



PROBLEM SOLVING WITH MICROFOSSILS: A BRIEF REVIEW OF THE ROLE OF THIN-SECTION STUDIES IN MICROPALAEONTOLOGY

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ABSTRACT

Foraminifera (single-celled protists) have a long geological record. They are both numerous and taxonomically diverse in assemblages throughout the Mesozoic and Cenozoic and have been used extensively in problem-solving. Both planktic and benthic foraminifera are used for biostratigraphy throughout the world, based on both processed residues and—where appropriate—thin-sections. In many cases, however, thin-section analysis appears to be undertaken reluctantly and relatively few micropaleontologists make use of standard (30 µm thick) thin-sections in their research and publications. This review will provide examples of the application of thin-section studies to problems relating to the Cretaceous-Paleogene (K–Pg) boundary, Cenomanian-Turonian boundary event (CTBE) and studies of Tethyan and Middle Eastern successions of the Mesozoic and Cenozoic. In all these examples, thin-sections provide key information on both biostratigraphy and paleoecology (including microfacies analysis).

INTRODUCTION

The majority of micropaleontologists prepare residues of their rock or cuttings samples and study the foraminifera and other microfossils they recover in three dimensions using a standard binocular microscope. In many cases, indurated parts of the sedimentary succession are not studied as this would involve the use of thin-sections. In an excellent paper on the Eagle Ford Group in Texas, Denne et al. (2014) made use of both disaggregated samples and thin-sections, both of which contribute to the biostratigraphic and paleoecologic interpretation of the succession. While some of the taxa in the thin-sections are identified to species level (Denne et al., 2014, their figure 17), some are not, while others (Denne et al., 2014, their figure 10) provide tentative identifications using a few inappropriate cross-sections of the taxa involved. Using thin-sections in such work makes us think in a different way about the characters that we can, or cannot, use in the identification of both genera and species. Thin section analysis of foraminifera (and other bioclasts) is important in three ways:

- In successions with intermittent indurated mudrocks or limestones, thin-section analysis is often required in order to avoid gaps in the acquired data, or to investigate specific events within the succession (e.g., hardgrounds, non-sequences, etc.);

- In the carbonate-rich successions of the Middle East and Tethyan regions biostratigraphic and microfacies analysis can only be undertaken by thin-section analysis (e.g., Wohlwend et al., 2016); and
- In the study of ‘larger’ foraminifera, identification to the species level often requires the use of oriented thin-sections.

In some situations limestones and some hardened mudrocks can be disaggregated using the hot acetic acid method of Lirer (2000). This approach does provide residues that can be studied in the normal way or it can also be used to enhance residues that have been incompletely processed (e.g., Bubik, 2011), giving specimens a final clean in order to reveal a greater level of detail. In some carbonate rocks dominated by agglutinated foraminifera either the acetic acid method or normal, HCl digestion, can be used to separate the assemblage from the matrix, though this can be problematic if the taxa have used a carbonate cement in the construction of their tests. One example of where the hot acetic acid method has been very important is in the preparation of limestones containing early, often Jurassic, planktic foraminifera. Though thin sections can be used effectively to detect the presence of planktic foraminifera (e.g., Hudson et al., 2005) in Jurassic limestones, Wernli and Görög (1999) and Görög and Wernli (2002) have made effective use of the hot acetic acid method in order to study these Jurassic assemblages at the species level.

In successions with occasional limestones, calcareous sandstones and indurated mudrocks, Carter and Hart (1977) and Hart et al. (2012) have used thin-sections in their investigations of the Albian–Turonian sediments of the Anglo-Paris Basin and the Cretaceous-Paleogene boundary in the Gulf Coast area, respectively.

This review will provide examples of the application of thin-section studies to problems relating to the Cretaceous-Paleogene (K-Pg) boundary, Cenomanian-Turonian boundary event (CTBE) and studies of Tethyan and Middle Eastern successions of the Mesozoic and Cenozoic.

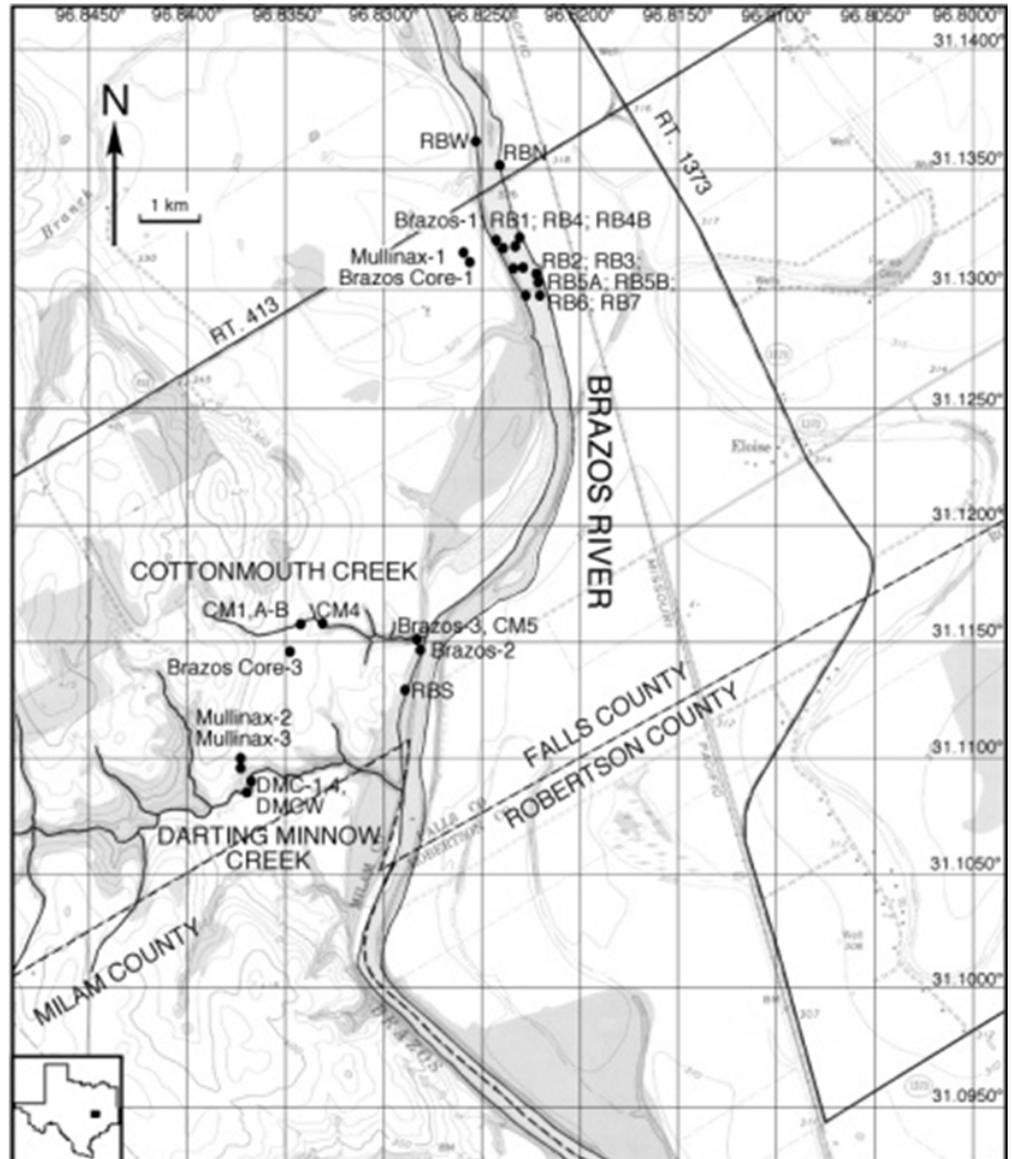
CRETACEOUS-PALEOGENE BOUNDARY EVENT

The Cretaceous-Paleogene boundary in the Brazos River area of Texas (Fig. 1) and the coeval successions in Alabama (e.g., Braggs, Mussel Creek, and Moscow Landing) contain a number of beds that cannot be processed for microfossils in the normal way. Using thin-sections also preserves information on microfacies and diagenesis, which is often lost in a powdered residue.

After Keller et al. (2004a, 2004b, 2007, 2008, 2009) claimed that the volcanic ash ~45 cm below the 'Event Bed' in the Cottonmouth Creek succession (Fig. 2) was the impact event and that this preceded the extinction event, it was important to determine the nature of the 'Event Bed' and, specifically, the characteristics of the spherule bed at its base (Fig. 3). While it was possible to process the various components of the 'Event Bed' by

crushing or the white spirit (Stoddart's Spirit) method (see Brasier, 1980; Hart et al., 2012), it was the use of selected thin-sections that showed the nature of the various lithologies and their diagenesis most accurately. In Figure 4A it is clear that despite the difficulties involved in making thin sections of such a friable lithology, the spherules are not graded and are mixed with both clastic grains and reworked Cretaceous foraminifera (Fig. 4B). This is completely different to the spherule bed on the Demerara Rise (Macleod et al., 2007, their figure 2) where the spherules are distinctly graded (Fig. 4F) and clearly represent settling in an open marine environment with little or no current activity. In the Cottonmouth Creek succession—and other sections in Darting Minnow Creek, RiverBank South and the bed of the Brazos River near the Rt. 413 bridge—the spherule bed is clearly re-worked, and mixed with other sediments and reworked bioclasts. The conglomeratic horizon (Fig. 5), below the spherule bed, represents the erosion and deposition of derived sediments, nodules and other material by the tsunami (Yancey, 1996; Hart et al., 2012; Yancey and Liu, 2013). In none of the thin-sections investigated, however, were any thoracosphaerids or calcispheres (pithonellids) detected, unlike in the immediately post-impact, Fiskeler Member of the Stevns Klint succession in Denmark (Wendler et al., 2001; Leighton et al., 2011). These

Figure 1. Location map of the Brazos River area, Texas, showing all locations and borehole sites used in the investigation of the Cretaceous-Paleogene boundary events (DMC, Darting Minnow Creek; RBN, River Bank North; RBW, River Bank West; and RBS, Riverbank South) (modified after Hart et al., 2012).



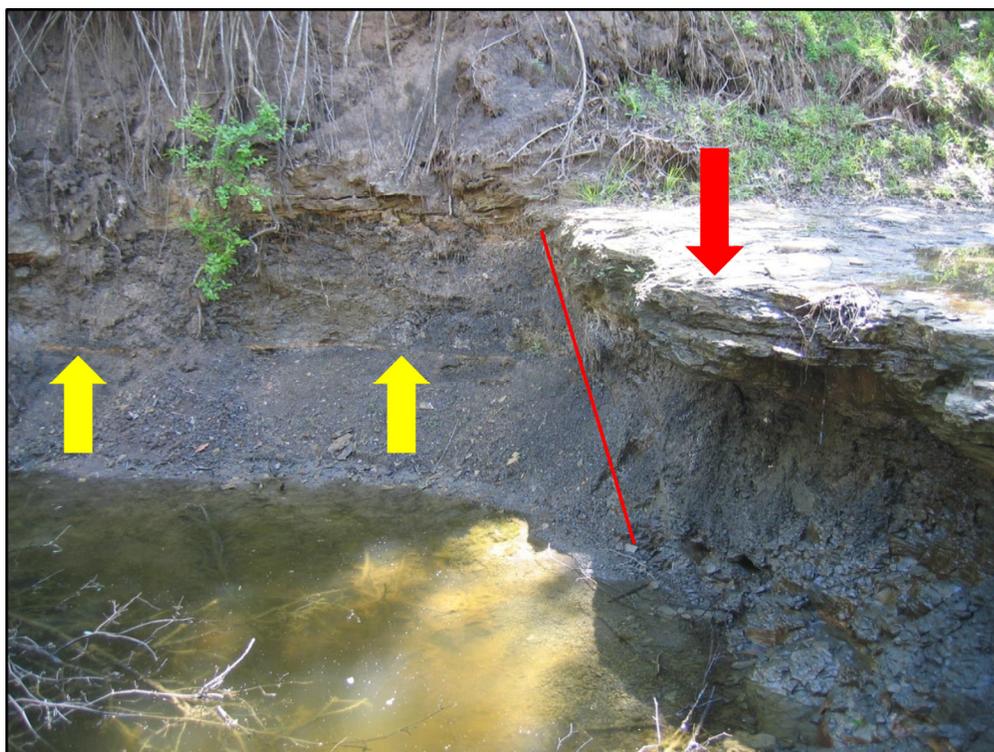


Figure 2. The waterfall section in Cottonmouth Creek, Brazos River Valley, Falls County, Texas. Note the location of the volcanic ash, described by Hart et al. (2012, p. 75–77, their figures 5 and 6) within the Corsicana Mudstone Formation (identified by yellow arrows). There is a small fault to the left of the waterfall (red line), with the top of the ‘Event Bed’ marked by the red arrow.

‘disaster taxa’ are often recorded immediately after significant biotic disturbance (Jarvis et al., 1988; Harries et al., 1996; Hart, 1996), but in this Texas example the immediate, post-impact, sediments are either highly disturbed or missing.

In deeper-water successions, well away from the Chicxulub impact site, pelagic limestones record the dramatic change in the size and taxonomic composition of the planktic foraminifera (Fig. 6). The most dramatic of these, in the Gubbio area of Italy, shows the white-colored Maastrichtian *scaglia* (argillaceous limestone) overlain by the pink-colored Danian *scaglia*, separated by a thin (1–5 cm) dark red mudstone that contains the green-colored, iridium-enriched layer at its base. In this succession none of the sedimentological events recorded in the Brazos River area are present, with only the cessation of carbonate sedimentation marking the turnover in the calcareous plankton over a period of ~30,000 yr (Hart et al., 2014) and a possible period of ocean acidification.

CENOMANIAN-TURONIAN BOUNDARY EVENT (CTBE)

The CTBE is often referred to as Oceanic Anoxic Event II (OAII) or the Bonarelli Event in European successions. It is one of the more significant of the Cretaceous anoxic events that have been described by many workers (e.g., Kauffman and Hart, 1996; Leckie, 1989; Leckie et al., 1998, 2002; West et al., 1998; Caron et al., 2006; Denne et al., 2014; Hart and Koutsoukos, 2015; Elderbak and Leckie, 2016). It was over 50 yr ago that R. P. S. (‘Dick’) Jefferies documented the micropaleontologic changes across the event in a pair of ground-breaking papers (Jefferies, 1962, 1963). His description of the changes in the foraminifera (e.g., extinction of *Rotalipora cushmani* Morrow), and the correlation of the event across the Anglo-Paris Basin provided some of the background stratigraphy for the seminal paper by Schlanger and Jenkins (1976) and the link between the biotic events and changes in Cretaceous ocean oxygenation. As indicated by Jarvis et al. (1988), the organic-walled dinoflagellate cysts (dinocysts) in the Dover succession appeared to be ‘replaced’ by a flood of calcispheres (pithonellids), much as

Wendler et al. (2001) and Leighton et al., (2011) have described at the K–Pg boundary in Denmark. This calcisphere event is almost global in extent (Hart, 1991) and characterizes the post-extinction interval within the CTBE (Fig. 7). Calcispheres were recorded by Robaszynski et al. (1993) within the Balhoul Formation of Tunisia and were illustrated by Denne et al. (2014, their figures 5 and 14) within the Eagle Ford Group of Texas. These floods of calcispheres are almost certainly coeval with records in Spain (Caus et al., 1997), France (Hart, 2013), Austria (Gebhardt et al., 2010) and Oman (Wohlwend, 2015; Wohlwend et al., 2015, 2016). In some of these carbonate platforms, the diagnostic planktic foraminifera—which tend to be keeled, deeper-water, morphotypes—may be absent due to the nature of the environment, but the calcisphere flood may still be recorded. Calcispheres, however, generally occur in the <63 μm size fraction (or even the <45 μm size fraction) and, while they are usually identified in thin section studies, they can be overlooked in processed residues unless all size fractions are investigated. The ‘filaments’ described by Robaszynski et al. (1993) and Caron et al. (2006) are rarely recorded in prepared residues as they almost invariably break up during preparation: this is often due to them being already cracked within the host sediments and, once liberated, they rarely survive intact.

CTBE Biostratigraphy

In the absence of diagnostic ammonite markers, planktic foraminifera can be used to both identify and sub-divide the CTBE interval. The diagnostic extinctions of *Thalmaninella greenhornensis* Morrow and *R. cushmani* are important markers and indicators of the oceanic changes operating at the time (Fig. 7). When studied in an expanded succession the two species become extinct within a few kyrs of each other although the record of these extinctions can be confused by the appearance of late-stage derivatives that lack many of the key rotaliporid features (*Anaticinella multiloculata* Morrow and *A. planoconvexa* Longoria): see, for example, Desmares et al. (2007) and Elderbak and Leckie (2016). Following the extinction of *R. cushmani* there is, usually, an interval of strata characterized by praeglo-

Figure 3. The northern end of the Riverbank South section on the west bank of the Brazos River on the Falls County boundary with Milam County, Texas (see Hart et al., 2012, for a full explanation): (A) The ‘Event Bed’ dipping towards the river with, beside the pick, the spherule bed that is shown in close-up in the lower image (B).



botruncanids, dicarinellids and large whiteinellids: the “*zone à grosse globigérines*” of earlier, often French, workers (Lehman, 1962; Salaj, 1980). Within this interval is the *Heterohelix* ‘shift’ that appears to mark a global change in ocean condition (Leckie et al., 1998; West et al., 1998; Keller and Pardo, 2004) coincident with the disappearance of most of the benthic foraminifera species (Carter and Hart, 1977; Jarvis et al., 1988; Hart, 1996). One of the important Turonian indicators is the appearance of *Helvetoglobotruncana helvetica* Bolli, but the first appearance of

this taxon is confused by the criteria used to separate it from the precursor *H. praehelvetica* (see Huber and Petrizzo, 2014). While the evolutionary lineage from *Whiteinella aprica* Loeblich and Tappan to *H. praehelvetica* Trujillo and *H. helvetica* can, no doubt, be identified using disaggregated, 3D material (and scanning electron microscopy) it is also a relatively simple task using thin-sections (Fig. 7). The distinctive appearance of the thickened chamber edge, which develops into a keel, and the associated turned-up edge of the chambers is clearly diagnostic and for

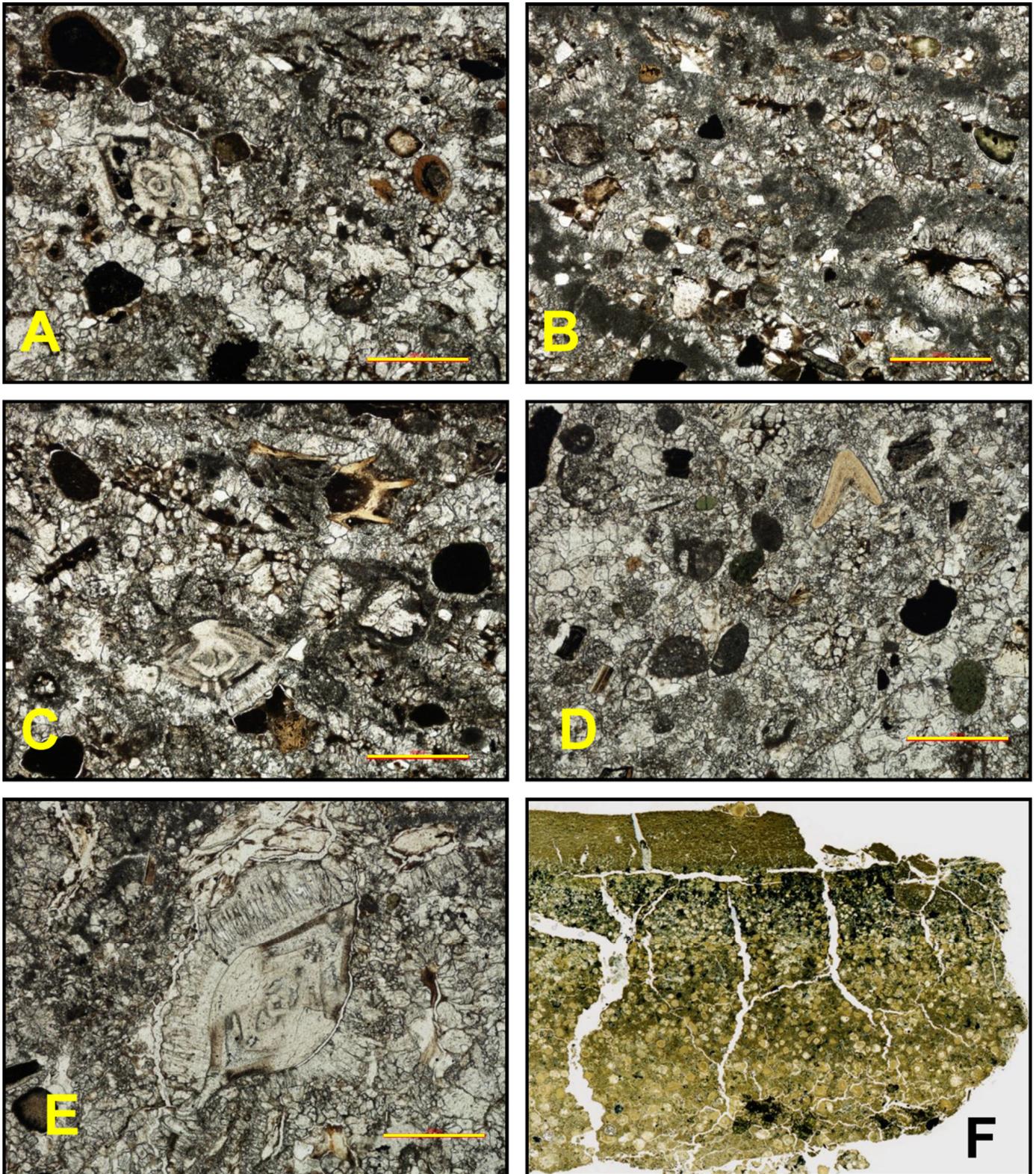


Figure 4. Thin sections of the spherule bed exposed in Cottonmouth Creek (see Hart et al., 2012, their figure 4): (A) *Lenticulina* sp. in recrystallized spherule and shell hash. Note the presence of bone fragments. Scale bar, 1 mm. (B) Small, unidentified, benthic foraminifera overgrown by later calcite. Scale bar, 1 mm. (C) *Lenticulina* sp. with fish vertebrae. Scale bar, 1 mm. (D) Ichthyolith debris with other bone fragments and glauconite. Scale bar, 1 mm. (E) *Lenticulina* sp. cf. *L. rotulata*, with calcitic overgrowth. Scale bar, 1 mm. (F) The spherule bed recovered by Ocean Drilling Program (ODP) drilling on the Demerara Rise, Atlantic Ocean, showing fresh, graded, spherules. Field of view, 6 mm. Image courtesy of Peter Schulte.

Figure 5. (A) The Cretaceous-Paleogene boundary succession on the bed of the Brazos River, immediately downstream of the Rt. 413 bridge: (B) Reworked calcareous concretions at the base of the event bed in the Brazos River section below the Rt. 413 bridge. These concretions from the Corsicana Mudstone Formation (Maastrichtian) must have been lithified during diagenesis prior to erosion and re-deposition at the K-Pg boundary.



the identification of *H. helvetica* the developing keel must be seen on *both sides* of a specimen seen in a transverse thin-section. Thin-sections from this interval also include the first twin-keeled marginotruncanids alongside the post-extinction event calcispheres.

One added problem is often ignored or, at best, mentioned briefly. In the chalks of southern England, *H. helvetica* is often less prominently keeled and may have only 4–5 chambers in the

final whorl rather than the 6–7 chambers seen in Tethyan areas. This is an ecological difference caused by paleolatitude as *H. helvetica* in the UK is at the northern limit of its distribution and it is rarely, if ever, recorded in the North Sea Basin (Dr. Haydon Bailey, 2009, personal communication). In the chalks of the UK off-shore areas the distinctive gamma-ray ‘spike’ of the Plenium Marls Member (or Black Band) is usually used to locate the CTBE and the base Turonian (van der Molen and Wong, 2007).

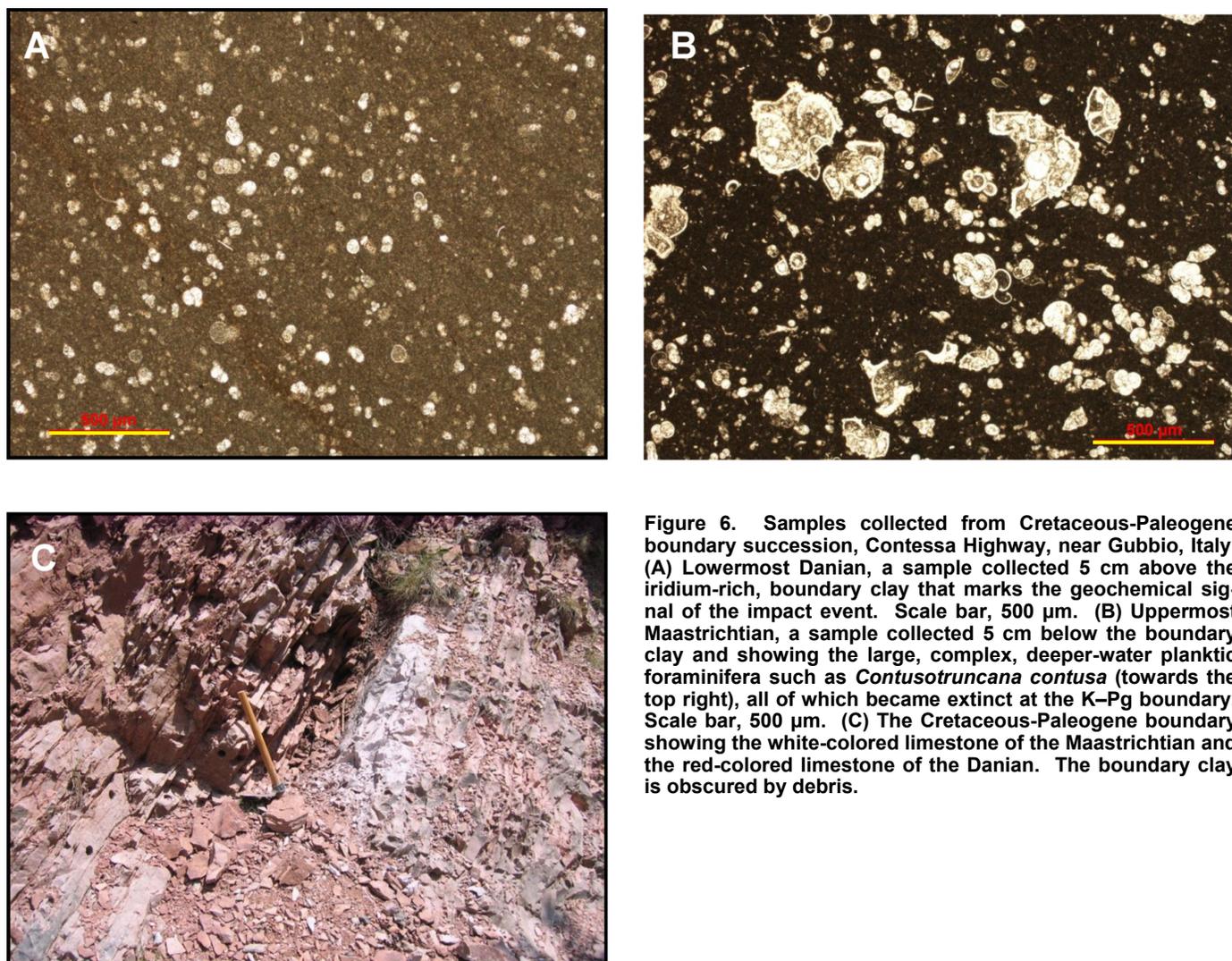


Figure 6. Samples collected from Cretaceous-Paleogene boundary succession, Contessa Highway, near Gubbio, Italy. (A) Lowermost Danian, a sample collected 5 cm above the iridium-rich, boundary clay that marks the geochemical signal of the impact event. Scale bar, 500 μm . (B) Uppermost Maastrichtian, a sample collected 5 cm below the boundary clay and showing the large, complex, deeper-water planktic foraminifera such as *Contusotruncana contusa* (towards the top right), all of which became extinct at the K-Pg boundary. Scale bar, 500 μm . (C) The Cretaceous-Paleogene boundary showing the white-colored limestone of the Maastrichtian and the red-colored limestone of the Danian. The boundary clay is obscured by debris.

CTBE Paleoecology

In the UK successions across the CTBE, radiolaria are absent apart from an anomalous occurrence in the basal Turonian (Melbourne Rock of Jefferies, 1962, 1963). The problem is one of preservation as the silica-based radiolaria are usually extremely rare, or indeed totally absent, from the chalks of northwestern Europe except for a few well-known, isolated, occurrences. Their abundance in parts of the North Sea Basin and in the limestones of Bornholm (Packer and Hart, 2005) testifies to their general presence in the water column, even though they are generally lost during taphonomy or diagenesis.

In thin sections of the Seewen Limestone Formation of the French Alps (Hart, 2013, his figure 5) no radiolaria are recorded while in the Rehkogelgraben section of Upper Austria (Gebhardt et al., 2010) radiolaria are quite commonly found, as they are in the coeval strata in Brazil (Koutsoukos and Hart, 1990), southern Russia (Fisher et al., 2005; Kopaevich and Vishnevskayaka, 2016), Colorado (Caron et al., 2006) and Oman (Wohlwend, 2015; Wohlwend et al., 2016); see Figure 8A and 8B). In the deeper water environments of the Carpathian Mountains in southern Poland (Bąk, 2007; Bąk et al., 2001, 2014) radiolaria dominate and the benthic foraminifera are represented by only deep-water, agglutinated taxa (Hart and Koutsoukos, 2015, p. 185–86). It is this paleoecological evidence that helped formulate the depth model for the CTBE suggested by Hart and Koutsoukos (2015,

their figure 8). Thin-sections are not normally used in the identification of radiolaria as their complex, highly ornate, skeletons cannot be fully appreciated in a thin-section. There are, despite this, a number of taxa that can probably be identified to the generic or family level using carefully selected thin-sections (Fig. 8). Even when identification is impossible it is important to record their presence in thin-sections as their occurrence may be important in the understanding of the paleoecology of the CTBE.

The CTBE is now associated with two or three, short-lived, cooling events that were first mentioned by Jefferies (1962, 1963). The information on these cooling episodes was recently reviewed by Hart and Koutsoukos (2015, p. 185) and there is now considerable speculation as to whether these are linked to events in the Caribbean Large Igneous Province (see Courtillot and Fluteau, 2010 and references therein) or the High Arctic Large Igneous Province (see Jenkyns et al., 2016 and references therein). In some areas (e.g., North Sea Basin, Rehkogelgraben [Upper Austria], and the Crimea) there are 2–5 discrete, black mudstones within the CTBE and appear to mark high productivity events (Marshall and Batten, 1988; Hart et al., 1993, their figure 4). While these records of sea floor dysaerobic or anoxic sediments occur *within* the $\delta^{13}\text{C}$ isotope excursion, there are many instances where organic-rich sediments are recorded *outside* the $\delta^{13}\text{C}$ isotope excursion interval (Mello et al., 1989; Robaszynski et al., 1993; Denne et al., 2014; Wohlwend et al., 2016).

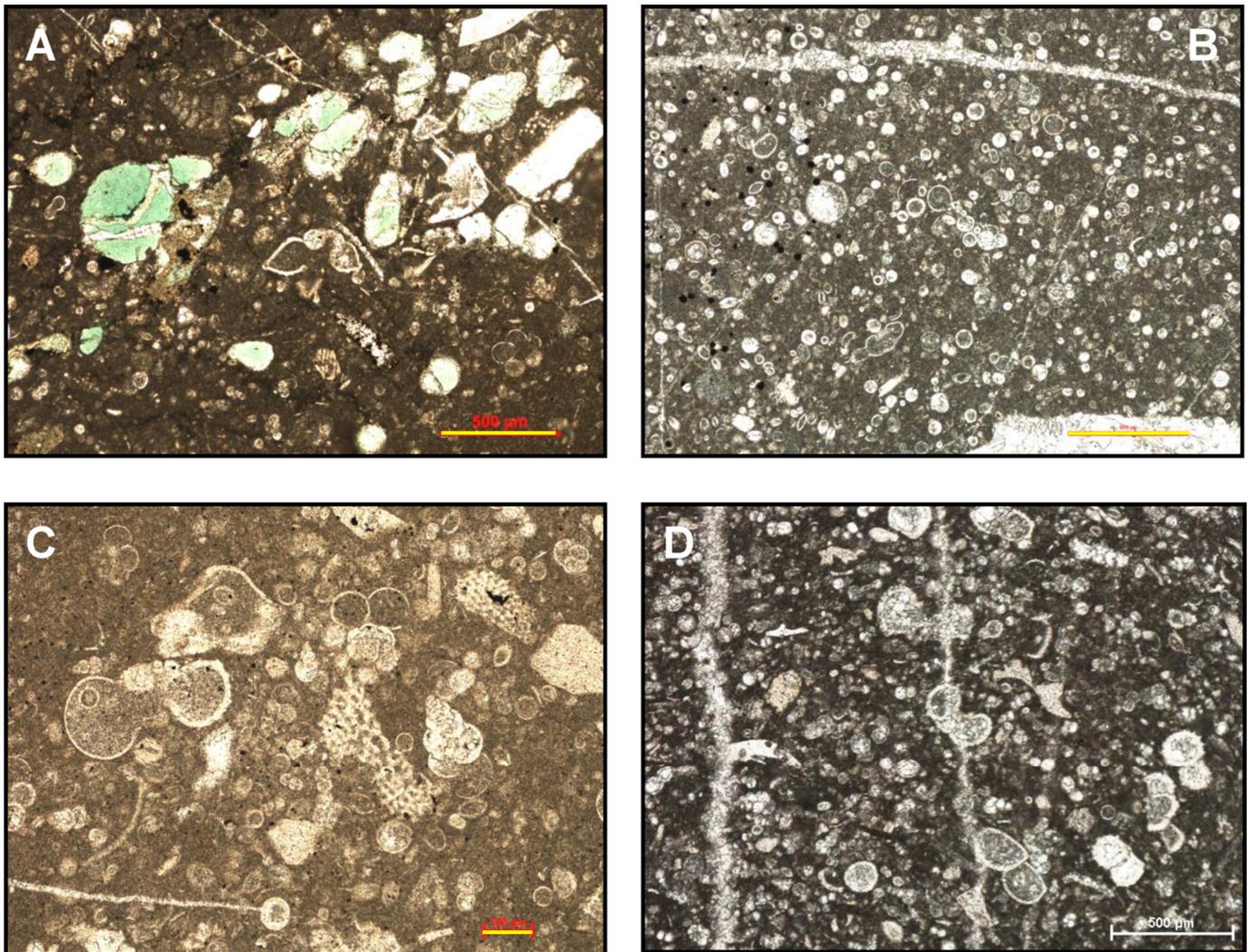


Figure 7. Calcispheres and planktic foraminifera from the Cenomanian-Turonian succession near Le Reposoir, Haute Savoie, France. (A) *Rotalipora cushmani* from the glauconite-rich basal Seewenkalk (Seewen Limestone Formation), uppermost Cenomanian, Scale bar, 500 μm . (B) Calcisphere-rich Seewenkalk from Flaine, Haute Savoie, France, lowermost Turonian. Note small specimen of *Hedbergella planispira* in the center of the field of view. Scale bar, 500 μm . (C) *Helvetoglobotruncana prae-helvetica* showing a developing keel on the older chamber and no sign of a keel on the, thinner-walled, final chamber. Note presence of calcispheres and *Heterohelix* sp. cf. *moremani*. Basal Turonian, Seewenkalk, Flaine, Haute Savoie. Scale bar, 100 μm . (D) An individual right on the transition from *Helvetoglobotruncana prae-helvetica* to *Helvetoglobotruncana helvetica* with faint keeps on both edges. Scale bar, 500 μm .

TETHYAN CARBONATE SUCCESSIONS

In many areas of the Middle East, the Mesozoic and Cenozoic successions are characterized by carbonate depositional environments. The normal processing of samples is, therefore, impossible and biostratigraphy is based, almost exclusively, on thin-sections. While it is possible to process thin, marl-rich, inter-beds these often give a distorted view of the species present and are frequently the result of specific taphonomic or diagenetic processes. Thin-section investigation of these important carbonate-rich successions often involves both biostratigraphic and microfacies analysis, the latter being key to understanding the hydrocarbon source and reservoir rocks in the region. Alongside the micropaleontologic studies, diagenetic fabrics are often the key to reservoir quality, especially the presence or absence of moldic porosity.

In the Oman Mountains, which provide a magnificent location in which to study Mesozoic carbonates, the Jurassic-Cretaceous rocks are accessible in a number of locations including the well-known Wadi Mi'aidin succession (see Simmons and

Hart, 1987, their figure 10.1). In the uppermost Jurassic and lowermost Cretaceous succession are fine-grained—often chert-rich—limestones that contain rare planktic foraminifera, rare calcified radiolaria and occasional calpionellids. While the planktic foraminifera and the radiolaria are interesting, they cannot be identified accurately (if at all), but the calpionellid zonation (Remane, 1978, his figure 8; Pop, 1997; Grün and Blau, 1997; Andreini et al., 2007; Lakova and Petrova, 2012) is extremely useful for biostratigraphic work and, in many places around the world, provide a valuable, inter-regional correlation of the Jurassic-Cretaceous boundary and lowermost Cretaceous (Wimbledon, 2015) (Fig. 9).

The overlying ~1 km of the Thamama and Wasia groups is often dominated by assemblages of miliolid foraminifera. While these cannot be identified to the species level, when an assemblage is composed on 90% (or more) of miliolids then it clearly represents a shallow-water, probably hypersaline, lagoonal environment (Murray, 1991, p. 192–199) by analogy to modern environments. In the Habshan Formation, the succession begins to change with the appearance of *Choffatella decipiens* Schlum-

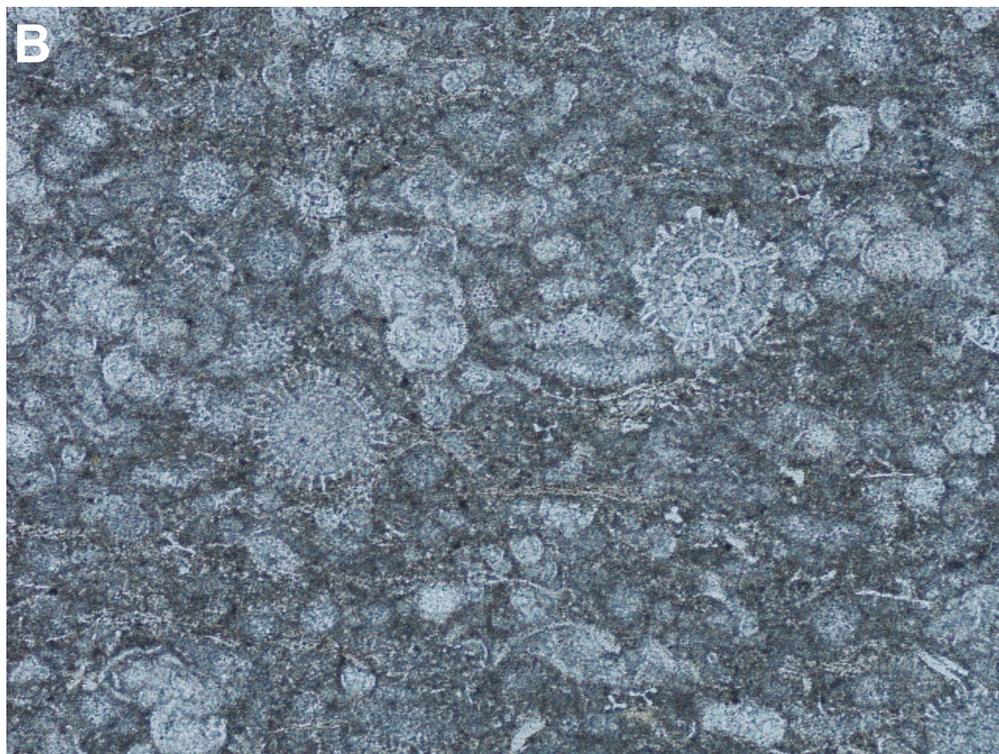


Figure 8. Radiolaria from the Cenomanian-Turonian boundary interval, Oman Mountains, Oman. (A) Large conical radiolarian referable to *Pseudodictyomitra* sp. cf. *P. pseudomacrocephala* (Squinabol), which is recorded at the Cenomanian-Turonian boundary in the Crimea by Kopaevich and Vishnevskaya (2016, their figures 7 and 12). Field of view, 800 μm . (B) Two genera that may be referred to *Patellula* and *Archaeocenosphaera*, both well-known from the Cenomanian-Turonian boundary interval in the Crimea (see Kopaevich and Vishnevskaya, 2016, their figure 9). Field of view, 800 μm .

berger, orbitolinids, praealveolinids, chrysalidinids and nezzazzatids progressively upsection (Fig. 10). These assemblages provide micropaleontologists working on the succession with a very precise biostratigraphy that can be used for both local and regional correlation.

Within this range of genera and species there are some taxa which are generally identified to the species level (e.g., *C. decipiens* and *Chrysalidina gradata* d'Orbigny) as they are so distinctive or represent monospecific genera. In some cases prevailing usage has, unfortunately, not looked for variations that may be

sufficient for the creation of new species (or sub-species) that could be more stratigraphically diagnostic. In other taxa, such as the genus *Orbitolina*, identification of sub-genera, species (and in some cases sub-species), relies on the presence of key features and randomly oriented thin-sections may not provide key information. In some cases it may be necessary to study 12 (or more) standard thin-sections from each sample in order to locate a critical section through the embryonic apparatus. In the case of commercial work where small 'plugs' have been taken from the core, this number of thin sections is probably unavailable.

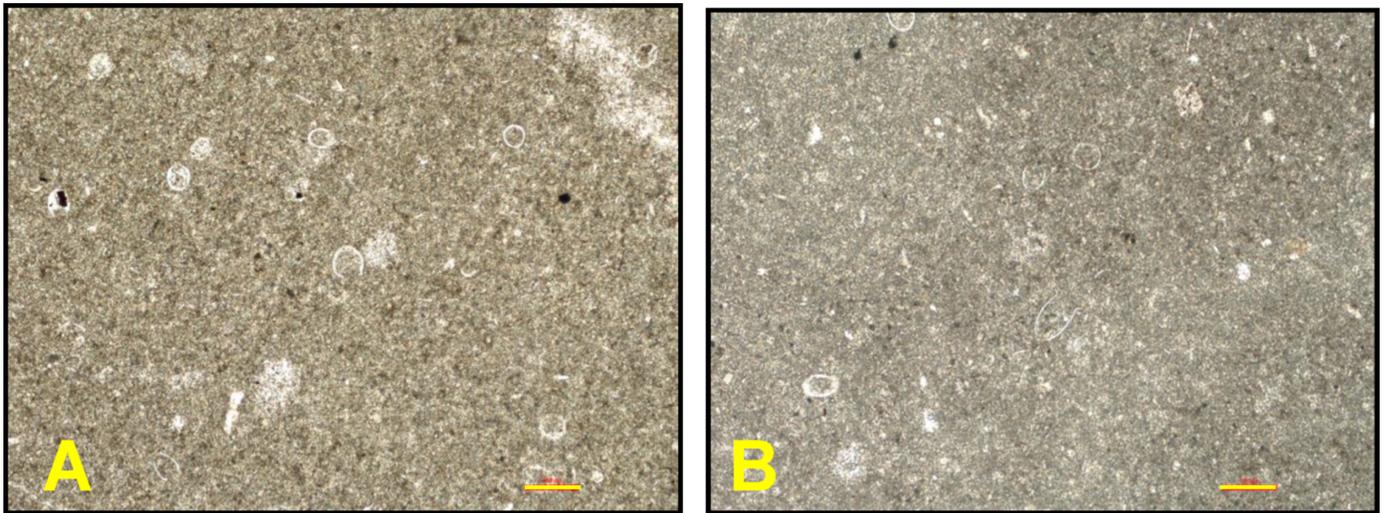


Figure 9. Calpionellids from the lowermost Cretaceous, near Digne, southeastern France. (A) *Calpionella alpina* Lorenz. Scale bar, 50 μm . (B) *Tintinopsella carpathica* Murgeanu and Filipsecu. Scale bar, 50 μm . The co-occurrence of these taxa in the same samples is indicative of zone B, which straddles the Jurassic/Cretaceous boundary (Remane, 1971).

Micropaleontologic investigations, especially those using thin-sections, have a vital role to play in hydrocarbon exploration in areas such as the Middle East. It is impossible to cover this topic in such a brief review, and several books have been written on the topic (e.g., Simmons, 1994; Jones, 1996, 2011). The orbitolinids are exceptionally valuable for biostratigraphy and microfacies analysis in the mid-Cretaceous (e.g., Witt and Gökdağ, 1994; Schroeder et al., 2010). The latter account provides a complete assessment of orbitolinid biostratigraphy and demonstrates how the microfauna can be used in the determination of sequence stratigraphy. Simmons et al. (2000, their figure 3), in an earlier paper, had suggested that the morphology of the orbitolinids could be used to assess water depth, and thereby sequence stratigraphic interpretations, but Schroeder et al. (2010, their figures 17 and 18) have demonstrated how powerful the technique has now become. Similar methodologies, along with stable isotope information, have also been used to develop sequence stratigraphic interpretations in the mid-Cretaceous of Oman by Wohlwend (2015) and Wohlwend et al. (2016). In the mid-Cretaceous of southwestern Iran, Adams et al. (1967) demonstrated that calcspheres can also be used to provide a viable zonation and supplement rather limited information from planktic foraminifera in a more open marine setting. Many of those working in the Middle East also rely on calcareous algae to support facies interpretations based on foraminifera (Banner and Simmons, 1994; Hughes, 2005a). This is particularly true of the Khuff Formation (Hughes, 2005b) of late Permian to Triassic age, and which forms important reservoirs in Saudi Arabia and which has a distinctive assemblage of both foraminifera and calcareous algae. Directional drilling of this formation has been developed by Wyn Hughes (Saudi Aramco) using thin sections prepared and analyzed on the well-site (in around 20 min). By 2014, >56 wells had been drilled using this well-site based approach (Anon., 2014; Dr. Saleh Sfoog M. AlEnezi, 2016, personal communication). The precision claimed for this technique is 12–18 in, although the Khuff Formation in Saudi Arabia appears to be a special case and this thin-section approach has not been replicated elsewhere

ALGAE

The larger, carbonate-producing algae (Rhodophyta and Chlorophyta) are important bioclasts in many shallow-water limestones (Wray, 1978). Though they are often best used as environmental indicators, there are instances where they are strat-

igraphically significant. One example of such usage is that of the Wadi Mi'aidin succession of the Oman Mountains where Simmons and Hart (1987, his figures 10.8, 10.10, and 10.11, and plate 10.3) used a number of algal taxa (e.g., *Salpingoporella dinarica* Radoicic, *Permocalculus irenae* Elliott, *Acroporella assurbanipali* Elliott) from the Lower to mid-Cretaceous succession to aid in their biostratigraphic interpretations (Fig. 11). Once again, it is often necessary to search a number of thin sections in order to see a suitable profile of the key features for a specific identification. As such taxa very often have quite limiting ecological requirements they are exceptionally valuable in paleoecological reconstructions (e.g., Hughes, 2005a).

In tropical regions, rhodophyte algae can encrust hard surfaces, including shells, but may also be unattached (Fig. 12). In tropical areas (e.g., Brazil) rhodoliths in near shore marine environments can be 10 cm in diameter and display a characteristic internal structure (Pascelli et al., 2013; Hart et al., 2016, fig. 3A; Rebelo et al., 2016). Rhodoliths are also well-known in the geological record, including the Tata Limestone Formation (mid-Cretaceous) of Hungary. Maerl is the collective name for a number of species of red seaweeds (Rhodophyta) that develop hard calcareous skeletons (Corallinaceae) in temperate waters. Maerl has twig like, branching forms which are found along the western coastline of northwest Europe (Southwest England, Brittany, Western Ireland, the Inner Hebrides and Iceland) down to depths of 51 m, though they are normally found in waters of <20 m (Peña et al., 2014; Hart et al., 2016, fig. 3C).

In many Tethyan limestones rhodophyte algae can be extremely abundant, often associated with larger benthic foraminifera (Fig. 12). In the French Alps, near Cluses, a section near Servey contains an exceptional assemblage that includes *Nummulites garnieri* Boussac, discocyclinids, asterocyclinids, actinocyclinids, operculinids, miliolids, and locally abundant *Lithothamnion* sp. and bryozoans (Fig. 13). The age of this assemblage is Late Priabonian (Late Eocene), and in its upper part becomes increasingly dominated by the algae. This may indicate a local shallowing, but the age of the sediments indicate that this sea level fall may be linked to the general sea level changes at the Eocene/Oligocene boundary (Zachos et al., 2001).

The Charophyta are represented by the charophytes, a group with a long fossil record back to the Devonian (Wray, 1978). Today, modern taxa are found only in fresh-water environments that are un-polluted and with limited current activity (Hart et al., 2016). As such environments are rarely fossilised, it is unsurprising that there is relatively little literature in their study in thin

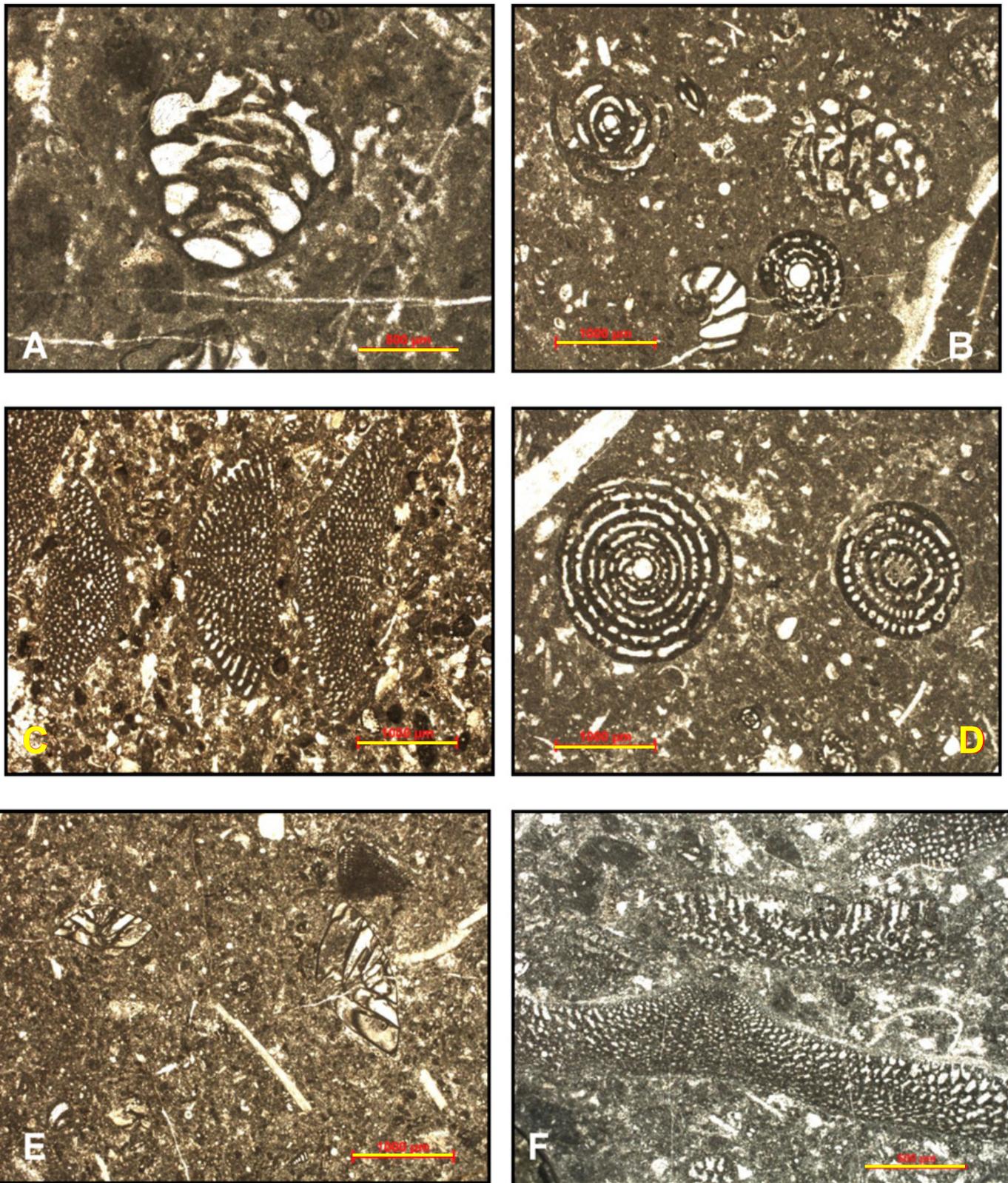


Figure 10. Mid-Cretaceous larger foraminifera from the Wadi Mi'aidin succession, Oman Mountains, Oman. (A) *Chrysalidina gradata* d'Orbigny from the Natih Formation (Cenomanian), Wasia Group. Scale bar, 500 µm. (B) *Chrysalidina gradata* d'Orbigny associated with miliolids and *Ovaleolina ovum* d'Orbigny. In the lower, center, of the image is *Nezzazinella picardi* Henson from the Natih Formation (Cenomanian), Wasia Group. Scale bar, 1000 µm. (C) *Palorbitolina lenticularis* Blumenbach from the Kharai Formation (Barremian), Thamama Group. Scale bar, 1000 µm. (D) *Cisalveolina fraasi* Gümbel and *Praealveolina* ex gr. *P. simplex* Reichel from the Natih Formation (Cenomanian), Wasia Group. Scale bar, 1000 µm. (E) *Nezzazata simplex* Omara from the Natih Formation (Cenomanian), Wasia Group. Scale bar, 1000 µm. (F) *Orbitolina* (*Mesorbitolina*) *subconca* Leymerie from the Nahr Umr Formation (lowermost Cenomanian), Wasia Group. Scale bar, 500 µm.

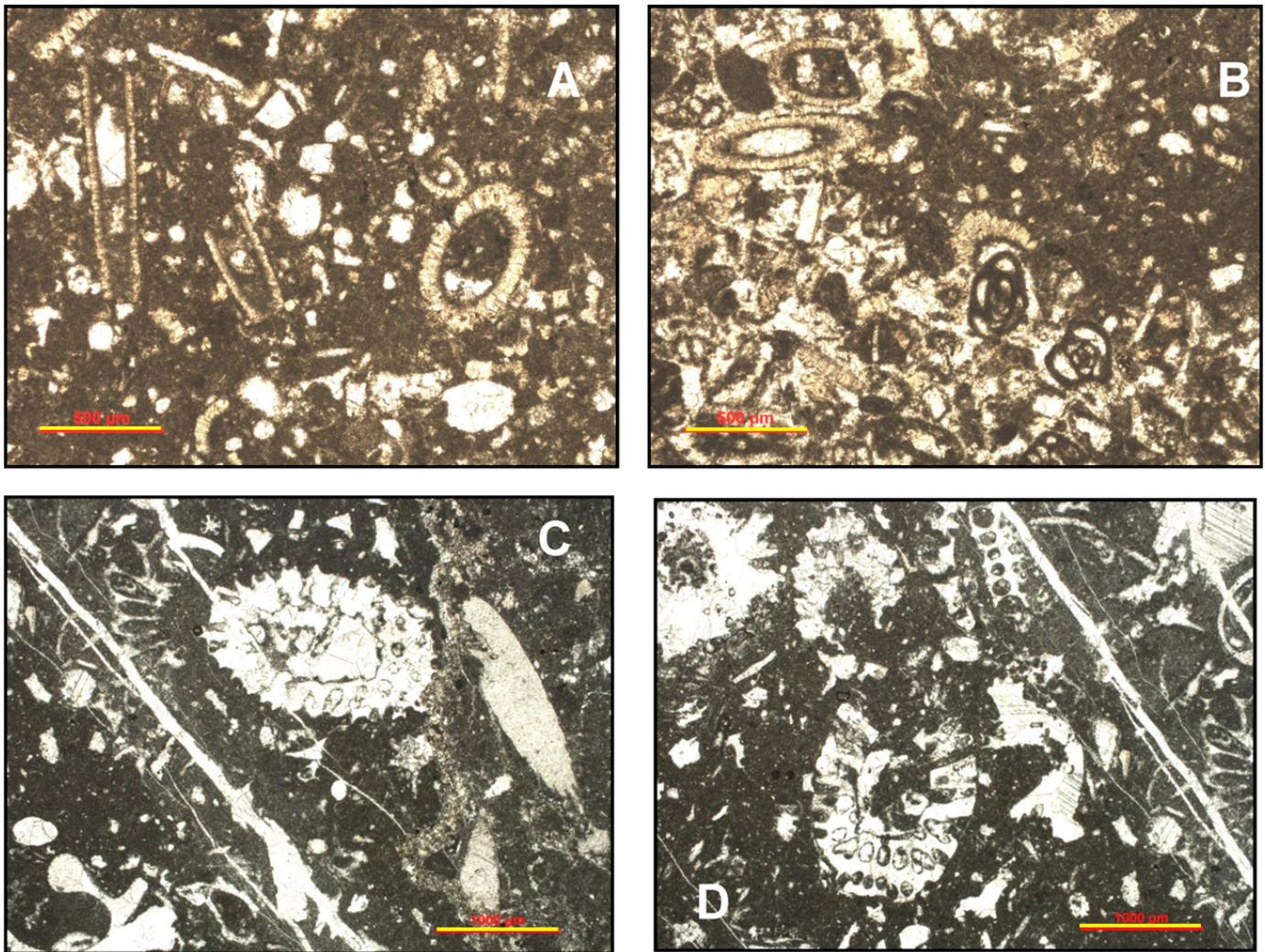


Figure 11. Mid-Cretaceous algae from the Wadi Mi'aidin succession, Oman Mountains, Oman. (A) *Salpingoporella dinarica* Radiocic from the Lekwhair Formation (Hauterivian), Thamama Group. In this field of view are a number of transverse sections of the stem (circular forms) together with some longitudinal sections (with sub-parallel sides). Scale bar, 500 μm . (B) Further sections through *Salpingoporella dinarica* Radiocic from the Lekwhair Formation (Hauterivian), Thamama Group, which are associated with abundant small (unidentifiable) miliolids. The dasyclad algae and the abundant miliolids indicate a shallow, quiet-water, lagoonal environment. Scale bar, 500 μm . (C) *Acroporella* sp. from the Lekwhair Formation (Hauterivian), Thamama Group. Scale bar, 1000 μm . (D) *Acroporella assurbanipali* Elliott from the Lekwhair Formation (Hauterivian), Thamama Group. Scale bar, 1000 μm .

sections. In the U.K., one succession that is well-known for charophytes is the Purbeck Group (Allen and Wimbledon, 1991; House, 1993; Hart, 2009; Cope, 2016) of the Durlston Bay succession on the Dorset Coast (Fig. 14). In the Middle Purbeck, below the Cinder Bed, *Clavator* spp. are locally abundant and are often seen on weathered surfaces or in thin-sections (Harris, 1939).

TAXONOMIC STUDIES

As indicated above, full specific identification often requires oriented thin-sections and the random slices seen in most thin-sections may not be sufficiently diagnostic. This is particularly the case, for example, in the *Orbitoides* and *Lepidorbitoides* lineages of the Upper Cretaceous. The *Orbitoides* lineage of the Santonian-Maastrichtian is stratigraphically diagnostic, but the identification of the individual species does require accurately located thin sections. This requirement may, of course, be superseded by the use of X-ray computed tomography (micro-CT): see Briguglio et al. (2011); Görög et al. (2012).

In the Campanian–Maastrichtian carbonate ramp succession of the Ariyalur-Pondicherry Depression (Cauvery Basin, south-eastern India) there is an important succession of exceptionally fossiliferous limestones, exposed in the massive quarries just east of Ariyalur (Fig. 15). The Cauvery Basin is an oil-bearing basin, recently described by Watkinson et al. (2007). In the uppermost Campanian and lowermost Maastrichtian the Kallankuruchchi Limestone Formation (Watkinson et al., 2007, their figures 2–4) forms an important carbonate ramp succession with abundant larger foraminifera. The Kallankuruchchi Limestone Formation contains a number of *Orbitoides* spp., as well as *Siderolites calcitrapoides* Lamarck in Faujas de Saint Fond. The later species is highly distinctive and can be separated from *Siderolites laevigatus* d'Orbigny by the distinctive lack of shell material between the radiating 'arms': see Renema and Hart (2012) for a guide to their separation and taxonomic history. The species of *Orbitoides* and *Lepidorbitoides* are less straightforward to identify without a critical view of the embryonic apparatus and early arrangement of chambers (Caus et al., 1996; Renema and Hart, 2012).

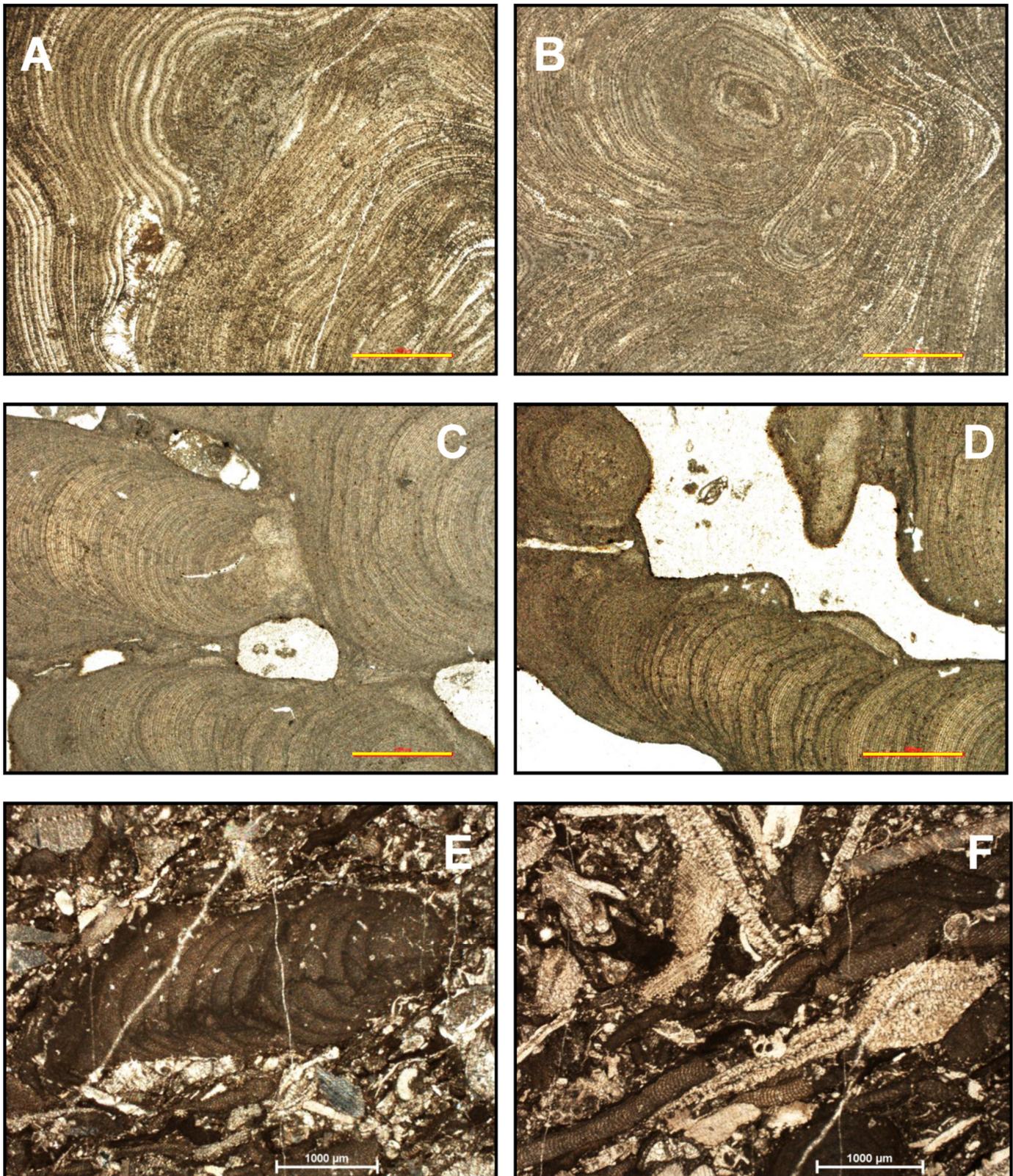


Figure 12. Rhodophyte algae including modern and fossil forms. (A & B) Modern rhodolith from the coast of Sergipe in north-eastern Brazil. Scale bars, 1000 µm. (C & D) Fossil rhodolith from the Tata Limestone Formation, mid-Cretaceous, Hungary. Note the presence of a miliolid foraminifera in D. Scale bars, 1000 µm. (E) *Corallina* from the Eocene of Serveray, near Cluses, Haute Savoie, France. Scale bar, 1000 µm. (F) *Jania* and *Corallina* from the Eocene of Serveray, near Cluses, Haute Savoie, France. In this thin-section the algae are associated with fragmentary *Discocyclus* and other debris. Scale bar, 1000 µm.

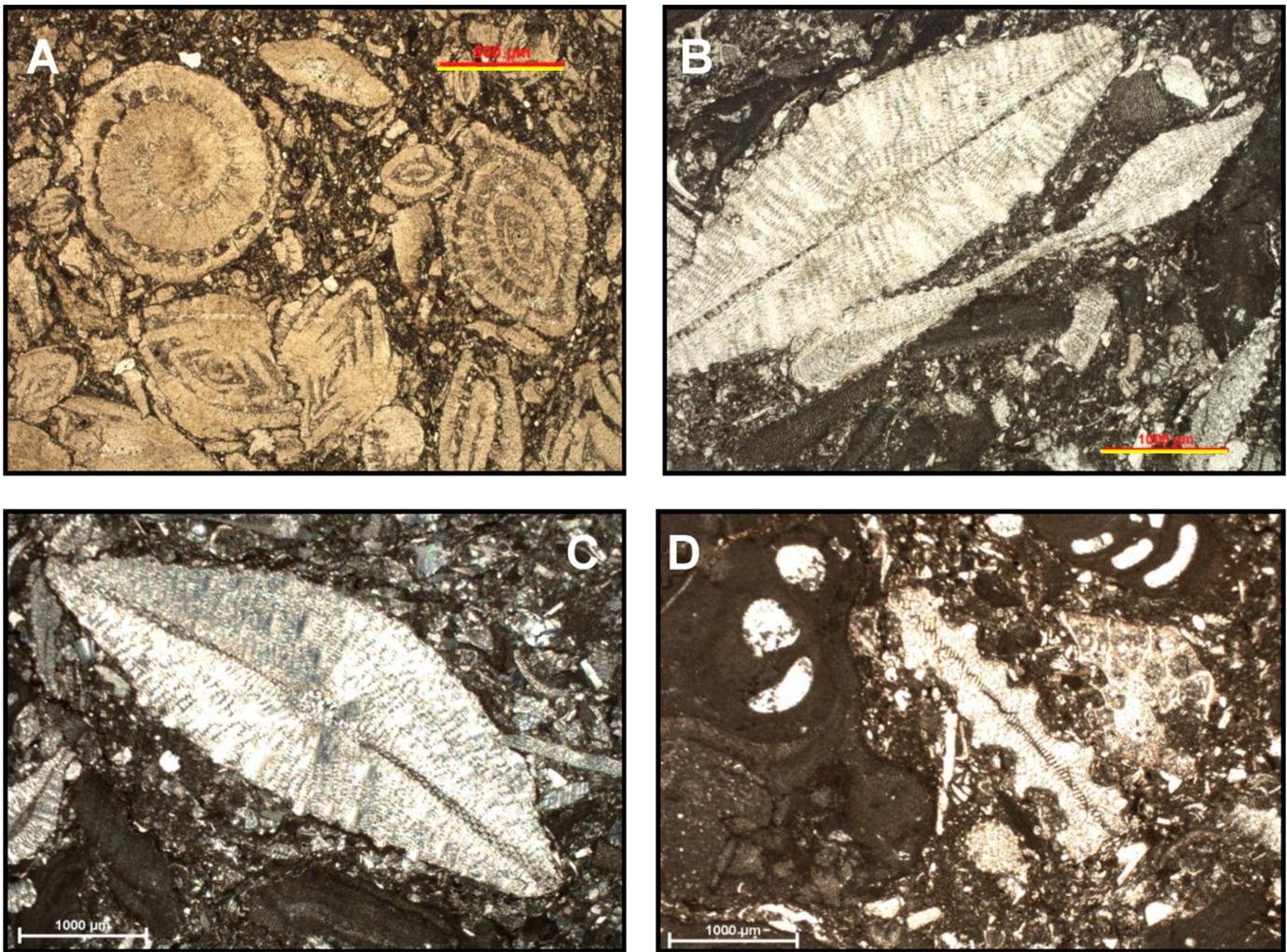


Figure 13. Cenozoic larger foraminifera from two locations in the French Alps near Cluses, Haute Savoie, France. (A) *Nummulites fabianii* Prever from the Eocene of the Col de la Colombière. This thin-section shows a number of sections through this monospecific assemblage. Scale bar, 500 μm . (B) *Discocyclina* and *Asterocyclina*. The latter genus is typified by ~5 ‘arms,’ which, in a thin-section, show up as two or three inflated areas. Scale bar, 1000 μm . (C) *Discocyclina* with the thin-section just missing the embryonic area. Scale bar, 1000 μm . (D) *Actinocyclina*, a genus characterised by multiple inflated areas radiating across the test from the embryonic apparatus. This gives a cross-section with multiple inflated areas. This specimen is associated with both algae and bryozoans. Scale bar, 1000 μm .

This requirement for examination of a critical thin-section is also true of the discoidal taxa (*Discocyclina*, *Nummulites*, etc.) that are known from the Lower Cenozoic and the large taxa (e.g., *Miogypsina*, *Lepidocyclina*, etc.) that characterize the Upper Cenozoic. In the Eocene limestones of Severay, near Cluses (Haute Savoie, France) the pale-colored rocks are crowded with *Discocyclina* sp., *Nummulites garnieri*, smaller benthic foraminifera, and rhodophyte algae. There are also good examples of the closely related *Actinocyclina* and *Asterocyclina*, the appearance of which does vary significantly with the orientation of the thin-sections (Fig. 13).

DISCUSSION

One question, often asked by both students of micropaleontology and those working in the hydrocarbon industries, is about the need for a statistical approach to the study of thin-sections. In the case of the Kharab Formation of the Oman Mountains it is common to find a thin section that contains little by way of matrix: the rock being 90% (or more) of *Palorbitolina lenticularis* Blumenbach. In other rocks, where matrix often dominates, there are two questions: (1) How many thin-sections should be studied

in order to gain a representative view of the assemblage; and (2) can one count the taxa present in a way that provides information on the paleoecology of the depositional environment.

In the case of (1) above, it is often suggested that 6 or 12 sections may be inspected, though it is probably more important to be consistent in the approach adopted. In the case of (2) above, there are doubts as to what counts may indicate. In the limestones from Severay (Haute Savoie, France) it may be possible to determine the percentage of discocyclinids or nummulitids, but should one count individuals, parts of individuals or adopt some form of point-counting methodology? If one uses point-counting, then the larger foraminifera will clearly ‘hit’ more of the points, while smaller foraminifera in the matrix could be missed completely, although this is obvious from even a quick scan of such slides.

In a recently published discussion of thin-section analysis, Flügel (2010, his figure 6.7) has presented information on how to inspect a thin-section in order to obtain the most information in a reasonable time. It was suggested by Flügel (2010) that thin-sections could be studied by either (A) point counting, (B) the line method, (C) the area method, or (D) the ribbon method. Point counting is probably inappropriate for micropaleontological

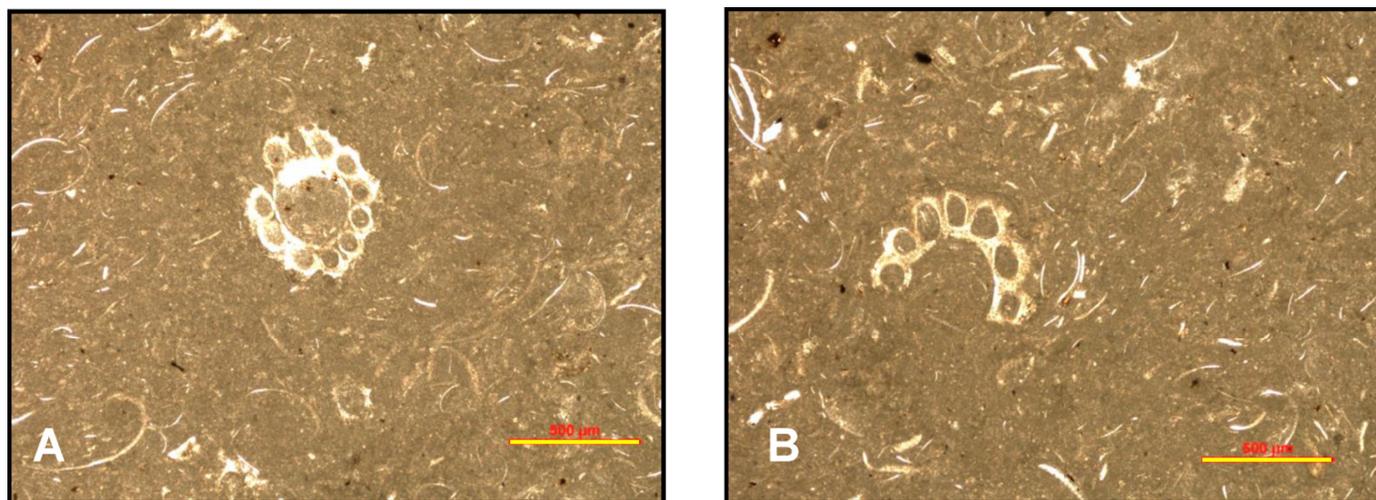


Figure 14. *Clavator reidi* Groves (1924), a charophyte stem from the Middle Purbeck Beds, Durlston Bay, Dorset, U.K. Located just below the Cinder Bed, these are possibly from the uppermost Jurassic, very close to the base of the Cretaceous (in U.K. stratigraphic terminology). These cross sections of the stem of *C. reidi* show a characteristic appearance with ~12 cortical cells visible. In the charophyte literature, stems are often included in *Charaxis*, a form genus created by Harris (1939, p. 39) with the type-species *Charaxis durlstonensis*. As the oogonium has not been found then, without a knowledge of the charophyte taxa in these rocks, these thin-sections should probably be included in *Charaxis*, as discussed in Granier et al. (2015, p. 209). Scale bars, 500 µm.

work as some species may only be present singly and would be easily missed, unless one had some additional ‘inspection’ process added to the point counting. The line method, which only records grains that intersect an imaginary line across the thin-section, suffers the same problems. The area method counts all the grains within a sub-area of the thin-section, but again would fail to pick up all the rare foraminifera (or other micro- and macro-fossils). The ribbon method counts all the gains within the ‘ribbon’ and, while more accurate than the line method, it still leaves parts of the thin-section uninspected. Some workers use the ‘consecutive ribbon method’ to scan the thin-section in the certainty that all grains (and foraminifera) would be seen. This involves repeated scans across the complete slide, effectively covering the whole area in detail. While clearly the longest process in terms of time, it will recover all the data required for a full analysis of both the biostratigraphy and the microfacies. In using this approach it is necessary to adjust the field of view to a size that will be both accurate and time-effective. In this approach it is also necessary to standardize the counting terminology used, with a well-tried scheme using the following terminology: present (one specimen), rare (2–5 specimens), common (6–20 specimens), abundant (21–50 specimens) and ‘flood’ (>50 specimens). While any scheme adopted is probably a compromise between accuracy and time, it is important to have a degree of consistency as this will allow variations up-section and between wells to be determined correctly. In the analysis of disaggregated samples some workers will count to what they regard as a statistically viable number (301?) while others use the rarefaction method of graphically determining when all taxa have (probably) been discovered (for discussion, see Siegel, 1990; Gotelli and Colwell, 2001; Bush et al., 2004).

SUMMARY

While the study of thin-sections is the norm in many areas of the world (e.g., Tethyan areas, Middle East, and parts of the Far East), many micropaleontologists elsewhere are hesitant about using thin-sections unless it is impossible to work without them. This is a slightly unfortunate situation as judicious use of thin-sections can provide valuable biostratigraphic and paleoecologic information that may be lost if only disaggregated samples are used (especially if poorly broken down). If microfossils are re-

moved (by sample preparation) from their host sediments, important information on paleoecology and microfacies can be lost. This is particularly important when there has been the loss of some taxa during diagenesis as the cavities observed in a thin-section can often allow these components to be identified. Very frequently, other bioclasts (e.g., echinoderm spines (both regular and irregular), asteroid laterals, inoceramid prisms, etc.) will be recorded in the analysis of a thin-section but can be omitted from the inventory produced in the assessment of a prepared residue.

In some successions, foraminifera are often seen to have micro-fractures that, when the sample is prepared, tend to break apart. Planktic foraminifera in the chalk facies of northwestern Europe are particularly susceptible to this problem and, if using ecological indicators such as planktic:benthic ratios, results can be distorted if the planktic taxa disintegrate more easily than the benthic taxa. Micropaleontologists should, therefore, be more conversant with thin-section usage, and encouraged to employ the technique where it is appropriate. In some mudrocks, which can often be prepared into normal residues, impregnation and judicious use of thin-sections can indicate the presence of, by example, rhythmic occurrence (cyclicity?) that would not be seen otherwise.

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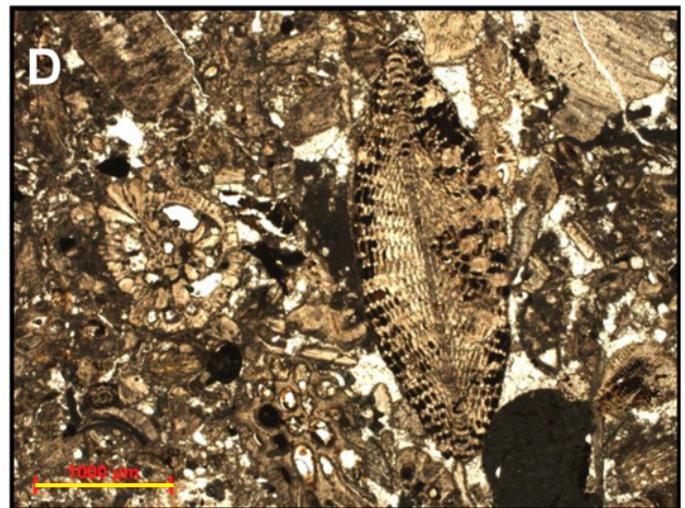
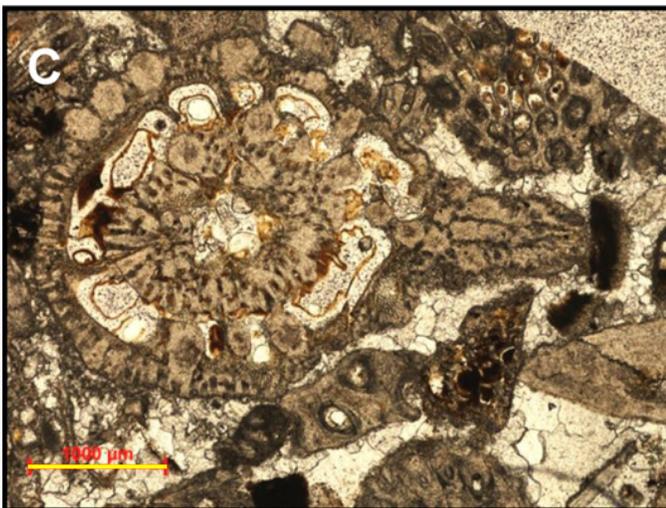
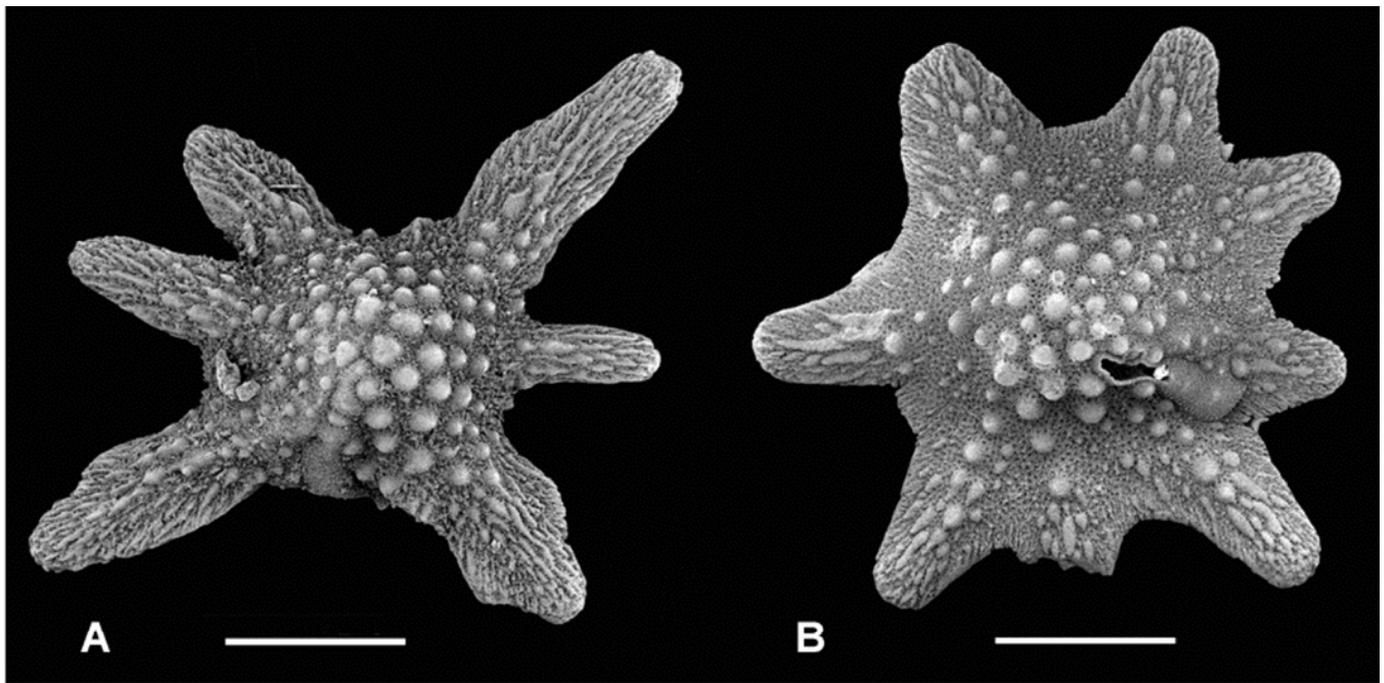


Figure 15. (A & B) Larger foraminifera from the Maastricht Chalk Formation, ENCI quarry, Maastricht, The Netherlands; and the (C & D) Kallankuruchchi Limestone Formation (Maastrichtian), east of Ariyalur, Tamil Nadu, India. (A) *Siderolites calcitrapoides* Lamarck showing the characteristic 'arms' and the highly tuberculate surface. Scale bar, 1 mm. (B) *Siderolites laevigatus* d'Orbigny with the characteristic infilling of the test between the 'arms.' There are gradational forms between these two morphotypes and the separation of the two species is, quite often, unreliable. Scale bar, 1 mm. (C) *Siderolites calcitrapoides* showing only one 'arm'. Scale bar, 1000 µm. (D) *Siderolites calcitrapoides* and *Orbitoides* sp. as well as numerous bryozoan fragments. Scale bar, 1000 µm.

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