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"A la recherche du temps perdu": On geological condensation, with examples from the Jurassic Subbetic Plateau in Southeastern Spain [1]

By

Alexander Fels and Hartmut Seyfried, Stuttgart

With 5 figures in the text

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Abstract: A condensed deposit is a marine rock residue that accumulated autochthonously over a large time-span; it should have a recognizable and chronologic biostratigraphic record. Condensation is a continuous process working during sedimentation by mechanical concentration (filtering/sieving, screening, by-passing, winnowing, or scouring of mud) or shortly after sedimentation (bioerosion on hardgrounds in combination with mechanical erosion and exhumation of underlying strata). In the Subbetic Plateau (formerly "external Subbetic") of the eastern Betic Cordillera, the threshold for the development of a condensed situation is controlled by a tectonic process: emergence, subsidence or drowning of adjacent carbonate mud supplying platforms regulate retention or releasing of mud. As a consequence, the Plateau experienced four episodes of strongly reduced sedimentation: Carixian - Early Domerian (condensation episode 1), Late Toarcian - Early Bajocian (condensation episode 2), Early Bathonian - Early Oxfordian (condensation episode 3), and Earliest Kimmeridgian (condensation episode 4). Hardgrounds in condensed successions produced during these condensation episodes are often covered by goethite crusts and goethite oncoids. The most abundant types of goethite crusts show extremely thin (20 - 50 μm) laminae with clotted, globular or pseudofilamentous fabric which point to an origin as microbial crusts or consist of structureless, "sterile" goethite ore. From an estimation of growth rates we conclude that most of the time which is buried in these crusts must be concentrated in some millimetres of massive, "sterile" goethite crust or lost within hardgrounds or erosional discontinuities. Condensed

[1] This paper is an extended version of a talk given under the title "Tethyan Jurassic Unconformities: Sea-Level Dipsticks, Deformation Memories, and Recorders of Complex Sealing Processes" at a meeting of the Geological Society of London on "Diagenesis at unconformities" in Burlington House, London, May 8-9, 1991. We dedicate it to the memory of Manfred Gwinner.

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successions often contain a hierarchy of sequences ranging from metre to millimetre-scale. Independently of their hierarchical level, these sequences commonly start with reduced sedimentation, pass through an omission stage and end with an overgrowth by goethitic crusts. The process controlling this trend most probably is a eustatic signal. Bundles of condensed deposits containing goethite crusts are therefore interpreted as pelagic parasequences.

Zusammenfassung: Eine kondensierte Ablagerung ist eine marine Rückstandsbildung, die sich autochthon und kontinuierlich über einen längeren Zeitraum hinweg gebildet hat. Kondensation kann synsedimentär durch Abschirmung, Ablenkung oder Abtragung von Schlamm erfolgen; diagenetisch läuft Kondensation vor allem über Bioerosion auf Hartböden in Verbindung mit unterschiedlich tiefgreifender Erosion ab. Im Jura des subbetischen Plateaus (früher "externes Subbetikum") wird das Umkippen in eine Kondensations-Situation durch tektonische Bewegungen gesteuert, indem benachbarte Plattformen den Export von Schlamm selbssteuernd regulieren. Das subbetische Plateau durchlief vier Phasen stark reduzierter Sedimentation: Carixien - Unter-Domerien (Kondensationsepisode 1), Obertoarcien - Unter-Bajocien (Kondensationsepisode 2), Unterbathonien - Unter-Oxfordien (Kondensationsepisode 3) und unterstes Kimmeridgien (Kondensationsepisode 4). Hartböden, die sich während dieser Episoden bildeten, sind meistens von Goethitkrusten und Goethitonkoiden bedeckt. Die meisten Goethitkrusten bestehen entweder aus sehr dünnen (20 - 50 μ) Laminae mit krümeligem und pseudofilamentösem Gefüge, die für einen mikrobiellen Ursprung der Krusten sprechen, oder sie bestehen aus strukturlosem, "sterilen" Goethiterz. Aus einer Abschätzung der Wachstumsraten folgern wir, daß der überwiegende Teil der Zeit, die in solchen Krusten versteckt ist, entweder im nur wenige Millimeter dicken Goethiterz dokumentiert ist oder in Hartböden bzw. Erosionsflächen gelöscht wurde. Kondensierte Abfolgen zeigen meistens eine hierarchische Gliederung in Sequenzen, die vom Meter- bis zum Millimeterbereich reichen und nahezu stets denselben Aufbau haben: sie beginnen mit reduzierter Sedimentation, auf die ein Omissionsstadium folgt und schließen meistens mit Goethitkrusten ab. Unter den vielen Faktoren, die für eine solche Abfolge verantwortlich sein können, kristallisiert sich als kleinster gemeinsamer Nenner ein (nicht eindeutig kalibrierbares) eustatisches Signal heraus. Wir betrachten deshalb kondensierte Sequenzen, die Goethitkrusten enthalten, als pelagische Parasequenzen.

Introduction

G e o l o g i c a l c o n d e n s a t i o n is a complex phenomenon defined differently in a stratigraphic, sedimentologic, or paleontologic sense. In most cases, the term is used in context with a certain break in the rock-stratigraphic record commonly referred to as a "hiatus". Many condensed deposits do not allow any detailed reconstruction of what really happened in the time-span that has no (or little, or sporadic) rock-stratigraphic documentation. Most hiatuses, especially the pelagic ones from the Tethyan Jurassic, appear in the disguise of an apparently simple case of one single condensation event; upon closer inspection and with good lateral outcrop control, however, they often turn out as cases of total geologic amnesia, with dozens of genetic steps erased by one local but strong event. On the other hand, hiatuses which obviously are the product of multiple breaks, producing bundles of well-defined hardgrounds (such as, for instance, the ornamental hardgrounds from the Ordovician of Öland in Sweden) might reveal themselves as the result of a series of small, trifling changes to the environment that had the good luck of filigree preservation. Under this premise, a definition of the meaning of condensation must consider the common denominator behind both the most complicated and the most simple cases. In the following, we shall primarily try to discuss different cases of condensation from a theoretical point of view and then turn to real examples from the Jurassic of Southeastern Spain which we have studied in detail.

Geological condensation

Physically, condensation is the process by which a vapour becomes a liquid or a solid. Geologically, condensation refers to a strongly reduced rock-stratigraphic record commonly associated with a hiatus (HEIM 1934, RAD 1946, JENKYNS 1971, LOUTIT et al. 1988). Obviously, geologists have other things in mind when speaking of condensation than physicists or chemists. Different from common scientific usage, they mean time being condensed and preserved as a physical residue. In the sedimentary regime, condensation of time can be achieved through mechanical, chemical or biological concentration of specific particles which otherwise would be diluted with other materials deposited elsewhere in the same sedimentary basin.

Condensation through mechanical concentration can be produced by filtering (sieving), screening, by-passing, winnowing, or scouring of clastics. The filtering or sieving principle is well-known from neptunian dykes (WIEDENMAYER 1963, WENDT 1971, 1976, LEHNER 1991, 1992). Sieving also works positively on carbonate ramps during episodes of sea-level rise (retention of clastics in flooded valleys, condensation on microbial reefs); examples from the northern border of the Tethyan Ocean during the Late Jurassic are shown by Leinfelder et al. (this volume; see also DROMART 1989, SCHLAGER 1989). The screening principle works well across strongly rifted passive continental margins, examples are known from both sides of the Tethyan ocean during Jurassic times (CASTELLARIN 1972, BERNOULLI & JENKYNS 1974, SEYFRIED 1980, BICE & STEWART 1990). The by-passing principle produces condensation in carbonate ramp systems during episodes of sea-level lowstand (WINSEMANN & SEYFRIED 1991). Winnowing is very common on clastic shelves; Middle Jurassic sequences from the northern border of the Tethyan ocean contain numerous condensed deposits produced by burial-exhumation-reworking cycles (compilations in DIETL 1977, URLICHS 1977, FÜRSICH 1979, HALLAM 1988). Shell concentrations on clastic shelves and bonebeds on carbonate platforms are often clearly related to episodes of rising sea-level; in most cases, they are the result of a combination of filtering and winnowing (KIDWELL 1985, 1986, 1987; FÜRSICH & KAUFFMAN 1984; NUMMEDAL et al. 1986; NUMMEDAL & SWIFT 1987; HAGDORN & REIF 1988, FÜRSICH et al. 1991). Scouring requires previous lithification and is mostly the result of current activity (BROMLEY 1975, MARTIRE 1992, WILSON & PALMER, 1992).

Condensation through chemical concentration can be produced by dissolution below the CCD. Karstification of an emerged carbonate platform is not considered a condensation process, although it works to quite comparable principles. Condensation through dissolution below the CCD was once strongly advocated for Jurassic Tethyan cephalopod limestones (HOLLMANN, 1964; GARRISON & FISCHER, 1969), but became questioned soon after. SCHLAGER (1974) and, more recently, MARTIRE (1992) argued that a combination of winnowing and bioerosion working on a differentially cemented substrate might cause the same features. Since then, an increasing number of publications favour relatively "shallow" rather than abyssal depositional environments for Tethyan condensed successions and establish a context between relative sea-level fluctuations and condensation in carbonate systems (SEYFRIED 1983, WENDT & AIGNER 1985, MARQUES et al., 1991, MARTIRE 1992). Definite bathymetric criteria, however, have still not been found.

Condensation through biological concentration is achieved through bioerosion on hardgrounds. As to borings in Triassic and Jurassic Tethyan pelagic discontinuities, SCHLAGER (1974), SEYFRIED (1978, 1981) and SCHMIDT (1990) emphasized the good record, especially of microborings. The hiatus corresponding to an individual hardground is mostly beyond the limits of biostratigraphical detection. Bundles of densely spaced hardgrounds, however, may sum up more than one biozone; then, with good luck, condensation becomes demonstrable. In Tethyan Jurassic condensed successions hardgrounds are often covered by goethite crusts and goethite oncoids. As a rule, the hiatus attributed to such goethite crusts is considerable; it is mostly measured through the fossil content of underlying and overlying rocks. However, traditional biostratigraphy fails to quantify the time included in the goethite crusts as compared to the time which might have no rock record at all.

Tethyan pelagic hardgrounds are often covered by rudstones containing hardground debris and lithoclasts of older rocks. This indicates concomitant mechanical erosion and exhumation of underlying strata. The lithoclasts often contain determinable bioclasts. In our opinion, reworking-breccia layers full of clasts with largely differing ages are not condensed deposits just as ordinary conglomerates are not. Such deposits are often the product of one local, but strong scouring event which erased a complex history of previous condensation.

In summary, a condensed deposit may be defined as a marine rock residue that accumulated autochthonously over a large time-span and should have recognizable and chronologic biostratigraphic documentation. The condensation process is achieved by more or less continuous mechanical, chemical or biological concentration. Ideally, a condensed deposit is a strongly reduced, but uninterrupted sedimentary sequence. Condensation is a continuous process working during sedimentation (e. g., winnowing) or shortly after (e. g., bioeroded hardgrounds with or without reworking). Thus, from a process-oriented point of view, the terms "minimal, considerable, and extreme condensation" (JENKYNS & TORRENS, 1971) or "begonnene, fortgeschrittene und abgeschlossene Kondensation" (GEYER & HINKELBEIN, 1971; GEYER et al., 1974) are not adequate. According to WENDT (1970), condensation lies on the verge of erosion, but is not erosion.

Following JENKYNS (1971), we use the term condensation episode for a period of extremely concentrated stratigraphic record. The term condensed succession is used for the products of such condensation episodes.

Jurassic Paleogeography of the eastern Subbetic area

We here adopt the model proposed by BLANKENSHIP (1992); this model maintains the traditional subdivision based on the facies units of the Jurassic (GARCÍA-HERNÁNDEZ et al., 1989), but tectonically reunites "external" and "internal" Subbetic into one "Platformal" Subbetic which originated at the southern border of the basin. However, even after successful reunification, there is still a necessity to differentiate between the more "external" and the more "internal" parts of this "Platformal" Subbetic. We therefore propose the terms "Subbetic Ramp" as a substitute for the former "Internal" Subbetic and "Subbetic Plateau" as a substitute for the former "External Subbetic (Fig. 1).

The carbonate system

The Jurassic system of the eastern Subbetic is essentially a carbonate system. Carbonate mud derived almost exclusively from the southern rim of the basin. During the Hettangian and Sinemurian, the Ramp and Plateau together formed an enormously productive shallow carbonate ramp which gradually turned into a deeper ramp in the area of the "Basinal Subbetic" (sensu BLANKENSHIP 1992).

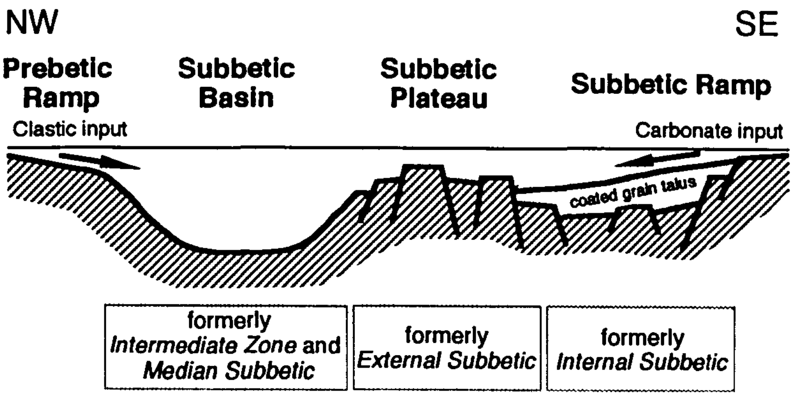

Fig. 1. Cross-section of the eastern Subbetic, based on the early Mid Jurassic situation.

During the Carixian and Early Domerian large areas of the ramp emerged during sea-level lowstands. The Plateau, on the other hand, submerged rapidly, disintegrating into a rifted margin. Along the hingeline, small coral reefs formed temporarily, shedding debris into the adjacent inproductive Plateau area.

From the Late Domerian until the Late Bajocian, large areas of the Ramp joined the Plateau in the drowning and rifting process. Analogously to the case of the Friuli Platform and the adjacent Belluno Trough in the Southern Alps (Bosellini et al. 1981) the newly created platform edge started to produce huge amounts of coated grains and bioclasts which mainly accumulated as a wedge-shaped talus along the basinward margin of the Ramp (Fig. 1). By the Mid-Bajocian, this area was already in a deep ramp position, being by-passed by ooidal flows which penetrated deep into the basinal area (Seyfried 1978, 1980).

From the Bathonian onward, a drastic decrease in carbonate mud supply suggests that ongoing rifting had further reduced the available productive carbonate platform areas. Continuous rifting is evidenced by the pronounced contemporaneous tectonic relief in the Plateau area (compare the following chapter on condensation episode 3). Most probably, the productive regions receded as far as towards the shorelines of the Alkapeca massif. The Ramp and the Plateau together now formed one sedimentologically coherent, but tectonically strongly rifted pelagic limestone province. This situation prevailed until the end of the Jurassic.

The mixed carbonate-clastic system

Clastic mud entered the basin only sporadically. Coming from the Iberian land mass, most of it by-passed the Prebetic ramp and accumulated in the Basinal Subbetic. This area was flushed with siliciclastic mud from Late Domerian until Aalenian times. Only once, during the time-span from Late Domerian to Early Toarcian, did siliciclastic mud onlap onto the opposite flank of the basin, thereby spreading (but rapidly wedging out) across the Plateau. The remaining time of the Jurassic was an episode of relatively low clastic input.

As a consequence of this differential interplay between mud retention and mud release, the Plateau experienced four episodes of strongly reduced sedimentation (dating after Seyfried, 1978 and García-Hernández et al., 1989): Carixian - Early Domerian (condensation episode 1), Late Toarcian - Early Bajocian (condensation episode 2), Early Bathonian - Early Oxfordian (condensation episode 3), and Earliest Kimmeridgian (condensation episode 4). Without the clastic interlude during the Late Domerian to Early Toarcian one continuous regime of reduced pelagic red limestone sedimentation would have developed in the Plateau area. In some well-protected areas such as, for instance, the "Sierrecica de las Cabras" (Seyfried 1978): section C7), such situations existed indeed: there, the sequence representing the entire time-span from Pliensbachian until Tithonian does not exceed a thickness of 70 metres.

Condensation episodes in the Jurassic of the eastern Subbetic area

Condensation episode 1 (Carixian - Early Domerian)

The Pliensbachian rifting event converted both the Basinal Subbetic and the Subbetic Plateau into deeper areas. The Ramp emerged during this episode. Especially in the Plateau area, the new morphology resulted in a very effective screening of clastics and in a better circulation in the entire basin. As a result, a wide variety of facies developed. From the fault-controlled boundary between Ramp and Plateau, TURNSEK et al. (1975) reported close interfingering of small coral reefs, brachiopod biostromes, *Placunopsis* reefs, crinoidal sands, and ammonite-bearing reworking breccias on goethite-encrusted hardgrounds. The latter facies represents the first condensed deposit which appears on a regional scale. It mostly consists of bioeroded, goethite-encrusted (very seldom phosphatized) hardgrounds followed by reworking breccias and glauconite-rich mudstones. Bioclasts from the breccia layer commonly indicate only an Early Domerian age. Locally, however, goethite-coated reworked bioclasts indicate that condensation must have started as early as in the Early Carixian, but the details of this episode have been lost in an erosion event (SEYFRIED 1978: C2).

Condensation episode 2 (Late Toarcian - Early Bajocian)

After the clastic interlude from Late Domerian to Early Toarcian, condensed deposits appear again on a regional scale with the onset of the Late Toarcian. Depending on the interaction between block-faulting, filtering/sieving, screening, by-passing, winnowing, scouring, and biological concentration, condensation was differently effective in different areas. The maximum duration of this condensation episode CE 2 ranges from early Late Toarcian until Early Bajocian; in places, it comprises only the Late Toarcian. Facies types range from uncomplicated goethite-coated hardgrounds to chaotic reworking breccias. The time involved in condensation is a function of the timing of mud import: in well-screened areas, condensation lasted longer than in areas where mud coming from the Ramp had easy access to the Plateau. This suggests that block faulting was still very much effective.

Condensation episode 2 was ended by a flush of carbonate ooze which expanded over the entire Plateau. Platy lime-mudstones deposited nearly everywhere and almost immediately started to slump along the slopes of the submarine relief accentuated during the previous episode of reduced sedimentation. As mud supply gradually decreased towards the next condensation episode, *Bositra* shells became prominent, radiolaria accumulated to provide biogenic silica for the formation of chert nodules, textures changed from laminar to nodular, and colours graded into brick-red or violet-blue.

Condensation episode 3 (Early Bathonian - Early Oxfordian)

This episode began as early as in the Early Bathonian and lasted until the Early Oxfordian. After a fairly good biostratigraphic documentation of the Early Bathonian, the Late Bathonian commonly lacks biostratigraphic proof. Good control in turn is mostly available for the Early and Middle Callovian, whereas the Late Callovian and the Early Oxfordian have no biostratigraphic record at all.

Rock-stratigraphic documentation of condensation episode 3 starts with a *Procerites* pavement that can be interpreted either as a transgressive shell lag concentration or as a mass mortality layer. It is present throughout the Subbetic Plateau of the entire eastern Betic Cordillera. Upper Bathonian rocks are only locally preserved; if preserved, they consist of some centimetres to decimetres of red nodular limestones. Where a hiatus exists, strong evidence is at hand that an erosional event has been scouring a preexisting (and at least partly condensed) succession down to the level of the *Procerites* pavement, cutting most of the ammonites in half (see Seyfried 1980, 1981). The following Lower Callovian to Lower Oxfordian deposits mostly consist of a thin veneer of goethite-coated reworked bio- and lithoclasts spread over and covered by a thin microbial goethite crust. Condensation is mainly due to strong bioerosion and, to a lesser extent, to winnowing or scouring. The determinable specimens among the reworked bioclasts give Early to Mid Callovian ages. A large variety of microfacies which can be identified only among the reworked clasts suggests that a considerable part of the history of this condensed succession has been deleted by episodic erosion. A rock-stratigraphic equivalent to the Late Callovian to Early Oxfordian hiatus might be unrecognizably hidden among the upper (massive, unstructured) parts of the goethitic crusts, but the total lack of any biostratigraphical evidence for this time-span suggests that indeed this is one of the few real cases of omission (zero net sedimentation).

Condensation episode 3 comprises a far too long time-span as to be explained solely by the effect of one single cycle of sea-level fluctuation. In our opinion, a new rifting pulse (most probably with a strong transcurrent component) could have been responsible for the drowning of most of the remaining productive carbonate platforms. Under these circumstances, highstands could no longer substantially increase the accumulation rate in the Plateau area. Accordingly, the observed zero net sedimentation during the Late Callovian and Early Oxfordian might be explained as a lowstand episode.

Like condensation episode 2, condensation episode 3 was also abruptly ended by a flush of carbonate ooze which started in the earliest Mid Oxfordian and filled up a preexisting tectonic relief. Facies commonly correspond to the *Protoglobigerina*-rich red nodular limestones of the Rosso Ammonitico type. The relatively high clay content of the red nodular limestones suggests that now mud supply was coming again from the Prebetic. Starting in the Mid Oxfordian (Behmel, 1970), this palaeogeographic province became an increasingly important supplier of mixed mud (García-Hernández, 1978).

In some places such as the Sierra del Reclot (dealt with in the following chapters), red nodular limestones are substituted by massive red lime-mudstones. A feature particular to the very base of the red limestone unit is an accumulation of huge (Ø max. 15 cm) goethite oncoids. This accumulation can be observed throughout the entire Plateau area. Although embedded in Mid Oxfordian mud, these oncoids probably represent the only legitimate rock record of the Late Callovian to Early Oxfordian hiatus.

Condensation episode 4 (Earliest Kimmeridgian)

The area between La Romana and Algueña (see Fig. 2) is the type locality for a well-developed fourth goethite crust which is intercalated within the before-mentioned massive red lime-mudstones. Less well-developed, but similar discontinuities have been found throughout the plateau area, but never yielded any determinable faunas. The common lack of *Ataxioceras* in this area, however (Seyfried 1978: section groups B, C, and D), as compared to its occurrence within the Basinal Subbetic (Seyfried, 1979), suggests that in the Plateau area, condensation episode 4 equals more or less the biostratigraphical coverage of this genus, that is, the earliest Kimmeridgian.

Condensation episode 4 ended with the sudden appearance of centimetre- to decimetre- bedded pink and grey intraclast mudstones which dominate the sedimentary record until the end of the Jurassic. They are interpreted as sheet-flow-like debris flows; their occurrence is remarkably constant throughout the Plateau area. They sometimes are accompanied by deka- to hektometre-sized slumps. The change from the limestone-dominated regime of the Jurassic to the marl-dominated regime of the Early Cretaceous means a general opening of the basin to clastic mud, sand, and carbonate oozes coming in from every possible margin. Developing structural reliefs became rapidly buried beneath these voluminous sediments. Under such circumstances, filtering/sieving, screening, by-passing, winnowing, scouring, and biological concentration could only exceptionally lead to the formation of condensed successions.

A case study from the Subbetic Plateau: The Sierra del Reclot

The Sierra del Reclot represents one of the easternmost outcrops of the Jurassic Subbetic Plateau in Southeastern Spain (Fig. 2). There, the sedimentary sequence corresponding to the interval between condensation episode 1 and condensation episode 4 diminishes to a thickness of as little as 30 metres (Fels, 1990; Fig. 3). The Jurassic Sierra del Reclot section differs from other Plateau sections only through the absence of cherty limestones in the Mid Jurassic (Figs. 2 and 3). We have chosen this area because of the excellent exposures offered in numerous, fast-growing quarries and because of the occurrence of neptunian dykes which are particularly dense and well-developed in this area. The fillings of these dykes commonly correlate with certain levels among the condensed successions of the Jurassic sequence, most often with sediments sandwiched between couplets of goethitic crusts. This dates at least some of the tectonic pulses mentioned in the chapter on palaeogeography.

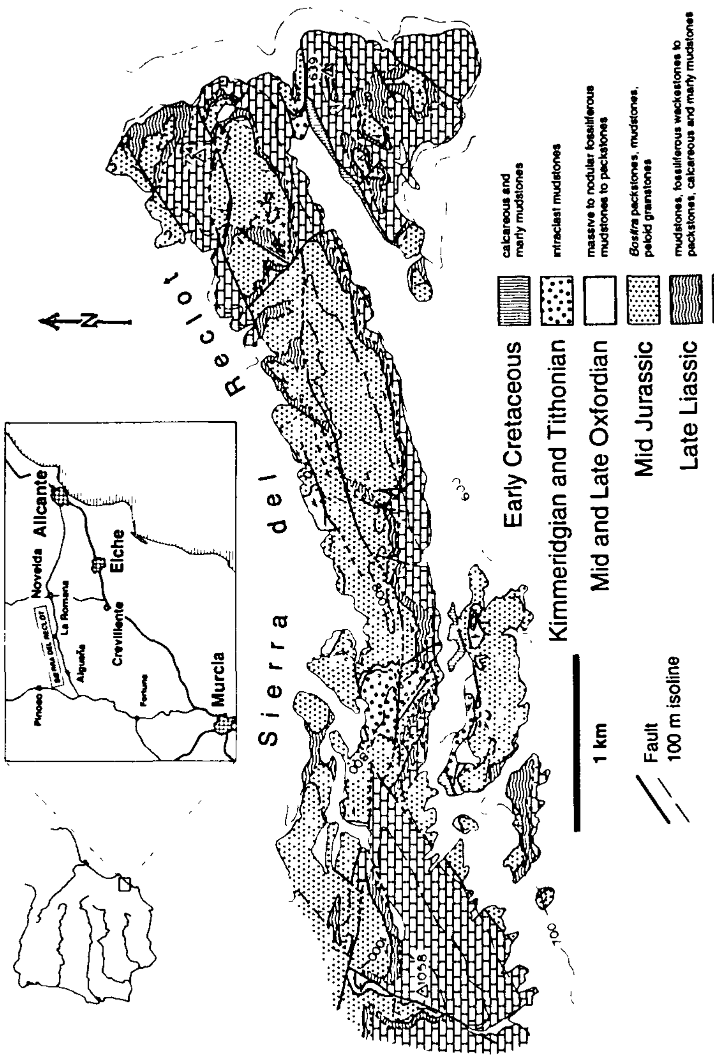

Fig. 2. Geological map of the Sierra del Reclot (Provincia de Alicante, Southeastern Spain).

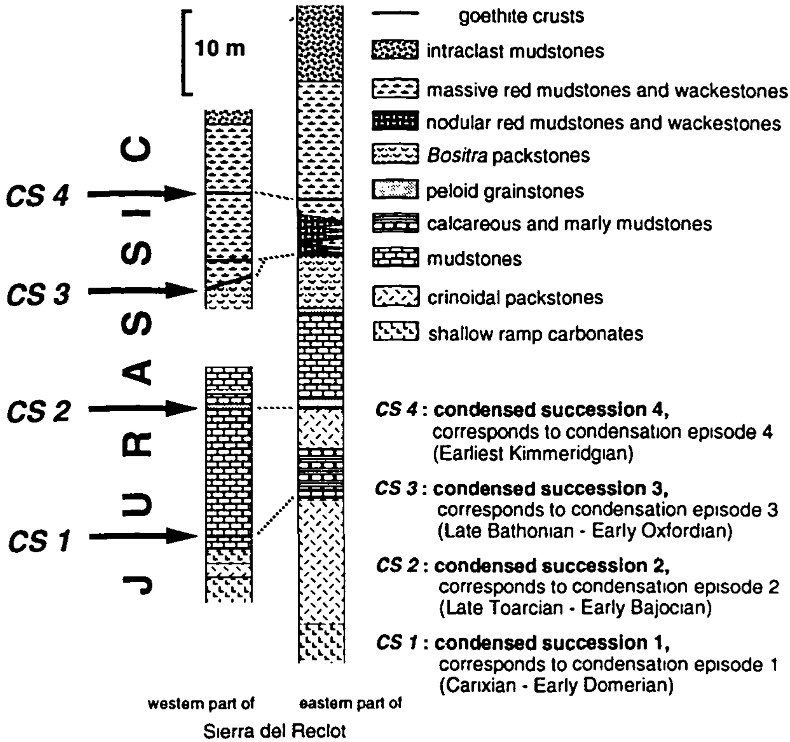

Fig. 3. Simplified lithologic sections of the Jurassic of the Sierra del Reclot.

Microstratigraphy of a condensed succession

Fig. 4 shows the main facies types which can be observed among the condensed successions in the Sierra del Reclot. The example shown in the blow-up has been chosen from the third condensed succession, which is the one with the most complicated microstratigraphy.

Facies

Sediments account for up to 80% of the volume of this succession. In most cases, these sediments are brick-red limestones with textures ranging from mudstones to grainstones. Rudstones containing hardground debris and lithoclasts of older rocks are common. Bioclasts are abundant and indicate well-fed benthic communities living beyond the depth range of green algae. Borings, especially microborings by fungi, can be observed on nearly all types of substrates. One feature common to all these sediments is the absence of sculptured steinkerns.

Aragonitic shells are invariably preserved as calcite neomorphs or goethite or mud pseudomorphs. This points to very rapid synsedimentary lithification.

Goethite crusts and goethite oncoids account for the rest of the volume of the succession. In the extreme, goethite crusts consist of one massive layer of ore without any visible primary structure (secondary dehydration cracks, on the other hand, are quite common). The most abundant type of goethite crust, however, shows extremely thin (20 - 50 μ) goethite laminae that alternate with slightly thicker yellowish sparitic layers. The clotted, sometimes also globular or pseudo-filamentous fabric of these laminae points to an origin as microbial crusts. The growth pattern of these crusts ranges from flat through dome-shaped to digitated structures and may thus be called stromatolithic.

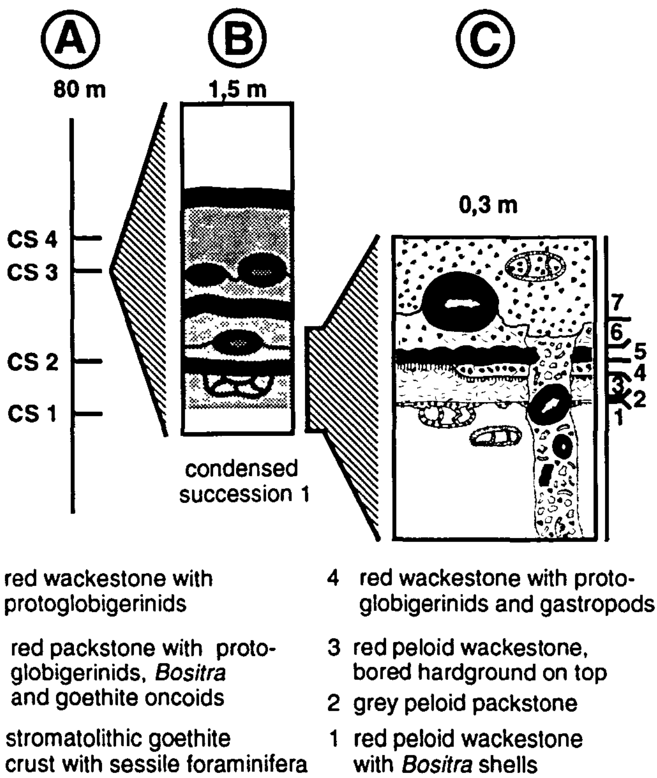

Fig. 4. Architecture of condensed succession 3 (Late Bathonian - Early Oxfordian) from the Sierra del Reclot.

In some horizons, sessile foraminifera characterized by very small (> 50 μ) irregular chambers become extremely abundant (in other condensed successions, these foraminifera are associated with serpulids and some few solitary corals). Their association with microbial crusts, together with the absence of other biota, suggests some kind of symbiotic or commensal relationship which may have allowed survival under conditions hostile to other forms of benthic life. SEM studies revealed that many of the sessile foraminifera aggultinated silt-sized (wind-blown ?) quartz grains.

Goethite oncoids can attain diametres of up to 15 cm. Their nuclei often consist of debris reworked from adjacent hardgrounds or rockgrounds. The laminae always contain large amounts of sessile foraminifera; hence, their formation should be coeval to the corresponding layers among goethite crusts. Large oncoids often contain broken remnants of other oncoids, indicating strong reworking processes. Oncoids sometimes appear densely packed within one layer, especially towards the top of a bundle of crusts. They also appear trapped and accumulated in the shallow parts of fissures, suggesting that neptunian dykes formed contemporaneously to some of the crusts and were open for infilling from the sea floor.

Time

As to the time involved in this condensed succession, only the last pre-condensation and the first post-condensation layer could be dated as Early Bathonian and Mid Oxfordian, respectively. This means that about 10 million years are concentrated in a one-metre-thick succession. The mudstones to grainstones in this succession, which account for 80% of the volume, would have deposited quite rapidly. Thus, time must be hidden among goethite crusts, hardgrounds, and erosional discontinuities. As to growth rates of goethite crusts, we can only relay on data referring to growth rates of modern manganese nodules which show a wide range from 0.04 mm/year to 40 mm/million years (WENDT, 1974; HEUSER, 1988; CRONAN, 1980). The high estimate would correspond to our foraminiferal crusts, which in turn account for more than nine tenth of the volume of all goethitic crusts. This leaves roughly some 9.5 million years concentrated in some millimetres of massive, structureless goethite crust or lost within hardgrounds or erosional discontinuities. As it seems virtually impossible to mechanically stop sedimentation over such a long time, only the following processes seem to be eligible for an explanation: a) stop of carbonate mud import through emergence or drowning of supplying platforms, b) extreme concentration through extreme dissolution of carbonate and silica, c) emergence of parts of the Plateau, d) intermittent scouring, and e) nutrient depletion. Over the last years, we have collected a wealth in arguments (including geochemical data) in favour and against every one of these possibilities; so far, the philosopher's stone has not yet been found among these rocks.

Parasequences in condensed successions ?

Poor biostratigraphical control and the lack of unambiguous environmental criteria can partly be compensated by good outcrop control which allows a relative, at least qualitative correlation of sequences. Excellent outcrop control is available again in the third condensed succession of the Sierra del Reclot. Fig. 5 shows coalescing goethite crusts which obvioulsy are following a metre-scale relief. In the bathygraphic lows (site 1), the condensed succession is split up into numerous goethite crusts, hardgrounds, and erosional discontinuities, whereas on the bathygraphic highs all crusts are obviously amalgamated into one single layer (site 3). Under these circumstances, correlations can be made both physically and genetically. Physical correlation of such complex sequences at the outcrop to microscope scale results in the recognition of dozens of sedimentary and diagenetic steps per stratum and hundreds per metre of thickness.

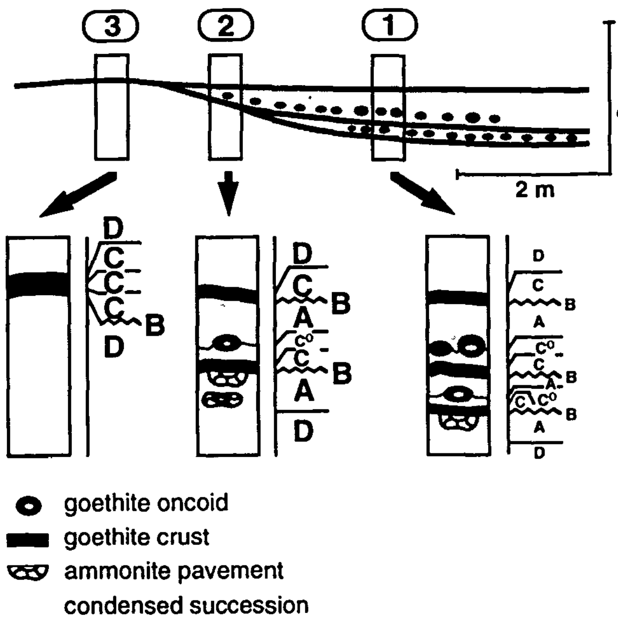

Fig. 5. Correlation of sequences within condensed succession 3 (Late Bathonian - Early Oxfordian) from the Sierra del Reclot.
A: reduced sedimentation stage
B: omission stage
C: stage of overgrowth by goethitic crusts
C°: accumulation of goethite oncoids on top of a bundle of crusts
D: sedimentation outside a condensation episode.

Genetic correlation is easier to perform, but necessarily less precise. Following the ideas and examples of GOLDRING & KAZMIERCZAK (1974), BROMLEY (1975), and FÜRSICH (1979), we attempted to make a genetic correlation. In the process, we reduced the history of a condensed unit - independently of its hierarchical level within a condensed succession - to a mere 3 steps (see lower part of Fig. 5).

Step A is the reduced sedimentation stage. At the beginning of a condensation episode, sediments show ammonite pavements, shell concentrations, or pre-omission burrows which record a gradually hardening substrate. Sediments from within a condensed succession commonly contain reworked goethite crust or hardground fragments as well as bored and colonized bio- and lithoclasts. Planar crosslamination within decimetric beds, current alignment of belemnites, and concentration of shark teeth are additional features.

Step B is the omission stage. Irregular, bored and colonized surfaces representing bioeroded hardgrounds can be distinguished from surfaces abraded by scour (including truncated pre-omission burrows). Laterally, these surfaces may grade into reworking breccias. In places, large cavities strongly resembling karst cavities developed in the subsurface.

Step C is the stage of overgrowth by goethitic crusts. Step C° marks an accumulation of goethite oncoids on top of a bundle of crusts. In the upper parts of these oncoid layers, oncoids commonly became fixed in goethite-coated microhardgrounds which merge onto the oncoids and are millimetre-spaced in the surrounding sediment.

Stage D represents sedimentation outside a condensation episode. According to the arguments presented in the last paragraph, the A → B → C – sequences presented in Fig. 5 can be explained in terms of a) stop of carbonate mud import through emergence or drowning of supplying platforms, b) extreme concentration through extreme dissolution of carbonate and silica, c) emergence of parts of the Plateau, d) intermittent scouring, and e) nutrient depletion. Whereas it is extremely difficult, or perhaps impossible, to choose among or reject one of these arguments, it is much easier to name a common denominator: eustatic signals meet all requirements, although admittedly by only a very narrow margin. Still, this means that the above mentioned A → B → C – sequences, in a sequence-stratigraphic sense, could be interpreted as a kind of pelagic parasequences. Poor biostratigraphical control and the lack of unambiguous palaeoenvironmental interpretations, however, do not allow a physical sequence-stratigraphic calibration of such parasequences: it is very difficult to define highstand, lowstand, or transgressive "systems tracts". On the other hand, we tentatively risk to correlate interpretations: episodes of observed zero net sedimentation such as the above-mentioned Late Callovian and Early Oxfordian interval can be interpreted as episodes of zero productivity; in a carbonate system, this might be interpreted as a lowstand episode (cf. GARCÍA-HERNÁNDEZ et al., 1989; MARTIRE, 1992).

Conclusions

It seems obvious that in a particular palaeogeographic province such as the Subbetic Plateau, the critical threshold for the development of a condensed succession is controlled by tectonic processes: emergence, subsidence or drowning of carbonate mud supplying adjacent platforms is the parameter which mainly controls the retention or releasing of mud. Tectonic movements on the Plateau proper, in combination with eustatic sea-level fluctuations, may also be responsible for changements in the bottom current regime. Once starved of sediment supply, a condensation situation registers the slightest changes to the environment such as, for instance, the distant effects of sea-level changes on the pelagic sea floor. Small variations in the current regime might have had drastic consequences on the properties of the substrate, the availability of construction material, and nutrients, thus altering the structure of benthic communities. The microbial goethite crusts obviously formed under extreme conditions of starvation; they might be interpreted as biological response to a eustatic lowstand signal.

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Anschrift der Verfasser:

Dipl.-Geol. ALEXANDER FELS und Prof. Dr. HARTMUT SEYFRIED, Institut für Geologie und Paläontologie der Universität Stuttgart, Herdweg 51, D-70174 Stuttgart, Germany.