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Eustatic and Tectonic Controls on Coral Reef Morphology and Porosity: The Torrecilla en Cameros Fm. Early Kimmeridgian, Northern Spain

Growth geometry and porosity of early Kimmeridgian reefs formed in the north-western Iberian Basin (Fig. 1) record a complex interaction between tectonic and eustatic effects during sedimentation followed by a history of prolonged diagenetic modification. Primary sedimentologic factors, distinctive for each sector of the basin, and early diagenetic processes related to Late Kimmeridgian subaerial exposure of the reefs were the dominant controls on the formation and evolution of porosity. The sequence and timing of diagenetic events were derived from an integrated geochemical and petrographic analysis.

Sedimentological factors and syn-depositional diagenesis

Depositional architecture of reef complexes was controlled by the prevailing positive eustatic conditions during Kimmeridgian (Haq et al., 1988), also apparent across the Iberian and North Tethys domain (Alonso and Mas, 1990; Bádenas y Aurell, 2001), and by basin tectonics.

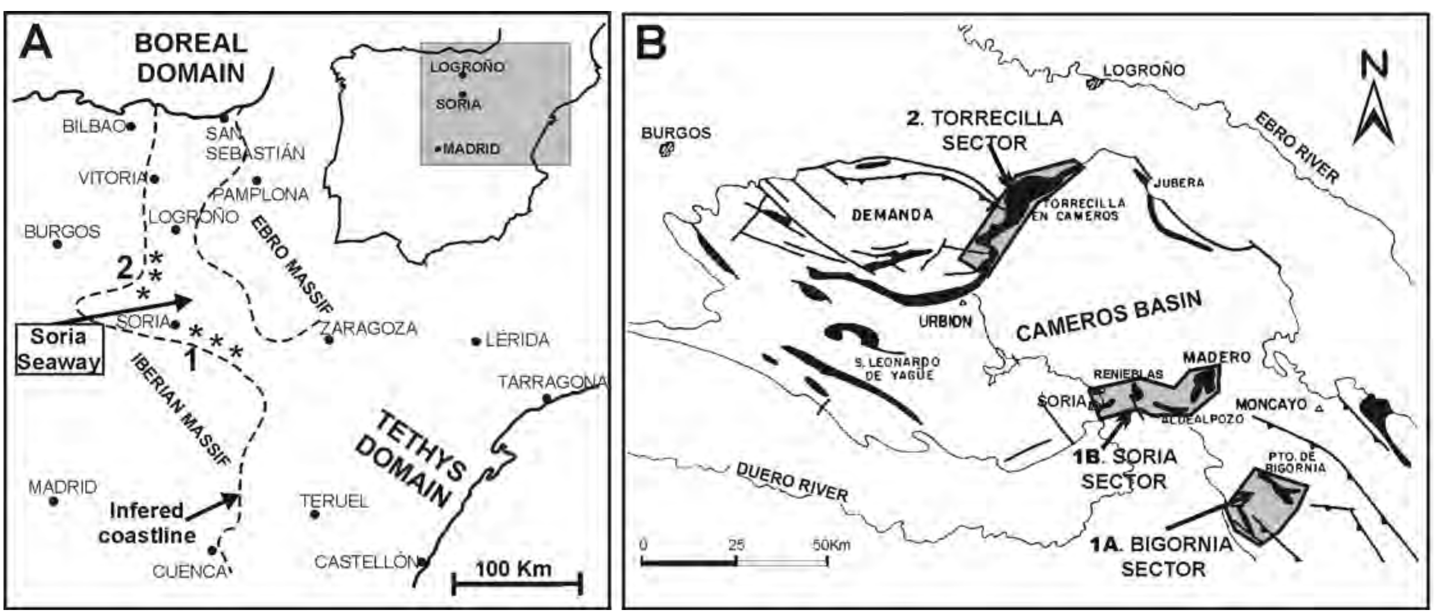

Fig. 1. A. Palaeogeographic map of northeastern Iberia during Kimmeridgian times. The location of the two main reefal complexes is shown by asterisks: 1. Soria and Bigornia areas; 2. Torrecilla area (see also Fig. 1B) (modified from Alonso and Mas, 1990). B. Location map of the marine Jurassic outcrops in northern Iberian ranges (in black). A, B and C correspond to the three studied sectors where the Torrecilla en Cameros Fm. is best developed: 1A. Bigornia sector; 1B. Soria sector; 2. Torrecilla sector.

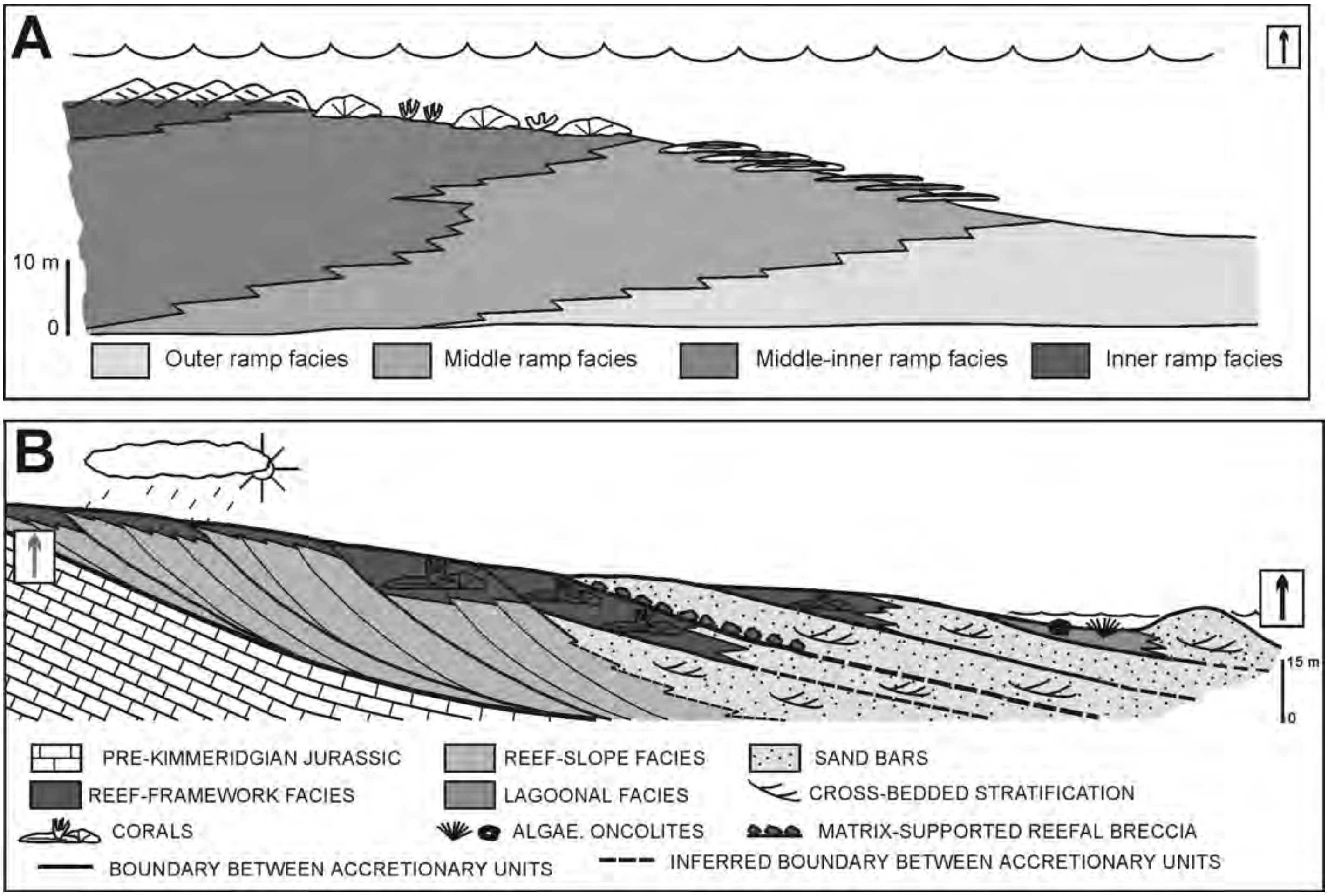

Fig. 2. Idealized sketches illustrating the sedimentary evolution of the reefal complexes of the Torrecilla en Cameros Fm. in the three studied sectors: A. Southern sectors (Bigornia and Soria); B. Torrecilla. Modified from Benito, 2001. Black arrows: Sea-level rise. Grey arrow: Tectonic uplift.

In the southern region, reef geometry is dominated by vertical and seaward accretion, suggesting that despite the combination of positive eustatism and subsidence, the high rates of carbonate production controlled overall reef growth (Alonso and Mas, 1990; Benito et al., 2001) (Figs. 1; 2A). In the Bigornia sector, reef-framework facies dominate, comprising platy and minor branching and domal corals, and back-reef deposits are rare to absent. In contrast, reef-framework facies in the Soria Sector, comprising mainly branching corals and minor massive corals, are dominated by allochtonous sediment composed of storm-deposits interbedded with the reef-framework. Moreover, in this sector, oolitic grainstone and packstone were deposited in the back-reef. In both southern sectors, micritization and precipitation of peloidal micrite and minor fibrous calcite were the dominant syn-sedimentary diagenetic processes (Fig 3A-B).

In the northern Torrecilla region, the depositional architecture and evolution of reef complexes suggest relative sea-level fall during deposition. They exhibit down-lapping, off-lapping and top-lapping geometries (Fig. 2B). Moreover, reef-slope and reef-framework facies, which are associated with microbialites and marls, dominate in the earlier accretionary units; whereas, cross-bedded sand and oolitic bars, and lagoonal deposits prevail in the last accretionary units (Fig. 2B). As the Early Kimmeridgian was a period of rising sea-level, it is probable that the evolution to progressively shallower facies and forced regressive geometries occurred as a consequence of local tectonism. In this region, syn-sedimentary peloidal micrite and minor fibrous calcite was precipitated. However, diagenesis was more

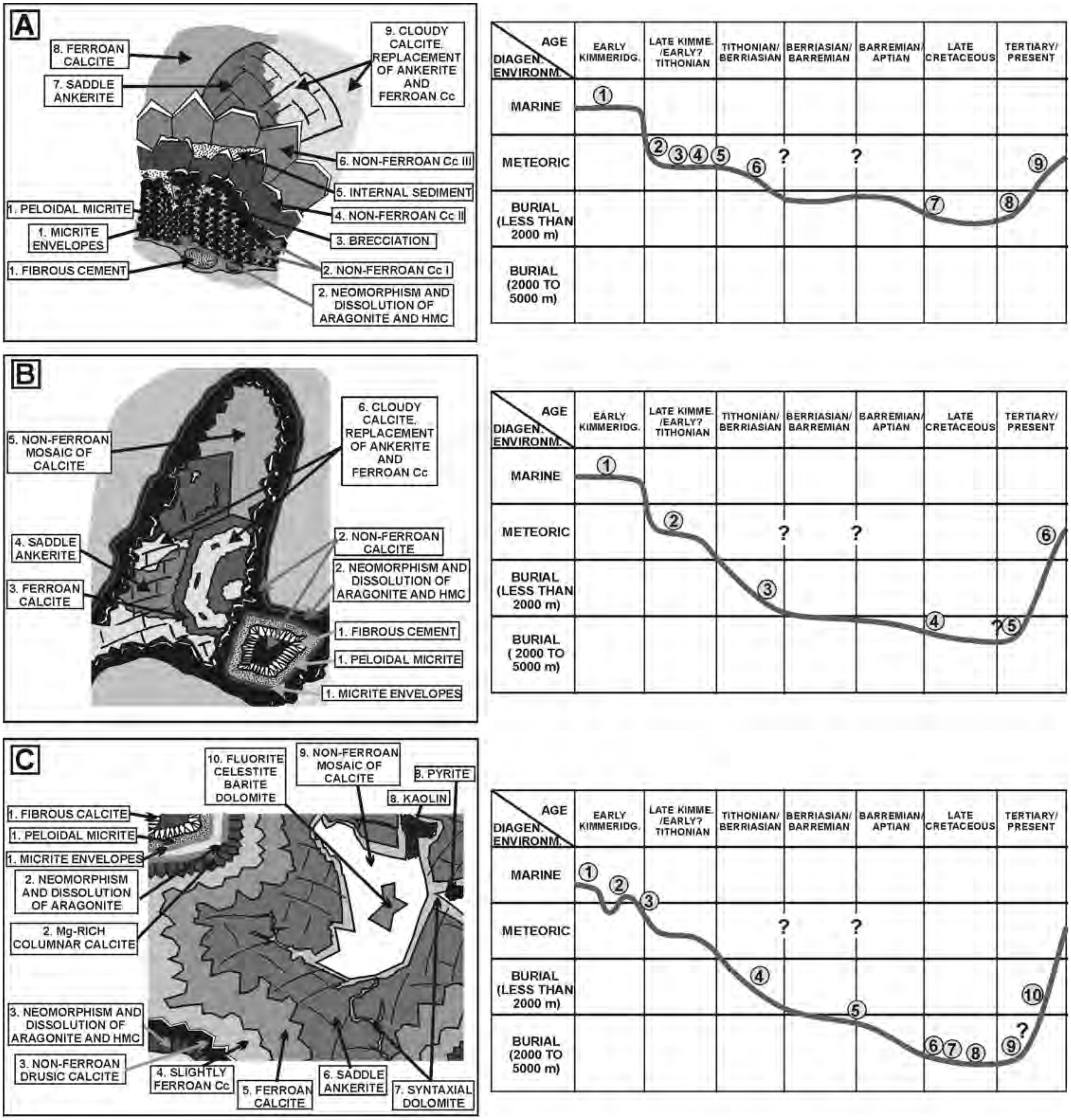

Fig. 3. Idealized sketches of paragenetic sequences and their respective environments of precipitation (to the right) for the main diagenetic phases and events affecting the reefal complexes in the three studied sectors: A. Bigornia; B. Soria; C. Torrecilla. Modified from Benito (2001).

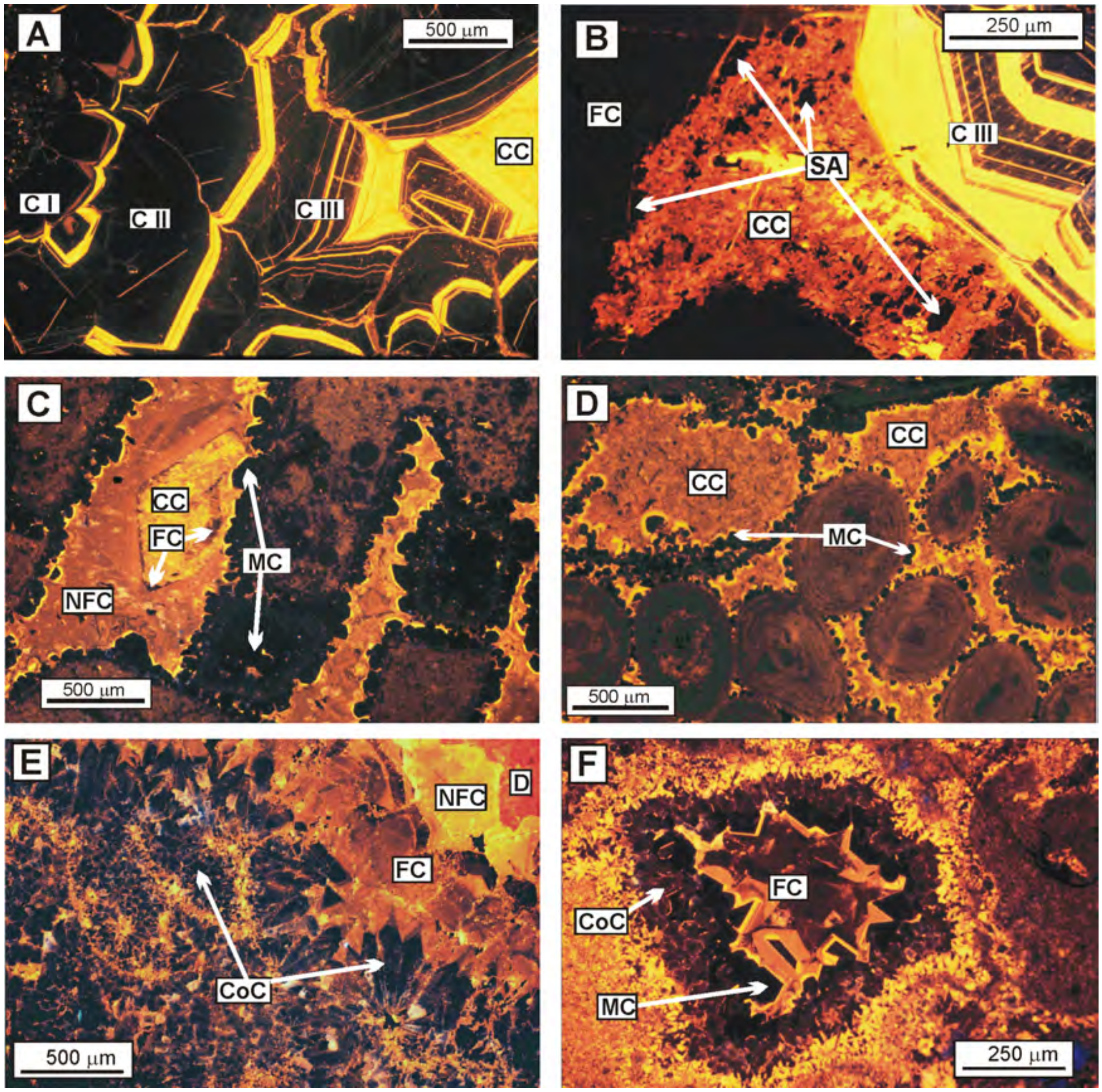

Fig. 4. Photographs A and B are from the reefal complex of the Bigornia Sector. Photographs C and D are from the Soria Sector; and photographs E and F are from the Torrecilla sector (from Benito, 2001). A. Cathodoluminescence (CL) photomicrograph of zoned, nonferroan meteoric calcite developed in the reefal unit. The cement sequence is as follows: (C I) Non luminescent (NL) with a thin bright-luminescent (BL) subzone, corresponding to Cement I generation of calcite. (C II) Cement II and (C III) Cement III are formed by an initial NL zone and terminate with a BL zone. Porosity is completely occluded by a generation of BL cloudy calcite (CC), which replaces ankerite and ferroan calcite. B. CL photomicrograph showing relicts of NL saddle ankerite (SA) enclosed within a matrix of replacive, BL to light DL cloudy calcite (CC). Here, ankerite nucleated on meteoric cement (C III) and is followed by a dark-DL ferroan calcite (FC). C. CL photograph showing a moldic pore of a branching coral that is cemented by a first thin generation of nonferroan NL-BL meteoric calcite (MC). This generation is followed by a euhedral ferroan calcite cement (FC) that is partially replaced by cloudy calcite (CC). Porosity is later occluded by a nonferroan and dull luminescent (DL) mosaic of calcite (NFC). D. CL photomicrograph showing intergranular and moldic porosity first cemented by an early and thin generation of nonferroan NL-BL meteoric calcite (MC). Porosity is later occluded by cloudy calcite (CC) that replaces former cements of ankerite and/or ferroan calcite. E. Partially dissolved massive coral in which primary and secondary porosity is first cemented by a generation of NL hig-magnesium columnar calcite cement (CoC). Columnar calcite is followed by a dark DL ferroan calcite (FC) and subsequently by a nonferroan and light DL calcite (NFC). Porosity is occluded by nonferroan and red luminescent saddle dolomite (D). F. CL photograph showing a primary pore, first cemented by dark DL columnar calcite (CoC) that is followed by nonferroan NL-BL meteoric calcite (MC). Porosity is occluded by light to dark DL ferroan calcite (FC).

complex here than in southern areas, as it was controlled by rising sea-level and tectonism leading to an alternation of reef exposure and submergence. While reefs were exposed, coral skeletons were neomorphized and dissolved; neomorphism was more common in massive corals whereas branching corals were generally dissolved. When reefs were submerged, smaller pores of both primary and newly secondary porosity were filled by high-magnesium columnar calcite cement (Figs 3C; 4E-F). Towards the upper part of the unit, a later mosaic of meteoric calcite cement was precipitated after this columnar calcite, as older accretionary units were definitively exposed while younger units were still being deposited (Figs. 2B; 3C; 4F).

Early diagenesis

In the Late Kimmeridgian, reef complexes were subaerially exposed in response to latest Jurassic sea-level fall (Haq et al., 1988), and Late Jurassic-Early Cretaceous rifting that led to the formation of the Cameros Basin (Fig. 1B). This basin was subsequently filled, from the Tithonian to the Early Albian, with up to 5 Km of fluvial and lacustrine sediments (Mas et al., 1993) that unconformably overlie the Early Kimmeridgian Torrecilla en Cameros Fm. The boundary between the reefal units and these continental deposits is marked by an erosional surface that is usually associated with a palaeosoil (Alonso and Mas, 1990).

In the southern region (Fig. 1), the majority of porosity was generated by dissolution of coralline aragonite during subaerial exposure and alteration with meteoric waters. In the Bigornia sector, where reef-framework facies dominate, a significant proportion of porosity was generated, although most of it was occluded early by three distinct generations of meteoric calcite cement (Fig. 3A, 4A). Precipitation of each generation of cement corresponds to a temporally and compositionally distinct episode of alteration of the reefal unit by meteoric fluids during exposure associated with development of the unconformity (Benito et al., 2001). In contrast, the amount of newly-created moldic porosity in the Soria sector was lower as the proportion of original reef-framework was less. However, the duration of exposure was relatively short in this area, as the burial of reefs, associated with formation of the Cameros Basin, started earlier here than in the Bigornia sector (Fig. 3A-B). As a result, only a thin generation of non-ferroan meteoric calcite was precipitated during reef exposure despite the extensive dissolution of corals (Figs. 3B 4C-D), and most of the primary and secondary porosity was only partially occluded at this time (Benito and Mas, 2002).

In northern Torrecilla reefs, the exposure and alteration of the upper part of the reefal unit by meteoric waters continued to the Late Kimmeridgian, leading to neomorphism and dissolution of previously unaltered aragonite and HMC and precipitation of meteoric calcite cement. As in the Soria sector, continental sedimentation led to burial of the reefs, following the formation of Cameros Basin. This burial began relatively early such that a significant portion of larger pores remained unfilled or incompletely cemented (Figs. 3C, 4E-F).

Late diagenesis

From the Tithonian to the Early Albian, diagenetic evolution in the Soria and Torrecilla areas was characterized by burial of the reefal unit by continental sediments of the Cameros Basin, and precipitation of ferroan calcite cements (Figs 3B-C; 4C,E-F). In the Bigornia sector, however, the Torrecilla en Cameros Formation was not deeply buried as sedimentation began later, resulting in deposits less than 400 m thick and precipitation of meteoric calcite (Fig. 3A).

Saddle ankerite precipitated in the remaining porosity, postdating ferroan calcite cement in the Soria and Torrecilla sectors, and following meteoric non-ferroan calcite in the Bigornia area (Figs. 3, 4). Precipitation of ankerite was likely associated with the hydrothermal metamorphism that affected the Cameros Basin during the mid-late Cretaceous (Benito, 2001, Benito et al., 2001; Benito and Mas, 2002). Moreover, in the Torrecilla sector, a generation of slightly- to non-ferroan saddle dolomite, followed by kaolin and pyrite, precipitated after corrosion of ankerite.

Most of the porosity remaining after saddle ankerite was subsequently occluded by a non-ferroan sparry calcite cement, in the Soria and Torrecilla sectors, and by ferroan calcite, in the Bigornia area, that likely precipitated during Alpine contraction (Figs. 3; 4). Subsequently, fluorite, celestite, sphalerite and non-ferroan, red-luminescent saddle dolomite were precipitated only in the Torrecilla area (Figs 3C; 4E). These minerals are directly associated with solid hydrocarbons (Benito, 2001).

In response to tectonic uplift, renewed erosion and subaerial exposure, the reefal unit was again modified by meteoric diagenetic processes. Under such conditions, diagenetically-unstable ankerite and ferroan calcite were replaced by non-ferroan and BL to light DL cloudy calcite containing abundant inclusions of iron oxides and hydroxides (Figs. 3, 4).

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