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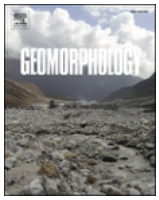

Exceptional halite speleothem variety in a limestone environment: Goat Cave, Nullarbor (Western Australia)

Jo De Waele [a,*], Gareth Thomas [b], Peter Downes [c], Marjan Temovski [d,e]

[a] Department of Biological, Geological and Environmental Sciences, Bologna Alma Mater Studiorum University, Via Zamboni 67, Bologna, Italy
[b] Australian Speleological Federation, Orange Speleological Society, New Zealand Speleological Society, New Zealand
[c] Western Australian Museum, Locked Bag 49, Welshpool DC, Western Australia, 6986, Australia
[d] Isotope Climatology and Environmental Research Centre (ICER), HUN-REN Institute for Nuclear Research (ATOMKI), Bem tér 18/C, H-4026, Debrecen, Hungary
[e] Department of Mineralogy and Geology, University of Debrecen, Egyetem tér 1, 4032, Debrecen, Hungary

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ABSTRACT

Major discoveries in Goat Cave (6N-745, Hampton Tableland, Nullarbor, Western Australia) between 2022 and 2025 have brought this limestone cave, originally a doline with underlying large entrance chamber and passages totalling 300 m long and 40 m deep, to reach a development of 9.7 km and depth of 94 m. It is a complex carbonate cave system with a lateral extent of about 1800 m from WSW to ESE and several close-to-horizontal levels. Despite being a cave carved in fossiliferous Tertiary limestones with some calcite speleothems, it hosts a large variety of halite speleothems, along with minor gypsum and calcite speleothems. The halite and gypsum salts derive from meteoric waters brought inland by rainfall enriched in Na^+, Cl^-, and SO_4^{2-}, and other ions, as shown by historic rainfall analyses and as indicated by sulphur isotope analyses. The uplift of seawater-derived (sea salt) aerosols high into the troposphere increases the concentration of ions in rainwater, and brings these dissolved salts into the continent, with generally decreasing amounts at increasing distance from the coastline. The salt and sulphate ions resulting from rainfall since the Nullarbor limestones emerged from the ocean ~14 Ma were gradually brought deeper into the limestone during infiltration events. These salts re-appear as halite and gypsum speleothems in the currently dry caves of the Nullarbor. Goat Cave arguably hosts the most abundant and diverse display of halite speleothems in the Nullarbor. Despite being in a limestone cave, the speleothems of Goat Cave rival the secondary salt deposits of the famous halite caves of Iran, Israel and Atacama in Chile. Moreover, the dry and salty deep subterranean environment has allowed the preservation of a stunning abundance and variety of mummified invertebrates and mammals.

1. Introduction

Speleothems are "*Secondary mineral deposits that form in a cave*" (Moore, 1952).

Cave minerals are defined as "*secondary deposits precipitated inside a human-sized natural cavity*"; this means they derive from a primary mineral existing in the bedrock or cave sediment which is converted into a new mineral by some physical and/or chemical reaction (Hill and Forti, 1997; Onac and Forti, 2011).

Caves can be defined in many different ways (White and Culver, 2019; De Waele and Gutiérrez, 2022). From the anthropocentric viewpoint, caves are openings in the Earth large enough for human exploration. For a biospeleologist any opening able to host cave-adapted organisms can be called a cave. For people studying karst aquifers, caves are voids and conduits that transmit water flow. Caves can form by a multitude of processes, not only bedrock dissolution (karstic caves), but also by tectonic movements, differential erosion, accumulation (e.g., travertine and talus caves), draining of flowing lava or melting of glacial ice (De Waele and Gutiérrez, 2022). Cave-hosting soluble rocks are mainly carbonates (limestone and dolostones) and evaporites (gypsum and halite), but caves can also form in less soluble rocks (e.g., quartzarenites) with dissolution playing a key role in the initiation of speleogenesis (Sauro et al., 2013; Sauro, 2014; Wray and Sauro, 2017).

Most secondary mineral deposits in limestone and some other caves are carbonates, with calcite and aragonite being the two most abundant minerals. These two carbonate minerals form the classical speleothem

* Corresponding author.
E-mail addresses: jo.dewaele@unibo.it (J. De Waele), gareth.w.thomas@xtra.co.nz (G. Thomas), peter.downes@museum.wa.gov.au (P. Downes), temovski.marjan@atomki.hu (M. Temovski).

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shapes decorating most limestone caves (Hill and Forti, 1997). The third most abundant mineral found in caves is gypsum. It is abundant not only in gypsum caves, but also in limestone caves, especially in sulphuric acid caves, where it replaces calcite (De Waele et al., 2024).

Three hundred and sixty four different mineral species have been described from caves worldwide, approximately 30% of which are sulphates, 17% are phosphates, 11% are silicates, 11% carbonates, and 11% oxides-hydroxides (Onac, 2025). Only 11 halides are known to form in natural cave environments. Halite, sylvite, fluorite, and carnallite are the most common halides found in caves. Fluorite generally occurs in carbonate caves (Maltsev and Korshunov, 1998; Onac and Forti, 2011; Palmer and Palmer, 2012; D'Angeli et al., 2018), whereas carnallite is a very rare cave mineral found in small evaporite caves in Siberia (Beltyukov, 1969) or in small coastal volcanic caves in Surtsey (Iceland) (Jakobsson et al., 1992). The occurrence of carnallite in Liquid Crystal Cave in Mount Sedom is believed to be related to evaporation of Dead Sea brines that entered the cave in the mid Holocene and is thus not a true cave mineral (Frumkin and Forti, 1997). Sylvite occurs mainly in volcanic and rock salt caves (Hill and Forti, 1997), but due to its high solubility tends to disappear in caves where air humidity reaches moderate to high levels. Halite (NaCl) speleothems are commonly found in rock salt caves (Dzen-Litovsky, 1940; Frumkin and Forti, 1997; Cardona and Vivier, 2002; Filippi et al., 2011; De Waele et al., 2017; Forti, 2017; Tîrlă, 2019; Alexandrowicz et al., 2021), in salt mines (e.g., potash mine near Carlsbad, Komensky, 1966, or Wieliczka in Poland, Kowlaczyk and Sawłowicz, 2013; Sawłowicz et al., 2014), in small cavities beneath halite crusts (e.g., Aref and Mannaa, 2021). Halite has also often been found in volcanic caves (Jakobsson et al., 1992; Huerta et al., 2019), and as an evaporation product of sea or brine waters in coastal tafoni (e.g., in granites, Twidale and Bourne, 2008). NaCl is seldom reported from limestone caves worldwide, unless they are in direct contact with sea water (e.g., Bahamas, Onac et al., 2009). Halite is, nevertheless, one of the main cave minerals found in the arid limestone caves in the Nullarbor region of southern Australia (Lowry, 1967; Broughton, 1971; James and Webb, 2023).

The Nullarbor caves of southern Australia are so dry (Lipar and Ferk, 2022) they cause salty infiltration waters reaching them to evaporate and form large halite speleothems. These halite speleothems occur in both shallow (e.g., Webbs Cave (6N-132), Prostate Pit Cave (6N-1639)) (Goede et al., 1990) and deep caves (e.g., Thampanna Cave (6N-206), James, 1991) and are generally accompanied by gypsum speleothems. In Webbs Cave a broken halite stalagmite almost 2.8 m tall was collected for the Western Australian Museum (Goede et al., 1992). Both gypsum and halite speleothems are still actively forming, as droplets have frequently been seen hanging from their tips (Goede et al., 1990, 1992; James, 1991; personal observations of Gareth Thomas in 2024 and 2025). Dating of gypsum and halite speleothems gave ages of ~185 ka and ~2.5 ka respectively (Goede et al., 1990, 1992), showing these are Middle to Late Pleistocene and Holocene in age.

An important feature of most Nullarbor caves, and Goat Cave (6N-745) in particular, is the movement of air through the caves (airflow). This is caused by natural air currents induced by minor elevation and thermal differences in some of the shallower caves, and in many blowhole caves and the larger volume and deeper caves, by the effects of changes in atmospheric (surface) air pressure on those voids. Air speeds through cave entrances have been recorded as high as 70 km h^{-1} (James et al., 2004) when surface air pressure changes relative to cave air pressure. The changes in air pressure cause cycles of in and out airflow at cave entrances, referred to as "breathing" by speleologists (who are otherwise referred to herein as cavers). The movement of dry air through the caves has affected the formation of some speleothems, and keeps the atmosphere breathable for modern human exploration.

The Nullarbor caves, including those located north of the Hampton Scarp on Mundrabilla Station, are characterised by old (Pliocene), often brownish and dark calcite speleothems, occurring mostly in the shallow caves. Although occasionally found, calcite speleothems are rare in the deeper parts of Nullarbor caves (James and Webb, 2023). Most of these carbonate formations are inactive and often broken into pieces by internal salt crystal growth causing speleothem fragmentation, sometimes referred to as salt weathering. In some caves calcite stalactites and stalagmites are still actively growing (e.g., Webbs Cave, Mallett et al., 2025). Calcite speleothems occur in some of the deeper passages of Goat Cave.

The characteristic dark brown colour of some of the layers in these speleothems is due to the presence of minor detrital iron and manganese compounds, and abundant organic compounds, including lipids and lignins (Caldwell et al., 1982), pointing to an increased soil activity (thus wetter and warmer climate) and microbially mediated degradation of peat and grass-related vegetation indicating the presence of wetlands (Blyth et al., 2010). Most of these stalagmites, stalactites, and columns gave U/Pb ages of about 5–3.5 Ma, but some taken in caves in the northern part of the Nullarbor gave an older age of 8.6 ± 0.4 Ma, showing the caves to be of Pliocene age or older (Woodhead et al., 2019). It is generally believed that speleogenesis must have taken place during a climate wetter than the one present today (Doerr et al., 2012), and some authors hypothesise that the deeper and larger cave trunks mostly carved in the Wilson Bluff limestone might even be of Oligocene age, when climate was suitable for extensive dissolution to take place (Webb and James, 2006; White et al., 2017). The over 2500 karst features (blowholes, cave entrances, etc.) documented over the last 25 years using an ultralight aircraft and successive field reconnaissance have shown a roughly east-west distribution along parallel-to-the-coast bands (Burnett et al., 2013). Known caves can be grouped in four classes, based on their general morphology and position: 1) deep caves; 2) shallow caves closer to the present coast; 3) a band of blowholes parallel to the coast; and 4) a possible group of caves at or north of the Transcontinental Railway (White et al., 2017). The shallower caves of group 3, such as Prostate Pit and Webbs Cave, have a diagnostic horizontal flank margin cave (spongework) pattern. However, the general characteristics, the depth, vertical extent, and other specific characteristics of the deep Goat and Thampanna Caves are very different to those of caves such as Prostate Pit which are closer to a known near-coastal escarpment and former sea cliff, now called the Hampton Scarp. The lower parallel passages of Goat Cave appear phreatic in origin. They would have been below the water table not only when Hampton Scarp sea cliff was formed, but also during earlier, wetter periods. Goat Cave and Thampanna Cave require further investigation before making interpretations as to their origin.

The discovery of important and deep extensions in Goat Cave (Mundrabilla, Hampton Tableland) has allowed speleologists to survey over 9 km of previously unknown passages during 2023–2025, reaching a depth of over 90 m below surface. Future research on this cave, its morphology and its speleothems will contribute to the understanding of the different speleogenetic phases that occurred in this area of the Nullarbor.

The main subhorizontal level of this cave, located at ~80 m depth from the surface, is extremely rich in a wide variety of halite speleothems, some reaching considerable size. This paper will report on these findings, describing the many different speleothem shapes, with some hypothesis on their genesis, and their mineralogy.

2. Goat Cave

2.1. Geographical and geological setting

Goat Cave is located on the limestone plateau north (inland) from the Eyre Highway, on Mundrabilla station (located within Mirning native title country), and in the Eucla Basin of the Nullarbor region in southern Australia (Fig. 1). This uplifted plateau is known as the Hampton Tableland. It is separated from the coastal Roe Plain by the Hampton Scarp, an old late Pliocene sea cliff reaching heights between 40 and 80 m. The plateau appears relatively flat but rises gently from ~90 m a.s.l.

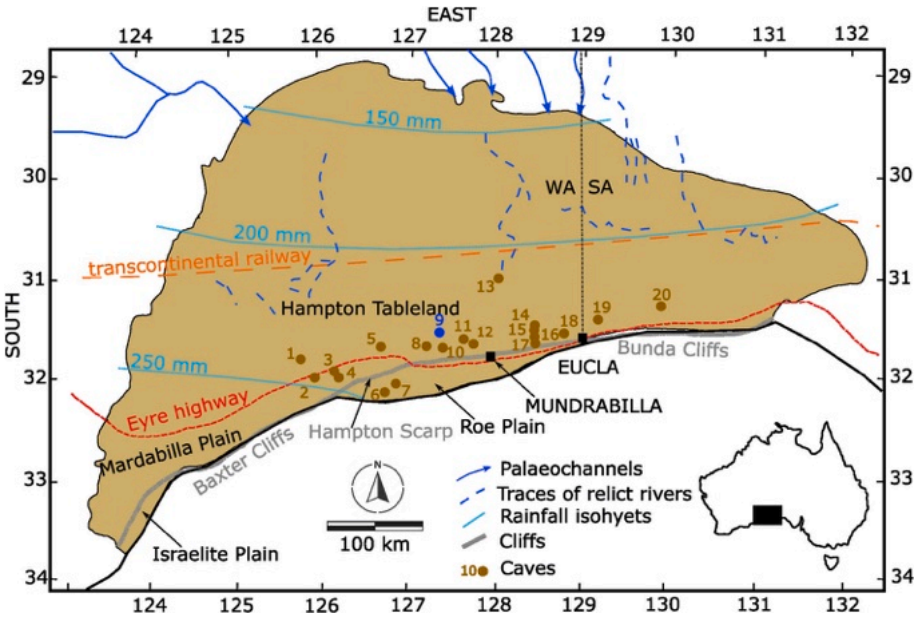

Fig. 1. The Nullarborkarst area with some of the most important caves (Goat Cave in blue, number 9): 1. Cocklebiddy (6N-48); 2. Murra-el-Elevyn (6N-47); 3. Pannikin Plain (6N-49); 4. Tommy Grahams (6N-56); 5. Moonera Tank (6N-53); 6. Burnabbie (6N-305); 7. Olwogin (6N-25); 8. Mullamullang (6N-37); 9. Goat (6N-745); 10. Prostate (6N-1639); 11. Thampanna (6N-206); 12. Webbs (6N-132); 13. Old Homestead (6N-281); 14. Chowilla Landship (6N-17); 15. Abrakurrie (6N-3); 16. Kutowalla Doline (6N-44); 17. Winbirra (6N-45); 18. Weebubbie (6N-2); 19. Warbla (5N-1); 20. Koonalda (5N-4).

above the cliffs to ~240 m a.s.l. in the extreme NW (over 330 km away), with a slope of less than 0.05%.

The Eucla Basin is located on Australia's southern margin, and extends ~900 km (E-W) and ~370 km (N-S), forming one of the most extensive continuous continental outcrops of Cenozoic marine carbonate sediments in the world (Clarke et al., 2003). These marine carbonates cover a basement composed of Mesozoic sandstones and shales, and a thin middle Eocene sandstone layer. Three limestone formations were deposited in the slowly subsiding Eucla basin (Hou et al., 2008). The lowest is the Middle-Late Eocene Wilson Bluff Limestone, a fine-grained, poorly-sorted calcarenite up to 300 m thick which deposited in calm and shallow cool temperate coastal waters (James and Bone, 1991). This limestone is composed of bryozoan fragments and foraminifera embedded in a micritic calcite matrix. The fossil fragments form separate vugs, making the Wilson Bluff limestone poorly permeable despite its high porosity (ca. 30%). After uplift and relative sea-level retreat in the Early Oligocene, this limestone was exposed to 10 million years of erosion and weathering in a monsoon-type climate, leaving a prominent reddish paleosol and calcrete layer on its upper surface (Alley et al., 1999).

The well sorted, coarse-grained and up to 100 m thick Abrakurrie Limestone was then deposited between the Late Oligocene and Early Miocene. This limestone, restricted to the Central Nullarbor area, is made of abundant bryozoan and mollusc fragments and poorly preserved foraminifera. It has a high porosity (ca. 40%) and permeability. Its coarse grain and fossiliferous content indicate it deposited in a swell-dominated, embayed shelf environment (Li et al., 1996).

After less than 1 My of surface exposure, the Abrakurrie Limestone was drowned again in the Middle Miocene and covered by the Nullarbor Limestone, a very fine to very coarse, poorly sorted grey-yellow calcarenite rich in macrofossils. This final layer of limestone is very extensive across the entire Nullarbor and is 20–45 m thick. The Nullarbor Limestone, deposited in a warm subtropical climate, generally has low porosity and permeability (Lowry and Jennings, 1974; James and Bone, 1991; Benbow et al., 1995; O'Connell et al., 2012; Burnett et al., 2013).

The whole area emerged above sea level ~14 million years ago and was subjected to an increasingly hot and dry climate, but still with a strong seasonal character and high annual rainfall variability (Finlayson and McMahon, 1988; Alley et al., 1999). By the start of the Pliocene the climate evolved towards aridity similar to today, and the Nullarbor must have resembled the sparsely vegetated low woodland cold desert we see today. The early Pliocene, however, was characterised by a 2-to-4 times higher annual rainfall (~1200 mm/a) lasting for approximately 1.5 Ma, as indicated by pollen records showing a biome turnover from shrub and woodlands characteristic of a semi-arid climate, to mesic forests typical of a wetter climate with substantial rain during summer (Sniderman et al., 2016). The climate has become arid to semi-arid since the late Pliocene (~3 Ma) with fluctuations related to interglacial (slightly wetter) and glacial periods (drier) during the Quaternary (Gillieson and Spate, 1992).

The present landscape around Goat Cave is an undulating plain of limited relief. Minor rises are interspersed with claypan depressions, locally known as “dongas”. Vegetation is dominantly low shrubland of chenopods including saltbush, bluebush, minor samphire and a variety of grasses, from which the name Nullarbor (“no trees” in Latin) derives. Some myall and mulga trees grow mainly on the ridges surrounding Goat Cave. The ground surface has a cover of shallow, red-brown calcareous soil with some exposed limestone on the ridges and calcrete here and there.

At 94 m depth below surface, Goat Cave does not reach the water table, which is now probably at least 100–120 m deep (Gillieson and Spate, 1992). The water table must have been shallower during the wetter early Pliocene phase, and during the late Pliocene when Roe Plain was submerged under the ocean and Hampton Scarp was being formed, then as a sea cliff.

The present annual rainfall ranges from up to 400 mm/a near the southwest coast to less than 150 mm/a inland, whereas potential evapotranspiration varies from about 1250–2000 mm near the coast to 2500–3000 mm in the north. The area around Goat Cave falls in Köppen's BWk (cold desert) climate zone.

2.2. *Cave exploration and description*

The large Goat Cave entrance doline was probably known when the Mundrabilla sheep station was established in the early 1870s and settlers

started roaming around the Hampton Plateau. From those early days, also because of the easy cave access, the large entrance chamber had undoubtedly already been visited. This upper part of Goat Cave was surveyed by cavers of VSA and CEGSA (Max Meth, Ray Gibbons, and Ken Boland) during an expedition in April–May 1996 (MacLucas, 1996), but it was not until the late 1990s to early 2000s that a couple of strongly air-venting cracks and holes in between rocks were investigated further by cavers, but none appeared to give access to important leads.

The most interesting of these strong air flows was targeted as a possible lead in 2021, and one year later, after digging a series of narrow squeezes, a vertical, tricky and tight rift was descended giving access to a steep sloping passage, later named the "Goat Track" (Fig. 2). The survey of this part was not completed during the 2022 expedition, and in 2023, on return to complete the mapping, a narrow route through the rockpile descended to a distinctly new and large level extending both to the east and to the west (De Waele et al., 2023). From this moment on, exploration and mapping yielded hundreds of metres of passage each day, and subsequent expeditions in 2024 and 2025 brought Goat Cave to reach 9.7 km in surveyed length, for a depth of about 94 m (Pryke, 2025) (Fig. 2).

The entrance to Goat Cave is a 50 m wide collapse doline giving access to a large descending chamber, with traces of occasional water flow and scattered bones of large and small animals including bats and birds. A more or less flat sediment-covered floor is reached approximately 40 m down, and the chamber continues to the SW leading to an adjacent large room where some living bats are usually seen. The passage giving access to the deeper parts of the cave is situated in the southern lower part of the entrance chamber, starting with an awkward rift followed by two dusty horizontal squeezes leading eastward into a small collapse chamber. A narrow vertical descent through these rocks (named the "Traffic Jamb") brings one into a tight rift that eventually drops, through a narrow hole, into a larger steep and E-W elongated chamber below. This is the "Goat Track". The way through is located in the eastern limit of this chamber, up and down through some loose boulders, and through a small flat chamber with the skeletons of a snake (adult Dugite *Pseudonaja affinis*), and a possum (*Trichosurus vulpecula*). Finally, the rather uncomfortable "Entrance Series" passages reach a wide but low horizontal passage, in reality two parallel passages, the "Jewel Carriageway", which constitutes the main level of Goat Cave, at about 80 m below the entrance. This 50 cm to 4 m high ESE-WNE directed passage extends for 1180 m westward and 470 m eastward. The "Jewel Carriageway" has a few larger upper galleries in the west, located approximately 15 and 25 m higher (e.g., "Overpass" and the overlying passage leading upwards into the "Dipluradome", which comes within ~30 m of the overlying surface). In the extreme east, on the other hand, the "Peak Hour Passage" gently rises for about 25 m, before abruptly climbing another 20 m, and turning 140°, continuing westward ("the Switchback"). This larger gallery rises into a collapse room (the "G. O. A. T. Chamber"), with some passages reaching almost to the surface.

In the central part of the "Jewel Carriageway", a low and narrow 50 m long NNW-SSE passage (perpendicular to the direction of the main passage) ends in a series of three potholes. One of these holes allows cavers to descend, an ~9 m vertical drop, from the arched roof to the floor of an ~30 m wide underlying passage. The size and morphology of this lower level contrast with the above lying passages, as if it were a different and likely older cave, incidentally intersected by later water flow from above. The western extension of this lower passage (the "Undercarriage") gradually rises very steeply and ends in a rockfall, 200 m away from the potholes and approximately at the altitude of the entrance chamber (~40 m from the surface above). The eastern passage, which goes down and up, and down and up again, is much longer (~600 m) and ends in a very low but wide, collapse passage, ~50 m from the land surface. This passage has airflow indicating continuation beyond the accessible area.

Whereas the dark-coloured calcite speleothems are only locally seen with some old, corroded remains displayed in the entrance chamber, and very infrequent localised occurrences elsewhere, halite speleothems are widespread throughout the cave, especially in the deeper parts, and come in variable sizes and shapes. Both the abundance, size, and morphologies of these halite deposits, remarkable in itself for a cave carved in limestone, make Goat Cave unique among the Nullarbor caves and are the main subject of this paper.

3. Methods

Observations on speleothems were made since the first explorations were carried out in the lower Goat Cave passages, in 2023, 2024, and in 2025. During the first two expeditions, while exploring and mapping, pictures were taken of the most exceptional speleothem formations. This documentation made it clear that Goat Cave contained a great variety of secondary mineral forms and shapes that needed a more detailed investigation including mineralogy and speleothem morphology. During the 2025 expedition broken fragments of both gypsum and halite speleothems were sampled from several locations in the newly discovered passages in Goat Cave, and some samples were also taken from nearby

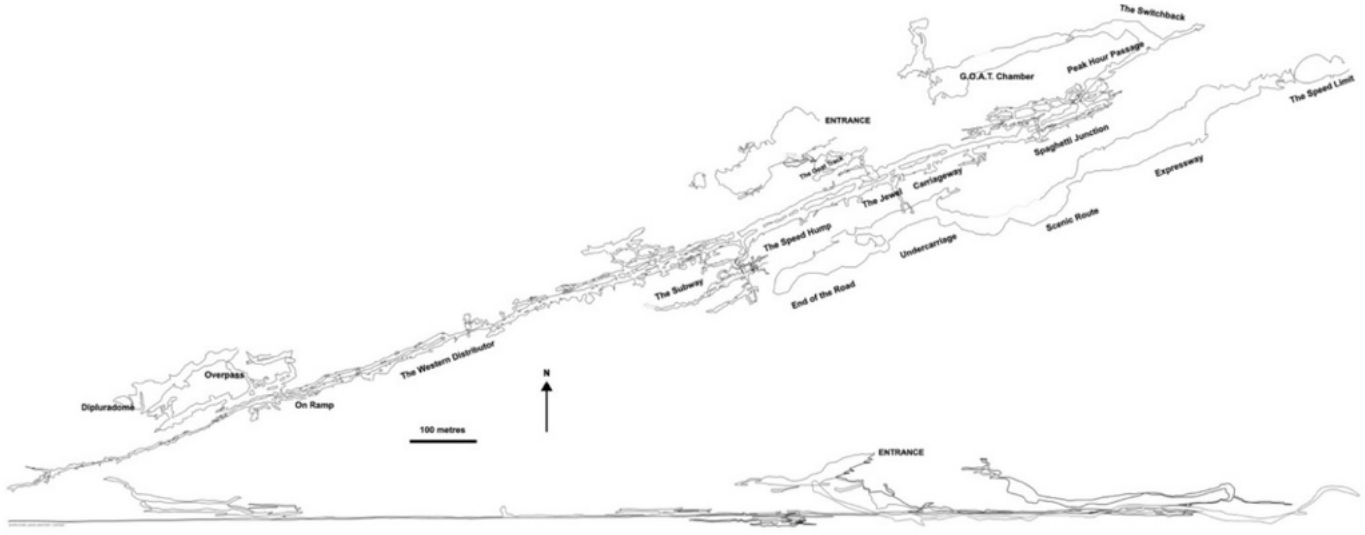

Fig. 2. Plan and elevation of Goat Cave.
(Drawn by Pryke, 2025).

Thampanna Cave and Prostate Pit for comparison.

Mineral identifications were carried out using energy-dispersive X-ray microanalysis (EDS) on a Hitachi TM3030Plus Benchtop scanning electron microscope with an integrated Bruker Quantax 70 EDS system at the Western Australian Museum. Lautarite unit cell parameters were obtained by Gus Mumme and Ian Grey (CSIRO Mineral Resources) using a single-crystal diffractometer (XtaLab Synergy 4-circle diffractometer equipped with a Dualflex Hypix detector using CuK radiation and $\lambda = 1.54184$ Å) operated by Robert Gable at the University of Melbourne.

Bulk sulphur and oxygen isotope composition of gypsum samples were performed at the HUN-REN Institute for Nuclear Research (ATOMKI), Debrecen, Hungary on a Thermo Finnigan DeltaPLUS XP Isotope Ratio Mass Spectrometer, coupled to a ThermoFisher Scientific EA IsoLink CNSOH (Temovski et al., 2018). The stable isotope ratios are reported as $\delta^{34}S$ and $\delta^{18}O$ values in permil (‰), relative to VCDT and VSMOW, respectively, with measurement precision better than ±0.3‰.

4. Mineralogy

Speleothems in Goat Cave have shown to contain a total of 7 primary cave minerals: halite, gypsum, calcite, epsomite, hexahydrite, celestine, lautarite, and quartz.

Halite is the most abundant mineral composing spectacular speleothems in many Nullarbor caves. Commonly these crystals have an elongated prismatic to acicular habit, which is unusual for halite, but distinctive of the evaporitic cave setting of these samples (Fig. 3A, E, F; Forti, 2017). Gypsum also occurs, but in minor amounts compared with halite. Many curls and flowers, thought to be composed of gypsum, were halite instead (their salty taste allowed easy in-the-field recognition).

In some places typical underwater speleothems have been found, and were composed of a layered alternation of calcite, gypsum, and halite. These show progressive and alternating stages of infilling and evaporation of large cave pools; when around 50% of the water is evaporated, calcite starts to form. With continuing evaporation, when only 19–20% of the water is left, gypsum starts precipitating. When evaporation is greater than 90%, halite begins to precipitate.

Hydrated sulphates encrust halite forming white fine-grained patches and showing dehydration cracks. These are indicative of the transformation of epsomite ($Mg(SO_4)\cdot 7H_2O$) into hexahydrite ($Mg(SO_4)\cdot 6H_2O$) (Fig. 3A, B). Patches of fine-grained mixed evaporitic salt crusts composed of Na—K—Ca—Mg chlorides and sulphates also occur on these specimens, but their low quantity did not allow for their mineral

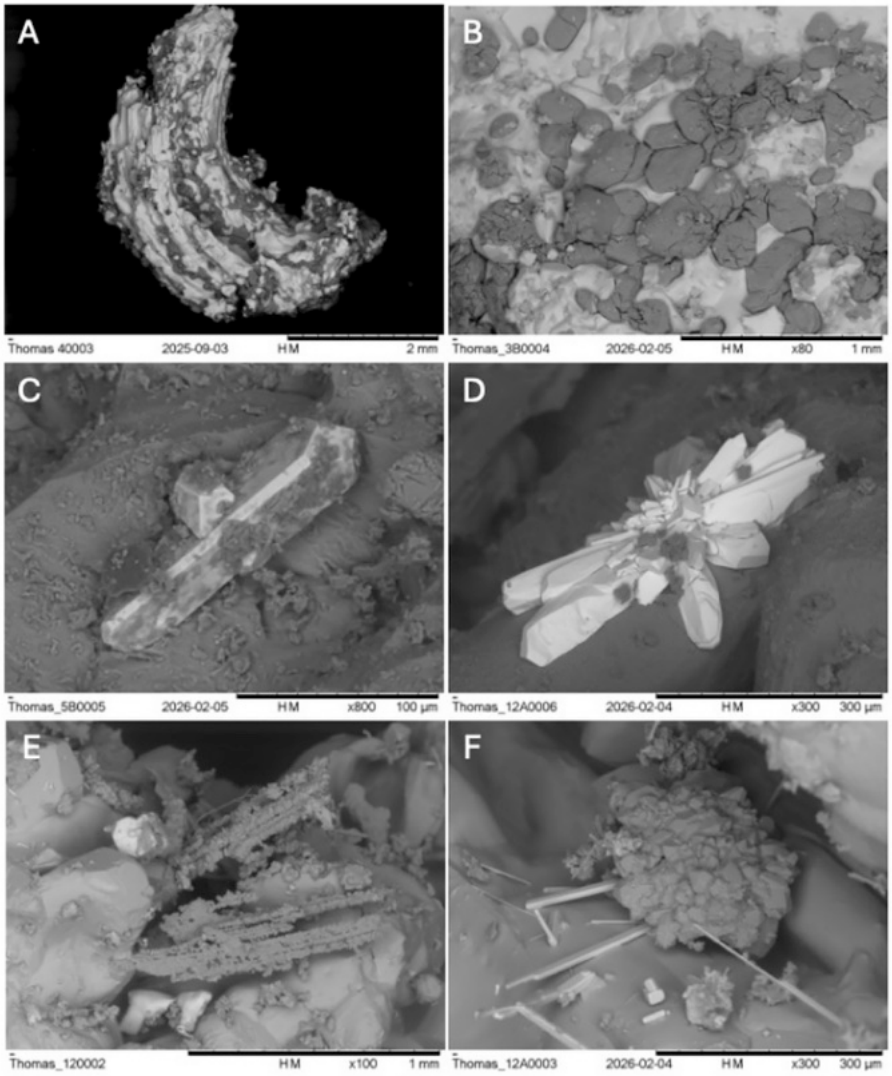

Fig. 3. A. Halite coated with epsomite–hexahydrite; B. epsomite–hexahydrite showing desiccation cracks on halite; C. crystals of celestine on gypsum; D. a spray of lautarite crystals on gypsum; E. microcrystalline quartz and halite on the surface of gypsum; F. elongated crystals of halite associated with microcrystalline quartz on the surface of gypsum.

identification.

Celestine ($SrSO_4$) forms small prismatic crystals on the surface or within gypsum crystals, and is easily distinguished for its rather high refractive index (Fig. 3C). Other isolated crystals or sprays of colourless prismatic crystals on gypsum are instead composed of a calcium iodate, which turned out to be lautarite ($Ca(IO_3)_2$) (Downes et al., 2026) based on single-crystal structure determination, the crystal morphology and the oxygen content suggested by the EDS analysis which matches better lautarite than the hydrated form, brüggenite ($Ca(IO_3)_2{\cdot}H_2O$) (Fig. 3D). Single crystal XRD analysis has confirmed it to be lautarite. This is the first recorded occurrence of lautarite in Australia and outside of Chile. Lautarite was discovered in the late XIXth century in the nitrate deposits of Pampa Pique III, near Oficina Lautaro (Antofagasta, Chile) (Dietze, 1891). In 1971, analysis of lautarite from this same location showed the presence of its hydrated version, which was named brüggenite (Ericksen et al., 1974). Lautarite was later also found in the Yumbes Mine near Paposo (Antofagasta) and in Salnitrera Pedro de Valdivia in the Salar de Miraje (Tocopilla, Chile).

Finally, authigenic quartz occurs as small crusts and frameworks of microcrystalline coatings, associated with halite, covering gypsum (Fig. 3E, F).

5. Halite speleothems

In Goat Cave, despite being hosted in limestone, halite is much more abundant than calcite and gypsum. Calcite occurs as up to over a metre-long (-tall) dark-brownish stalactites, columns, and flowstones, most of which are likely to be 3.5 to 5 million years old (Pliocene) based on

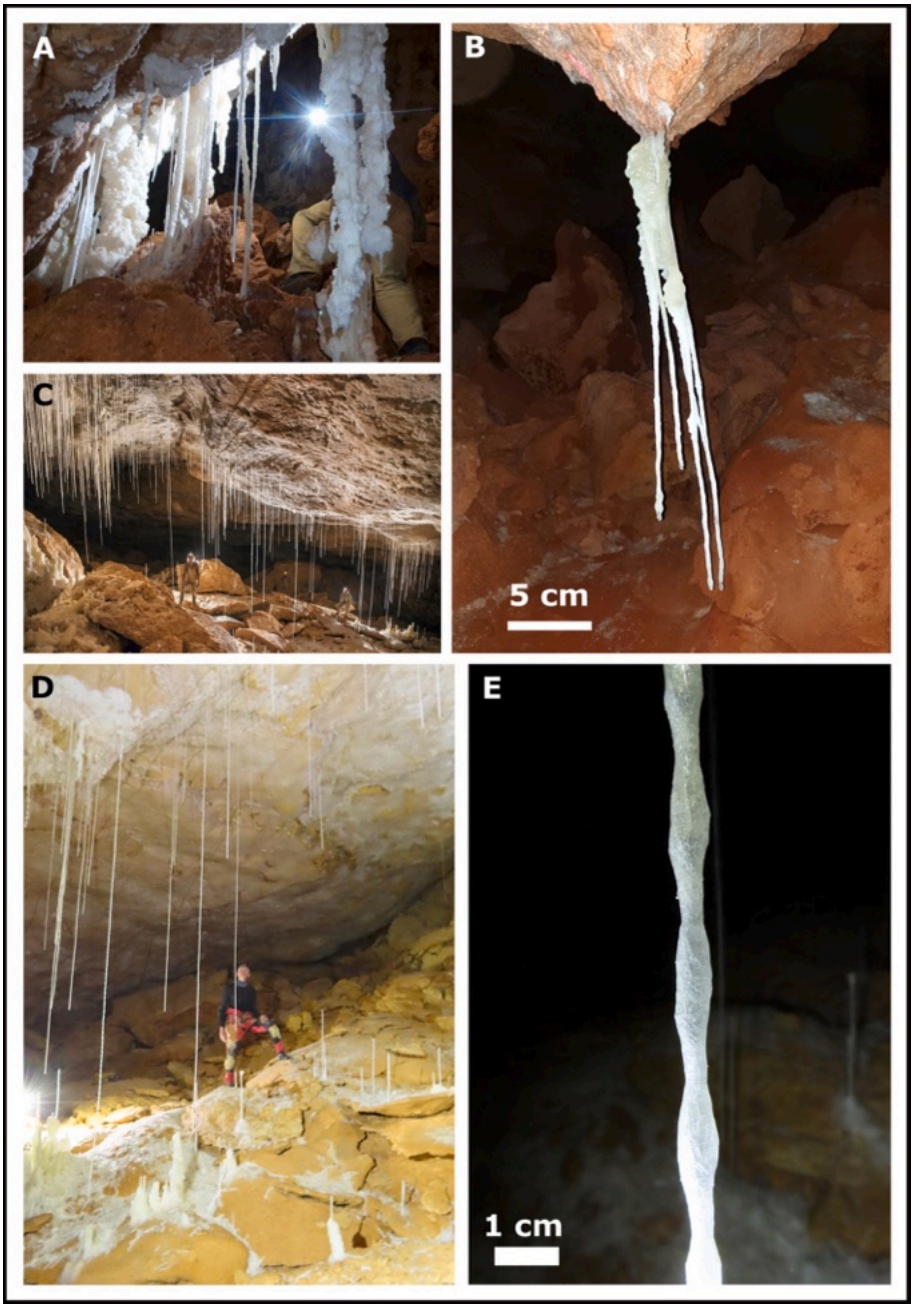

Fig. 4. A. Glassy stalactites and botryoidal columns and; B. botryoidal stalactites; C. halite straws in "Goat Chamber"; D. the longest halite straws and; E. detail of the beaded halite straw.
(Panel B photos by Brett Wiltshire; panel C photo by Alan Pryke; panel E photo by Gareth Thomas).

dating of calcite speleothems elsewhere. Gypsum, on the other hand, mainly occurs as small orange to pink or yellowish stalactites, crusts, and curving flowers. In shallower caves, such as in Prostate Pit, gypsum appears to be more abundant, also forming often yellowish speleothems which appear to be of the selenite gypsum variety.

Halite speleothems occur in exceptional abundance in Goat Cave, especially in the main passages about 70–80 m below the surface, making it unique among the Nullarbor limestone caves. Following the general classification of Hill and Forti (1997), nine types of halite speleothems have been recognised in Goat Cave, the fibrous speleothems being split in four subtypes.

5.1. Stalactites and straws

Straws are abundant in discrete areas of Goat Cave, with a few being transformed into glassy conical-tip-down stalactites or, more often, into white botryoidal stalactites (Fig. 4A–B). Their origin is due to evaporation of water from drops hanging from their tips, and accretion of halite. In straws, this downward growth progressively extends the length of the speleothem, and in conical stalactites, layers grow outwards more or less perpendicular to the speleothem surface, thickening them. The process leading to supersaturation of the fluid is evaporation. This causes halite stalactites to be affected by air movement running through the cave passages, as they are sometimes 'bent' or otherwise change directions. Halite stalactites and straws tend to curve towards the wind, where evaporation is more favourable, and are especially influenced by airflow in restrictions of the passages, where wind becomes stronger. This may cause crystal development towards the airflow rather than away from it. Straws are hollow tubes of halite crystals, generally less than 10 mm in diameter (most are between 5 and 8 mm), and are extremely fragile. Droplets of water can be seen occasionally dripping from straws in Goat Cave, showing they become active after rainfall events.

The botryoidal stalactites and halite speleothems in general are characterised by a "broccoli"-like appearance, with many compenetrating subspherical accretions formed by the evaporating water film wetting the surface from the internal feeding tube. This occurs when the feeder tube gets blocked by crystals, or touches the ground (eventually transforming the straw into a juvenile column). Fine filiform anthodites (helictites lacking the internal feeder channel), widely present on halite straws and stalactites in salt caves worldwide (Iran, Israel, Atacama), appear to be completely missing in Goat Cave. For anthodites to form, water should exit the speleothem surface at discrete places (small fractures, open contact surfaces between adjacent crystals), thus giving rise to a hairy halite crystal growing perpendicular from this cracked surface. The porous and less fractured halite speleothems found in Goat Cave do not appear to present suitable conditions for anthodite growth. When the feeding tube of these speleothems gets blocked, water reaches the outside surface of the speleothem almost uniformly, wetting its entire surface. Initial irregularities on this surface define areas where evaporation is greater (extruding or convex areas) with respect to adjacent sheltered ones (concave or inflections), also resulting in positive feedback. This explains the "bubbled" appearance of these botryoidal speleothems.

Deposits also accumulate on the floor below stalactitic halite speleothems. Many sites of halite straws have broken ones on the cave floor around them, where it is likely that they have fallen under their own weight as they grow, before new ones form.

The longest straw measured at Goat Cave is 4.8 m from ceiling to floor (Fig. 4C–D). It appears that these are the longest halite straws known in the world (in Iran the longest reported halite straw is 3 m long (Filippi et al., 2011), whereas in Mount Sedom (Israel) the longest one appears to be about 4 m (Forti et al., 1984)). Speleothem growth velocity at Mount Sedom was measured at ~1.3 mm/day over a 7-month period (Frumkin and Forti, 1997), whereas growth rates in Iranian salt caves were as high as 2–4 mm/day (Filippi et al., 2011). The higher rate can be easily explained by the higher rainfall (2-to-4-fold) in this latter area. Growth rates for Nullarbor halite straws have not yet been measured but might reasonably be similar to the Iranian values. In fact, the morphology of the halite straws is sometimes like beads on a string, with centimetric alternations of widening and narrowing of the straw (Fig. 4E). These might correspond to single feeding periods, straws thus growing after each infiltration event for about 1 to 3 cm. Drops on the end of straws were frequently observed, and might be hanging there for weeks or more, justifying a growth rate similar to the Iranian one.

The preservation of extremely long and delicate halite straws in Nullarbor caves such as Goat Cave is most likely due to the relative tectonic stability of the Australian continent, compared with Iran and other places where halite straws occur. Lack of human or animal activity in the Nullarbor caves has also helped to limit damage to halite straws.

5.2. Stalagmites

The lower counterparts of stalactites are much less frequently found, and are normally less than 50 cm tall (Fig. 5A). In general the volume of halite speleothems is much greater in shallow caves than in deeper ones. In Webbs Cave, for example, very tall halite stalagmites have been found (one, displayed at the Western Australian Museum, was 2.8 m tall and found broken in many pieces) (Goede et al., 1992). Prostate Pit also has large halite stalactites, columns and stalagmites all exceeding 1 m in length.

Halite stalagmites always occur in areas of abundant growth of straws and stalactites, and their dimensions increase in shallower areas of Goat Cave. Several stalagmites reach a height of 50 cm and more in the large collapse "G. O. A. T. Chamber", probably located at less than 40 m from the surface lying above. Halite is brought in solution downwards by infiltrating waters, but when these droplets reach below-lying voids, evaporation causes it to deposit rapidly. Once halite is deposited, given the absence of flowing water, it cannot be removed by dissolution, as if "frozen" there forever. The halite stalagmites found in Goat Cave are irregular, with knobs and deviations from the vertical, and are all white, with a dull or glassy (shining) appearance (Fig. 5A). This results from the fact that the feeding points of these stalagmites, generally straws, change their position regularly (are deviated by air currents), thus causing the irregular growth of the stalagmite below.

5.3. Columns

As in calcite speleothems in limestone caves, when halite stalactites touch the stalagmite growing below, or reach the ground, the feeding tube will be occluded. This gives rise to columns, which have significantly different shapes compared to their calcite relatives (Fig. 5B). First of all, in halite columns the water flow is extremely reduced, and no water film flows along the external surface of the speleothem. Calcite columns, on the other hand, are fed by water flowing along their sides, at least over certain periods of time. When a halite straw touches ground, the water from the feeder tube will start seeping out homogeneously along the entire length of the speleothem. These tiny amounts of halite-saturated water will evaporate, creating the typical botryoidal shape (a process similar to the one described above for occluded straws). The continuing concentric lateral growth of these botryoids will enlarge the column progressively, giving them a "knobby" or a "toothed" shape. If the process continues this may lead to a more than decimetre thick botryoidal column (Fig. 5C). These columns, both slender (straw-like) and large diameter ones, are often bent, sometimes taking on the shape of zigzag columns (cavers called one of the passages with these speleothems the "Moonwalk", from Michael Jackson's move on the stage) (Fig. 5D–E). Halite, in fact, is a much more ductile mineral compared with calcite (Picard et al., 2018), and is also subdued to pressure-solution (Martin et al., 1999). It is thus probable that when the straw touches the ground, it continues growing outwards, deforming the vertical shape, especially in deviations that were already present in the

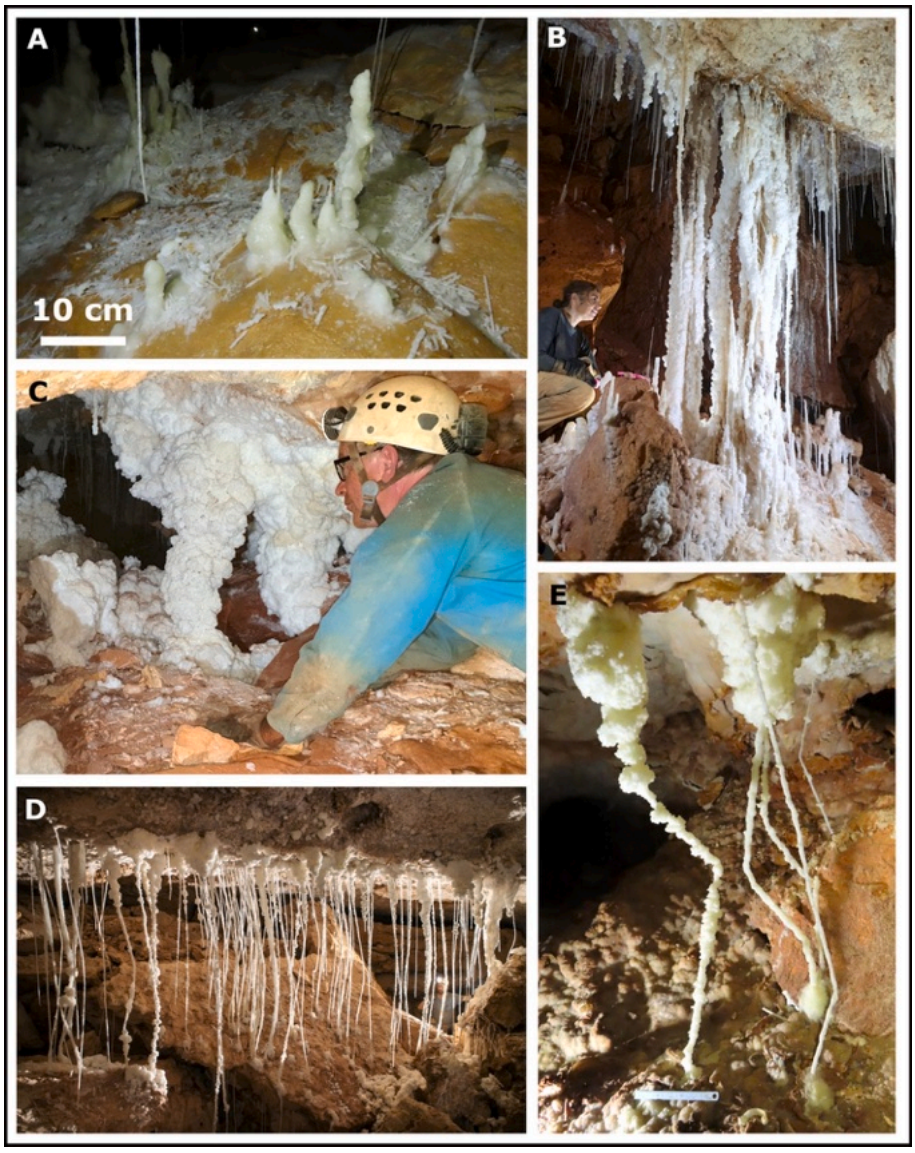

Fig. 5. A. Group of small halite stalagmites; B. big "glassy" column formation and; C. Botryoidal columns; D. bent columns originated from straws; E. The "moonwalk" straw columns.
(Panel A photo by Gareth Thomas; panel C photos by Brett Wiltshire; panel D photo by Alan Pryke; panel E photo by Gareth Thomas).

original straw before the column was created. Columns can have several deviations, going in different directions (Fig. 5E) and not always following the main axis of the passage, showing these changes in growth might not be strictly related to changing wind directions in the passage in which they grow. This is in contrast to how these zigzag columns and stalactites were explained in Filippi et al. (2011) and in Forti (2017). The changes in growth direction in Goat Cave speleothems must therefore be related to other causes, possibly to crystal growth changes in direction, rather than wind direction-induced crystal growth.

5.4. Fibrous speleothems

Cave halite, similar to gypsum, often displays a fibrous or filamentary crystal habit. Maleev (1971) distinguished four subtypes; lonely crystals (single fibres, often named "hair" or "needles"), more or less disorganised bunches of single fibres (which cavers often describe as "cotton", or "beards" when they hang from the ceiling), parallel-tied bunches (resembling unspun flax, often called "ropes"), and split bunches (fibres which split, described by many cavers as "flowers").

Fibrous speleothems in the Nullarbor are all formed by evaporation of capillary water from porous rock along the cave walls, and only rarely by condensation-evaporation processes (near entrances and close to important restrictions connecting larger passages). Crystallisation occurs in the pore spaces of the rock, and this process progressively pushes the older parts of crystals out of the rock (Maleev, 1971). The dimensions and distribution of the crystal fibres thus greatly depend on the pore size of the hostrock, and the density of these pores, respectively (Huff, 1940). Well-isolated tiny little pores give rise to single needles (hair) or an aggregation of these (cotton), whereas more closely-spaced and generally larger pores will give rise to flowers. Ropes, instead, form in places where porosity/permeability is locally high compared with the surrounding rock.

The disintegration of the different kinds of fibrous speleothems gives rise to powdery deposits and mounds on the cave floor, known by cavers as "snow" (Fig. 6A–B).

5.5. Hair-needles

Halite is often found in single, very delicate elongated crystals, forming needles (less than half a millimetre thick) or, when forming

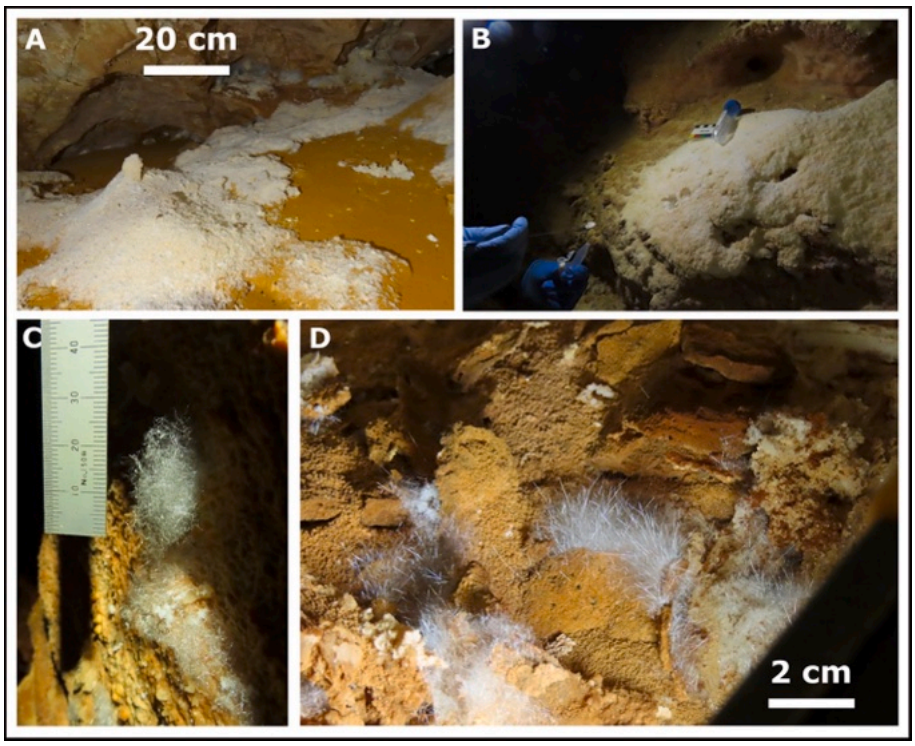

Fig. 6. A–B. Snow deposits derived from the disintegration of fibrous speleothems; C–D. halite hair.
(All photos by Gareth Thomas).

patches of intricate very fine fibres (with diameters of some tens of microns (Kowlaczyk and Sawłowicz, 2013), becoming a subtype known as hair (Fig. 6C–D). The longest of these needles form especially on detrital fine sediments on the floor, or in recesses on the wall, where they are sustained underneath and do not fall. When hanging freely from roof or wall, because of the elastic properties of elongated halite crystals, they tend to bend before breaking off under their own weight. The halite needles can reach over a decimetre in length (mainly those lying on the floor), but generally they are less than 2 cm long. Goat Cave is not the only cave having abundant deposits of halite hair. Salt fibres are abundant hanging from the roof of Mullamullang Cave, Western Australia (Wigley and Hill, 1966; Lowry, 1967).

5.6. Cotton-beards

When the patches of intergrown, fibrous halite crystals become very dense, so that voids between the single crystals can hardly be seen at naked eye, the fibrous speleothem is called cotton (greatly resembling the fibres in a cottonball) (Fig. 7A). Cave cotton usually lies on poorly inclined surfaces (floor or wall ledges), but is sometimes found sticking to cave ceilings. Halite cotton is usually white, but can be coated with a greyish hue in restrictions of the passage in Goat Cave, in areas exposed to strong airflow (Fig. 7B). Since there are no blackish or greyish sediments in the cave, we believe this greyish coating derives from soot, produced by bushfires at the surface, and brought far into the cave as airborne particles. Sometimes the white and dense patches of fibrous halite form hemispherical clumps, which is why cavers name these "cottonballs".

When the cotton clumps or densely packed fibres remain attached to ceilings or overhanging walls the combination of gravitational and crystallisation forces result in these formations looking somewhat like vertical waves, resembling whiskers (when a number of individual intertwined fibres hang down) (Fig. 7D) or beards (much denser cascading fibres) (Fig. 7C). These speleothems can take on a greyish coating, as some of the cotton described above. Some beards in Goat Cave reach lengths of over a metre, in some places forming 2 m wide "waterfalls". Most beards are free-hanging, and do not touch the passage floor. Several of them break open crusts that coated the ceiling and higher walls, and fragments of these crusts are still attached to their extremities. In some cases the beards reach the passage floor, their base surrounded by broken strands of fibres and needles (Fig. 7E). These are probably produced by the progressive breakage of the lower parts of the speleothem due to the ongoing growth of the beard above.

5.7. Ropes-helices

Isolated bundles of parallel strands curling down from ceilings, overhanging walls, or winding upwards from the floor or from ledges, somehow resembling unspun flax, are called cave ropes. There is often no clear distinction between beards (described above), ropes, and curls (described hereafter). The first have more slender (hair-like) strands (several tens of microns in diameter), the second are composed of thicker bundles (~1 mm in diameter) (Fig. 8A), curls, instead are even thicker (some millimetres or even centimetres). In ropes the speleothems are more isolated, whereas in beards the intertwined fibres of halite are much more densely packed.

Exceptional examples of ropes are the spiralling ones (Fig. 8B–C). Elsewhere in the world's caves most of these spiralling ropes are made of gypsum, but in Goat Cave they are all made of halite. These speleothems, looking like a spring with regular coils, are made of bundles of parallel fibrous crystals that curl around the central vertical axis of the speleothem. One of these helices is over 1 m long; it is marked for avoidance with an orange tape to prevent damage by cavers, but even with a person passing slowly at half a metre distance (the passage here is only 2 m wide) it oscillates in the moving air (Fig. 8B). Another helix, much smaller, is about 1 cm long, has eight coils turning counter-clockwise (Fig. 8C), like all the other helices seen in Goat Cave. It is possible but highly unlikely that this direction is caused by the Coriolis Effect where moving objects are deflected to the left in the Southern Hemisphere. Examination of photographs of similar gypsum helices from the

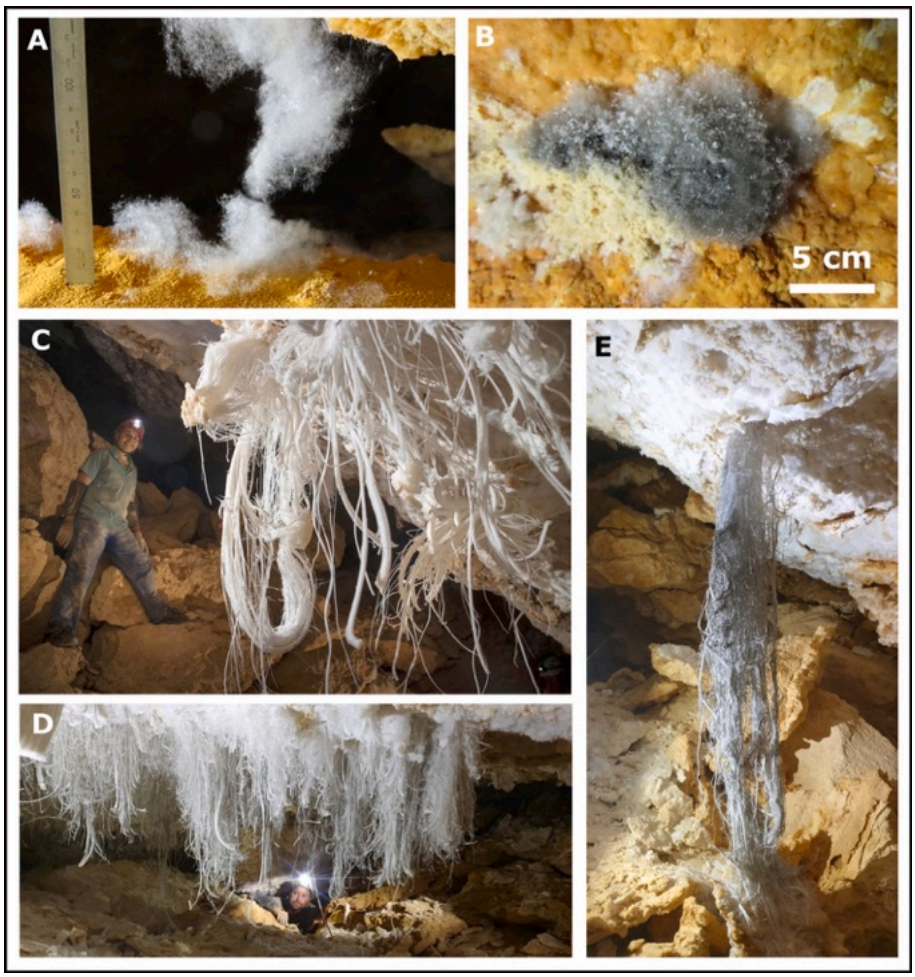

Fig. 7. A. White and; B. grey cottonballs; C. one-metre tall white beard; D. white curtain of halite beards (whiskers) and; E. grey beard; note the broken fragments of the floor.
(Panel B photos by Gareth Thomas; panel C photo by Alan Pryke; panel E photos by Brett Wiltshire).

Northern Hemisphere appears to show that they spiral in the opposite direction. This phenomenon in natural crystal growth direction appears not to have been reported in literature previously, deserves further research, and would need to be confirmed.

5.8. *Flowers-spiders-curls*

Both gypsum and halite flowers occur in Goat Cave, with the first occurring only sporadically, and the last being very abundant and widespread throughout the cave. Halite flowers consist of bundles of parallel crystals starting at a common central point and progressively curving outwards, forming a speleothem resembling the shape of a white lily flower (Fig. 9B). They occur on the floor of the cave, growing directly from the rock, from halite crusts (Fig. 9A), or on sediments, and on the walls and roof where they break gypsum and halite crusts or exit directly from the limestone (Fig. 9D). Halite flowers up to half a metre in diameter have been found in Goat Cave, although most are only a few centimetres wide.

A crystallographic study on gypsum flowers by Ghergari and Onac (1993) showed them to be composed of both fibrous and prismatic crystals growing in approximately parallel orientation, which brought Hill and Forti (1997) to classify cave flowers as a separate speleothem type.

Halite flowers, like all fibrous speleothems, grow from their base, their often coloured tips being the oldest parts and the ones touching the underlying rock or sediment the youngest. The curving of the fibre bundles is due to the faster growth in one of the sides of the bundle. Since the growth of the crystals depends on the quantity of feeding solution and its concentration in salts, the central part of the base of the flower is generally the place where most of the moisture arrives (and crystals grow more rapidly), causing the petals to curve outwards. This mechanism of cave flower growth was described by Locke (1842) for the beautiful gypsum flowers in Mammoth Cave (Kentucky, USA). Most bundles of parallel halite crystals do not appear to show "steps" or generations of growth (Fig. 9C), which might indicate they are the result of a single growth stage; they might have formed by recharge following a single infiltration event.

Halite flowers sometimes start forming beneath crusts, breaking through cracks and uplifting remnants of the crust which form a sort of hood upon the flower petals. Crusts are generally composed of halite, but in one area in Goat Cave a rounded mammillary calcite crust was broken by the growth of a thick halite fibre bundle, forming a sort of "mushroom", about a decimetre tall (Fig. 9E).

When the formation of the halite beneath a crust starts from a point, a normal flower with remnants of crust will form (Fig. 9D). Often the flower growth occurs along a linear fracture in the crust, creating spider- or octopus-like speleothem formations.

The thick bundles of halite fibres do not always produce flowers, but can also create single curls, or intermediate forms (mixtures of isolated flower petals and curls) (Fig. 9C). These curving halite speleothems are composed of parallel fibrous and prismatic salt crystals, the outermost bundles creating curving hooks, splitting away from the main

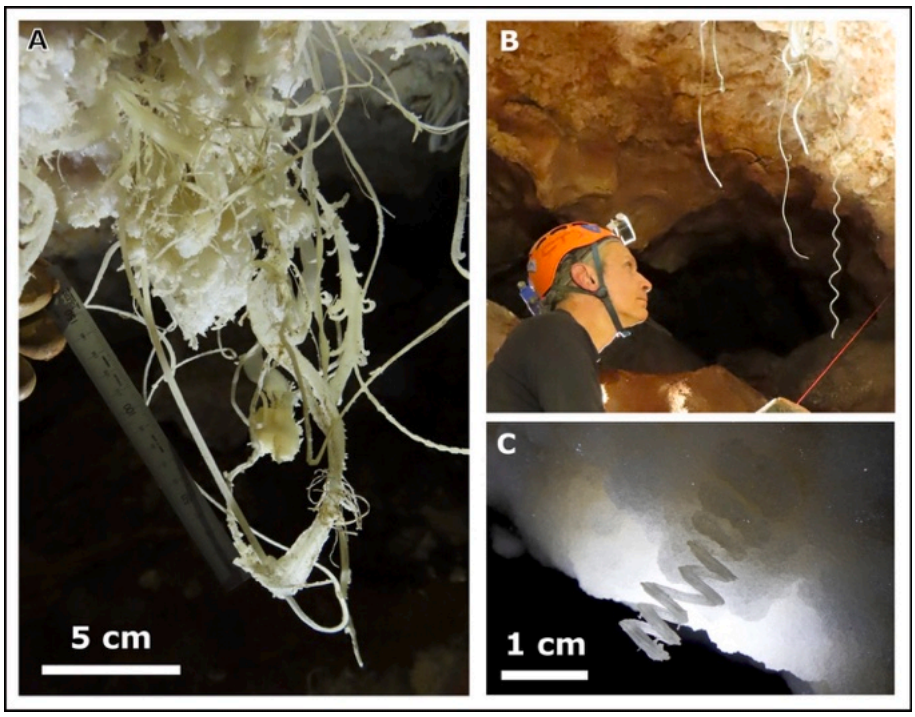

Fig. 8. A. Halite ropes (the finer ones) and curls (thicker); B. a long rope forming a delicate helix; C. a shorter helix with eight coils. (All photos by Gareth Thomas).

speleothem stem (Fig. 9F–G). Looking carefully at these strands of halite, small sugar-like crystals are often spotted on their outside (Fig. 9C), whilst most will be halite, some may be composed of sulphates such as gypsum, epsomite, or celestine. Epsomite has been confirmed on one halite speleothem by SEM analysis. Although the curving is often regular, deviations in direction are sometimes noticed (Fig. 9G), probably related to preferred orientation towards sites of major evaporation. In this case these curls might be confused with helictites, which have a capillary feeding channel. True halite helictites have not been identified in Goat Cave.

5.9. Crust-lace

One of the most abundant halite speleothems in Goat Cave are crusts, which cover wide portions of cave walls, ceilings, and floors (Fig. 10A). These crusts are generally white and have a sugary appearance, sparkling in caver's helmet lights, but sometimes take on a more orange, brownish or even reddish colour (Fig. 10B). These orange-red tones are caused by the inclusion of the so-called "coffee-and-cream" sediments that cover parts of the floors of the Nullarbor caves. Similar deposits were studied by Caldwell et al. (1982) at the start of the Easter Extension of Mullamullang Cave (N37). The "coffee" is a reddish-to-yellow silt-sized deposit, mainly composed of low magnesian calcite mixed with gypsum and halite fibres and some kaolin. The reddish colour comes from residual iron oxides (mainly hematite), with minor presence of manganese oxides. The "cream" is a more pinkish crystallised powder, of the same composition but with higher amounts of low-Mg calcite and less salts, and smaller concentrations in goethite and hematite, mixed with kaolin. These "coffee-and-cream" sediments appear to be produced mostly by salt-wedging of the Abrakurrie limestone and its insoluble residues, with some input from airborne and infiltrating weathering material coming from the surface.

Halite crusts form from evaporation of water seeping out of porous rock or from the loose fine sediments on the floor. In general water uniformly wets the cave walls, creating continuous crusts, and newly forming layers push the older crust outwards. In some cases the coating forms around cracks (fractures or bedding planes, or more permeable linear areas), forming ribbons often fading into the normal crusts on their sides (Fig. 10C). Cracks in the crust, or its own permeability, allow the air to remain in contact with the seepage water, so that evaporation can continue making crusts grow thicker and heavier. The crusts in Goat Cave are up to 2 cm thick, especially along the "Jewel Carriageway" where strong airflow assists evaporation. Eventually these halite shards, especially those hanging from roofs and vertical-to-overhanging walls, fall to the floor. When they cover the floor sediments, they grow from the capillary rise of waters retained in the fine granular deposits. These crusts unavoidably break under the weight of cavers, which is why tracks have been signed with reflecting tags or orange tape to encourage cavers to avoid disturbance of other areas.

Crusts can be very thin (some microns), composed of a network of interconnected crystals. The uneven growth of these crystals often causes these thin blankets to curve and detach from the wall or roof on which they form. This type of very fragile and porous net-like crust is here called "halite lace", which generally has surfaces of less than a decimetre (the bigger ones falling under their own weight) (Fig. 10D–E). Some of these halite lace speleothems have also been documented in Mullamullang Cave (e.g., https://adventureswithm.com/2013/09/28/nullabour-mullamullang-cave-september-2013/, consulted March 2026).

In one location along the "Jewel Carriageway", a millimetre thick crust has extended from the upper wall forming a curved drape-like crust which might be referred to as a shawl if it was larger (Fig. 10F–G).

5.10. Halite balls

In some areas of Goat Cave halite forms from a solution-feeding point source, creating hemispherical speleothems resembling small balls (Fig. 11A). One of these reaches a size of 15 × 11 cm, and its surface is composed of mm-sized protrusions resembling small coralloids, which are probably the vertices of small halite cubes. Unfortunately (or luckily) none of these speleothems were found broken, therefore no samples were taken to avoid damage. As a result, their internal parts have not been investigated. Most halite balls form along linear discontinuities,

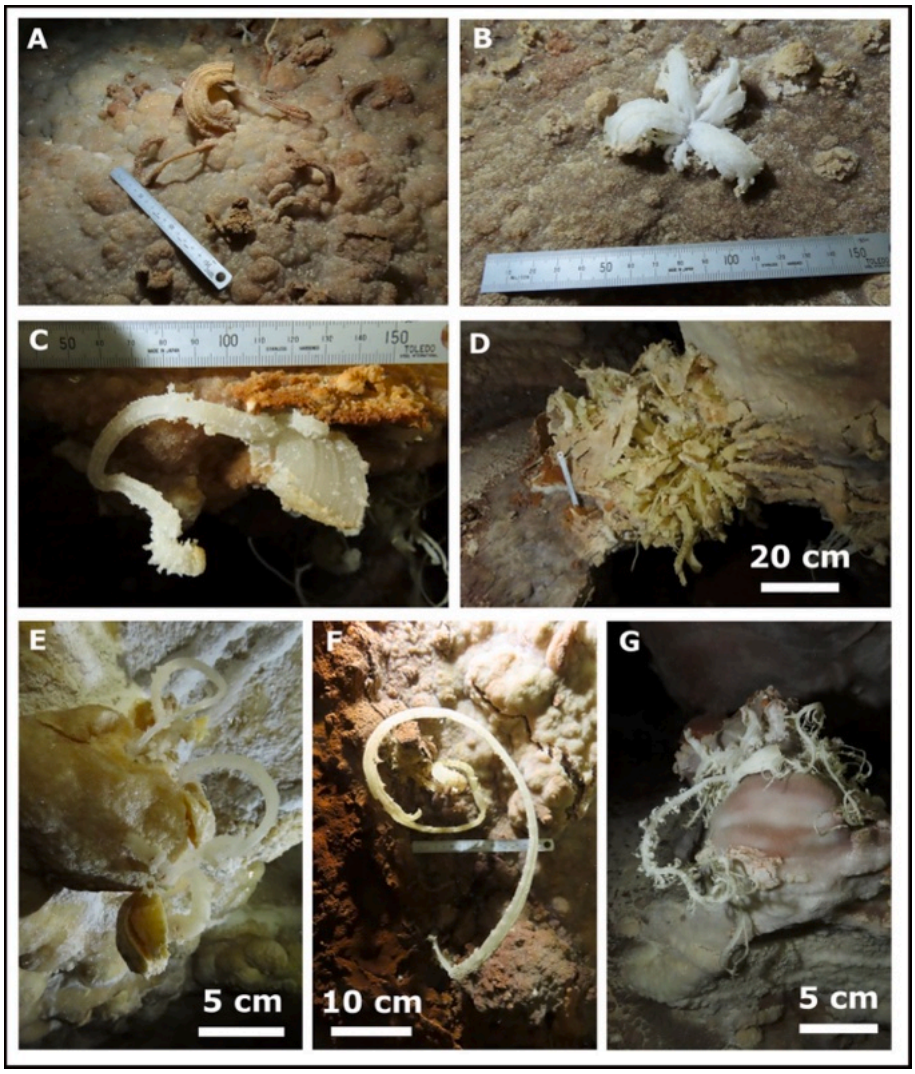

Fig. 9. A. Pinkish gypsum curls shown for comparison; B. a white halite flower; C. two halite curls with "sugary" overgrowth; D. spider-like (octopus) curls with remnants of crust on their ends; E. the "mushroom" curl and mammillary calcite hood; F. an almost 1 m long curl with some splitting; G. curls with "hooks"; note the reddish halite crust. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
(All photos by Gareth Thomas).

visible by a thicker halite crust, probably in places where capillary seepage water was faster and greater. Although we are not completely certain that its inner part is hollow, it appears (sounded) to be empty. The genesis of these speleothems should be similar to the halite blisters found on salt plains (e.g., Atacama, Chile, De Waele and Forti, 2010) and can probably be explained in the following manner; fast capillary seepage evaporates upon surfacing in the cave, leading to the precipitation of halite crystals as a crust around the recharging orifice. When the crust is thick enough, the seepage water does not evaporate fast enough, allowing it to remain under-saturated, dissolving part of the lower crust, and transporting this halite to the outer surface where it is redeposited. This continuous dissolution-reprecipitation process will eventually increase the ball's size. The fact that the halite is perfectly white makes us believe there are no reddish or brownish sediments inside the ball, as opposed to what was observed in the mud-filled gypsum balls of Sorbas (Calaforra and Forti, 1993). If this is the case, this would be the halite version of a gypsum ball, first described from Cueva del Agua in Sorbas (Spain).

5.11. Rafts-flakes

Evaporation of brines gives rise to the formation of halite rafts. These speleothems have been reported from all major halite karst areas in the world; in caves on Mount Sedom (Frumkin and Forti, 1997), in many Iranian areas (Filippi et al., 2011), and from Atacama (De Waele et al., 2009, 2017). These floating halite rafts also form on hypersaline lakes and have been described from the Dead Sea (Talbot et al., 1996; Sirota et al., 2017), from a saline acid lake in Southwestern Australia (Benison et al., 2000) and also from artificial salt ponds (e.g., Saudi Arabia, Aref et al., 2020).

In Goat Cave, where the host rock is limestone, salt rafts occur in association with calcite rafts. As the salty water contains, besides NaCl, also sulphates and carbonates, the progressive evaporation (and initially also CO_2 degassing) of the brine will deposit the less soluble minerals first, in the calcite-gypsum-halite order. Halite rafts crystallise in a final stage, covering the previously deposited minerals (Fig. 11B). Evaporation occurs everywhere in the caves because of airflow and the aridity of the Nullarbor climate. When the water bodies become supersaturated in NaCl, very thin flakes of halite, up to several tens of cm^2 in size, precipitate on the brine surface. When the halite rafts become too heavy they settle on the pool bottoms, or are left on the floor when the pools dry out completely. Rafts are overgrown by subaerial microcrystalline halite crystals, making them glitter in the light.

Rafts have been found mainly in now dry pools in association with

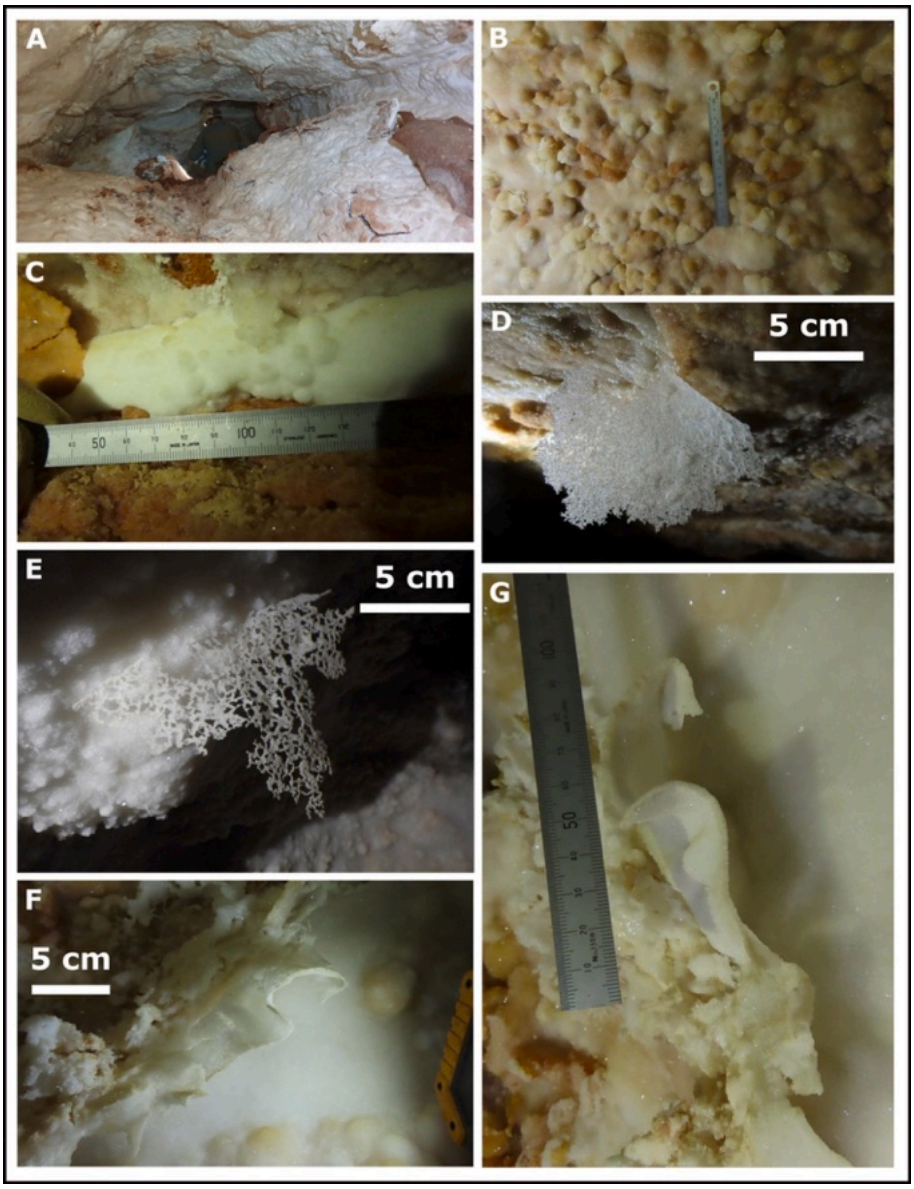

Fig. 10. A. Crusts covering all sides of the passage; B. typical "sugary" and variously tinted crust; C. a "ribbon" crust along a bedding plane; D–E. paper thin "lace" halite crust; F–G. detached crust resembling a drapery.
(Panel A photo by Brett Wiltshire; all photos B–G. by Gareth Thomas).

mammillary calcite, calcite rafts, folia, and gypsum. They are lying on horizontal ledges of mammillary calcite (cave clouds) as white transparent and very fragile flakes. In the same area also thicker flat chips are found composed of alternating layers of calcite and gypsum, finally covered with a thin white-to-transparent halite coating (Fig. 11C).

5.12. *Macrocrystalline (skeletal) stalactites*

Although macrocrystalline (skeletal) stalactites have been reported from Atacama (De Waele et al., 2009, 2017) and in many of the Iranian salt caves (Filippi et al., 2011), they have been seen only in a few wetter spots in Goat Cave. These few white and "shiny" stalactites have a sort of botryoidal shape, but at a closer look, the botryoids have the faint shape of salt cubes with rounded edges and corners (Fig. 12A–B). The edges of these crystalline shapes reaches up to 1 cm. All faces of the halite cubes appear to be oriented in the same direction, with the corner pointing downwards (but not perfectly vertical) corresponding to the long diagonal of the crystal. They occur in a narrower section of the "Jewel Carriageway", on a side wall. The outer surface of the stalactites is milky-glassy white and has a wet appearance, with a partial water droplet hanging from the end of the shorter one. Similar halite stalactites are found at the back of the entrance chamber, close to surface (Fig. 12C).

Whereas the macrocrystalline skeletal stalactites in the Iranian caves are clearly linked to the presence (at least occasionally) of irregularly splashing brine, and the related gravity- and capillary-induced water movement, this cannot be the case for those of Goat Cave, where brine streams are not present. In a certain sense, although less perfectly formed, they resemble more the macrocrystalline stalactites occurring in Atacama caves, in an extremely arid climate where water flow and sprays in the caves occur only very rarely. In Goat Cave, the source of water for the development of these speleothems comes from infiltration such as after heavy rainfall events, and condensation. In the very evaporative conditions of this cave, dripping is less important than capillary seepage, and this explains why these stalactites are not perfectly vertical.

Fig. 11. A. Halite ball; B. transparent white halite rafts coating the surface of a subaqueous mammillary calcite crust; C. calcite rafts with an external halite coating. (All photos by Gareth Thomas).

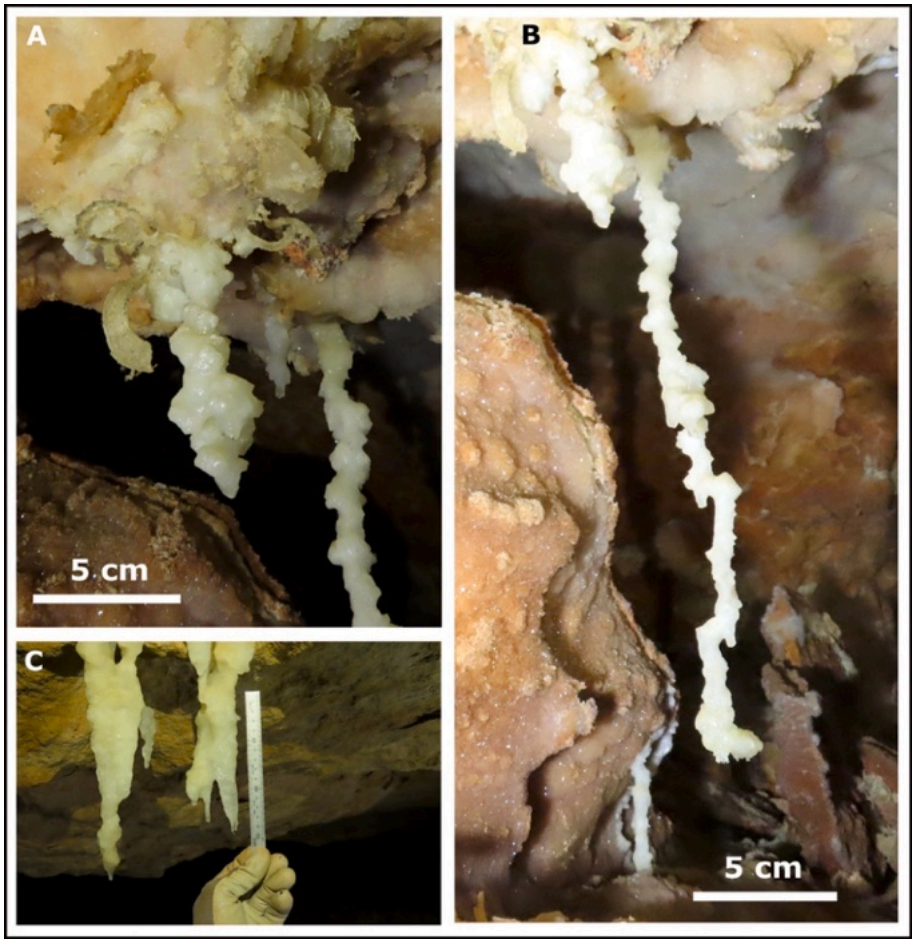

Fig. 12. A–C. Among the few macrocrystalline halite stalactites found in Goat Cave.
(Photos by Gareth Thomas).

6. Stable isotope composition of sulfate minerals

Stable isotope composition of studied sulphate mineral samples in Goat Cave (Table 1) ranges from +14.5‰ to +21.7‰ $\delta^{34}S$ (mean + 19.2 ± 2.5‰) and +3.9‰ to +9.9‰ $\delta^{18}O$ (mean + 7.2 ± 1.8‰). Except for three samples which have somewhat lower $\delta^{34}S$ values, the other cluster at ~21‰. Prostate Pit samples have similar isotopic composition (Table 1) with mean values of +19.3 ± 0.5‰ $\delta^{34}S$ and +8.7 ± 1.7‰ $\delta^{18}O$.

7. Preservation of animals and organic remains

The aridity and significant quantities of halite in some Nullarbor caves makes these places hostile to present-day life. Extant life forms are generally found in shallow caves, or close to entrances, but in the absence of water, or humidity, Nullarbor caves become generally lifeless as they get deeper. A good example of a cave-adapted animal (probably following the progressive aridification of the Nullarbor) is the spider Troglodiplura, a genus of blind arachnid only found on the Nullarbor (Fig. 13A). This genus contains five described species and molecular studies show that it occurs in caves from South to Western Australia, and in caves that show ancient (or still extant) connections between these underground habitats through subterranean pathways (Marsh et al., 2023).

Halite is a hygroscopic mineral, absorbing moisture from the surrounding environment. The presence of halite makes Nullarbor caves extremely suitable for the preservation of fossil remains of all kinds of animals (Prideaux et al., 2007; MacNamara and Murray, 2010). Cavers found a mummified carcass of a Thylacine (*Thylacinus cyanocephalus*, Tasmanian wolf or tiger) in a 250 m long and 27 m deep cave near Eucla (Thylacine Hole, Lowry and Lowry, 1967), and another specimen with traces of whiskers and skin in 2015 (White et al., 2017). The first Thylacine was dated at about 4600 years B.P. (Lowry and Merrilees, 1969) and is on display in the Western Australian Museum. This marsupial carnivore, once present in mainland Australia and in Tasmania (where the last specimen died in 1936), disappeared from the continent over 2000 years ago, before the arrival of Europeans, but when the dingo had already spread along the Australian mainland (about 3500 years BP). An extinct Marsupial Lion (*Thylacaleo carnifex*) together with extinct species of tree kangaroos and birds were discovered in the years following 2002, hinting to periods of much higher rainfall during the Pliocene and into the early Pleistocene (Prideaux et al., 2007). Many mammal remains have been found in several caves across the Nullarbor (Baynes, 1987), shedding light on the past biodiversity of this region, and the impact of human settlement on indigenous fauna (Travouillon and Phillips, 2018; Reed, 2023).

Goat Cave is no exception to the common finding of preserved animals in Nullarbor caves, with a large number of dead animals (mammals and arthropods) found in shallow cave areas right through to the deepest ones (Travouillon et al., 2025). Among the mammals, >10 mummies of possums (Common Brush-tailed Possum, *Trichosurus vulpecula*) were found in different parts of the cave, up to 80 m below ground (Fig. 13B). Several of these are so well preserved that fur and whiskers are still in perfect condition, and dried out decomposition fluids are still present. A well-preserved Chuditch (Western Quoll, *Dasyurus geoffroii*) has been found lying on a rock in the "Jewel Carriageway" (Fig. 13C), and a mummified bat (Chocolate Wattled Bat, *Chalinolobus morio*) was discovered in an area not too far into the "Entrance Series". Two possums and the quoll were extracted during a delicate operation in 2025, and one possum will be displayed at the Western Australian Museum, Kalgoorlie. Samples of fur of several specimens will allow C^{14} dating, and molecular and genetic studies. Dating of mammal fur samples is being carried out by the Western Australian Museum (Travouillon, pers. comm., May 2026).

Exceptional numbers of a wide variety of spiders (Fig. 13A–D), opilionids, cockroaches (Fig. 13D–E–F), and centipedes (Fig. 13G) have been found in many places, most of which are probably new to science (Marsh, pers. comm.). The most astonishing discovery has been a species of blind wasp (Fig. 13H), probably connected to the widespread occurrence of Troglodiplura or other cave-adapted spiders in Goat Cave (spider wasps are parasitoids, laying their eggs on live spiders, from which the larvae feed and develop) (Rodriguez et al., 2026). All species are currently under study by the South Australian Museum and Adelaide University.

Table 1
Stable isotope composition of sampled sulphate minerals.

No	Sample code	Cave	Description	$\delta^{34}S$ (‰, VCDT)	$\delta^{18}O$ (‰, VSMOW)
1	G4	Goat Cave	Down the ramp, gypsum crusts-coralloids	+20.8	+7.7
2	G5		Western Distributor (station 52) yellowish salt	+17.4	+3.9
3	G6		Rocktopus gypsum crusts	+20.8	+9.9
4	G7		Speed Hump gypsum crystals (station 23072)	+21.0	+7.3
5	G10		White gypsum crust coating sample G8	+14.5	/
6	G12		Gypsum fibres from the extreme western end (G12)	+21.7	+6.7
7	G13a		Sulphur (yellow) (survey station 25A154)	+20.0	/
8	G13b		Gypsum (survey station 25A154)	+20.4	+7.6
9	G14		Yellowish salt (survey station 25M002)	+16.6	+7.1
10	P1	Prostate Pit	Gypsum blisters on roof of first room	+19.3	+6.9
11	P2		Yellow gypsum stalactite	+18.8	+9.1
12	P3		Brown gypsum column just before the stegamite chamber	+19.7	+10.2

8. Discussion and conclusions

Halite and gypsum speleothems are abundant in many of the limestone caves on the Nullarbor.

The sulphur isotope composition of gypsum from Goat Cave and Prostate Pit is similar to the one from Mullamullang Cave (Lipar et al., 2019). These values are much more positive than what is typical for gypsum from sulphuric acid caves (Fig. 14), where microbial sulphur reduction leads to rather negative $\delta^{34}S$ values (e.g., Galdenzi and Maruoka, 2003; Chervyatsova et al., 2016; Temovski et al., 2018; De Waele et al., 2024), although higher values can be found in some cases (e.g., Onac et al., 2011). Nullarbor cave gypsum $\delta^{34}S$ are very similar to the range of marine sulphate, with modern seawater value having +21.15 ± 0.15‰ $\delta^{34}S$ (Johnston et al., 2014). A similar range is characteristic for Miocene (21.6–22.7‰) and Eocene (17.4–22.5‰) seawater, the periods representing the age of the limestone on the Nullarbor (Claypool et al., 1980; Paytan et al., 1998). The seawater source of sulphate for Nullarbor cave gypsum is also supported by their $\delta^{18}O$ values, which are within the range for modern (Johnston et al., 2014) as well as Miocene and Eocene (Waldeck et al., 2022) marine sulphate (Fig. 14). The sulphate within the Nullarbor caves is derived from either marine evaporite gypsum, (Lipar et al., 2019), or more likely from sea salt aerosols. The $\delta^{18}O$ values are within the range of gypsum from South Australian playa lakes, where values decrease from +21‰ at the coast to +14‰ inland, suggesting a seawater source for the sulphur (Chivas et al., 1991).

Fig. 13. A. Troglodiplura; B. one of the best preserved possums; C. the Western Quoll; D. troglodiplura and cockroach; E. cockroach; F. small cockroach on a halite curl; G. centipede; H. *Troglopompilus miracaecatus*, a blind spider wasp.
(All photos by Gareth Thomas).

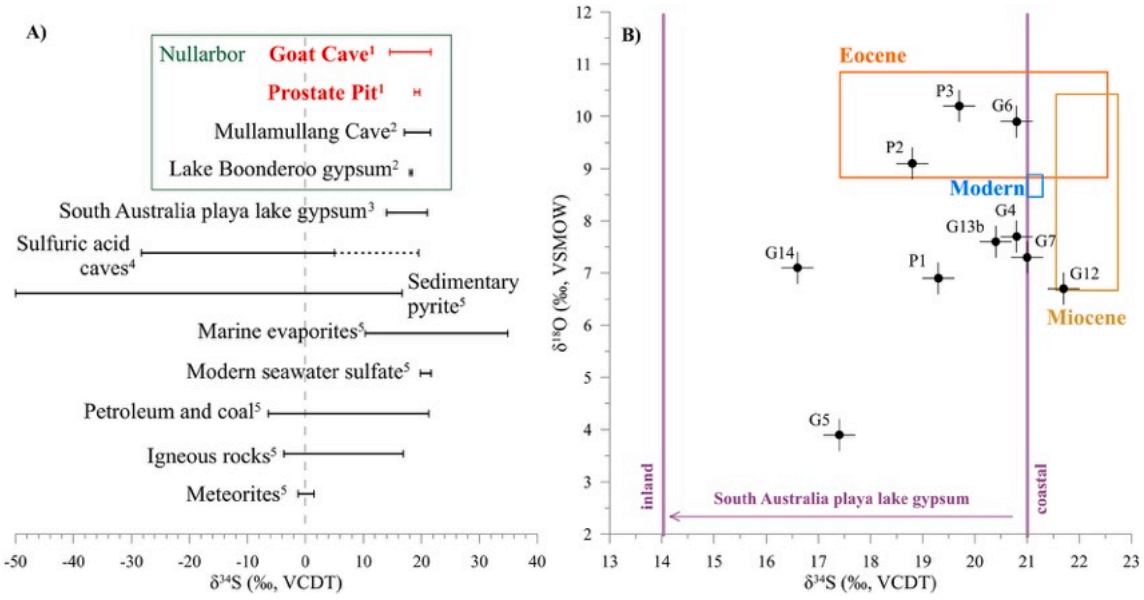

Fig. 14. Stable isotope composition of gypsum from Nullarbor Caves: A — Nullarbor cave gypsum $\delta^{34}S$ values compared to various sulphur reservoirs (1 — this study; 2 — Lipar et al., 2019; 3 — Chivas et al., 1991; 4 — De Waele et al., 2024; 5 — Seal, 2006); B — Cross-plot of sulphur and oxygen stable isotope composition of gypsum samples from Goat Cave and Prostate Pit compared to seawater sulphate (Johnston et al., 2014; Claypool et al., 1980; Paytan et al., 1998; Waldeck et al., 2022) and the $\delta^{34}S$ range of South Australia playa lake gypsum (Chivas et al., 1991). Note that cave gypsum $\delta^{18}O$ values represents bulk oxygen isotope composition.

Some of the Na^+, Cl^-, and SO_4^{2-} ions may originate from seawater evaporite deposits, likely to exist in claypans and elsewhere on the Nullarbor, with salt and gypsum having been reported in claypans (Lowry, 1967), and minor, possibly pedogenic, gypsum further inland

near the Transcontinental rail line (pers. comm. Lipar, 2025). The presence of seawater evaporite deposits from ca. 14 Ma on the Nullarbor is possible, but requires further investigation. Otherwise, the Na^+, Cl^-, and SO_4^{2-} needed for the halite and gypsum in Nullarbor caves would originate from the uplift of sea salt aerosols (SSA) into the higher troposphere, getting incorporated in cloud moisture. The re-dissolved ions return to the ground in rainfall, with a decreasing concentration of dissolved salts typically occurring with increasing distance from the coastline (Carroll, 1962; Hingston and Gailitis, 1976). The term "sea spray" has been used in other papers in the past, but the term should be avoided and more accurate terminology used for clarity. Sea salt aerosols (SSA) are well documented as a major source of ions in rainwater (e.g., Jiang et al., 2019). Transportation of these SSA ions through the troposphere is a global phenomenon (for reference: https://svs.gsfc.nasa.gov/5552/).

The marine salts have accumulated in the Nullarbor's limestone and in its caves since at least the late Pliocene (~3 Ma) when the climate became arid to semi-arid, if not even earlier (Woodhead et al., 2019). Runoff occurred only very rarely and was very local, getting swallowed by the many solutional openings that characterise these limestones. In consequence, salts are dissolved by infiltrating waters and are continuously transferred downwards. To understand the scale of this process, rainwater delivers about 3 million tonnes of sodium chloride (NaCl)/million years/km^2 to the Nullarbor (Thomas, per. comm, 2026). Additional ions are also deposited from the sea salt aerosols dissolved in rainwater. Apart from retention of sodium chloride (salt) in saltbush, bluebush, samphire and other vegetation, none of this salt remains on the surface of the Nullarbor. It is all washed into the ground by the limited rainfall before any residual moisture evaporates in the dry climate. The dry conditions of the caves, and the airflow through them, causes salts to deposit in these voids, with abundant and spectacular decorations especially in the deeper sections of Goat Cave. Some of these salts will eventually reach the groundwater table. The groundwater below the Nullarbor is saline, with the salinity increasing towards the coast, as the groundwater slowly moves towards it (James et al., 1991).

Seven secondary cave minerals have been found in the samples from Goat Cave. Alongside halite, gypsum, and calcite, and the expected hydrated magnesium sulphates epsomite and hexahydrite, small amounts of celestine were also found growing on and within gypsum. Similarly to celestine, also the very rare calcium iodate lautarite has been found, forming well-developed small crystal bundles on gypsum. This is the first mention of this mineral outside of Chile, and the first in Australia. Finally, also authigenic microcrystalline quartz has been found coating halite and gypsum.

Goat Cave hosts large volumes of precipitated salt, with nine types of halite speleothems, the fibrous speleothems being split in four subtypes (following the classification of Hill and Forti, 1997). Variety is not so great compared with Iranian and Israeli salt caves, due to the lack of running water in Goat Cave. However, Goat Cave is probably among the most important limestone caves for its halite speleothems. It hosts the longest halite straws in the world (up to 4.8 m), probably due to the tectonic stability of the area and the lack of animal frequentation (including cavers), and also contains the only known halite ball in the world (similar to the gypsum balls in Sorbas, Spain). The very dry and salty conditions, moreover, have created ideal conditions for the conservation of all animal and organic remains in the cave. Many mummies of preserved mammals have been found, along with many thousands of dead arthropods. All these animals seem to have been "frozen" by sudden death, possibly related to the emptying of water pools in deep areas of the cave due to lowering groundwater levels, possibly related to the cessation of or lack of any recent infiltrating fresh water, and to the current presence of large amounts of sodium chloride (salt; halite) in the cave. Investigations on this rare biodiversity and its fate are currently being carried out by specialists in South and Western Australia.

CRediT authorship contribution statement

Jo De Waele: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gareth Thomas:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peter Downes:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Marjan Temovski:** Writing – review & editing, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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