios as indicative of proximity to the land source. That these ratios are highest in the east, decreasing westwards, and higher in the CAM than the other members, suggest that pelagic-carbonate-charged turbidity currents incorporating the more proximal terrigenous material are most evident in the CAM and flowed from east to west. If the silica content of the calcilutites is interpreted as being derived from pelagic siliceous organisms, then the calcite/silica and silica/feldspar ratios support the concept of

more pelagic-dominated sedimentation in the west and also indicate greater primary productivity during deposition of the LCM and UCM.

- (7) A number of beds show a very clear sequence from the coarse-grained calcirudites/calcarenites through a very fine-grained massive calcilutite to a coarser-grained, mottled and bioturbated calcilutite. The former we interpret as turbiditic and the latter as pelagic. The reverse-grad- ing between the turbiditic and pelagic calcilutites is due to the presence of relatively large planktonic foraminifera (and recrystallized siliceous planktonics?) in the latter. These same two structural types, massive fine-grained and bioturbated coarse-grained, occur without the associated calcarenites throughout the Scaglia Rossa, and we presume are due to relatively more turbiditic and more pelagic inputs respectively. The indistinct lamination in some calcilutites is more difficult to interpret; in part it probably results from bioturbation, in part from diagenesis, and in part from current (turbidity current?) activity.

Nevertheless, the overall aspect of the Scaglia Rossa calcilutites confirms the importance, and perhaps dominance, of pelagic deposition.

- (1) The very low rates of sedimentation are those most commonly associated with pelagites.
- (2) The limestone-marlstone (limestone-shale) rhythmic bedding, together with chert bands, is very typical of pelagic sequences.
- (3) The very high CaCO<sub>3</sub> content, the silica of probable biogenic origin, and the abundance of planktonic fossils all indicate a pelagic composition. However, for the calcilutite turbidites, we suggest that it is largely pelagic material that has been redeposited.
- (4) The extensive bioturbation and burrowing throughout is reminiscent of many pelagites, but also occurs where there has been a very long time interval between turbidity-current events. The burrow assemblage appears rather mixed, but is mainly of the *Nereites* (bathyal) and *Zoophycos* (slope) zones (Seilacher 1967, 1978). However, both Crimes *et al.* (1981) and Wetzel (this volume) have shown that trace fossil assemblages in deep water are the result of a more complex set of variables than simple palaeobathymetry, including sub-environment, grain-size and sedimentation rate.

### Turbidite and pelagite characteristics

We can identify, therefore, both turbiditic and pelagic calcilutites as distinct end members in the Scaglia Rossa Formation (Fig. 10). The turbidites are very fine-grained, micritic, very rich in  $\text{CaCO}_3$ , probably originally mainly nannofossils and other fine carbonate detritus, and have a terrigenous signature in the small non-carbonate fraction. They are massive and structureless, with rare indistinct lamination and burrowing, and may be either white or pale red in colour.

The pelagites are coarser-grained, similar in composition but with relatively less  $\text{CaCO}_3$ , composed of nannofossils, large scattered planktonic foraminifera and recrystallized siliceous microplankton, and relatively more non-carbonate material with a non-terrigenous silica-rich signature. They are mottled, extensively bioturbated and burrowed, and may have irregular foraminiferal concentrations and shale wisps.

The characteristics we attribute to the turbidite end-member, although dissimilar from terrigenous mud turbidites (e.g. Piper 1978; Stow & Shanmugam 1980; Stow & Piper, this volume), have nevertheless been documented in a number of earlier studies of Palaeozoic to Recent limestones (e.g. Meischner 1965; Garrison 1967; Thomson & Thomasson 1969; Davies 1977; Anatra *et al.* 1980; Kelts & Arthur 1981; Faugères *et al.* 1982 and this volume). All these authors describe fine-grained limestones or lime muds that are between 5 and 100 cm thick, even-bedded, commonly with thin argillaceous interbeds, massive, ungraded or with slight positive grading especially near the base, some with bioturbation near the top, and mainly of pelagic carbonate composition with or without a minor terrigenous component. They may occur individually or as part of clear calciturbidite beds (calcirudite-calcarenite-calcilutite), commonly in base-of-slope and basinal environments. Stanley's (1981) unifites and Wezel's (1973) omogeniti are both thick-bedded, featureless, homogeneous, calcareous muds which they interpret as a result of large fine-grained turbidity currents that became ponded in relatively small basins.

Also recognized as fine-grained calciturbidites are beds that show distinctive current-induced structures, mainly parallel lamination, some of which are similar to our indistinctly-laminated structural type (van An del & Komar 1969; Bissell & Barker 1977; Yurewicz 1977; Kennedy 1980; Faugères *et al.* 1982 and this volume).

However, many of the Scaglia Rossa calcilutites lie somewhere between the turbidite and pelagite end-member types, and thus appear to have had either a greater turbiditic or a greater

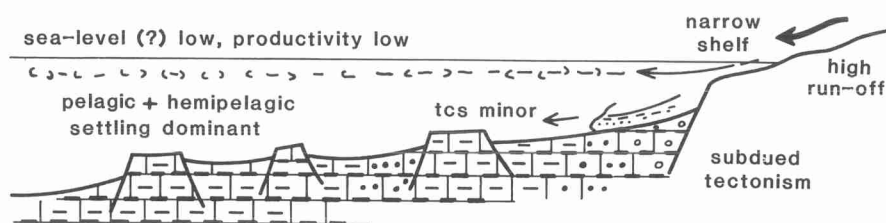
pelagic influence but not to be wholly one or the other. In fact, many previous authors have encountered similar problems in distinguishing between turbiditic and pelagic limestones and modern lime muds or oozes. Wilson (1969) drew attention to this in his description of deeper-water lime mudstones from basinal settings which he hesitated to interpret as true pelagic turbidites. Hesse (1975) attempted to give field and laboratory criteria for the recognition of fine-grained turbidites and non-turbidites in both carbonate and non-carbonate basins. His pelagic turbidites deposited in low-latitude basins above the carbonate compensation depth are very similar to our Scaglia Rossa ones, and show similar subtle differences from the interbedded pelagics. Carrasco (1977), Cook & Taylor (1977), Enos (1977) and Reinhardt (1977), in discussing thick limestone successions of various ages, all concluded that the dominant fine-grained facies was part pelagite and part turbidite (or contourite) but admitted difficulty in clearly distinguishing between the different processes. Homewood & Winkler (1977) recognized that the fine-grained parts of graded calcisiltite-calcilutite beds in Upper Jurassic rocks of the Pre-Alps were almost identical to the interbedded homogeneous pelagic calcilutites, and that there appears to be a complete gradation of facies and processes.

### Depositional model for Scaglia Rossa

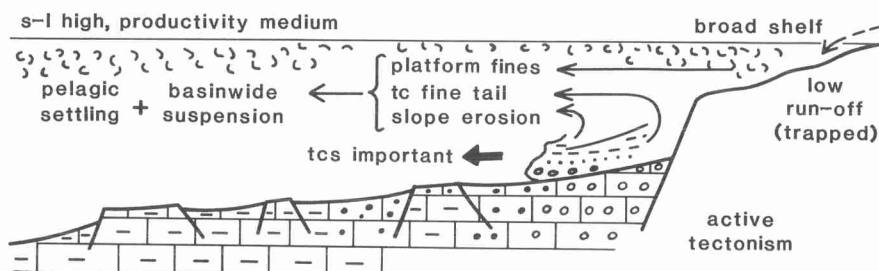
It seems clear that deposition of the Scaglia Rossa formation took place in a basin, or more probably, a series of tectonically-controlled basins (Fig. 11) that became progressively deeper to the west, but that were never below the regional carbonate compensation depth. Sedimentation in the western (Gubbio) and central (Furlo-Monte Vicino) basins was dominantly pelagic during the LCM and again during the UCM periods (Fig. 11 (c)), with widespread accumulation of siliceous and calcareous oozes, now cherts and limestones. The rhythmic alternation of carbonate-rich and carbonate-poor facies was mainly due to the fluctuation in carbonate productivity, secondarily accentuated by diagenetic dissolution and transfer. There was also variation in turbidity current input of carbonate as, at Monte Conero in the east, there is a predominance of calciturbidites in the lower and middle parts of the LCM.

The LMM and particularly the UMM mark a distinct change in the sedimentation regime, with the introduction of a large amount of terrigenous material (Fig. 11(a)). In the LMM this may in fact be a result of reduced carbonate input. The actual depositional processes of the marlstones and shales are unclear although the very slow sedi-

(a)



(b)



(c)

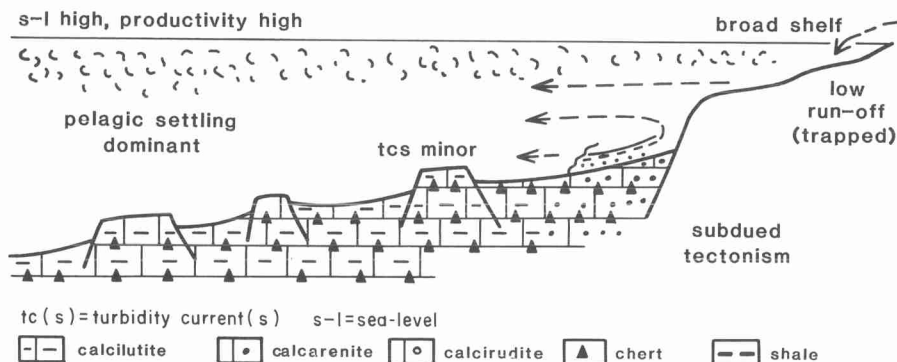


FIG. 11. Depositional model and hypothetical cross-sections for the Scaglia Rossa Formation: (a) Upper Marly and Lower Marly members, (b) Calcarenite Member, (c) Upper Cherty and Lower Cherty Members. Model (b) is believed to be appropriate for many deep-water carbonate systems with evidence of turbidity current input.

mentation rates suggest that they were, in large part, hemipelagic. It is interesting to note that both members, the LMM in mid-Cenomanian and the UMM at end-Maastrichtian, occur at times of global lowering of sea-level (Vail *et al.* 1977), though whether these eustatic changes would have had any influence on terrigenous supply in this region is uncertain. Certainly the occurrence of slumping in these members sug-

gests local tectonic activity was also important. The particularly abrupt and widespread lithological change at the CAM-UMM boundary may also be marked by a discontinuity.

Deposition of the middle CAM (late Campanian-Maastrichtian) was more variable regionally and, on average, three to five times more rapid than the other members (Fig. 11(c)). A shallow-water carbonate platform in the east

(present Adriatic Sea) shed material across its (faulted?) margin in mass gravity-flows. Thick calcarenitic turbidites were deposited up to 50 km to the west in the Furlo-Monte Vicino basin, although a more local platform origin for some of these turbidity currents was deposited directly over the coarser-grained calciturbidite, but much of it rapidly dispersed into the water column as a basin-wide suspension that settled more slowly and mixed with the background pelagic material.

Thus the CAM, characterized by an increased rate of sedimentation, thicker calcilitite beds, higher  $\text{CaCO}_3$  content and a more proximal terrigenous signature, was greatly influenced by turbidity current input of fine-grained carbonates. The dispersion and relatively slow-settling of this fine material makes it difficult to distinguish from the background pelagic sediments and a true gradation of facies and processes appears likely. In the CAM, therefore, much of the increased carbonate of the limestone-shale couplets was due originally to turbidity current input.

#### Broader implications

This depositional model (Fig. 11(b)) for fine-grained and pure limestone (i.e. without significant terrigenous components), involving a mixed turbiditic-pelagic process, we believe is more widely applicable. There are many examples in the literature of slope and basinal carbonate systems where the facies recognized include re-sedimented calcirudites, calcarenites, calcidebrites, slump deposits and interbedded, distal pelagic limestones (e.g. Wilson 1969; Price 1977; Hubert *et al* 1977; Crevello & Schlager 1980). It seems clear to us that the calcilitite turbidites are conspicuously missing from or have been overlooked in these successions. Even McIlreath & James (1978) in their synthesis of facies models for carbonate slopes describe coarse peri-platform talus, lime breccias and graded calcarenites, but then simply pelagites and hemipelagites for the fines.

Fine-grained pure carbonate, carried into a basin by a turbidity current or similar process, is

more likely to disperse into the water column than the equivalent fine-grained terrigenous material. This is because  $\text{CaCO}_3$  does not develop to the same degree the surface electrostatic charges that are so important in the flocculation of aluminosilicate clay minerals (van Olphen 1978; Flugel 1982). Hence, the fine-grained and low-concentration tails of carbonate-charged turbidity currents will mix with mid-basin pelagics and surface or mid-water suspensions from marginal carbonate platforms and settle slowly through the water column. This kind of process is very similar to that envisaged from the modern periplatform oozes of the Bahama basins (Crevello & Schlager 1980; Crevello *et al.* this volume; Heath & Mullins, this volume) and also postulated for some Mesozoic limestones in south central Turkey (Waldron 1981). Piper (1978) observes that carbonate commonly occurs towards the top of mixed clay-carbonate mud turbidites. Nisbet (1974) and Robertson (1976) also draw attention to the probable difference in hydrodynamic behaviour of carbonate and terrigenous grains, when discussing the origin of calciturbidites in Cyprus and Greece. It is not surprising, therefore, that calcilitite turbidites are difficult to recognize in both modern and ancient sediments. Careful study of regional, compositional, geochemical, textural and structural criteria, however, should allow the recognition of, at least, the end-member turbidites and pelagites, and some estimation of the relative importance of each process.

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