Secondary gypsum: The other end of the burial cycle

Introduction
Gypsum (CaSO$_4$·2H$_2$O) is a common evaporite salt, first precipitated as a primary-textured bedded deposit at the initial eogenetic end of the burial cycle. With burial into the mesogenetic realm, gypsum dehydrates and compresses into various forms of nodular anhydrite (CaSO$_4$) showing variable textural retention of original gypsum textures. Later, at the other end of the burial cycle during uplift into the telogenetic realm, exhumed mesogenetic anhydrite rehydrates as secondary gypsum precipitates.

During telogenetic rehydration, the most common process forming secondary gypsum takes place where once impervious mesogenetic nodular anhydrite beds move into regions of increasing phreatic undersaturation and meteoric crossflow, before finally entering the vadose zone (Figures 1, 2a, b). In more humid settings, a newly-formed telogenetic gypsum unit can redissolve before reaching the land surface. Another common telogenetic rehydration scenario is where exhuming halite beds or diapiric masses undergo differential dissolution on their way to the surface (Figure 2c). This leaves behind layers of coalesced residual nodular anhydrite (aka fractionated dissolution residue). Residual CaSO$_4$ then converts to gypsum as the ascending anhydrite interval interacts first with more-deeply circulating then shallower meteoric waters (Figure 1). This is how a caprock forms around the upper and outer edges of a diapiric and bedded salt masses.

Secondary gypsum textures
The term secondary gypsum was first used by Murray (1964) and later by Mossop and Shearman (1973) to describe all forms of gypsum generated by the hydration of anhydrite. Three secondary gypsum fabrics typify rehydration and replacement of anhydrite: 1) Coarse porphyroblastic gypsum and 2) Fine-grained alabastrine gypsum, 3) Satin-spar gypsum (Figure 1; Holliday, 1970; Mossop and Shearman, 1973; Warren et al., 1990). Alabastrine, porphyroblastic and satin-spar textures are easily distinguishable with the naked eye or a hand lens (Figure 2). Anhydrite inclusions and corroded relics can be numerous in secondary gypsum (Figure 3). These highly birefringent anhydrite remains are microscopic and can make up irregular shreds with random orientations (Figure 3b), while others can show a more aligned or felted texture (Figure 3c).

In hand specimen, alabastrine gypsum is white to buff-coloured, a homogeneous massive to compact fine-grained variety of gypsum, usually white and translucent but sometimes delicately shaded or tinted with light tones of yellow, brown, red, orange, or grey (Figure 2a, b). Its generally fine-grained
Gypsum (buff) via rehydration of bedded anhydrite (grey)

Accretionary (micronodular) anhydrite caprock grows from its base

Dissolution contact at top of halite with fractionated nodule layer above contact

Daisy-bed gypsum with hollow or dolomitic centre

‘Nodule-in-nodule’ texture

Satin-spar gypsum (bed parallel)

Figure 2. Secondary gypsum textures. A and B) are rehydration in bedded Jurassic Hith Anhydrite (Dahl Hit, Saudi Arabia) C) Fractional dissolution of halite to form accretionary nodular anhydrite, Cretaceous Maha Sarakham Fm, Thailand, D) Daisy Bed textures, Permian Zechstein, coastal UK. E) Alabastrine core with later coarser gypsum selenite rim. F) Displacive pale oval-shaped botryoidal nodule, formed by the coalescence of smaller pure microcrystalline gypsum nodules. G) Sequence of three horizontal-accreting satin spar patterns enclosed into one single bed-parallel interstratal vein. Hammer is 33 cm long (E-G from coastal Namibia, see Gindre-Chanu et al., 2015).
appearance resembles that of finely crystalline white marble (Figures 1, 2e). Alabastrine gypsum tends to contain lesser amounts of anhydrite than porphyroblastic gypsum, typically in the range 0-2%. Gypsum textures tend toward equigranular and interlocking, with growth-sutured crystal edges (Figure 3d). This texture is often described as granoblastic (Holliday, 1970). Granoblastic textures indicate grain boundary equilibration in the solid-state. This texture is also seen in metamorphic rocks, as when limestone converts to marble. Granoblastic describe an isotropic aggregate of polygonal grains of more or less similar size, perhaps with crystal diameters within an order of magnitude.

At the meso and microscale, a range of related secondary gypsum textures indicate a standard set of nearsurface diagenetic (telogenetic) mechanisms and processes, that through multiple dissolution and reprecipitation cycles create ever-increasing proportions of purer gypsum and ever-decreasing amounts of residual anhydrite.

Anhydrite in an exhumed, now outcropping bed, in a desert environment can constitute more than 5-10% of the calcium sulphate in a sample (Gindre-Chanu et al., 2015; Warren 2016). Anhydrite relics in secondary gypsum are typically present as scattered, variably-etched, oriented to non-oriented prismatic crystals and laths, surrounded by more coarsely crystalline poikiloblastic gypsum (Figure 3a-c). No uplifted outcrop is ever composed of pure anhydrite and, even in arid settings, typical outcrops with anhydrite still present are dominated by gypsum as either finely crystalline alabaster or coarsely crystalline and porphyroblastic forms.

In thin section alabastrine gypsum is composed of sucrosic interlocking anhedral gypsum crystals, generally less than 60-80 microns diameter. Individual crystals show circular, irregular, or patchy slightly coarser crystals, many with uneven extinction (Figure 3a, d). Crystals construct an interlocking meshwork, sometimes with local preferred directions of crystal growth elongation. Compared to relic anhydrite crystals in the coarser (selenitic) gypsum, anhydrite residuals in equigranular granoblastic alabastine gypsum tend to show more evidence of etching (Figure 3e-f).

Porphyritic gypsum in hand specimen is composed of larger crystals (phenocrysts or porphyroblasts) up to a centimetre or two across, set in a fine-grained gypsum groundmass. Some of the individual porphyroblasts are sufficiently large and clear to be called selenite. Porphyroblasts, range from 1 mm to 2 cm

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1 Geological usage of the term alabaster is restricted to specimens composed of fine-grained homogenous gypsum, archeological usage also includes marble (calcite from a metamorphosed limestone).
and can retain ghosts of smaller crystals outlined by impurities (Figure 3a, 3c). Sometimes these coarser crystals are growth-aligned, especially if growth has expanded into open cavities. Porphyroblastic and alabastrine textures generally occur together, along with satin-spar veins (Figures 2, 3).

Outcrop samples of porphyroblastic gypsum with relic anhydrite typically have anhydrite present as felted-aligned to less-aligned masses of lathes encased in coarsely crystalline gypsum. Such crystals can lie adjacent to coarser gypsum crystals that contain few to minor anhydrite relics (Figure 3a-c). These larger gypsum porphyroblasts without remnants are thought to be later (Figure 2e; Holliday, 1970; Artieda, 2013; Gindre-Chanu et al., 2015). Coarsely-crystalline gypsum tends to show open porosity between crystals (intercrystalline polyhedral porosity; Figure 3a, b). It typically precipitates as relatively inclusion-free gypsum pore linings adjacent to the open pores implying a possible mesoscale replacement front is involved in its formation. That is, porosity is created by the dissolution of its precursor (gypsum-anhydrite), and this is followed by precipitation of gypsum in the resulting pore space. This gives the appearance of a clear gypsum rim to some crystals, that is actually a response to a dissolution front moving through the crystal and precipitating pure gypsum (Figure 3c).

Porphyroblastic gypsum rosettes, especially in the lower parts of the telogenetic realm, can retain dispersed relics of the precursor anhydrite in the core of the nodule. The crystals radiate from a central sausages-like stringer that in two dimensional exposures creates a texture sometimes described as gypsum “daisies” or “daisy-bed gypsum.” Individual daisy crystals or petals tend to be coarse and elongate, up to a centimetre or two long. Crystals and can be euhedral or anhedral, thin and acicular or thick and stubby (Figure 2d). Radiating porphyroblasts typically aggregate into centimetre to metre-scale layers, rosettes or blebs with acicular gypsum rinds (Gindre-Chanu et al., 2015).

Satin-spar gypsum: This style of gypsum is made up of growth-aligned, fibrous elongate crystals that infill veins or fractures. (Figure 2g, 3g, h). Most satin spar samples lack significant amounts of intercrystalline porosity, although some veins do show geopetal accumulations of anhydrite or dolomite on the lower sides of the fractures. Such geo-petalled fractures were likely created via fractional dissolution of precursor CaSO₄, leaving behind a residuum of less soluble materials (anhdrite, dolomite). Veins and fissures filled with fibrous satin-spar (typically gypsum, but can ve hakite or anhydrite) are widespread in the mudstones and shales adjacent to near-surface evaporite units undergoing dissolution (Figures 2g, 3g, h).

Satin-spar-filled fractures may be subhorizontal and lie roughly parallel to the contact with the bedded evaporite unit, or may form as conjugates. The fractures form and fill with fibrous cement in response to stresses set up in the bed by the formation of nearby stratiform cavities or accommodation space (Figure 4; Gustavson et al., 1994). The fracture filling is usually zoned and made up of two or more parallel layers of either fibrous CaSO₄ or fibrous halite (Figure 2g). Fracture-fill crystals are oriented with their long axes perpendicular to the fracture walls. Coarse calcite crystals can occasionally fill the centre of the fracture. Most fracture fills are monomineralic, and gypsum is the dominant mineral in most nearsurface fracture systems. Internal fracture zonation is pronounced and reflects episodic and ongoing opening and filling of the fractures. Some fibrous fills are sigmoidally deformed showing fracture fill was ongoing as adjacent blocks slid and rotated in response to changes in nearby dissolution cavities (Figure 5; El Tabakh et al., 1998).

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Figure 4. Conceptual model of deformation above salt dissolution zone showing structural sequence and proposed location relative to dissolution front. Stage 1 occurs prior to salt dissolution and is characterised by jointing resulting from normal burial. Late stage 1 and stage 2 occur as salt dissolution begins. Early stage 2 is characterised by a few vertical gypsum veins with horizontal fibres. Later stage 2 is characterised by normal faults and uncommon reverse faults. In stage 2 layer parallel extension results from the onset of dissolution and subsidence. Stage 3 is characterised by gypsum veining of bedding planes and faults. In stage 3 vertical extension results from widespread dissolution and collapse of underlying evaporites (after Gustavson et al., 1994).
Textural inter-relationships

The change from porphyroblastic to alabastrine may be depth-related (Warren et al., 1990; Gindre-Chanu et al., 2015). Porphyroblastic gypsum defines the re-emergence of nodular anhydrite from the stagnant phreatic into the deep portion of the zone of active phreatic flow. Daisy-bed gypsum, a form of porphyroblastic gypsum, is a likely response to rehydration under the relatively homogenous conditions of uplift hydrology in a massive nodular anhydrite unit entering the lowermost parts of the telogenetic zone with gypsume nucleating off the higher permeability zone defined by impurities that define the anhydrite nodule edges (Warren et al., 1990). Rates of fluid crossflow are low, so chemical dissolution is slow, and dissolution fronts tend to be focused about the bed contacts between aquifers and the anhydrite (gypsum is not stable at such depths).

Alabastrine gypsum forms in the zone of more diffuse active phreatic flow. This re-emergence is also associated with the formation of gypsum karst and the formation of evaporite-dissolution breccias (Warren, 2016; Chapter 7). As an anhydrite bed is uplifted into the telogenetic zone, it once again comes into contact with low-salinity, low-temperature waters. In many uplift situations, there is also an artesian flow system established so that both karstification and rehydration to gypsum tends to first be focused on the edge of the bed. There satin-spar gypsum tends to dominate in the fractures as fissures form in adjacent beds due to collapse into accommodation space created by dissolution.

As rehydration to gypsum becomes more pervasive within a bed, it tends to penetrate first along the impurity-rich more permeable edges of anhydrite nodules. Sparry aligned gypsum crystals grow into the nodules to form daisy-wheel gypsum (Warren et al., 1990; Gindre-Chau et al., 2015). As the rehydration proceeds through the bed, some of the gypsum then dissolves to provide further access to undersaturated waters that create additional caverns and fissures (Figure 2a). Because of the texturally-destructive nature of porphyroblastic overprinting, interpreting the original depositional environment is next to impossible in nearsurface and outcropping CaSO4 units, they are composed almost entirely of diagenetically regenerated gypsum.

Alabaster is the other form of telogenetic gypsum and is created where anhydrite pervasively rewaters to gypsum in the zone of active phreatic flow. Individual gypsum grains are typically less than 50 µm, with grain boundaries that range from poorly defined to equidimensional granoblastic.

Excess amounts of trace elements, especially strontium and boron, are released from some bedded anhydrites as they reconvert to gypsum. The released elements may precipitate in the regenerating alabastrine gypsum as celestite or boron-bearing minerals, such as proberite, ulexite, tyerskite and priceite. Daisy-bed gypsum, a form of porphyroblastic gypsum, is a likely response to rehydration under the relatively homogeneous conditions of uplift hydrology in a massive nodular anhydrite unit entering the lowermost parts of the telogenetic zone. Rates of fluid crossflow are low, so chemical dissolution is slow, and dissolution fronts tend to be focused about the bed contacts between aquifers and the anhydrite (gypsum is not stable at such depths).

References


