Diagenetic evolution of Aptian evaporites in the Namibe Basin (south-west Angola)

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ABSTRACT

The widespread and dissected nature of the Angolan gysiferous salt residuals offers a uniquely detailed view of the lateral and vertical relations inherent to secondary evaporite textures, which typify exhumed salt masses worldwide. Such secondary textures are sometimes misinterpreted as primary evaporite textures. Thin, metre-scale and patchy, dome-like gypsum accumulations are well-exposed within strongly incised present-day river valleys along the eastern margin of the Namibe and Benguela basins (south-west Angola). These sections are time equivalent to the main basinward subsurface evaporites (Aptian Loeme Formation) which mostly consist of halite. The gypsum (here called the Bambata Formation) is interpreted to represent the final residual product of fractional dissolution and recrystallization of the halite mass that occurred during Late Cretaceous margin uplift and continues today. This halite underwent multiple episodes of diagenetic alteration between its deposition and its final exhumation, leading to the formation of various secondary gypsum fabrics and solution-related karst and breccia textures that typify the current evaporite outcrop. Four different diagenetic gypsum fabrics are defined: thinly bedded alabastrine, nodular alabastrine, displacive selenite rosettes and fibrous satin-spar gypsum. Current arid conditions are responsible for a thin weathered crust developed at the top of the outcropping gypsum, but the fabrics in the main core of the current at-surface evaporite unit mostly formed during the telogenetic stage of uplift prior to complete subaerial exposure. Alteration occurred as various dissolving and rehydrating saline minerals encountered shallow aquifers in the active phreatic and vadose zones. Geomorphological and petrographic analyses, mostly based on the cross-cutting relations and crystallographic patterns in the outcrop, are used to propose a sequence of formation of these different fabrics.

Keywords Angola, Aptian, Bambata Formation, diagenetic gypsum, dissolution, karstification, Namibe basin, South Atlantic.
INTRODUCTION

Worldwide, Mesozoic evaporite outcrops are mostly represented by thin gypsum and, to a lesser degree, anhydrite units, which display a broad spectrum of diagenetic textures, often associated with less soluble residuals made up of variably textured mudstones, claystones, silticiclastics and carbonates. This lithological hegemony is a consequence of the high solubility of most buried evaporites. It means that, prior to their exhumation, most buried salt masses are inherently unable to reach the ground surface without being partially or completely removed by dissolving ground waters (Braitsch, 1964; see also p. 455 in Warren, 2006). After being deposited, buried, possibly subject to halokinesis, and finally exhumed, most of the original impure halite mass has been removed, leaving behind cumulated bedded residuals composed of gypsum and fine-grained materials entrained in the former dissolving halite beds (Schreiber & Schreiber, 1977; West, 1979; Lambert, 1983; Warren et al., 1990; Babel, 1991; Uthan-aroon et al., 1995; Warren, 1997; El Tabakh et al., 1998; Hovorka & Nava, 2000; Warren, 2006). Dissolution can begin syndepositionally and at shallow depths where the halite is flushed by refluxing plumes of under-saturated phreatic waters (Warren, 1997; Holt & Powers, 2010). The alteration continues during burial, as basinal, compactional and thermobaric waters come into contact with the salt edges, forming, respectively at the top and bottom, a heterogeneous cap-rock and ‘upside-down’ caprock carapace (Hallager et al., 1990; Uthan-aroon et al., 1995; El Tabakh et al., 1998). Typically, complete halite removal occurs during margin uplift, where exhumed salt beds are entirely dissolved by re-entry into a zone of active phreatic aquifers and vadose hydrologies (Longman, 1980; Warren, 2006). Consequently, some exhumed gypsum beds are not the result of primary evaporation of a saturated brine; rather, they are the result of the partial dissolution of more soluble evaporites (i.e. mainly halite). These evaporites are diagenetic cumulates, residuals with textures indicative of recrystallized stacks and slumps, made up of the less soluble components after complete halite removal (Babel, 1991; Hovorka & Nava, 2000; Warren, 2006).

At the eastern margin of the Namibe Basin, the Bambata Formation crops out as patchy well-stratified gypsum beds. Its subsurface, more basinward (seaward) equivalents dominantly consist of as yet undissolved salts (mostly halokinetic halite, which is called the Loeme Formation). Outcrops of the gypsum beds yield several secondary hydrated fabrics that are interpreted here to represent solution-related diagenetic products, rather than evaporation-derived primary deposits. Such secondary textures are sometimes misinterpreted as primary evaporite textures.

The great diversity of the diagenetic gypsum fabrics seen at outcrop is characterized by particular crystallographic patterns (alabastrine, porphyroblastic, poikilotopic, fibrous satin spar) and show distinct cross-cutting relations at the land surface that provide the basis for the proposed sequence of formation. The breadth and continuity of outcrop exposure of evaporite residua along the Namibe Basin margin appear to be unique and allow the proposal of a comprehensive model that integrates many of the diagenetic textures documented in more patchy exposures of evaporite residua and features elsewhere. The aims of this study were: (i) to unravel the textural ambiguities by illustrating and examining in detail the various at-surface diagenetic gypsum fabrics and solution-related landform features; and then (ii) to discuss their mode of formation across time as framed by the uplift of the margin of the Namibe Basin. Additionally, this paper focuses on tentatively distinguishing the different dissolving mesogenetic and telogenetic water reservoirs that have overprinted now-exposed evaporites along the Namibe Basin. From the time the halite mass first began to dissolve, throughout its burial, until its final exhumation, these evolving hydrologies drove the incremental alteration and dissolution of the halite and the associated crystallization of the various diagenetic gypsum textures.

GEOLOGICAL SETTING

Aptian salt basins in south-west Africa

Rifting occurred in the South Atlantic Ocean during the Late Jurassic – Early Cretaceous, forming a series of rifted half-graben sub-basins distributed along the continental conjugate Brazilian and African margins (Rabinowitz & LaBrecque, 1979; Torsvik et al., 2009). The margins underwent a period of relative tectonic quiescence during the Barremian – early Aptian, characterized by larger subsident ‘sag’
depressions that were active prior to the accumulation of widespread massive evaporites deposited during the Aptian (Karner et al., 2003; Karner & Gambão, 2007). Trending along-strike near the coast, the conjugate margins are segmented by transverse fault zones that define normal, oblique and transformed rifted end-members (Guiraud et al., 2010). Sedimentation history, between rift initiation and deposition of the Aptian evaporites, was broadly dominated by lacustrine siliciclastics and carbonates; with increasing marine incursions up to the base of the main evaporite body (Grosdidier et al., 1996; Braccini et al., 1997; Bate, 1999).

Models predicting the timing of continental breakup for the South Atlantic Ocean vary greatly in the literature (Rabinowitz & LaBrecque, 1979; Szatmari, 2000; Karner et al., 2003; Fort et al., 2004; Hudec & Jackson, 2004; Moulin et al., 2005; Rouchy & Blanc-Valleron, 2006; Davison, 2007; Karner & Gambão, 2007; Dias, 2009; Torsvik et al., 2009; Lentini et al., 2010). The question of whether salt accumulation occurred prior to, during or after the break-up is highly relevant to the understanding of the lateral connectivity of the salt basins both across and along the margins. In spite of efforts by petroleum companies to acquire new data sets, the Aptian palaeogeography for the South Atlantic Ocean and the distribution of salt basins still remain obscure. Nevertheless, their lateral continuity along the West African margin is considered likely, therefore defining a unique and significant lateral connectivity of the salt basins both across and along the margins. In spite of efforts by petroleum companies to acquire new data sets, the Aptian palaeogeography for the South Atlantic Ocean and the distribution of salt basins still remain obscure. Nevertheless, their lateral continuity along the West African margin is considered likely, therefore defining a unique and single giant salt basin extending from northern Gabon to southern Angola (Rouchy & Blanc-Valleron, 2006; Davison, 2007; Dias, 2009). The Aptian evaporites mostly consist of massive halite, except for the southerly South Gabon Basin, where almost 750 to 800 m of intercalated bischofite, carnallite and halite beds are reported (Teisserec & Villemin, 1990). The evaporites in Angola are assumed to be mostly represented by halite in the outer offshore Kwanza Basin (Von Herzen et al., 1972; Fort et al., 2004; Hudec & Jackson, 2004; Rouchy & Blanc-Valleron, 2006) that once extended into the inner onshore Kwanza Basin (Brognon & Verrier, 1966), even if today much of the original halite is highly halokinetic and a significant portion of the original salt mass and continuity has been lost via a combination of salt tectonic deformation and allochthon dissolution (Hudec & Jackson, 2002). The southward extension of the Aptian salt mass is poorly known due to the lack of subsurface data. Prior to the present study, anhydrite, gypsum and dolomitic carbonate layers exposed landward in Namibe Basin were only briefly mentioned (De Carvalho, 1961; Pautot et al., 1973) and no salt has yet been reported seaward. It is assumed, however, that the area north of the Walvis Ridge, where Aptian mounded platform carbonates have been identified, constitutes the southern flank of the African Salt Basin (Coterill et al., 2002). The northern flank of the salt basin is located at the Ascension fracture zone, north of the Gabon Basin (Davison, 2007). Aptian evaporites are well-known in West Africa as the Ezanga Formation in Gabon (Teisserec & Villemin, 1990), the Loeme Formation in Congo (Bate et al., 2001), the Massive Salt Formation in the Kwanza basins (Brognon & Verrier, 1966), the Dombe Grande Formation in onshore Benguela (Guiraud et al., 2010) and the Bambata Formation in the Namibe Basin. These evaporites are interpreted as the capping unit of a regional transgressive sequence where the onset is identified at the base of the Pre-Salt Barremian – lower Aptian Chela, Red Cuvo, Como or Gambo sandstones (Teisserec & Villemin, 1990; Bate et al., 2001; Karner & Gambão, 2007). On the basis of ostracod assemblages discovered in the uppermost Pre-Salt strata, and the occurrence of planktonic foraminifera (Hedbergella sp.) found in the overburden of the Deep Sea Drilling Project (DSDP) 363 and 364 wells in the Benguela Basin, the evaporites are reasonably dated as not younger than mid-Aptian (Caron, 1978; Grosdidier et al., 1996; Braccini et al., 1997; Bate, 1999). Interpretations of the Pre-Salt to salt contact vary significantly in the literature. It is often argued that the offshore transition is progressive (Bate, 1999; Bate et al., 2001). The Pre-Salt deposits pass conformably upward into patchily distributed anhydrite (for example, Penesaline 2 formation in the outer Kwanza Basin; Bate et al., 2001) followed by the massive halite succession. The evaporites in all West African basins are overlain by post-break-up upper Aptian–Albian mixed carbonates and clastics, which are interpreted to have been deposited in shallow to deep marine environments (Pinda Group and counterparts; Eichenseer et al., 1999).

The Namibe Salt Basin and the onshore Aptian to Albian stratigraphy

The Namibe Basin, formerly called the Mocâmedes or Mossamedes Basin, is a narrow and elongated marginal depression located in
south-west Angola and northern Namibia, ranging from 50 to 100 km in width (east–west) and ca 570 km long. It lies along an interpreted oblique rifted segment of the African margin of the South Atlantic, bounded to the north by the transform faulted Benguela Basin (Guiraud et al., 2010) and to the south by the volcanic Walvis Ridge, which extends adjacent to the major north-east to south-west oriented Namibe transform fault. While exposed crystalline basement marks its eastern flank in onshore Angola, its basinward western border remains imprecise, because the continent–ocean boundary is still poorly defined. The Namibe Basin also constitutes the southernmost and narrowest Aptian salt basin in the South Atlantic.

The Bambata Formation is well-exposed in the Namibe Basin, cropping out in clean sections adjacent to rivers where it has been surprisingly preserved from complete dissolution (Fig. 1). It forms patchy decametric to kilometic long dome-like confined pockets or hills, cross-cut by a complex network of small gullies, gorges and secondary valleys, offering active solutional conduits that get larger at the confuence with major rivers (Figs 2 and 3). Gorges and gullies constitute upslope inter-connected narrow and linear upstream incisions, whilst downhill valleys exhibit a more meandering and wide configuration. Formation-confined fractures and faults are common in the Bambata Formation.

A typical at-surface Bambata Formation section is composed of three distinct lithological units (Figs 2 and 4) and consists of: (i) the basal Unit A made up of 50 m thick massive gypsum (inner gypsum layer); (ii) the intermediate Unit B made up of a 1 to 10 m thick clastic marlstone and shale unit; and (iii) the upper Unit C, consisting of up to 10 m of thinly bedded gypsum (outer gypsum layer). These units are widespread and can be regionally mapped out and correlated over 170 km from Namibe city to Lucira (Fig. 1). Whilst the gypsum of units A and C is interpreted as purely diagenetic, the marlstones of Unit B are considered in this study as mainly depositional. The uppermost part of Unit C consists of a 1 to 2 m thick tight gypsum carapace, termed the ‘weathering crust’ (Macaluso & Sauro, 1996; Ferrarese et al., 2002).

The Bambata Formation is overlain by the Albian Pinda Group that consists, at the base, of dominantly fluvial to marginal marine clastics, including tidal reworked distributary mouth bars (Fig. 2). The sandstones are succeeded upward by organic-rich lagoonal micrites (Binga member) that pass upward into progradational mixed deposits. Mixed sediments are capped by algal carbonates with thrombolites and rhodoliths, and locally include oolites, peloids, gastropods, echinoderms and bryozoans. In some areas (for example, Gaio), the algal oolitic limestones are overprinted by solution-related karstification due to exposure. This succession is unconformably cut by conglomeratic and coarse-grained sandy alluvial fans of the Middle to Upper Albian Giraul Formation (Dondo Formation equivalent in the Kwanza Basin).

The exposed Bambata Formation thickness ranges between 0 m and 70 m, and averages 50 m over the study area. Gypsum deposits are mainly stratiform and conformable, mostly characterized by horizontal planar to undulating bedding, with local highly folded and faulted strata (Fig. 3C and D). Locally, the gypsum is completely removed.

Current landforms of the Bambata Formation are mostly a mosaic of medium sized topographic mounds with edges bounded by incisions and fractures slightly downfolded by gravity to form convex-up outer lips. The outermost gypsum layer yields many dissolutional microforms including cavities, polygons, voids, karren and cracks, but few morphogenic features resulting from recrystallization processes, such as tumulis or pressure ridges, were observed.

At and immediately beneath the current land-surface, the Bambata Formation gypsum experiences arid and desertic conditions, with less than 10 mm of annual run-off (http://www.macedes-namibe.climatetemp.info). The current dynamic evolution of the outcropping Bambata gypsum beds is not, however, only influenced by rainfall intensity. Being a coastal desert, the region also has high humidity, an effect of the northward-flowing Benguela longshore current whereby humidity averages 60% onshore, with a maximum of 75% during the summer. Pervasive fogs and mists occur during mornings and nights, providing significant water supply to the coastal area. Moreover, the condensation associated with daily temperature contrasts is also quite common and constitutes a non-negligible fresh water input. Fog-water and condensation exceeds, in volume, the average annual rainfall rate. Besides that, aquifers are fed by severe flooding during the humid season, which occurs eastward to the Namibe desert between
Fig. 1. Map of the onshore eastern margin of the Namibe Basin, highlighting the locations where the gypsum Bambata Formation has been examined. The locations are, from south to north, Bero, Piambo, Ponta Negra, Gaio and Tumbalunda.
February and April and constitutes an additional water source to the area.

**METHODOLOGY AND STUDY AREA**

All observations were carried out where the Bambata Formation is exposed between Namibe city and Lucira (Fig. 1). From south to north, the gypsum cropping out in Bero, Piambo, Ponta Negra, Gaio, Tumbalunda and Lucira was examined. In the Tumbalunda area, the formation has been described entirely to reveal the transition with underlying strata, the vertical distribution of lithofacies and diagenetic gypsum fabrics, and also the nature of the stratigraphic contact with the overlying Albian Pinda Group deposits (Figs 2 and 4). Focus was also placed on the analysis of mesoscale solution-related morphological features and the examination of gypsum textures and inclusions. All descriptions of micro-fabrics relied on the classification of Holliday (1970) and Ortí Cabo (1977). Some gypsum samples were pulverized and then analyzed by X-ray diffraction to identify the minerals present.

**EVIDENCE OF ANCIENT AND RECENT SOLUTION-RELATED LANDFORMS AND KARSTIFICATION**

Broad karstified surfaces and solution-induced features have been identified throughout the exposed gypsum across the study area. These metric to kilometric-scale features are located at the top, the base or even within the stratified gypsum beds and can be classified into three types, according to their size and morphology. These features consist of: (i) open fractures, conduits, incisions and local truncations (for example, Bero; Fig. 5B and C); (ii) small-scale steep-sided V-structures associated with brecciated materials (for example, Piambo, Fig. 5D); and (iii) recent semi-regional spoon-shaped immature shallow karstified depressions (for example, Gaio, Fig. 6; ‘subsidence trough’, sensu Warren, 2006).

In the Bero area, local funnel-shaped fractures and gullies entirely or partially cross-cut the gypsum, forming with inter-bed surfaces an interconnected network of conduits (Fig. 5B). The top of the formation is also locally cut by decimetric to metric-scale sharp-edged incisions.
that are entirely filled up by Albian conglomerates of the Pinda Group (Fig. 5C). None of these morphological features evolved into mature karst, but remained efficient conduits for water flow, in contrast to the Castile Formation in Texas, where hypogene rather than epigene caverns dominate (Stafford et al., 2008).

Well-exposed V-structures occur within the Bambata Formation in the Piambo area (Fig. 5D). V-structures are defined as being karstification features in the subsurface caused by the collapsed roof of a solution-related cave. The structures are characterized upward by the downward flexure of the overlying strata, which create a local funnel-shaped (or V-shaped) morphological bowl at the karst entrance (Eliassen, 2002; Eliassen & Talbot, 2005); they are often associated with chaotically organized breccia blankets and are interpreted as mature solution-collapse structures. Similar features have been described at the base of the upper Carboniferous to lower Permian Wordiekammen Formation of central Spitsbergen (Eliassen, 2002).

In the Gaio valley, spectacular north–south oriented elongate and coalescent bowl-like karstified depressions occur at the top of the gypsum (Fig. 6A to C). The depressions are up to 600 m wide and 10 m deep, mostly filled by recent alluvial un lithified fine-grained sandstones and marls that were transported down into the karst via small converging and branching fluvial systems initiated in the vicinity of the gypsum-basement contact, which is exposed...
Fig. 4. Detailed log of the Bambata Formation exposed at Tumbalunda (14°0'37.72"S – 12°3’33.29"E). The Bambata Formation is composed of three widespread units that consist from the base to the top: the gypsum Unit A, the marlstone Unit B and the gypsum Unit C. The contact between the basal Unit A and the underlying silty and muddy deposits is progressive. The transition between the uppermost Unit C and the first deposits of the lower Albian Giraul Formation is also conformable.
towards the east (Fig. 6A and B). Heterogeneous solution-related collapse gypsum breccias commonly rim the edge of the depression. The gypsum is overlain by steeply rotated and highly faulted lower Albian marine deposits made up by tidally influenced cross-bedded clastics, conglomerates and highly bioturbated packstone to grainstone limestones rich in benthic foraminifera (*Miliolidae* sp.). Karstification affects the top of the carbonates and is characterized by pinkish patchily distributed dolomitized zones. The strata are organized into small east-dipping raft-like fault blocks breached by well-developed wide and sub-vertical fault zones filled by reddish conglomerates and sandstone derived from the overlying middle to upper Albian Pinda Group. The faults are intimately connected to the karstified surface lying at the top of the carbonates and act as vertical flow corridors cutting through the lower Albian beds down to the roof of the gypsum. Moreover, the unit tends to take the concave shape of the underlying depression and displays a slight thickening towards the centre.

**Fig. 5.** (A) Exposure of a Campanian–Maastrichian growth syncline south of the Caranjamba River. Short and large wave-length folds associated with significant progressive unconformities occur at the rim of these mega-scale structures. The section is ca 7 km long and 250 m thick. (B) Funnel-shaped open fracture in Bero (15°14.88′S – 12°14.34′E). The section is ca 12 m thick. (C) Top gypsum sharp-edged incision exposed at Bero (15°14.88′S – 12°14.34′E). Arrows illustrate the base of the incision. The incision is ca 6 m wide and 2 to 4 m deep. (D) V-shaped solution structure or V-structure at Piambo (14°4′54.27″S – 12°2′51.78″E). Persons for scale are ca 1.8 m tall.
Fig. 6. Example of a north–south-oriented elongated bowl-like karstified depression or ‘subsiding trough’ located at the top of the gypsum Bambata Formation at Gaio (14°24.14’S – 12°3′27.31″E). Karstified surfaces are up to 600 m wide and 10 m deep and are mostly filled by recent unlihified fine-grained alluvial sandstones and marls. They converge down into the depression via small cross-cutting fluvial branching drainage systems initiated in the vicinity of the gypsum-basement contact, located towards the east Gaio. (A) Satellite image of Gaio area (source: Google Earth). (B) Oblique view of one of the karstified depressions at Gaio. The section is ca 1 km in size with gypsum 30 m thick to the right (east) and Albian clastics and limestones 20 m thick to the left (west).
DESCRIPTION AND INTERPRETATION OF SECONDARY GYPSUM FABRICS

Thinly bedded alabastrine gypsum

Description

The most common texture consists of thinly bedded banded gypsum beds characterized by horizontal and concordant stacked lamina of very fine to fine-grained gypsum crystals (Fig. 7A). The fabric represents ca 80% of the outcropping gypsum textures observed at the land-surface. Millimetre to centimetre-thick laminae typically show internal plastic deformation in the form of undulated and folded structures, with local small boudinage preserved (Fig. 7B). Gypsum beds form a series of massively organized thickening-up and thinning-up patterns. Depending on the insoluble residue and mud content, bed colours range from whitish, to grey to brown. The bedded fine-grained gypsum is often cross-cut by a network of polygonal porous fractures (Fig. 7C).

In thin section, the dominant texture corresponds to a microcrystalline equigranular aggregate made up of a xenotopic mosaic of 10 to 100 µm size anhedral gypsum crystals (Fig. 8A). The gypsum forms an interlocking granoblastic meshwork, with local preferred directions of crystal growth elongation. Under crossed polarizers, the intercrystalline boundaries show irregular curved growth-sutured edges. Some subhedral crystals can also be viewed dispersed within the microcrystalline matrix, either as single crystals or as crystal aggregates. The gypsum crystals are even coarser in places, ranging from 100 to 500 µm, and display sharper edges, forming a well-sorted idiopic to hypidiotopic granoblastic texture (Fig. 8B). Very locally, some non-uniform extinction gypsum components (sensu Ortí Cabo, 1977), rich in aligned needle-like anhydrite inclusions, are mixed with the microcrystalline matrix or transitionally fringe the coarser porphyroblastic gypsum crystals (Fig. 8C).

Few scattered isolated lath-shaped anhydrite inclusions with local protrusions and irregular edges are observed in some gypsum crystals (Fig. 8D). The matrix also encases some isolated disseminated dolomite crystals; they are preserved as single subhedral crystals floating within the matrix or as intriguing aggregates (Fig. 8E). The borders of dolomite aggregates display a ‘stair-step’ pattern with re-entrants or irregular cleavage-related fringes, whilst their cores show a darkened peloidal micritic texture.

Interpretation

Similar laminated textures are commonly described as fine-grained alabastrine secondary gypsum textures (Ogniben, 1957; Mossop & Shearman, 1973; Ortí Cabo, 1977; West, 1979; Babel, 1991). In the Namibe Basin, the microcrystalline aggregates and the coarser granoblastic textures correspond to the type 2 hydrated alabastrine gypsum fabrics (sensu Holliday, 1970), whilst the non-uniform extinction components could be attributed to type 1. The few anhydrite and dolomite inclusions show evidence of etching and dissolution-related corrosion, which tend to demonstrate that these relics underwent leaching by under-saturated waters prior to gypsification (see also Schenk & Richardson, 1985, and Lugli, 2001, for comparison). In contrast to porphyroblastic gypsum texture, alabastrine gypsum fabrics may result from rapid re-crystallization of pre-existing fine-grained secondary sulphate crystals under unstable hydration conditions (Holliday, 1967, 1970; Mossop & Shearman, 1973; Ortí Cabo, 1977). It is likely that most of the alabastrine matrix was originally created by the hydration of a former fine-grained anhydrite fabric (‘net texture’; sensu West, 1979). However, the lack of anhydrite relics and the present-day tight but disordered texture of the alabastrine matrix probably represent several crystal growth and hydration phases, long after the initial anhydrite to gypsum conversion.

Millimetre-thick lenticular-shaped coarse-grained sandy pockets occur locally enclosed within the fine-grained gypsum layers (Fig. 7D). Locally, some layers display aligned undulations in map view, forming, respectively, crests and lows, giving the appearance of wavy or pseudo-cross-bedded intersections on bedding planes (Fig. 7E). The crests of such structures are mostly made up of fine-grained gypsum crystal patches, while coarser grained crystals form the lows. In cross-section, these structures match with local layered boudinage and microfolded textures and clearly are not bed-transport features.
Fig. 7. (A) Horizontal thinly bedded alabastrine gypsum beds with interlayered satin spar veins and dispersed stellate-selenite clusters. Notebook is 29 cm long. (B) Common soft-sediment deformation structures and slight boudinage in the alabastrine gypsum host. (C) Solution-related polygonal network of fractures cutting through alabastrine gypsum strata. Hammer is 33 cm long. (D) Remnant well-sorted coarse-grained sandy lens embedded into thinly bedded alabastrine gypsum beds. Clastic grains are dispersed in the host rock. (E) Interstratal ripple-like surface in plan view of a gypsum bed displaying aligned lows and crests, features formed, respectively, by fine-grained and medium-grained gypsum crystallographic growth patterns.
Fig. 8. Photomicrographs of some alabastrine gypsum textures (cross-polarizers). (A) Example of a fibrous microcrystalline aggregate composed of a xenotopic mosaic of poorly defined elongated and interlocking gypsum crystals (<100 µm). (B) Example of an equigranular granoblastic alabastrine texture with few dispersed anhydrite remains. Note that the grain boundaries are straight and easy to distinguish. (C) Example of a non-uniform extinction component texture made up of poorly sorted coarse gypsum grains (>100 µm) rich in curved needle-like anhydrite inclusions. (D) Example of an etched rectangular anhydrite relic within an alabastrine gypsum texture. (E) Details of ‘stairstep’-edged dolomite aggregates floating within an alabastrine matrix. Note that some show clear curved re-entrants at the periphery of the crystals (arrow) illustrating leaching and alteration.
and boudinage) or the influence of both, detailed examination of layers excludes the possibility that these structures record a primary depositional brine flow.

Coarse-grained sandy pockets preserved within the secondary alabastrine gypsum also developed during dissolution. These pockets were probably formed by either: (i) the stacking of insoluble clastics, originally trapped in evaporites prior to dissolution; or (ii) a pervasive allochthonous clastics influx; instead, the materials being gravitationally transported by weathering waters moving, via anastomose cavity networks, throughout the actively dissolved gypsum mass in the vadose zone.

**Nodular alabastrine gypsum**

**Description**

Nodules can be grouped into three distinct sets according to their shape, size, clay content and relation with the alabastrine gypsum host.

The first group is made up of horizontally elongated and oval-shaped gypsum nodules, which are characterized by pure white to opal-like microcrystalline core textures (Fig. 9A); they form decimetre to metre long botryoidal nodules that are composed of clusters of smaller nodules sometimes forming enterolithic structures. These structures vertically displace the laminated alabastrine gypsum host and typically occur between layered strata as interstratal nodules. The main core normally consists of fine-grained alabastrine texture passing outward transitionally into centimetre-thick centripetally aligned clusters of coarser euhedral crystals (Fig. 9B).

The second group consists of whitish to greyish massive centimetre to metre across irregular but stratiform meganodules, which occur as aligned bedded bands within alabastrine host strata (Fig. 9C). Nodule borders are well-defined and rounded, locally characterized by coarser grained gypsum rinds and greyish mud coatings. Meganodules mostly appear as floating cylindrical features, whilst some display more concentrically nucleated flower-like structures. The cores appear ‘impure’ with a flow-like appearance because quite significant volumes of enclosed argillaceous materials are preserved. Smaller nodules can join together to form larger nodular aggregates. Typically, adjacent coarsely crystalline satin spar gypsum veins conformably surround the meganodules as a halo or gradually go across them giving the appearance of merging (Fig. 9D).

The cores of the nodules consist of a hypidiotopic mosaic of anhedral to subhedral gypsum crystals, ranging in size from 50 to 100 μm across, which form a granoblastic alabastrine texture, devoid of porosity. The gypsum crystals contain a few scattered but highly altered anhydrite relics.

The third group consists of centimetre across elongated botryoidal nodules made up of horizontally oriented coarse fibrous gypsum blades (Fig. 9E). These coalescent nodules are strat- about and widespread following the current bedding of the Bambata Formation. A section through the most flattened nodular aggregates shows a core made up of horizontal seams of coarse satin spar gypsum veins.

**Interpretation**

Sulphate nodules (anhydrite and gypsum) can form in a large variety of diagenetic realms (see summary in Machel & Burton, 1991), including depositional sabkha-like settings (Dean et al., 1975; West et al., 1979; Warren & Kendall, 1985), emerged massive salt pans (Marchal, 1983; Lugli, 1999; Lugli et al., 1999), deep burial environments (Machel & Burton, 1991; Machel, 1993) and shallow telogenetic domains influenced by pervasive fluid flow during uplift (Ortí Cabo, 1977; West et al., 1979; Warren et al., 1990; Ortí et al., 2012). Widespread and coalescent anhydrite nodules can also occur as diagenetic products derived from sulphate-rich water precipitation resulting from the dissolution of basal halite mass in a deep burial environment (‘up-side-down caprock’; El Tabakh et al., 1998).

Secondary gypsum alabastrine core nodules with peripheral tangential porphyroblastic crystals have been described in ancient exhumed diagenetic gypsum deposits, and constitute part of the so-called ‘daisy wheel’ group of gypsum textures (West, 1975; West et al., 1979; Warren et al., 1990). Such gradational crystallographic patterns, composed of fine-grained alabastrine cores and coarser grained peripheries, encompass genetically different gypsum crystallization rates and phases (Holliday, 1970), which are characterized by specific equilibrium-related hydration conditions during uplift (Mossop & Shearman, 1973). Indeed, daisy wheel gypsum is typically interpreted to form in response to re-hydration under the specific conditions of uplift hydrology when a nodular anhydrite unit enters the lowermost parts of the telogenetic zone (Warren, 2006). In
contrast, porphyroblasts result from slow crystal growth at near-equilibrium hydration conditions, occurring first at depths where stable aquifers are located (stagnant phreatic zone, \textit{sensu} Longman, 1980). Formation of the finer grained alabastrine fabrics occurs later within rapid crystal growth environments, typically nearer the surface in the active phreatic zone (Mossop & Shearman, 1973; Warren \textit{et al.}, 1990).

\begin{figure}
\centering
\includegraphics[width=\textwidth]{images}
\caption{(A) Example of a displacive pale oval-shaped botryoidal nodule, formed by the coalescence of smaller pure microcrystalline gypsum nodules. (B) Internal crystallographic texture of an interstratal nodule displaying alabastrine gypsum texture in the main core and a peripheral radial and tangentially aligned coarse-grained gypsum halo. (C) Example of aligned cylindrical meganodules (Bero). Note that the nodules are 50 cm high. (D) Detail of a displacive gypsum meganodule (ca 70 cm high and an average of 40 cm wide; Bero). (E) Horizontal botryoidal nodules formed by the suture of bladed coarse gypsum veins (Piambo). Hammer is 33 cm long.}
\end{figure}
The characteristics of nodular facies are different from those derived from a sabkha setting. Deformation of layering in gypsum beds above and below the growing nodule layers and the fact that most of the larger nodules result from the coalescence of smaller ones with the conjugate merging of coarse satin spar veins imply a displacive rather than replacive origin. Furthermore, because the nodules do not display any compactional features, they should have formed in or after the unit experienced the deep burial environment. The displacive character, their abnormal size (meganodules), the lack of associated microbial carbonates and of capping erosion/dissolution surfaces or inter-nodular filling matrix further diminish the possibility of preserved depositional Aptian nodular textures prior to burial. It is difficult to determine with accuracy the exact origin of the precursor anhydrite nodules. Any fine-scale original texture was probably homogeneously altered multiple times during gypsum conversion and recrystallization by the different hydration episodes that occur during exhumation.

**Displacive selenite rosette gypsum**

**Description**

Elongated radial porphyroblastic gypsum crystals can form individual round clusters that are centimetres across. These internally centripetal clusters occur uniformly distributed throughout some layers or groups of layers as stratiform aggregates of connected patterns (Fig. 10A) or as floating individual crystals (Fig. 11A). Individual centimetre-sized gypsum crystals do not show preferred growth orientations, yielding multidirectional growth patterns. Some are vertically squeezed, displaying elongated motifs (Fig. 10D).

Numerous clusters cross-cut the crystallized thinly laminated alabastrine gypsum matrix and, in some cases, can also be cross-cut by another generation of clusters. The patterns are locally highlighted and sharply cut by a dividing line, which is outlined by coloured stripes (Fig. 10B). Some form half-flowers and blades, nucleated from overlying or underlying horizontal beds. Most of them appear to have grown displacively upward or downward into the alabastrine gypsum host from the interstratal joints (Fig. 10C and D).

In thin section, the clusters are seen to be coarse-grained gypsum crystals characterized by straight intercrystalline boundaries with local curved sutures. The textures vary as radial arrangements of elongated tied crystals forming different sizes of stellates (ranging from 0.5 to 3 cm in length; Fig. 11A and B) or mosaics of large crystal aggregates (Fig. 11C). The latter tend to show open porosity between crystals (intercrystalline polyhedral porosity; Fig. 11C and D) but also contain the highest proportion of relic anhydrites. As previously described by Og niben (1957) and Ortí Cabo (1977), some of the selenitic gypsum stellates display a progressive outboard transition with the finer microcrystalline alabastrine matrix, either directly or via a thin peripheral rim of non-uniform extinction components (Fig. 11B).

In the literature, these larger gypsum crystals are termed porphyroblasts and the texture is typically described as poikilotopic (Holliday, 1970; Artieda, 2013). In other papers, including here, this coarsely crystalline texture is also described as selenitic secondary gypsum (Ogniben, 1957). The anhydrite inclusions present as aligned to less-aligned masses of laths encased in coarsely crystalline gypsum and typically adjacent to other larger gypsum crystals that contain few to minor anhydrite relics (Fig. 11D). These inclusion-free gypsum crystals are clearly aligned adjacent to the open pores. The anhydrite laths are commonly broken into smaller pieces with re-entrants and wafer-like cleavage-related fringes (Fig. 12A). Some smoothed isolated laths show local thickness variations that are evidenced by birefringent zonations (Fig. 12B).

As with the alabastrine matrix, some porphyroblasts enclose a significant amount of scattered euhedral to subhedral corroded dolomitic rhombs or aggregates. Thirty per cent of these grains consist of dolospars to microspar coating a losangic to cubic porous core (Fig. 12C).

**Interpretation**

These isolated or grouped flower-like selenite crystal clusters are mostly observed in gypsum outcrops and commonly described as ‘fleurs de gypse’, ‘rosettes’, ‘stellates’, ‘sand roses’ or ‘daisies’ (Cooke, 1941; Mossop & Shearman, 1973; Schreiber et al., 1976; Warren et al., 1990). In the Namibe Basin, most of these clusters constitute displacive features because they inherently grow in all directions within the alabastrine matrix. The inclusion-free coarse crystalline aggregates that are aligned with the open polyhedral pores imply a possible micro-scale replacement front involved in their formation. Porosity was created by dissolution of its precursor (gypsum + anhydrite) and was followed...
Fig. 10. (A) Banded selenite gypsum ‘daisy’ beds. Pen is 15 cm long in (A), (B), (C) and (E). (B) Preservation of a fossil water table surface (arrow) underlined by a reddish band of insoluble residues. Note that the water table surface coincides with a truncation surface highlighted by the sharp contact of one of the precipitated rosette (‘daisy’) beds. (C) Example of selenite half-flower clusters (ii) nucleated from interstratal horizontal satin spar vein walls (i) and growing upward and downward throughout the alabastrine gypsum matrix (iii). (D) Example of sub-vertical fractures cross-cutting alabastrine gypsum beds and connected to horizontal interstratal joins filled by satin spar gypsum veins. Notice that selenitic flowers grew and expanded outboard from the fractures that acted as conduits for saturated fluid percolation. Pen is 14 cm long. (E) Example of a satin spar fibrous gypsum pattern filling an interstratal horizontal vein. The vein filling is composed of two seams of elongated and dense gypsum fibres separated by a central parting line. (F) Sequence of three horizontal accreting satin spar patterns enclosed into one single interstratal vein. Hammer is 33 cm long.
Fig. 11. Photomicrographs of porphyroblastic gypsum textures and fibrous gypsum satin spar (cross-polarizers). (A) Radial selenitic rosette enclosed into a finer grained alabastrine matrix. (B) Details of radial elongated porphyroblastic gypsum crystals of a stellate, rich in anhydrite and dolomite grains. Note that, here, the transition from the porphyroblasts and the alabastrine fibrous matrix is progressive. (C) Intercrystalline polyhedral porosity indicating a meso-scale dissolution front within a poikilotopic coarse-grained gypsum texture. (D) Example of inclusion-free gypsum rim lined adjacent to polyhedral porosity in a porphyroblastic texture. Anhydrite inclusion-rich porphyroblasts are separated from the inclusion-free gypsum rim by a dividing line parallel to the intercrystalline pores. (E) Example of a fibrous gypsum satin spar vein. (F) Details of a fibrous gypsum satin spar filling with anhydrite residue along vein walls.

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by precipitation of gypsum in the resulting pore space. This gives the appearance of a gypsum rim to some crystals, but it is actually a dissolution front that moved through the crystal and precipitated pure gypsum. Similar but larger and vertical metre-sized polygonal patterns are also observed at outcrops, indicating that the dissolution fronts also operated from micro-scale to meso-scale (Fig. 7C).

The anhydrite inclusions display a large variety of highly corroded crystals testifying to abundant but slow leaching prior to gypsification (Schenk & Richardson, 1985). The euhedral shapes of the dolomitic rhombs prove that they grew in situ from a currently porous sharp-edged core, which might be interpreted to be small, formerly precipitated halite pseudomorphs. Similar early to late burial polyhedral authigenic dolomite spars characterized by cloudy nuclei have been observed in other evaporites, floating as individual crystals or aggregates either in halite (Naiman et al., 1983) or with re-crystallized anhydrite in cap rocks at the top or the bottom of salt masses (Taylor, 1937; Goldman, 1952; Machel, 1993; El Tabakh et al., 2003).

The formation of the selenitic gypsum fabrics resulted in a series of near-equilibrium hydration phases that enabled slow coarse-grained gypsum crystal growth, via free and isolated nucleation sites within a porous and fractured host rock (Mossop & Shearman, 1973). A first generation of clusters probably occurred when the evaporites

Fig. 12. Photomicrographs of altered anhydrite and dolomite inclusions within selenitic gypsum (cross-polarizers). (A) Example of highly segmented anhydrite lath-shaped remains within a porphyroblast gypsum crystal. The crystal edge displays dissolutional features like cleavage-related fringes and re-entrants. The anhydrite crystal grains are dispersed as they were slightly removed. (B) Example of a smoothed and elongated rectangular anhydrite lath within a gypsum porphyroblast. Note that the leaching is emphasized by the curved edge and the local birefringent zones indicating different localized thicknesses along the lath. (C) Details of a right-angle prismatic porous core of a dolomite aggregate.
Satin spar fibrous gypsum veins

Description

Whitish to yellowish satin spar gypsum occurs in horizontal interstratal and cross-cutting vertical to inclined veins, forming a three-dimensional mesh of coalescent and connected fibrous patterns (Fig. 11E and F). Vein thickness (space between the vein wall surfaces) ranges from a few millimetres to 10 cm. Vein walls are mostly flat, parallel and conformable with small irregularities. In Bero, veins remain partially open, yielding 7 to 10 cm wide convex open cavities, whilst they are entirely filled in other sections. Satin spar filling patterns consist of a greyish to creamy central thin dividing line (‘parting line’ according to Richardson, 1920), which is oriented roughly parallel to the vein walls, and two isopachous seams filled by dense and parallel gypsum fibres, roughly perpendicular to the walls (Fig. 11E). Some veins enclose fragments of host rock that float in the fibrous gypsum. In thin section, growth aligned, fibrous elongate and straight gypsum crystals infill individual veins. Most satin spar samples lack significant amounts of intercrystalline porosity, although some veins do show geopetal accumulations of anhydrite residues on the lower sides of the fractures (Fig. 11F).

Within some of the horizontal veins, fibres locally show slight convex curvature or bend outward from the central parting line. Under the microscope, these are characterized by a homogenous optical extinction. The upper seam is commonly thicker than the lower seam. Like the surrounding strata, the veins can be folded or offset by fractures; the vein filling tends to follow the folds without thickness variations. The veins are mainly singular, composed of one unique filling of two seams, but some are composite, consisting of two or three horizontally accreted satin spar patterns (for example, Tum-balunda section). Some veins show oblique filling patterns within horizontal interstratal veins, with some forming duplexes of stacked thrust-like thin satin spar layers.

Interpretation

As Warren (2006) emphasized, satin spar formation may have resulted both from active and passive hydrological processes, for which there could be several episodes of available under-saturated waters input at different stages in the uplift. Meantime, substantial volumes of hyper-concentrated waters are necessary to precipitate dense pure gypsum fibres (Machel, 1985). It is also argued that satin spar formation might have commenced at significant depths within the mesogenetic realm, where buried overpressured waters might have acted as first concentrated waters sourcing fibrous gypsum crystallization (Shearman et al., 1972). Although other models predict saturated waters derived from the host rock contraction and dehydration during burial (for example, marls or others; Richardson, 1920), most models involve downward migrating dissolving waters that come from the telogenetic domain and that volumetrically constitute suitable external water reservoirs to allow satin spar gypsum precipitation. However, as Schreiber & Walker (1992) pointed out, the temperature greatly influences the solubility of saline brines and so the saturation of migrating telogenetic waters may change during burial.

The geometry and mode of vein filling imply particular mechanisms inherent to the sedimentary basin history between deposition and exhumation. Overpressure-related hydraulic fracturing (Shearman et al., 1972), gel contractions (Von Gaertner, 1932), mechanical forces induced by in situ gypsum crystallization (Bundy, 1956), collapse induced by dissolution of underlying salt (Gustavson et al., 1994), and vertically oriented effective tensile forces (pore fluid pressure exceeds overburden) related to external tectonic regime (Machel, 1985; Cosgrove, 2001) have all
been cited as being major driving mechanisms accounting for vein formation.

Because the horizontal vein filling consists of single to composite patterns, it is assumed that the dilation filling of the studied veins must have occurred as incremental vertically oriented stress-induced sequences (Ramsay, 1980). Furthermore, the vertical effective tensile stress is locally accompanied by a lateral shear component along the veins, as indicated by fibre curvatures and satin spar duplexes in the Tumbalunda area. The homogenous optical extinction characteristic of some curved fibres also implies a strain during crystal growth. The question of whether a shear component occurred simultaneously with, or after, fibre growth is crucial because it will help to better constrain the timing of satin spar vein formation with regard to the deformation of the gypsum in the basin margin in its passage to exhumation. Machel (1985) argued that, even if the vertical effective tensile stress responsible for the interstratal vein dilation remains speculative, the crystal bending post-dates the crystal growth, and then the shear component is interpreted to result from a subsequent upward buckling. The models of Tanner (1989, 1992) are favoured here, which depict the formation of intra-veining duplexes during flexural-slip folding, implying a shear component along veins synchronously acting as the interstratal veins open and the gypsum fibres grow. The exact causes and the relative timing of vein formation and buckling could nevertheless be determined individually for any area by mapping the regional distribution of the veins. Extension oriented orthogonal to bedding and local slumping/shear are considered to be the dominant controls on spar vein orientation and development, and both are related to pervasive halite volume loss and are most intense once the salt mass passed into the telogenetic zone.

The veins with geopetalled cumulates were probably created via fractional dissolution of precursor sulphates, leaving behind a residuum of less soluble materials (anhydrite). To form this texture requires dissolution and fracture opening prior to cementation. It supports the notion of some near-surface spar in the Namibe Basin being the result of a mostly passive crystallization process, created during extensional collapse as adjacent halite and perhaps anhydrite dissolved. This may define a texture that allows passive satin spar formation to be distinguished from subsurface gypsum spar precipitated during hydrofracturing (Gustavson et al., 1994 versus Shearman et al., 1972).

**Solution breccia**

**Description**

Breccia blankets are abundant throughout all at-surface sections in the Namibe Basin and all display a broad range of clast sizes ranging from fine-grained, pebbles, cobbles to metre-sized fragments at different stratigraphic levels into the Bambata Formation (Fig. 13A and B). Although their textures vary from homogenously crystallized to thinly laminated and lithified fabrics, the breccias are monomictic and made of gypsum. Clasts typically form a mosaic of whitish to pinkish matrix-supported closely fitting to loosely fitting fragments that appear as chaotically distributed bodies, without predictable lateral or vertical grading. The matrix is composed of finely crushed and crumbled mudstone, silt, shale and residual gypsum, and also contains a few authigenic quartz grains and undetermined insoluble material. Although most of the breccia clasts show irregular smooth rounded edges, sub-angular to angular rectangular clasts are not uncommon. None shows evidence of specific coatings or calcitized rims. Internal fabrics in the breccia clasts do not differ from fabrics in the unfragmented portions of the host lithologies. Clasts constructed of gypsum breccias are themselves common within the breccia proper, forming poorly sorted composite bodies. Breccia accumulations typically occur above solution-related karstified features, forming discordant horizontally bedded clast blankets above intrastratal karstified surfaces (for example, Gaio), but also form chaotically imbricated trans-stratal clast bodies along fractures or on the steep limbs of the V-structures (for example, Bero, Piambo and Tumbalunda). Although stratabound breccias are not as equally preserved as cross-cutting breccias, they seem to be connected genetically. Stratabound fragment blankets grade transitionally downward into massive breccia accumulations preserved in karstified voids and cavities.

**Interpretation**

At-surface gypsum breccias constitute the ultimate solution-related products of the former record of depositional evaporites prior to complete dissolution (Middleton, 1961; Stanton, 1966; Beales & Oldershaw, 1969). As the breccia blankets pass from interstratal karstified surfaces...
into V-shaped structures in which they fill the voids, evidence indicates that they were concomitantly formed during the time that dissolution was active. Breccias and the matrix were produced by hydrologically focused dissolution of the well-stratified secondary gypsum host. The V-structures and associated trans-stratal breccias formed when the horizontal bedding was no longer supported, creating voids and cavities with subsequent collapse. The ‘rock-flour’ matrix is the accumulation of the finer grained residuals from the solution-related brecciation, filling the interstitial voids and cavities between the fragments. A re-brecciation mechanism is common when the degree of downward and sideward dissolution was relatively low. In this case, it also implies that the transportation of fragments was local and took place over distances measured in metres to tens of metres.

Detailed examination of breccias reveals whether former evaporite units were closely mixed with less soluble lithological units prior to dissolution (Friedman, 1997), and can also help account for whether the breccias are formed as a result of a unique or several dissolution episodes (Warren, 2006). The fact that some of the breccias, often those located at the bottom of the V-structures, are composed of gypsum fragments indicates that more than one phase of brecciation occurred during exhumation.

However, in Gaio, the solution-related landform preserved at the top of the Bambata Formation typifies a karstified surface formed by the overprint of two separate gravitational-fluid dissolution mechanisms that operated at two different times:

1 The first mechanism occurred during early burial, where weathering waters responsible for the karst development in the top carbonates during the lower Albian sank pervasively downward through the strata, via the fracture network, until they reached the halite and initiated dissolution. Similar regional solution-induced karstified surfaces (including pipes, dolines, gentle folds or collapse breccia pockets) occur at the top of Cenozoic and Mesozoic evaporites in Spain (Gutiérrez et al., 2001) and in the Carboniferous sulphates of central Spitsbergen (Elissen & Talbot, 2005).

2 The second mechanism was initiated later, during subaerial margin exhumation, when the sedimentary succession had been significantly eroded, exposing the gypsum to surface weathering. The concave karstified surfaces that had formed during the lower Albian were consequently exposed and acted as localized depositional depressions, capturing sediments from the recent drainage systems. Similar modern river capture along the feather-edge of exhumed evaporite masses is seen in the Ebro Basin of Spain, the Nam Theun valley in Laos and the Little Red River valley along the outcropping margin of the Hutchison Salt in Kansas (Warren, 2006).
DISCUSSION

Buried salt removal or dissolution-related deformational mega-structures

Remote sensing, fieldwork analysis and detailed field mapping of overburden strata indicate broad kilometre-long structures that affect distinct stratigraphic levels. For instance, along the north and south sides of the Inamagando River mouth (Fig. 1), Albian deposits are exposed in an east-west trending anticline where moderate-angle to low-angle listric normal faults, roll-overs and intra-formational unconformities are observed on the flanks of the structure. Moreover, north and south of the Caranjamba River, Campanian–Maastrichtian shallow marine sandstones are exposed in spectacular growth synclines, in which short and large wave-length folds, associated with significant progressive unconformities, occur at the rim of these structures (Fig. 5A). Similar geometries can be respectively compared to salt-core domes or pillar and peripheral depressions that develop at the flanks of growing salt diapirs (Hudiec & Jackson, 2011). Counterparts have been reported in Spain, where dissolution-induced subsidence structures recorded in the Mesozoic and Cenozoic sediments produce semi-regional synforms, antiforms and collapse features (Gutierrez et al., 2001).

The origin of the at-surface Bambata gypsum Formation in the Namibe Basin

All ancient marine giant salt basins required hydrographic isolation and water saturation to initiate evaporite precipitation. Such depositional conditions are usually attributed to rapid regressive pulse, palaeogeographical confinement and high evaporation rates, respectively, due to global sea-level drop, plate-order tectonic evolution and an arid climate (Hardie, 1991; Handford & Loucks, 1993; Warren, 2010). Primary sulphate beds are typically expected to occur as a marginal wedge, preceding mega-halite deposits that subsequently migrate in the centre of the basin (Hsu et al., 1973; Tucker, 1991; Warren, 2006). Among all Mesozoic salt basins, the Mediterranean Sea best illustrates this depositional style during the ‘Messinian crisis’ (Decima & Wezel, 1973; Rouchy, 1982; Decima et al., 1988; García-Veigas et al., 1995; Clauzon et al., 1996; Butler et al., 1999; Rouchy & Caruso, 2006; Lugli et al., 2010). However, sometimes, the evaporite filling initiates with bedded halite without requiring thick edged sulphate precipitation; this is the case for most of the Upper Cretaceous marine-fed salt basins dominated by sulphate-depleted sea water (Lowenstein et al., 2001, 2003). This means that, in such depositional conditions, the significance of gypsum (or anhydrite) at the onset of the evaporite succession may be misinterpreted, especially along the edges, where flushing by meteoric and basinal waters is most likely to occur (Kendall, 1988). The analysis of the gypsum fabrics of the Bambata Formation tends to provide criteria for recognizing the marginal telogenetic gypsification of a prevalent primary halite stockmass rich in sulphate impurities. This mechanism occurred throughout multiple stages of dissolution and recrystallization processes during uplift, rather than a pure replacement of a primary depositional gypsum wedge.

No collected outcrop sample is composed of pure anhydrite and all calcium sulphate samples with anhydrite present are dominated by gypsum. The apparent at-surface laminations are here believed to occur from dissolution fronts by incremental groundwater flushing rather than by depositional stratification. Similar patterns are reported from salt domes and from the upper part of some shallow basinal evaporite filling where diagenetic anhydrite cap rocks form widespread and thick solution-related horizontal parallel bands (Goldman, 1933; Lambert, 1983; Hallager et al., 1990; Uthan-aroon et al., 1995; Hovorka & Nava, 2000). Under the microscope, across the various meso-scale features described in the preceding sections, a range of related-sulphate textures indicate a set of near-surface diagenetic mechanisms and processes that created ever increasing proportions of purer gypsum and decreasing amounts of residual anhydrite. Anhydrite inclusions are best preserved in the porphyroblastic gypsum and, to a lesser extent, into the alabastrine textures, but all reveal alteration by abundant under-saturated fluids prior to gypsification (Schenk & Richardson, 1985). The euhedral dolomite grains disseminated into secondary gypsum textures suggest an in situ precipitation from magnesium-rich derived dissolving evaporites (Naiman et al., 1983; El Tabakh et al., 2003).

The relative timing of porphyroblastic versus alabastrine gypsum is difficult to determine. A review of the literature suggests that porphyroblastic gypsum tends to precede alabastrine gypsum in the uplift realm (when associated with anhydrite telogenesis) and that satin spar forms...
in fractures created by the dissolution and volume loss associated with meteoric flushing and uplift of a former anhydrite bed (Holliday, 1970; Gustavson et al., 1994; Warren et al., 1990). The Angolan examples also tend to suggest that alabaster and selenitic textures are typically intermixed at outcrop and that differences in gypsum style may be more related to the degree of gypsum supersaturation during anhydrite dissolution. In this scenario, porphyroblastic gypsum is favoured by sluggish water crossflows, slower crystal growth rates and less saturated pore fluids (with respect to gypsum), while granoblastic gypsum is favoured by supersaturation, multiple crystallisation nuclei, faster crystal growth rates and Ostwald crystal ripening.

The diversity of the at-surface secondary gypsum fabrics in the Namibe Basin is the result of dissolution and re-crystallisation as various invading under-saturated waters came into contact with soluble halite units. Dissolution episodes were probably first active syndepositionally, but continued during burial, subsequent uplift and during the exhumation of the margin (Warren, 1997, 2006). Ongoing halite dissolution implies that accumulation of residual anhydrite and insoluble material occurred in the deep burial environment wherever and whenever waters under-saturated with respect to halite came into contact with the salt mass. These anhydrite accumulations were subsequently hydrated and converted into gypsum during uplift, at the same time as any remaining halite was flushed out.

The growth of granoblastic and porphyroblastic textures from an anhydrite precursor, which in turn was formed by fractionated removal of halite, means that all of the textures seen at the micro-scale and meso-scale in gypsum outcrops are indicative of telogenetic processes. There is no possibility of these uplifted-related re-precipitation and re-crystallisation sulphate textures preserving primary (Cretaceous) depositional relics. Every mineral present (the gypsum, the anhydrite, the dolomite and the clay) are thoroughly mesogenetic or telogenetic and mostly related to the dissolution front or the cavity infill.

Dynamic diagenetic model and chronology of the various solution-related secondary gypsum of the Bambata Formation

Based on the petrographic and stratigraphic observations that account for the narrow relation between the secondary gypsum crystal size and the equilibrium conditions and flow regime in which hydration takes place (Holliday, 1970; Mossop & Shearman, 1973; Longman, 1980), a sequence of formation of these different secondary gypsum fabrics can be evaluated with respect to margin evolution from the moment the halite was deposited until today. A dynamic diagenetic model is proposed to explain the formation of the gypsum of the Bambata Formation cropping out at the eastern margin of the Namibe Basin (Fig. 14). Additionally, it highlights the influence of distinct dissolving water reservoirs on the original halite, resulting in its complete cannibalization and the formation in time of distinct solution-related diagenetic sulphate fabrics and features:

1. It is reasonable to infer that the onset of effective dissolution occurred in the near surface, in the very shallow burial environment, soon after the deposition of the Albian carbonates (Pinda Group), when invading under-saturated waters came into contact with the halite beds. The gravimetric flow was driven by the exposure of the Pinda carbonate platform. Weathering and salt wash-out was efficient enough to affect the top of the halite and develop solution-related subsidence troughs during the lower Albian. Salt deformation and/or dissolution continued to be active later in the burial as deformational growth structures in the overburden developed (for example, Campanian–Maastrichian growth synclines of the Caranjamba River, Fig. 5A).

2. The dissolution favoured the alteration of the halite edges as they came into contact with compactional and thermobaric pore-waters (Warren, 1997). It resulted in a subsequent accretion of diagenetic massive fine-grained anhydrite matrix and un-compacted nodular anhydrite beds, preserved at the top and base of the halite (Uthan-aroon et al., 1995; El Tabakh et al., 1998; Hovorka & Nava, 2000). Fission track analysis carried out on the Pre-Salt and overburden sedimentary samples gives an estimate of ca 1.5 to 2 km for the maximum burial depth, corresponding to less than 100°C in burial temperature.

3. During uplift, partially dissolved halite and the anhydrite beds at the basin edges came into contact with stagnant phreatic aquifers of the lower telogenetic zone (sensu Longman, 1980). This contact drove the complete removal of the halite and the final accumulation of fine-grained and nodular stratiform anhydrite beds. The conversion of the anhydrite into gypsum may have
Fig. 14. Dynamic diagenetic model and sequence of formation of the various solution-related secondary gypsum fabrics and landforms in the Aptian Bam-bata Formation exposed along the eastern margin of the Namibe Basin.
occurred during or after complete halite dissolution. The current horizontal stratified pattern of the exposed gypsum beds typifies incremental dissolution, where the uppermost part of the uplifted evaporites may have come into contact with horizontal flow lines of the aquifer front. That is, much of the anhydrite rehydration came from water flows in suprasalt rather than subsalt aquifers. As the uplifted dissolving halite and gypsum mass started to buckle up and deform, interstratal vein dilation and fracturing occurred, forming internal drainage conduits for sulphate-rich fluids (Tanner, 1989, 1992). Sluggish hydration, facilitated by the opened sub-horizontal veins, trans-stratal fractures and the inherent pore network of the host, enabled the formation of ‘daisy wheels’ nodular fabric, a first generation of rosettes, and fibrous gypsum crystal growth into the interstratal veins (satin spar fabric; Shearman et al., 1972; West, 1979; Warren et al., 1990). Because the layering of the Bambata Formation may develop weakly porous interstratal joints, the overpressured saturated water moves along the bedding boundary and initiates the upward growth of nodules and their subsequent sutures, reminiscent of bottom-nucleated primary features (meganodules).

4 Deformation and flushing persisted as the newly precipitated secondary gypsum beds reached fast-flowing under-saturated waters of the active phreatic zone. The dispersive and infiltrating water flow regime favoured rapidly precipitated finer grained crystal growth (alabasterine) in a still permeable former gypsum matrix characterized by closely spaced nucleation sites.

5 Solution-related karstification and collapse breccia were probably most intense once the gypsum entered the vadose zone, where downward-moving interstitial freshened (meteoric) waters percolated and migrated through the remaining pore network and along solution-enlarged fractures in the gypsum host. The formation of solution-related collapse features, like V-structures and karst, is indicative of a gravitationally focused dissolutional flow regime containing waters that are periodically freshened and that are under-saturated with the respect to gypsum (Warren, 2006).

6 The preservation of the last sets of selenite rosettes that cross-cut the laminated alabasterine gypsum beds implies a return to near-equilibrium hydration conditions enabling the precipitation of coarse-grained gypsum crystals. This still implies a sufficient permeable pore network within the gypsum beds that is sufficient to enable pervasive water infiltration and perching over relatively long periods of time (years or tens of years). Relic water table surfaces, sparsely distributed throughout the gypsum, show evidence that phreatic aquifers moved up and down within the gypsum mass, after the alabasterine gypsum precipitation. Stellate selenite defines at least two generations of clusters and their distribution within the Bambata Formation reflects these vertical fluctuations in the aquifer.

CONCLUSIONS

The Aptian gypsum-rich Bambata Formation exposed along the current coast of the Namibe Basin in south-west Angola provides an outstanding example of vanished evaporites. No collected outcrop sample is composed of pure anhydrite and all calcium sulphate samples with anhydrite present are dominated by gypsum. The gypsum beds are mainly stratiform and conformable, mostly characterized by horizontal planar to undulating bedding with local folds and faults. These beds include a great diversity of secondary fabrics, such as thinly laminated alabasterine gypsum, selenitic rosettes, different displacive gypsum nodules, solution-related monomictic breccia and interstratal fibrous satin spar gypsum veins.

All gypsum textures actually correspond to secondary hydrated fabrics, shown here to be solution-related diagenetic products rather than evaporation-derived primary deposits; they formed during uplift when various invading under-saturated phreatic to vadose waters came into contact with soluble salt units. Ongoing halite dissolution resulted in the accumulation of residual anhydrite and insoluble material that occurred in the deep burial environment. These anhydrite accumulations were subsequently hydrated and converted into gypsum during uplift, at the same time as any remaining halite was flushed out.

Anhydrite and dolomite inclusions are abundant in gypsum textures. Anhydrite relics are best preserved in the porphyroblastic gypsum and, to a lesser extent, in the alabasterine textures, but all reveal alteration by undersaturated fluids prior to gypsification. The disseminated euhedral dolomite grains suggest in situ precipitation from magnesium-rich derived dissolving evaporites.

In the telogenetic realm, the formation of porphyroblastic gypsum tends to precede alabasterine...
gypsum because it is favoured by sluggish water crossflows, slower crystal growth rates and less saturated pore fluids, while granoblastic gypsum necessitated less stable hydration conditions, faster crystal growth rates and supersaturation. Satin spar gypsum veins form in fractures created by the progressive dissolution and volume loss associated with meteoric flushing and uplift of a former anhydrite bed.

A dynamic model is proposed to depict the diagenetic evolution of the primary Aptian depositional impure halite mass through time, which involves episodic dissolution during burial and uplift. It appears that the exposed Bam-bata gypsum beds in the Namibe Basin represent the final residual product of fractional dissolution and recrystallization of the marginal Aptian Loeme Formation halite mass that occurred during the Late Cretaceous uplift of the margin. Similar features occur in the exhumed positions of many evaporite beds worldwide.

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