Geologica Acta, Vol.2, N°4, 2004, 271-284
Available online at www.geologica-acta.com

Oriented calcite concretions in Upper Miocene carbonate rocks of Menorca, Spain: evidence for fluid flow through a heterogeneous porous system

L. POMAR[1] **H. WESTPHAL**[2] **and A. OBRADOR**[3]

[1] **Departament de Ciències de la Terra, Universitat de les Illes Balears**
Ctra. de Valldemossa, Km 7,5, E-07122 Palma de Mallorca, Spain. E-mail: lpomar@uib.es

[2] **Institut für Paläontologie, Universität Erlangen**
Loewenichstraße 28, D-91054 Erlangen, Germany. E-mail: hildegard.westphal@pal.uni-erlangen.de

[3] **Departament de Geologia, Universitat Autònoma de Barcelona**
E-08193 Bellaterra (Barcelona), Spain. E-mail: aobrador@einstein.uab.es

ABSTRACT

Elongate calcite concretions in Upper Miocene dolomitic, shallow-marine grainstones and packstones of Menorca document fluid flow through heterogeneous systems. These post-dolomitization concretions are thought to have grown with elongation axes parallel to groundwater flow direction, and to reflect the hydraulic gradient and the anisotropy of the hydraulic conductivity. Differences in shape, size and orientation of concretions, as well as the spatial and crosscutting relationships reflect two phases of calcite-cementing fluids. This is in contrast to most examples in the literature that distinguish just one phase of precipitating fluids. The first phase of cementing fluids flowed horizontally, most likely in the phreatic zone, across hydraulic high-conductivity layers that resulted from sediment-packing heterogeneities and preferential dissolution during dolomitization. These first-phase fluids were most likely injected into the host rock through fracture zones and probably originated in deeper settings. The second phase of cementing fluids was downward directed and possibly of meteoric origin. First-generation concretions, acting as permeability barriers, partly controlled the fluid pathways, precipitation patterns, and concretion type and loci.

KEYWORDS **Calcite concretions. Carbonates. Fluid flow. Diagenesis. Balearic Islands. Miocene.**

INTRODUCTION

The study of calcite concretions is of interest from two points of view: (1) understanding fluid flow through heterogeneous systems is required for improved management of aquifers and hydrocarbon reservoirs. Besides other approaches such as flow modeling, the investigation of elongate concretions has evolved into a promising, yet still uncommon tool (Mozley and Davis, 1996; Davis, 1999). Calcite-cemented elongate concretions with a remarkably uniform orientation are thought to have grown along the direction of groundwater flow (Todd, 1903; Schultz, 1941; Colton, 1967; Jacob, 1973; Raiswell and White, 1978; Parsons, 1980; Theakstone, 1981; Pirrie, 1987; Johnson, 1989; McBride et al., 1994; Mozley and Davis, 1996; Davis, 1999). (2) In addition to illuminating the dynamics of ancient fluid flow, calcite concretions can add an important component to the petrophysical properties of sedimentary rocks. Whereas depositional heterogeneities have received considerable attention in recent years (Kupfersberger and Deutsch, 1999), diagenetically induced heterogeneities have received less attention. However, in order to predict the spatial distribution of reservoir properties, diagenetic overprint must be taken into account (Dutton et al., 2002).

In most occurrences of elongate calcite concretions described in the literature, the host sediment is a siliciclastic-dominated sandstone to conglomerate of relatively young age (Miocene: Schultz, 1941; Pliocene-Pleistocene: Mozley and Davis, 1996; Pleistocene: Theakstone, 1981; McBride et al., 1994), but also some older occurrences are known (Devonian: Colton, 1967; Triassic: Johnson, 1989; Cretaceous: Fastovsky and Dott, 1986; Pirrie, 1987). Descriptions of elongate concretions in carbonate sediments, in contrast, are rare.

Carbonate-cemented concretions, as manifestation of partial cementation of granular sedimentary rocks, exhibit a wide range of sizes and shapes. Elongate concretions are usually internally concentric and characterized by rod- and blade-shapes with the long axes aligned in a preferred orientation (McBride et al., 1994). The term “pipy concretions” also has been used for this type of cementation pattern (Schultz, 1941). Such concretions are usually a few centimeters in diameter and up to a few decimeters in length (McBride et al., 1994).

Elongate concretions are thought to form where preferential cementation occurs in high-permeability zones of a sediment body with preferential flow in the saturation zone at a time of calcite precipitation (Mozley and Davis, 1996; Dutton et al., 2002). Strong evidence for the assumption that elongate concretions grow parallel to groundwater paleo-flow direction has been provided by McBride et al. (1994). These authors demonstrate a coincidence of orientation of concretions with groundwater flow paths in Pleistocene and Holocene shallow-marine sandstones of Italy. These concretions, shaped like cigars, pencils and knife blades, grew preferentially parallel to the direction of water-table gradient. They were not influenced by grain fabric and crosscut sedimentary structures. In alluvial rocks, in contrast, a strong correlation between permeability and depositional paleo-current direction is observed (Pirrie, 1987; Jacob, 1973; Davis, 1999). The reason for this difference between alluvial and non-alluvial sediments is thought to be the stronger anisotropy in hydraulic conductivity of alluvial sediments (Mozley and Davis, 1996).

The present investigation deals with the origin of carbonate concretions within Upper Miocene carbonate rocks of Menorca, the same concretions that were illustrated by Obrador (1972-1973), Obrador and Freeman (1975), Freeman et al. (1983), and Obrador and Pomar (1983). The present study corroborates conclusions drawn by these earlier workers—specifically that Menorcan elongate concretions reflect groundwater flow paths—but assesses the roles of depositional and diagenetic heterogeneities in greater detail.

Based on the conclusions of previous papers that elongate concretions generally reflect the direction of paleo-groundwater flow, the Menorcan outcrops provide high-resolution information on how fluid flow in these carbonate rocks is controlled by depositional and diagenetic heterogeneities. This paper presents the first results derived from outcrop studies. Ongoing work includes chemical and isotope characterization of the different types of concretions to constrain the origin of the precipitating fluids. Here we aim at visualizing fluid-flow patterns through heterogeneous carbonate sediments by studying the variability in shape, size and orientation, as well as the spatial and crosscutting relationships between the different phases of carbonate concretions.

SEDIMENTOLOGICAL SETTING OF THE STUDY AREA

Menorca is the northeasternmost of the Balearic Islands, which are the emergent parts of the Balearic Promontory in the Western Mediterranean (Fig. 1A). The southern region of this island (Migjorn) (Fig. 1B) is composed of subhorizontally lying Upper Miocene dolostones that belong to two stratigraphic sequences. The lower sequence, Early Tortonian in age, has been deposited as a distally steepened carbonate ramp (Obrador et al., 1992; Pomar et al., 2002). This carbonate ramp unconformably overlies both Jurassic and Paleozoic basement and, locally, an older Miocene unit of uncertain age (Middle Miocene?), composed by siliciclastic and dolomitic coarse sand to pebble-boulder-sized conglomerate (fan-delta deposits). The Lower Tortonian ramp is overlain by the Upper Tortonian to Lower Messinian Reefal Complex (Fig. 1C) that, in the study area, has mostly been removed by erosion during Pliocene to Pleistocene times.

The Lower Tortonian carbonate ramp is composed predominantly of medium- to coarse-grained bioclastic packstones and grainstones (locally with significant contribution of dolomite lithoclasts derived from the hinterland) to rhodolithic rudstones and floatstones. With local

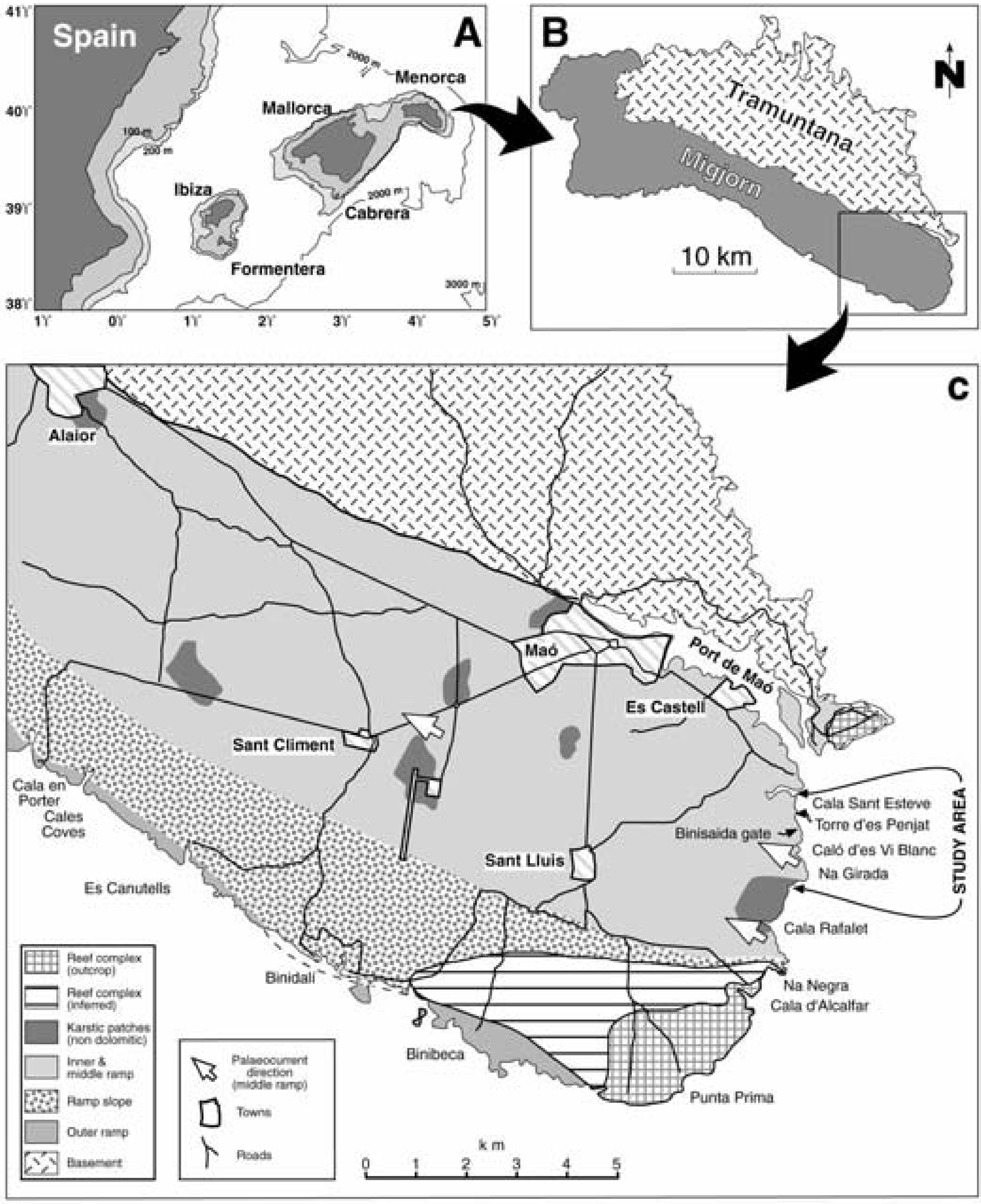

FIGURE 1 **A) The Balearic Promontory in Western Mediterranean. B) Simplified geological map of Menorca Island showing the Tramuntana and Migjorn regions. Upper Miocene rocks compose the whole Migjorn region. C) Lithofacies distribution of the Lower Tortonian ramp and overlying Reef Complex on the southeastern side of Menorca, with indication of the study area (modified from Pomar et al., 2002).**

exceptions, these sediments are pervasively dolomitized. Non-dolomitized parts are typically karstified (Fig. 1C). Strandline deposits that crop out at port de Maó include continental conglomerates and red sandstones, conglomeratic beachface deposits and structureless conglomerates and pebbly sandstones, representing small fan-deltas. Downdip, these deposits grade into unsorted and burrowed mollusc-foraminifer dolo-packstones with lithoclasts -a facies that is interpreted as having been deposited in the inner ramp, above the base of wave action and trapped in seagrass meadows (Pomar et al., 2002). Ghosts of large-scale cross-stratification dipping both landward and seaward are present. Basinward, this facies passes to middle-ramp lithofacies, composed of burrowed dolo-packstones interfingered with crossbedded grainstones that were deposited below the wave base where they were subject to transport by bottom currents. Farther downdip, the ramp slope lithofacies are composed of large-scale clinobeds dipping seaward at 15°-20° that consist of dolomitic rudstones and floatstones and coarse-grained dolo-grainstones. These sediments, in turn, pass into debris flows and turbidites deposits, and into fine-grained laminated, mostly dolomitic, wackestones and packstones to grainstones of the outer ramp. For a detailed description of the lithofacies distribution and architecture of this Lower Tortonian distally steepened ramp see Pomar et al. (2002).

The study area is situated at the cliffy eastern coast of Menorca (Fig. 1C). Here, spectacular elongate concretions occur in shallow-marine inner- and middle-ramp lithofacies that consist of crudely to well-stratified poorly sorted fine- to medium-grained mollusc-foraminifer dolo-packstones to dolo-grainstones with local patches of non-dolomitized rock. Dissolution during dolomitization has left abundant moldic pores by removing all skeletal components with the exception of red algal fragments, rhodoliths, and small agglutinated foraminifers. Poorly rounded detrital dolomite grains with dolomite cement overgrowths are typical of these lithofacies (Freeman et al., 1983). Detrital quartz grains are locally abundant. Porosity in the host rock is conspicuous and, locally, can reach as much as 60% (visual estimate of thin sections). Pore types include moldic, intergranular, intercrystalline, and intraskeletal within red algae fragments, rhodoliths and larger foraminifers.

CALCITE-CEMENT CONCRETIONS

On Menorca, concretions occur in all types of depositional facies of the Miocene sequences. However, they are particularly conspicuous in the Lower Tortonian carbonate ramp of the study area and, due to the soft host sediment that has been more strongly weathered than the indurated concretions, they form prominent features. The concretions are characterized by a remarkable variability of shapes and wide range of sizes, with distinct and mappable spatial orientations. Shapes range from vertical concretions to sheet-like subhorizontal zones, radiating clusters of elongated concretions, elongated ellipsoids, spheroids and large-scale horizontal rods. The concretions consist of poikilotopic calcite cement engulfing the dolomitized grains and dolomite crystals of the host-rock sediment. The exact timing of their formation is unknown, however it is clear that the concretions have formed after dolomitization.

Subhorizontal sheet-like concretions form extensive, tabular, 20-cm- to 1-m-thick layers. Lateral extension ranges from some tens to several hundreds of meters (maximum lateral continuity could not be determined due to limited outcrop extension). These sheet-like concretions commonly parallel and, locally, crosscut bedding surfaces (Figs. 2A, 2B and 2C). The sheet-like concretions are compact and tightly cemented. Locally, the origin of the sheets by coalescence of flattened ellipsoidal concretions is still apparent by faint concentric banding tracing individual ellipsoids. Colors grade from whitish to light pinkish and light brownish. The surfaces of compact concretions are sharp, crosscut large skeletal components such as rhodoliths and may show elongate undulations (Fig. 2D). However, the surfaces can also be strongly irregular. In many cases, the sheets are composed of coalesced elongate ellipsoids that trace bedding surfaces (Figs. 2A, 2B and 2C) or, locally, large-scale, low-angle cross-stratification. Massive pinkish sheet-like concretions branch laterally off to elongate concretions (Figs. 2E and 2F). These are horizontal to inclined, up to several meters long, thin out, and commonly show concentric light-pinky color bands (Fig. 4A).

Axes of elongate undulations and off-branches of the sheet-like concretions, and the long axes of pinkish coalescent ellipsoids show a consistent orientation at each of the individual localities. However, each of the different localities shows a different orientation of these features (Fig. 3). The orientation at each of the localities is perpendicular to tectonic fractures.

Vertical elongate concretions range from centimeter to meter scale and are characterized by rod and blade shapes (Figs. 4B and 4C). Groups of vertically elongated ellipsoids are also common, locally tied by thin subhorizontal concretions that may follow bedding planes (Fig. 4D and 4E). Most vertical concretions are whitish.

Huddles of horizontal, elongate concretions (cigar- to twig-like) usually diverge perpendicularly from vertical fractures (Figs. 5A and 5B). They are white and are centimeters to a meter in greatest dimension.

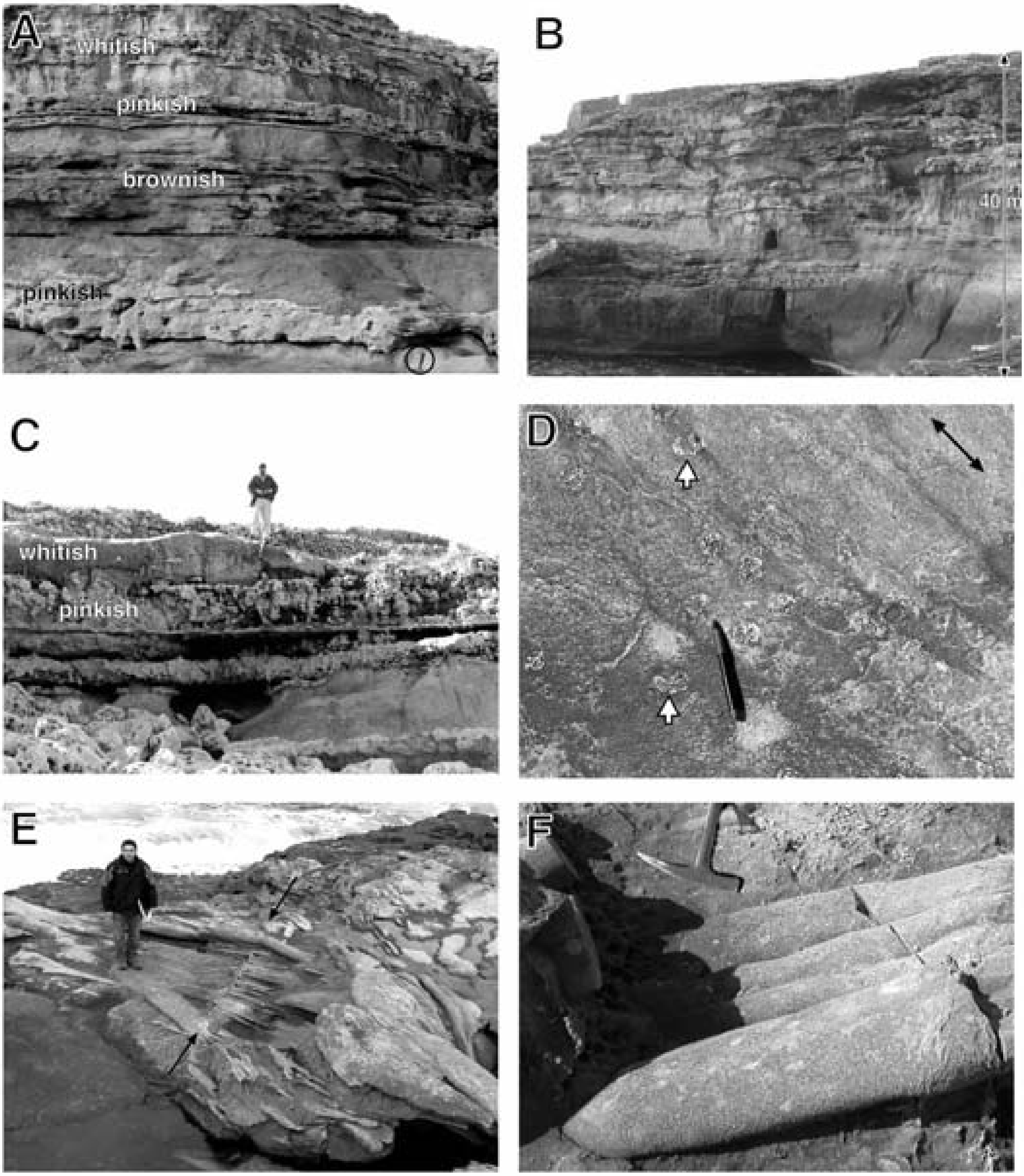

FIGURE 2 **A) Extensive, subhorizontal sheet-like concretions at Torre de Binisaida. Different concretion layers show different colors. Circle: hammer for scale. B) Extensive, subhorizontal sheet-like concretions at Binisaida gate; sea cliff is 40 m high. C) Massive whitish subhorizontal sheet-like concretion underlain by pinkish, non-massive concretion layers. D) Elongate undulations of the peripheral surfaces (double arrow indicates undulation axis) of pinkish, subhorizontal, sheet-like concretions. White arrows point to rhodoliths. Locality: Na Girada. E) Horizontal to slightly inclined, pinkish elongate concretions branching off from subhorizontal sheet-like concretion at Na Girada. Arrows point to a small fracture from which whitish, smaller elongate concretions diverge perpendicularly. F) Pinching out of elongated branching-off concretions at the same locality as E (inferred paleo-flow direction is towards the left of the picture).**

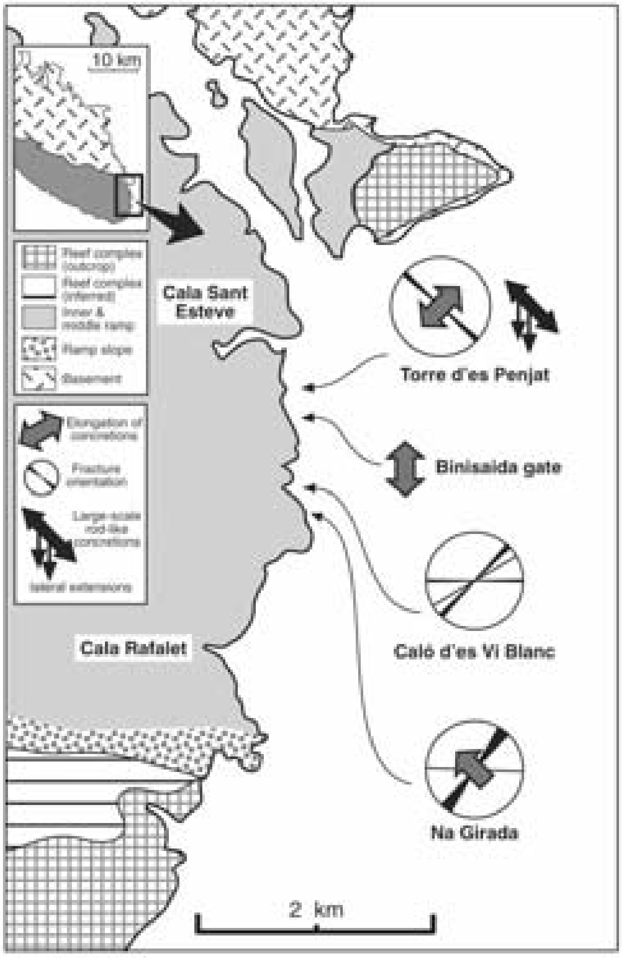

FIGURE 3 **Direction of elongation of concretions and orientation of fractures at four localities. Surface undulations, off-branching concretions and horizontally elongated coalescent ellipsoids that are associated with the pinkish sheet-like concretions, show consistent orientations perpendicular to tectonic fractures at each locality. In contrast, the large-scale, horizontal rod-like concretions are parallel to the dominant orientation of the fractures.**

Radiating clusters of elongated white concretions form spectacular "tree-trunk"- and "inverted palm-tree" shapes that in outcrop appear to have little to no relationship to bedding geometries (Figs. 5C, 5D, 5E and 5F). Sizes of these clusters vary from a meter to about 10 m in height, and individual concretions range from centimeters to a meter in size. Radiating clusters appear always to occur directly below subhorizontal sheet-like concretions (Figs. 6A, 6B, 6C and 6D). They always radiate from a small, discrete zone, and mostly diverge downwards ("inverted palm-tree"- and "tree-trunk"-shapes) but in few cases diverge upwards ("palm-tree"-shapes) (Fig. 6C).

Small-scale spherical concretions form clusters of separated or touching spheroids (Figs. 6E, 6F, 7A, and 7B). These spheroids vary from centimeter- to decimeter-scale and are pinkish. Some clusters of coalescent spheroids follow bedding surfaces and, locally, crosscut stratification. A second generation of more whitish calcite cement forms small vertical concretions (Fig. 6F) or irregular layers (Figs. 7A and 7B) that coalesces the spherical concretions in some localities.

Large-scale horizontal rod-like concretions vary from a meter to tens of meters in length and are up to 50 cm in diameter (Figs. 7C, 7D, 7E and 7F). These pink concretions are oriented horizontally and parallel small fractures. They are roughly cylindrical with small thin horizontal sheet- to rod- or blade-shaped lateral extensions perpendicular or oblique to the rod's axis (Figs. 7E and 7F).

SPATIAL DISTRIBUTION AND CROSSCUTTING RELATIONSHIPS OF CONCRETIONS

Spatial distribution of concretions and slight color differences allow differentiating two groups (Fig. 8A):

1) Subhorizontal sheet-like layers with elongate off-branching concretions, large-scale rod-like concretions and coalescent flattened ellipsoids are pinkish and occur in the same stratigraphic levels, and they may grade from one type to the other. Clusters of spherical concretions are also pinkish but they commonly occur at different stratigraphic levels.

2) Radiating clusters of "inverted palm-tree" concretions are white and always occur just below pinkish subhorizontal sheet-like layers (see Fig. 6), mostly downwards-diverging. Vertical elongate concretions are also white and may occur in different stratigraphic layers but preferentially between the intervals rich in pinkish concretions. Some horizontal layers, which are less tightly cemented than the pink layers, also are white.

Crosscutting relationships between these two groups of concretions (pinkish and white) can be observed in some localities, indicating that most white concretions postdate pinkish concretions. At Na Girada (Fig. 8B), a small fracture truncates both the host rock and the pinkish elongate concretions that branch-off from sheet-like concretions (Figs. 3 and 2E). Huddles of smaller white horizontal elongate concretions grew from the fracture plain in perpendicular orientation within the host rock (see Fig. 5A). At Caló des Vi Blanc, small pinkish spherical concretions are engulfed in small whitish vertical-elongate concretions (Fig. 6F) or embedded in tightly cemented, irregular concretion layers that, locally, follow cross-stratification (see Figs. 7A and 7B).

Another significant difference between these two groups of concretions is the orientation of elongation.

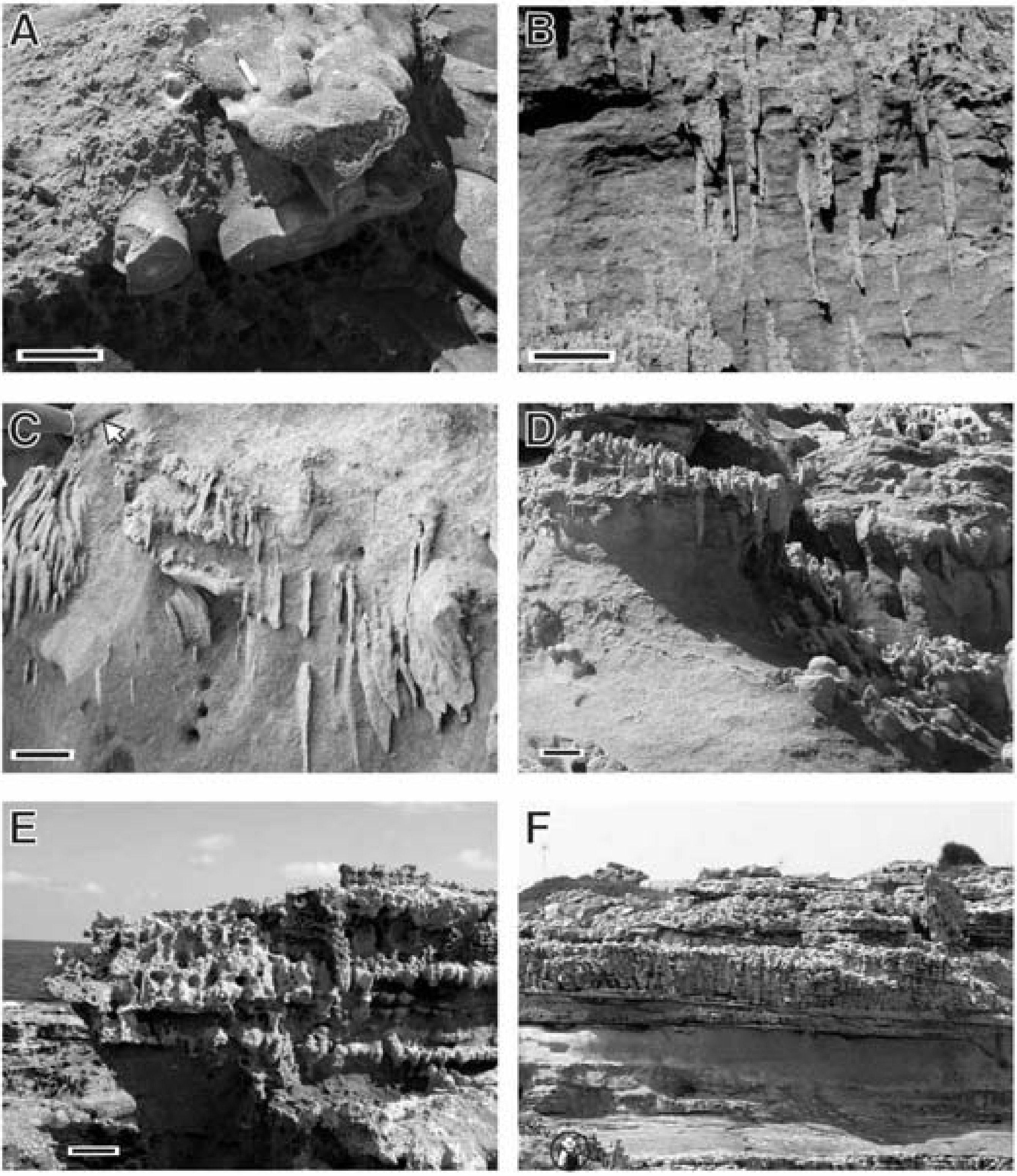

FIGURE 4 **A) Concentric light-pinkish color bands in sheet-like concretions branching off of massive layers. Locality: Na Girada. Scale bar: 15 cm. B) White, rod-shaped vertical elongate concretions at Caló des Vi Blanc. Scale bar: 15 cm. C) White, rod- and blade-shaped vertical elongate concretions at Torre de Binisaida. Scale bar: 15 cm. D) Group of white, vertically elongated ellipsoids connected by thin subhorizontal concretions. These are slightly inclined at the right side of the photograph. Scale bar: 20 cm. E) Group of whitish vertically elongated ellipsoids with horizontal amalgamation, following bedding plane. Scale bar: 15 cm. F) Coalescent ellipsoid layers developed along large-scale, low-angle cross-stratification. Locality: between Torre de Binisaida and Cala Sant Esteve.**

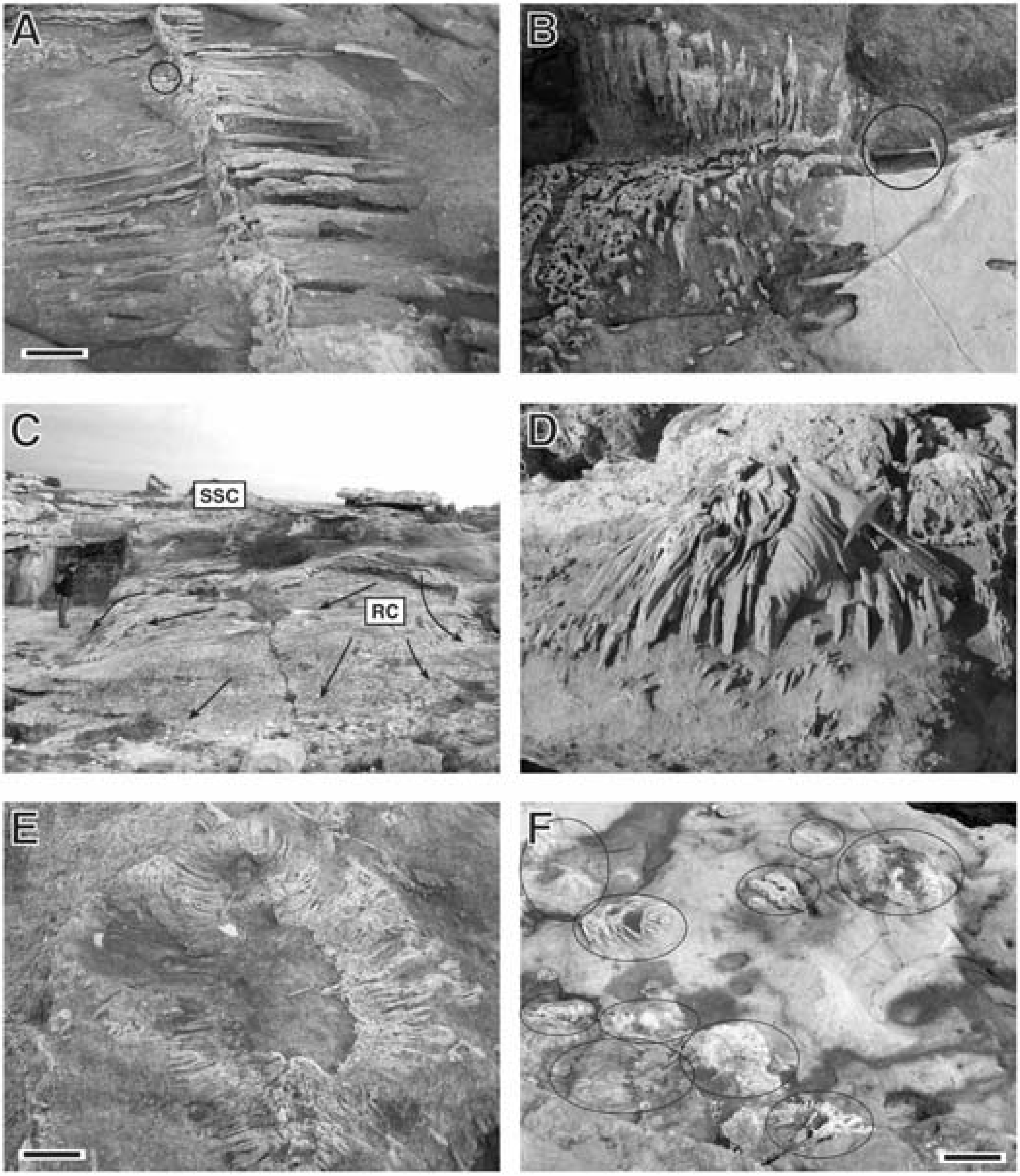

FIGURE 5| **A) Clusters of white, horizontal, elongate concretions perpendicular to vertical fracture. Locality: Na Girada. Scale bar: 20 cm. B) White, horizontal, elongate concretions perpendicular to a vertical fracture at the edge of a pinkish, horizontal, sheet-like concretion (lower right of the photograph). Locality: Torre de Binisaida. C) Downwards-diverging branching-out elongated concretions forming "inverted palm-tree"-like radiating cluster of white, elongate concretions. Locality: between Torre de Binisaida and Cala Sant Esteve. Arrows point elongation directions and pinching-out terminations, which are thought to indicate paleo-flow directions. (SSC: subhorizontal, sheet-like concretion; RC: radiating cluster). D) Small downwards-diverging radiating cluster of white elongated concretions. Locality Torre de Binisaida. E) Vertical photograph of a down-diverging, radiating cluster of white elongated concretions. In this example, the radiating center is elongated. Locality: Binisaida gate. Scale bar: 30 cm. F) Subvertically taken photograph of a group of downwards-diverging, radiating clusters of white elongated concretions (encircled). Locality: Binisaida gate. Scale bar: approximately 50 cm.**

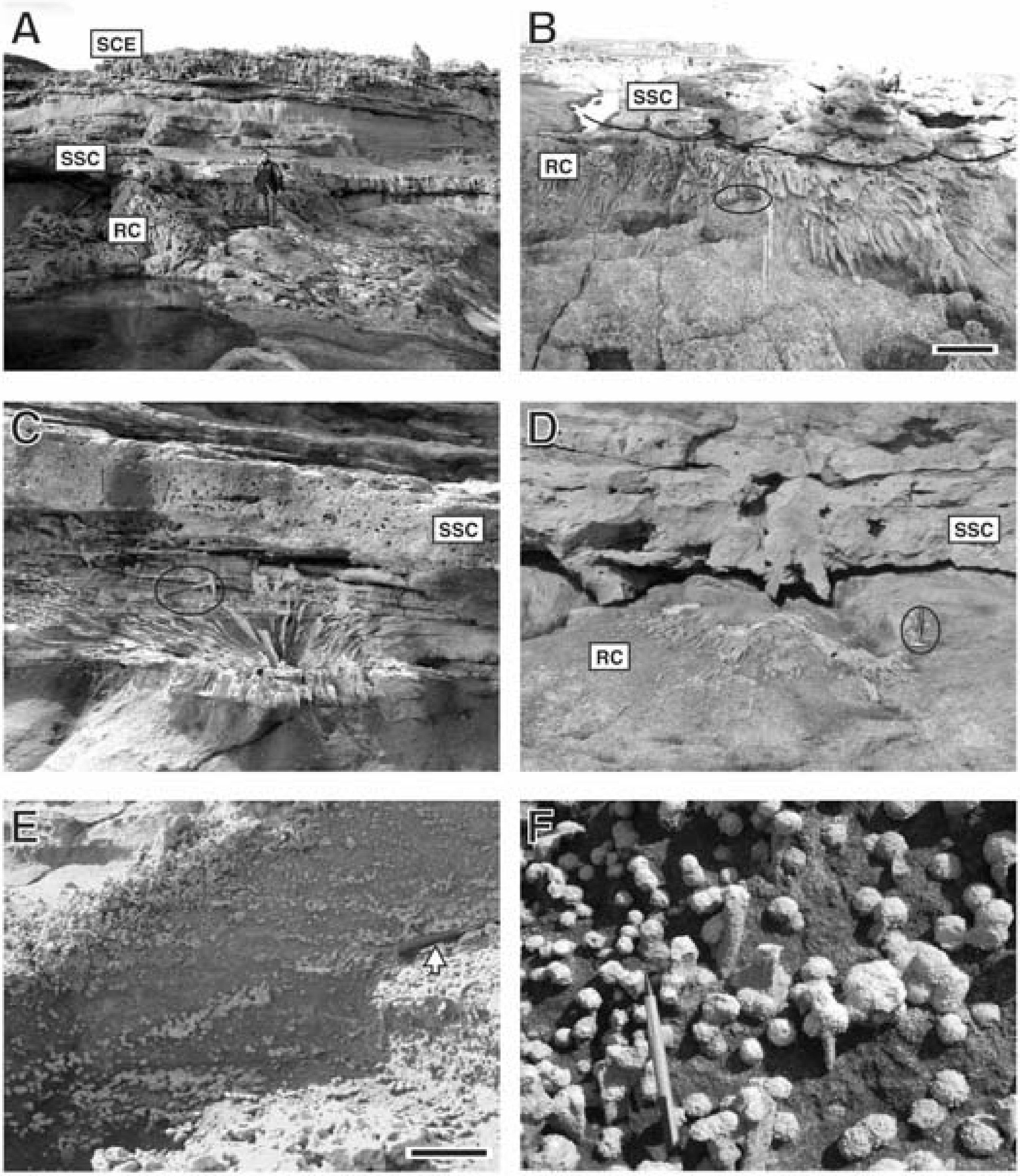

FIGURE 6 **A) Large radiating cluster (RC) of white, down-diverging elongated concretions below a pinkish, subhorizontal, sheet-like concretion (SSC). Locality: between Torre de Binisaida and Cala Sant Esteve. (SCE: sheet of coalescent ellipsoids). B) Small radiating cluster of white elongated concretions (RC) downwards-diverging under a pinkish subhorizontal sheet-like concretion (SSC). Locality: Torre de Binisaida. Scale bar: 30 cm aprox. C) "Palm-tree"-like cluster of white elongate concretions underlying a pinkish inclined sheet-like concretion (SSC) that crosscut horizontal bedding planes. Locality: Binisaida gate. D) Downwards-diverging radiating cluster of white elongate concretions (RC) below a subhorizontal sheet-like pinkish concretion layer (SSC). Locality: Torre de Binisaida. E) Cluster of small-scale, spherical, pinkish concretions that concentrate in horizontal and inclined layers, crosscutting stratification. Locality Caló des Vi Blanc. Scale bar: 25 cm approx. F) Detail of pinkish spheroids and later-generation white vertical elongate concretions that engulf the spheroids at Caló des Vi Blanc.**

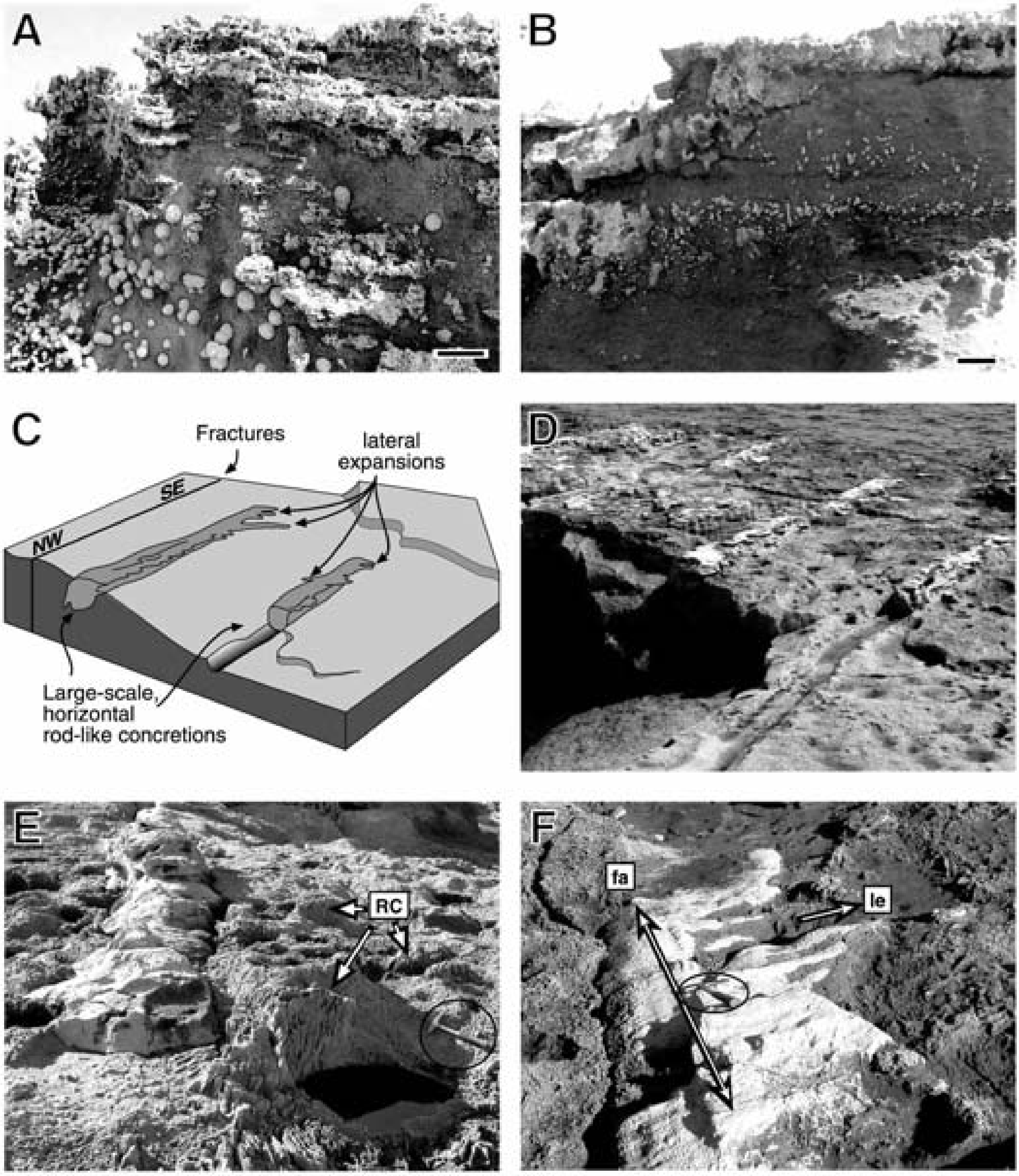

FIGURE 7| **A) Pinkish spherical concretions partly enclosed in whitish, non-massive concretions that upward grade into a subhorizontal sheet. Locality: Caló des Vi Blanc. Scale bar: 15 cm. B) Pinkish spherical concretions in soft dolomitic host sediment, and a whitish sheet-like concretion at the top. Note that preferred zones of spherical concretions and whitish sheet-like concretions do not coincide. Locality: Caló des Vi Blanc. Scale bar: 20 cm. C and D) The large-scale, horizontal rod-shaped concretions at Torre de Binisaida are pinkish and oriented parallel to small fractures. Lateral expansions are oblique to perpendicular to rod's axes. Locality: Torre de Binisaida. E) Downwards-diverging radiating cluster of white elongate concretions (RC) in the host rock adjacent to the large-scale, horizontal rod-shaped concretion. They are located below a subhorizontal sheet-like pinkish concretion layer (same as in Fig. 6B). F) Detail of thin, horizontal sheet- to rod- or blade-shaped lateral extensions (le) perpendicular and oblique to the large-scale, rod-shaped concretion axis (fa).**

Pinkish concretions are preferentially horizontally oriented. White concretions, in contrast, are dominantly vertically to sub-vertically oriented, except for the small clusters of horizontal concretions perpendicular to the small fractures.

PHASES OF CONCRETION GENERATION

A number of previous studies have demonstrated that elongate concretions form from flowing groundwater, with elongation axes paralleling groundwater-flow direction (Todd, 1903; Schultz, 1941; Meschter, 1958; Colton, 1967; Jacob, 1973; Raiswell and White, 1978; Parsons, 1980; Theakstone, 1981; Pirrie, 1987; Johnson, 1989; McBride at al., 1994; Mozley and Davis, 1996; Davis, 1999). According to McBride et al. (1994), cementation of such concretions occurs within the water-saturation zone (phreatic zone) in high-permeability zones with preferential fluid flow. Concretions develop preferentially parallel to the direction of groundwater flow and, in many cases, are not influenced by sedimentary structures or grain fabric. Groundwater flow is controlled by both the direction of the hydraulic gradient and the anisotropy of the hydraulic conductivity, increasing the tendency for groundwater to flow subparallel to the orientation of anisotropy (Freeze and Cherry, 1979; Mozley and Davis, 1996).

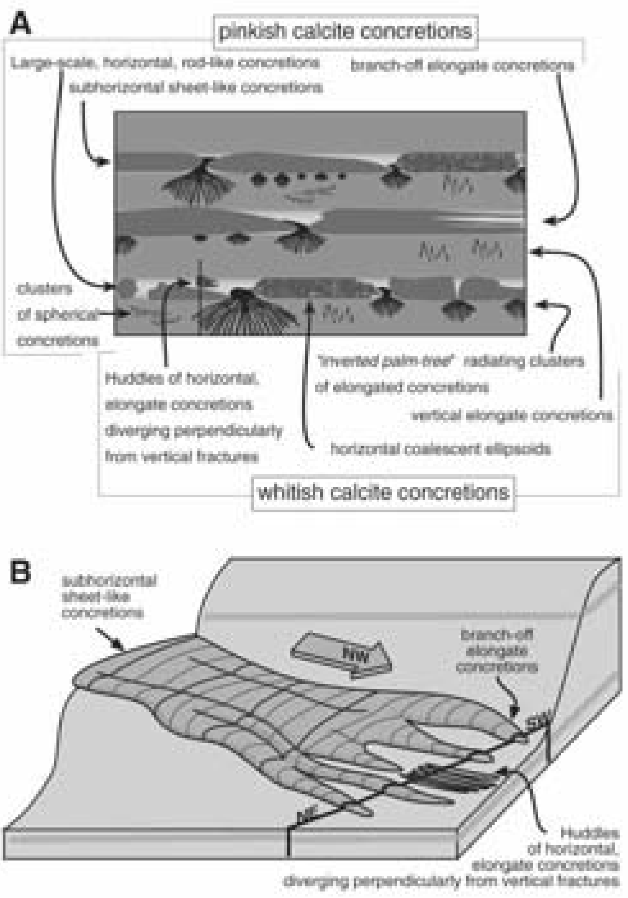

FIGURE 8 **A) Spatial distribution, orientation and color differences of calcitic concretions. B) Crosscutting relationships between concretions at Na Girada: a small vertical fracture, SW–NE oriented, truncates both the host rock and the pinkish, NW-directed, elongate concretions branching-off from a sheet-like concretion. Smaller, white, horizontal elongate concretions are oriented perpendicular to the fracture and developed within the host rock.**

The two groups of concretions discerned in the Miocene of Menorca represent two distinct phases of concretion formation (Fig. 9). The first generation of concretions, pinkish colored, roughly follows subhorizontal strata. The axes of off-branching concretions and undulations on peripheral surfaces are dominantly horizontal to subhorizontal. This indicates that cement precipitated in layers with prevailing horizontal hydraulic flow that resulted from greater porosity and permeability in some beds and sedimentary lamina after dolomitization. A horizontal hydraulic gradient appears to have been present. Orientation of concretion elongations and peripheral-surface undulations indicate cement-precipitating fluids were injected into the higher-conductivity dolomitic host-rock layers from vertical zones (Fig. 10). In the study area, two injection zones can be inferred: one at Port de Maó at the NE, and another one offshore to the SE. The injection zone at Port de Maó might be related to the paleo-escarpment existing at the contact between the Paleozoic basement and the Miocene rocks, whereby both lithologic units exhibit strong differences in porosity and permeability. The paleo-escarpment at Port de Maó might be related to previous faulting (Obrador, 1972-1973). The possible injection zone offshore to the SE could be related to a fault. The existence of this fault is consistent with sedimentological data: abundant northwest migrating subaqueous dunes in the middle ramp lithofacies between Binisaida gate and Cala Rafalet (see Fig. 1) are rich in both skeletal grains and detrital dolomite (Pomar et al., 2002). Both components were sourced from the southeast of present outcrops. This fact implies that the middle ramp extended to the east, in the present-day offshore area.

Rod-like concretions belong to this first generation of concretions and have developed along preferred fluid pathways that are related to small fractures, from which fluid was also injected into the host rock producing the lateral expansions (see Fig. 3). Groundwater flow is expected to flow obliquely toward the high-transmissivity host rock from the preferred pathway in which flow was parallel to the pathway axis. Davis (1999) demonstrated in alluvial deposits that concretion orientations in a channel scour infilled by gravel are parallel to the channel axis, whereas concretions in adjacent sand sheet are oriented oblique to the channel axis. The preferred pathways to form these rod-like concretions probably resulted from

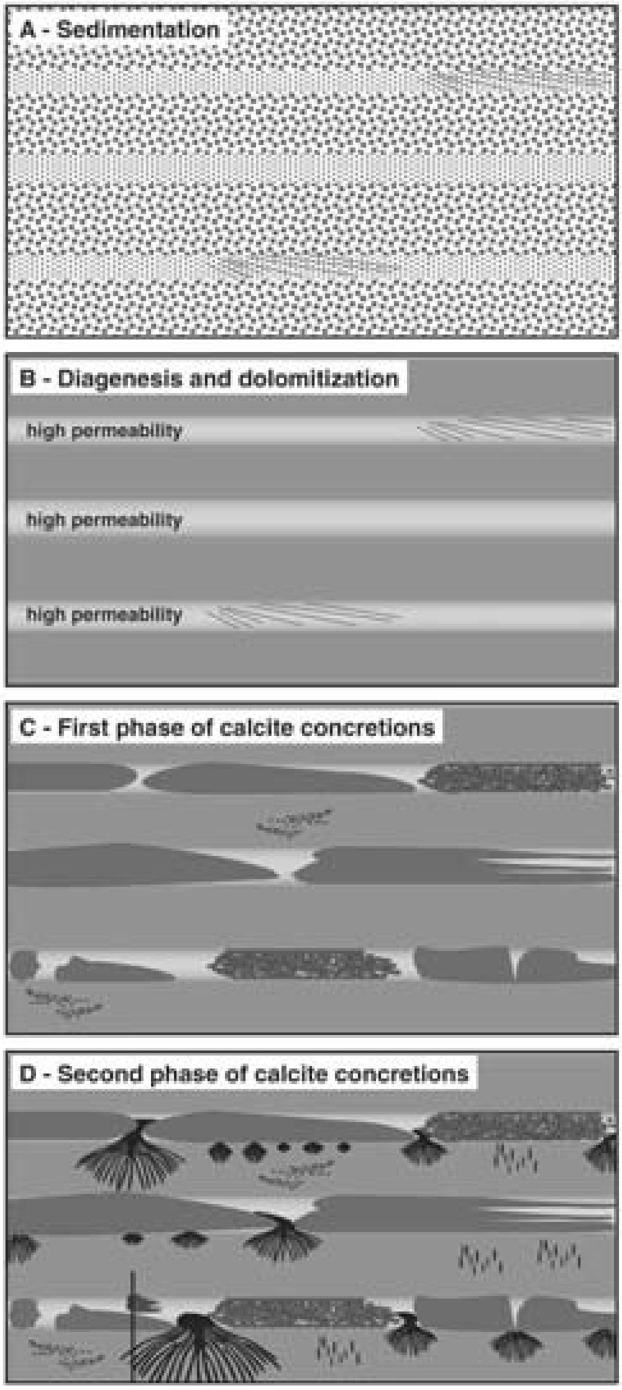

FIGURE 9 **Phases of calcitic concretions growth (types of concretions as in Fig. 8). A) Differences in depositional sediment packing affect initial permeability. In addition, different skeletal composition affects solubility. B) These initial differences in permeability may have affected further development of permeability during dolomitization and may have created high-permeability conduits. C) The first, pinkish, generation of concretions preferentially grew along higher-permeability strata, sedimentary lamina, and fluid pathways related to small fractures (large-scale, horizontal rod-shaped concretions), with horizontal to subhorizontal elongations. Clusters of spheroids precipitated in zones with low hydraulic gradient, isolated from the main fluid paths. During this phase, porosity in former higher-permeability layers was occluded. D) The second, whitish, generation of concretions has a dominant downward directed growth orientation. Downward radiating clusters ("inverted-palm-tree-like") spread out beneath permeability barriers (sheet-like concretions of first generation). Horizontal huddles of concretions grew from fluids spreading out from fractures, and vertical concretions where cementing fluids were not restrained by the first-phase concretions.**

enhanced permeability in linear zones at the intersection between small fractures and high-permeability horizons.

Clusters of pinkish spherical concretions occur at different localities. The absence of preferential elongations of these concretions might be indicative of cement precipitation in zones of the host rock with low hydraulic gradient that were isolated from the main fluid paths.

The second generation forms less massive, white concretions. The most outstanding white concretions are the closely spaced, downward radiating clusters ("inverted palm-tree-like"), but groups of vertical concretions also are common, and horizontal huddles growing perpendicularly from vertical fractures are also present. Two observations indicate that flow gradient was downward directed and gravitationally driven: first, the vertical elongation of most white concretions, and second, the down-diverging radiating clusters. The position of "inverted palm-tree-like" concretions, radiating under first-phase horizontal sheet-like concretions, indicate that precipitation loci were controlled by vertical permeability pathways through the impermeable sheet-like, first-phase concretions. Secondary fractures acted as preferential fluid pathways for the second generation of white concretions, from which fluids spread into the host rock.

The origin of the cementing fluids is still unknown. An intraformational origin of the dissolved calcium carbonate can be excluded, because the host rock was already strongly diagenetically altered and largely dolomitized before precipitation of the concretions. In the inner- and middle ramp lithofacies, red algae and small agglutinated foraminifers are the only preserved skeletal components, and significant moldic porosity developed by dissolution of other skeletal grains during dolomitization. This indicates that the calcitic cement in the concretions was not sourced from within the host-dolomitized rock (such as dissolution of mineralogically unstable components). Consequently, calcite-cementing fluids must have entered the formation from the outside. For the first phase, the aquifer is thought to have lacked a vertical gradient, which suggests that the cementing fluids were laterally injected through faults. Pinkish to light brownish colors of the first concretion phase point towards higher concentrations of staining elements that might be indicative of deeper origin. The second phase of concretion precipitation is dominated by vertical, downward directed flow, suggesting a meteoric origin of the fluids, which would also be consistent with the white color of the cal-

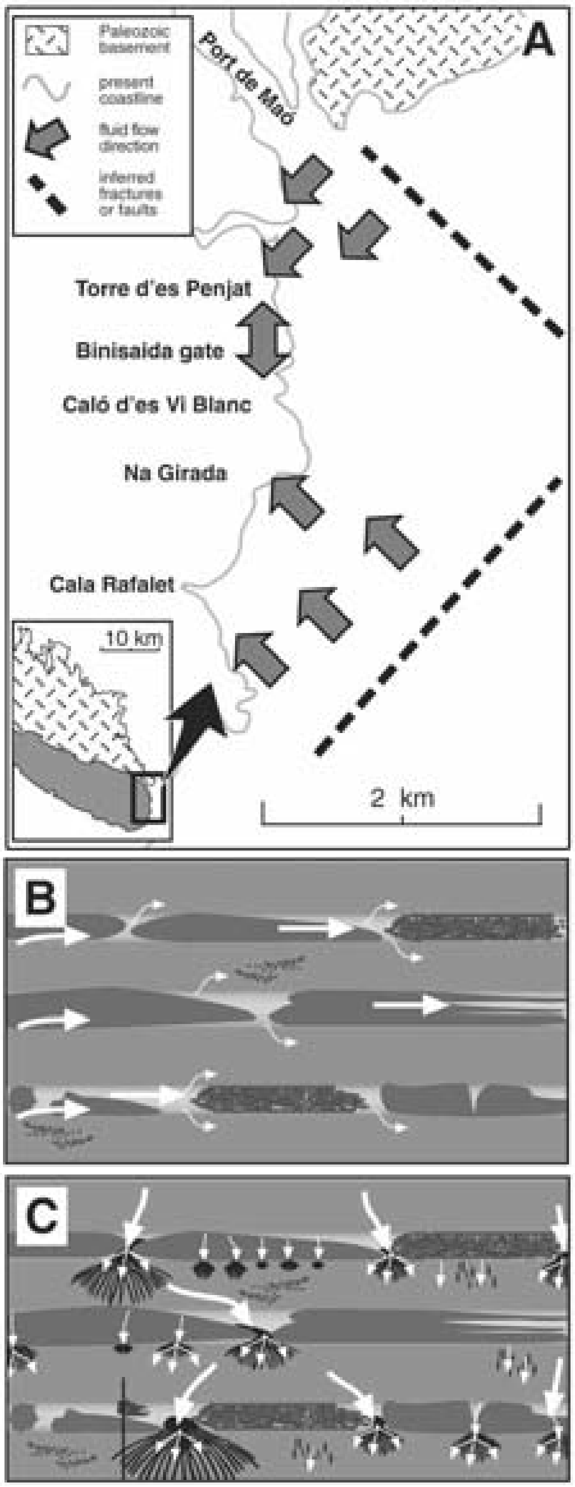

FIGURE 10 **Fluid-flow directions. A) Map of fluid-flow directions of pinkish, first-generation of calcitic concretions. At Na Girada, it has been inferred from concretion elongations and branching-off directions. At Torre de Binisaida it is provided by concretion elongations and lateral extensions of the large-scale, horizontal rod-shaped concretions. Scarcity of elongate concretions and occurrence of abundant small-scale, spherical concretions at Caló des Vi Blanc may be indicative of lacking hydraulic gradient at this locality. B) First-generation, pinkish concretions formed by preferential fluid flow through higher-permeability layers with dominant horizontal directions. C) Second-generation, white concretions grew under downward directed cementing fluid flow**

citic cement in these concretions. The change of paleoflow direction from horizontal (first phase) to the vertical, down directed (second phase) is, tentatively, attributed to the down-dropping of a tectonic block formerly situated to the SE of the studied area. This tectonic movement might have induced the change of hydraulic gradient from injection to drain through the fault zone. Ongoing work on geochemical characterization and isotope composition seeks to answer these questions.

CONCLUSIONS

Upper Miocene carbonates that crop out in the eastern coast of Menorca allow for interpreting fluid-flow patterns through heterogeneous carbonate rocks. Direction of groundwater paleo-flow as a function of hydraulic gradient and anisotropy of the hydraulic conductivity has been reconstructed through a study of calcite concretions that are thought to have grown with long axes parallel to the direction of groundwater flow.

The Menorcan elongate concretions represent a remarkable and distinct case in two respects compared to elongate concretions described elsewhere: (1) The Menorcan elongate concretions developed within granular, largely dolomitic carbonate deposits, and (2) they do not exhibit a common orientation. Instead, their orientation, shape, and size are highly variable, reflecting a complexity of conditions that influenced their development.

The variation in shape, size and orientation, as well as the spatial and crosscutting relationships between elongated carbonate concretions, reflect the effect of two different types of calcite-cementing fluids that flowed through shallow-marine porous grain-dominated dolostones, contrary to most cases described in the literature that refer to one phase of precipitating fluids.

The first phase of concretion development is believed to reflect injection of cementing fluids moving upward along earlier faults, from which it spread laterally through intervals with high hydraulic conductivity in part produced by previous dolomitization. Subhorizontal sheet-like layers with elongate off-branching concretions, funnel-shaped concretions and coalescent flattened ellipsoids are the most conspicuous types of first-phase calcite concretions.

The second phase of cementing fluids, which were probably of meteoric origin, are believed to have moved downward, driven by gravity. Those fluids that were confined into narrow vertical pathways that existed in relatively impermeable sheet-like, first-phase concretions spread out beneath these permeability barriers into the porous and permeable host rock, forming downward radiating clusters ("inverted palm-tree -like") of elongate concretions. Vertical elongate concretions developed where downward flowing cementing fluids were not restrained by the first-phase concretions.

This Menorcan case study provides a model for understanding the effects of multiple cementing fluids in a petrophysically heterogeneous system. Additionally, it offers insights into water-rock dynamics that bear on the broader subject of fluid reservoir assessment and management.

ACKNOWLEDGEMENTS

This paper is dedicated to the memory of Francesc Calvet, who is sorely missed. Reviews by William C. Ward and Tom Freeman considerably improved this paper. Funding from Spanish DGICYT project PB97-0135-C02-01 is acknowledged.

REFERENCES

Colton, G.W., 1967. Orientation of carbonate concretions in the Upper Devonian of New York. Geological Survey Professional Paper, 575-B, 57-59.

Davis, J.M., 1999. Oriented carbonate concretions in a paleoaquifer: Insights into geologic controls on fluid flow. Water Resources Research, 35, 1705-1711.

Dutton, S.P., White, C.D., Willis, B.J., Novakovic, D., 2002. Calcite cement distribution and its effect on fluid flow in a deltaic sandstone, Frontier Formation, Wyoming. American Association of Petroleum Geologists Bulletin, 86, 2007 –2021.

Fastovsky, D. E., Dott, R. H. J., 1986. Sedimentology, stratigraphy, and extinctions during the Cretaceous-Paleogene transition at Bug Creek, Montana. Geology, 14, 279-282.

Freeman, T., Rothbard, D., Obrador, A., 1983. Terrigenous dolomite in the Miocene of Menorca (Spain): Provenance and diagenesis. Journal Sedimentary Petrology, 53, 543-548.

Freeze, R.A., Cherry, J.A., 1979. Groundwater. Englewood Cliffs, New Jersey, ed. Prentice-Hall, 604 pp.

Jacob, A.F., 1973. Elongate concretions as paleochannel indicators. Geological Society of America Bulletin, 84, 2127-2132.

Johnson, M.R., 1989. Paleogeographic significance of oriented calcareous concretions in the Triassic Katberg Formation, South Africa. Journal of Sedimentary Petrology, 59, 1008-1010.

Kupfersberger, H., Deutsch, C.V., 1999. Methodology for integrating analog geologic data in 3-D variogram modeling. American Association of Petroleum Geologists Bulletin, 83, 1262-1278.

McBride, E.F., Picard, M.D., Folk, R.L., 1994. Oriented concretions, Ionian coast, Italy: Evidence of groundwater flow direction. Journal of Sedimentary Research, 64, 535-540.

Meschter, M.N., 1958. A study of concretions as applied to the geology of uranium deposits. United States Atomic Energy Commission Technical Memorandum Report, TM-D-1-14, 1-10.

Mozley, P.S., Davis, J.M., 1996. Relationship between oriented calcite concretions and permeability correlation structure in an alluvial aquifer, Sierra Ladrones Formation, New Mexico. Journal of Sedimentary Research, 66, 11-16.

Obrador, A. 1972-1973. Estudio estratigráfico y sedimentológico de los materiales miocénicos de la Isla de Menorca. Revista Menorca, 64, 37-197; 65, 35-97 and 65, 125-189.

Obrador, A., Freeman, T., 1975. Erosional features and multiple generations of dolomite in the Miocene of cala St. Esteve (Menorca, Baleares). IXe Congrès International de Sedimentologie. Nice 1975. Sedimentology, 159-162.

Obrador, A., Pomar, L., 1983. El Neógeno del sector de Maó. In: Pomar, L., Obrador, A., Fornós, J. J. and Rodríguez-Perea, A. (eds.). El Terciario de las Baleares (Mallorca-Menorca). Institut d'Estudis Baleàrics, Universidad de Palma de Mallorca, 207-232.

Obrador, A., Pomar, L., Taberner, C., 1992. Late Miocene breccia of Menorca (Balearic Islands): a basis for the interpretation of a Neogene ramp deposit. Sedimentary Geology, 79, 203-223.

Parsons, M.W., 1980. Distribution and origin of elongate sandstone concretions, Bullion Creek and Slope Formations (Paleocene), Adams County, North Dakota. M.S. thesis. Grand Forks, University of North Dakota, 133pp.

Pirrie, D., 1987. Oriented calcareous concretions from James Ross Island, Antarctica. British Antarctic Survey Bulletin, 75, 41-50.

Pomar, L., Obrador, A., Westphal, H., 2002. Sub-wavebase cross-bedded grainstones on a distally steepened carbonate ramp, upper Miocene, Menorca, Spain. Sedimentology, 49, 139-169

Raiswell, R., White, N.J.M., 1978. Spatial aspects of concretionary growth in the Upper Lias of northeast England. Sedimentary Geology, 20, 291-300.

Schultz, C.B., 1941. The pipy concretions of the Arikaree. University of Nebraska State Museum Bulletin, 2, 69-82.

Theakstone, W.H., 1981. Concretions in glacial sediments at Seglavatnet, Norway. Journal of Sedimentary Petrology, 51, 191-196.

Todd, J.E., 1903. Concretions and their geological effects. Geological Society of America Bulletin, 14, 353-368.

Manuscript received November 2003;
revision accepted February 2004.