Origin of gypsiferous intrusions in the Hawasina Window, Oman Mountains: Implications from structural and gravity investigations

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ABSTRACT

Gypsiferous intrusions are exposed in road-cuts in the south-central Hawasina Window in the central Oman Mountains. They are located at lower structural levels in the allochthonous Hawasina Complex and lie along faults that cut Upper Cretaceous structures related to the obduction of the Semail Ophiolite and Hawasina Complex deep-water sediments onto the Arabian Plate. The intrusions form gypsiferous pods that are up to 200 m long, in which the gypsum occurs as a dark, fine-grained matrix that contains a pervasive network of anastomosing veins of gypsum and anhydrite. The intrusions contain abundant sub-angular to sub-rounded litharenites, and less common fragments of chert and fine-grained limestone. Although these clast types are undated, their petrographic characteristics suggest they originate from the local Hawasina (Hamrat Duru Group) country rock. Very well-rounded pebbles and cobbles of feldspathic litharenites, some of which show a well-developed cleavage, and rarer cobbles of well-rounded vein quartz appear to have come from the basement. Gravity investigations indicate salt diapirs are not present beneath the Hawasina Window. Instead, the gypsiferous intrusions are interpreted as having been brought up from depth during compression to form disconnected pods along deep-rooted faults, bringing with them small amounts of the basement country rock. Strontium isotope analysis and regional considerations, in particular the distribution, age and nature of other evaporite units on the eastern Arabian Plate, suggest the gypsum may have its origins in the Neoproterozoic (Ediacaran) to lower Cambrian Ara Group evaporites, perhaps from a previously unknown extension of the Fahud Salt Basin beneath the Hawasina thrust sheets.

INTRODUCTION

The Hawasina Window in the central Oman Mountains (Figures 1 and 2) is an elongate diamond-shaped tectonic window through the Upper Cretaceous Semail Ophiolite that exposes a complicated substructure of allochthonous deepwater Neo-Tethyan oceanic sediments (the Hawasina Complex) and subduction-related sedimentary and tectonic mélanges, and metamorphic rocks that comprise the Haybi Complex (Glenie et al., 1974; Graham, 1980; Searle and Malpas, 1980, 1982; Cooper, 1986, 1990; Searle and Cooper, 1986; Béchennec et al., 1990; Rabu et al., 1993; Csontos et al., 2010a).

The tectono-stratigraphic framework of the Oman Mountains is well established (Figure 3). Rifting in the Permian initiated development of the Hawasina Ocean, that part of Neo-Tethys adjoining what is now northern Oman. A Permian and Mesozoic carbonate platform (Hajar Supergroup) formed along the edge of the Arabian Plate and passed laterally into the predominantly continental slope sediments of the Sumeini Group and continental rise sediments of the Hamrat Duru Group. These in turn passed laterally into a series of intra-oceanic carbonate-topped seamounts (Kawr Group), their talus apron (Al Aridh Group), and the deep-ocean sediment-starved cherts of the Umar Group.

The Semail Ophiolite was formed within the Oman segment of Neo-Tethys during the Cenomanian (Tippit and Pessagno, 1979; Tilton et al., 1981; Warren et al., 2005; Rioux et al., 2012). This was synchronous with subduction and the onset of closure of the Hawasina Ocean, based on ages derived from metamorphic sole rocks at the base of the ophiolite (Gnos and Peters, 1993; Hacker, 1994; Hacker et al., 1996; Rioux et al., 2013). The Semail Ophiolite and Hawasina and Haybi complexes were emplaced onto the Oman margin during the Late Cretaceous as a series of thrust sheets that, on a large scale, preserve a proximal to distal stacking order. Passive margin sedimentation returned during the Late Campanian–Maastrichtian (Nolan et al., 1990; Skelton et al., 1990).
Maps and descriptions of the structure of the Hawasina Window have been previously published by Glennie et al. (1974), Graham (1980), Open University (1981), Villey et al. (1986), Searle and Cooper (1986) and Csontos et al. (2010a). The presence of gysiferous intrusions was not recorded in geological mapping before Csontos et al. (2010a). They became apparent only following the excavation of road cuts through the outcrops that generally lie along valleys. These intrusions penetrate the structurally lowest exposed thrust sheets of the Hamrat Duru Group and are almost unique in the Oman Mountains. The only other outcrops of evaporite minerals in the Hawasina Complex are found in Jabal Sumeini (Ali et al., 2014).
Qumayrah, (Csontos et al., 2010a, b; Cooper et al., 2012, 2013), and along the western edge of Jabal Sumeini where they appear as poorly-exposed outcrops (Figure 1). Significant evaporite deposits are notably absent from the Permian and Mesozoic shelf carbonates of the Hajar Supergroup. They are also not found in the pre-Permian basement where it crops out in the Oman Mountains in the Al Jabal Al-Akhdar and Saih Hatat areas, and the Musandam Peninsula. Evaporites are, however, present to the SW in the Fahud and Ghaba Salt Basins (Ediacaran–early Cambrian Ara Group; Heward, 1990; Mattes and Conway-Morris, 1990; Peters et al., 2003; Al-Siyabi, 2005; Reuning et al., 2009; Schoenherr et al., 2010) and the Mesozoic and Tertiary of the Arabian interior (Ziegler, 2001).

Figure 2: (a) Satellite image of the Hawasina Window showing the main lithological units and location of the detailed mapping in Figure 5. (b) Geological map of the same area based on Glennie et al. (1974); Open University (1981); Villey et al. (1986), and Searle and Cooper (1986) locating the area of gypsum intrusions.

Figure 3: Schematic cross section through the Oman Tethyan continental margin and Hawasina Ocean in the central Oman Mountains showing the main tectonic units and distal-proximal stacking. The Haybi Complex includes dismembered remnants of the Al Aridh, Kawr and Umar groups.
This paper describes and interprets the stratigraphic and structural characteristics of the recently identified gypsiferous intrusions in the Hawasina Window based on field studies and geological mapping. In addition, two gravity transects were made at right angles to each other to help constrain the origin and emplacement of the gypsum bodies within the structural framework of the allochthonous Hawasina sediments and their autochthonous basement. An analysis of strontium isotopes in the gypsiferous material was undertaken to constrain the age of the source of the intrusions.

STRUCTURAL CONTEXT OF THE GYPSUM INTRUSIONS

Stratigraphic Framework of the Hamrat Duru Group

The south-central Hawasina Window in which the gypsiferous intrusions are located comprises various litho-stratigraphic units of the Hamrat Duru Group (Figure 4). These span the late Permian to Late Cretaceous and record the passive margin evolution of multiple submarine fan systems derived from off-margin carbonate and clastic transport, punctuated by periods of regional deepening through the carbonate compensation depth (CCD) and the deposition of cherts (Graham, 1980; Cooper, 1986, 1990; Searle and Cooper, 1986; Villey et al., 1986). The succession ends with a sequence of debris sheets that represent destabilisation of the margin edge as a response to the onset of subduction within the Hawasina Ocean beneath the oceanic crust that forms the Semail Ophiolite (Robertson, 1987a, b; Cooper, 1990).

The gypsiferous intrusions penetrate the upper Permian to Lower Jurassic Al Jil and Matbat formations along the central axis of the Hawasina Window, where higher stratigraphic levels have been removed by erosion and thrusting within the allochthonous thrust stack (Searle and Cooper, 1986).

Structural Overview of the Southern Hawasina Window

The broad structure of the southern Hawasina Window is formed by stacked thrust sheets of Hamrat Duru Group sediments that are structurally overlain by the Haybi Complex. These are, in turn, structurally overlain by the Semail Ophiolite,
which define the edges of the Hawasina Window. This sequence is modified in the central Hawasina Window by major culminations of Sumeini Group slope sediments that have penetrated the Hamrat Duru Group and Haybi Complex. The assembled thrust stack was later folded along a NW-SE axis into a major anticline. This lies along the NW continuation of the Al Jabal Al-Akhdar anticline in the shelf carbonate sequence which plunges beneath the Hawasina thrust sheets at the SE corner of the Hawasina Window (Figure 2b).

The distribution of thrust sheets is not symmetrical across the southern part of the window (Figures 5 and 6). Three main thrust sheets of the Hamrat Duru Group are exposed on the NE-dipping eastern side of the southern Hawasina Window, and it is into the structurally lowest of these thrust sheets that the gypsiferous intrusions occur. The upper two thrust sheets contain multiple imbricates that are folded round the SE end of the window, where they are progressively cut out so only the Lower Hamrat Duru Group Thrust Sheet is present along most of the steeply SW-dipping SW side of the window.

The Haybi Complex is a distinct structural unit that comprises dismembered alkali basalts and pillow lavas, thrust slices of the Kawr and Umar groups, sedimentary and tectonic mélanges, and greenschists and amphibolites belonging to the metamorphic sole of the ophiolite. The Haybi Complex along the southern part of the Hawasina Window is locally interleaved with thrust-bound slices of sedimentary rocks that have a close affinity to the Hamrat Duru Group and serpentinite sheets. The geometry suggests significant out-of-sequence re-thrusting and re-stacking within the structurally higher parts of the allochthon, as also noted by Searle and Cooper (1986) and Csontos et al. (2010a). Late-stage normal faulting along the western side of the Hawasina Window is linked to folding and uplift. This has eliminated most of the upper Hamrat Duru and Haybi thrust sheets so the Semail Ophiolite lies against the Lower Hamrat Duru Group Thrust Sheet. The entire Hawasina and Haybi complexes have also been eliminated by faulting around the plunging nose of Al Jabal Al-Akhdar to the SE of the area. There, a SW-facing anticline exposes shelf carbonates and their foredeep sedimentary cover (Aruma Group) which are structurally overlain by the serpentinite sheet at the base of the Semail Ophiolite. These features have been explained by a possible blind thrust within the shelf carbonates, and the development of normal faults associated with uplift of the Al Jabal Al-Akhdar anticline (Searle, 2007).

**Structure of the Lower Hamrat Duru Thrust Sheet Host Rocks**

The Lower Hamrat Duru Thrust Sheet has been intensely folded and internally deformed by small and medium-scale thrusts and shearing but, in the southern Hawasina Window, it remains essentially as a single unit without significant internal imbrication. At least four major phases of folding are recognised (Searle and Cooper, 1986; Searle 2007; Csontos et al., 2010a): (1) SW-facing folding and thrusting relating to detachment and emplacement, (2) compression, rotation and refolding of these folds into NE-verging backfolds, (3) continued compression creating large-scale box folding of the entire Hawasina Window, and (4) doming linked to the growth of the Al Jabal Al-Akhdar anticline to the SE. The gypsiferous intrusions are located along faults that cut across and thus post-date phases (1) to (3), which relate to emplacement in the Late Cretaceous of the Hawasina nappes and Semail Ophiolite. The relationship between the intrusions and phase (4), dated by apatite fission track analysis as Oligocene by Mount et al. (1998), is less clear.

At the broadest scale, the E-W structure of the Lower Hamrat Duru Thrust Sheet is a multi-kilometre-scale box fold (cross sections Figure 6). A complete Hamrat Duru Group stratigraphy is preserved along the NE and SW edges of the window where the Lower Thrust Sheet dips to the NE and SW beneath structurally higher units. NE-facing folds and NE-directed backthrusts affect all rocks along the NE-dipping NE margin of the Hawasina Window (point 1 on Figure 5). WSW-directed thrusts and SW-verging folds occur along the SW-dipping western side (point 2 on Figure 5, Figure 7a).

The Guwayza to Nayid formations are not preserved in the Lower Hamrat Duru Thrust Sheet at the southern end of the Hawasina Window, on either its eastern or western sides, and the roof thrust lies within the Matbat Formation. This thrust plane has been intruded by serpentinite that forms a band up to 1 km wide along the northern side of Wadi Qurta and locally penetrates the Lower Thrust Sheet along thrusts within the Matbat Formation (point 3 on Figure 5).
Figure 5: Geological map of the south-central Hawasina Window showing the main lithological and structural units and the location of the gypsum intrusions. Inset (bottom left) shows the distribution of the main thrust sheets. Note that areas shown as Haybi Complex locally include interleaved thrust slices of Hamrat Duru Group lithologies, which are not mapped separately at this scale. Numbers locate features described in the text or figure captions. See Enclosure I for details.
The core of the anticline along the central part of the southern Hawasina Window exposes rocks of the Al Jil and Matbat formations. The anticline fold axis is broadly marked by the NNW-trending Wadi Ad Dil and Wadi Qurta tributary which also mark the line of major faults along which most of the gypsiferous bodies are found. On the east side of this line, structures form a broad fan that exposes mostly Al Jil Formation rocks, with steep NE-facing folds to the west of Jabal Milh/Qarn Harmali that become tight, upright and en échelon along the eastern side of Wadi Ad Dil where they are associated with laterally discontinuous top-to-the-SW thrusts (point 4 on Figure 5). Folds become...
Figure 7: Photographs of the structure of the south-central Hawasina Window. AJ1, 2, 3: informal members of the Al Jil Formation; MbL, MbU: lower and upper members of the Matbat Formation; Gw, Si, Ny: Guwayza, Sid’r and Nayid formations. Note that implied dips from annotated boundaries may be distorted from actual due to perspective effects. (a) Composite panorama of the western side of the Hawasina Window. SW-dipping folded Nayid, Sid’r, Guwayza and Matbat formations (left side of photo) give way to the east to flatter and NE dipping lower Matbat sandstones and shales (brown centre). Vertical to steeply SW-dipping Al Jil Formation member 3 cherts form the centre and eastern (right) skyline. (b) Gypsum body lying on fault (f) running along the upper reaches of Wadi Qurta tributary separating upper Matbat Formation (west side) from Al Jil Formation member 1. Dotted area top left enlarged in photograph (c). (c) Zoom of Jabal Milh showing NE-verging recumbent syncline in upper Hamrat Duru Group stratigraphy. (d) Panorama of the col between Wadi Qurta tributary and Wadi Ad Dil showing location of gypsum along the Wadi Qurta tributary fault and folding and thrusting in the Hamrat Duru Group country rock.
more generally WSW-facing to the south where beds dip at about 50° to the east (point 5 on Figure 5). The Lower Hamrat Duru Group Thrust Sheet eventually becomes S-dipping as it wraps around the southern side of the Hawasina Window. The west of Wadi Ad Dil and Wadi Qurta tributary is marked by a wide zone of Matbat Formation rocks that are deformed by open, west-vergent folds and thrusts.

The faults along Wadi Ad Dil and the northern part of Wadi Qurta tributary, along which most of the gypsiferous bodies are found (stars 8 on Figure 5), offset structures and stratigraphy down-to-the-west. At its maximum, the fault along Wadi Ad Dil places the lower member of the Matbat Formation against the lowest Al Jil Formation member 1, indicating a throw of at least 150 m (point 6 on Figure 5). Displacement diminishes to the south before increasing along the northern half of Wadi Qurta tributary where, at its maximum, the lowest Al Jil Formation member 1 on the east side is faulted against the upper part of the upper member of the Matbat Formation on the west side, suggesting a throw of at least 400 m (point 7 on Figure 5). Locally, dismembered slices of Al Jil Formation sandstones and cherts (members 2 and 3) are exposed along the line of the fault. The fault dies out to the south where Al Jil Formation cherts (member 3) are continuous across Wadi Qurta tributary.

Hydrothermal sinters that are locally sulphurous with vuggy and highly altered country rock are found to the north along the Wadi Ad Dil fault and in a side tributary to the west. Sinters, while comparatively rare, are developed more widely in the Hawasina Window, for example along the east side of Jabal Rastun to the north.

**DESCRIPTION OF THE GYPSUM INTRUSIONS**

The main gypsum intrusions are exposed along the segment of the Wadi Qurta tributary fault that shows its greatest displacement, close to the col between Wadi Qurta tributary and Wadi Ad Dil (stars 8 on Figure 5). Here, the gypsiferous outcrops are seen in road-cuts for a distance of about 600 m (Figures 5 and 8). The two main outcrops in the road cuts are each about 200 m long and up to about 10 m high. These dimensions are a product of the road building excavations. The gypsiferous bodies are not exposed outside the road cuts due to their low weathering and concealment beneath recent talus and wadi gravels, and the road itself. However, their distribution is constrained by nearby exposures of the Hamrat Duru Group country rock. These exposures suggest the gypsum forms, at least at the surface level, a series of elongate pods up to about 50 m wide oriented NNW-SSE, parallel to the line of Wadi Ad Dil/ Wadi Qurta tributary. It is not possible to determine whether these pods are separated or joined by thinner segments. The tops of at least two other gypsum pods may be present further to the SSE along Wadi Qurta tributary. These are suggested by the presence of highly weathered pink-orange breccia with gypsum veining. The second outcrop area is seen towards the top of Wadi Hawasina (star 9 on Figure 5), where a single, irregular intrusion is exposed over approximately 100 m along a road-cut through rocks of the Hamrat Duru Group. It is located along a high-angle late-stage fault that cuts through the folded and Hamrat Duru thrust stack and juxtaposes the Al Jil Formation members 1 and 3 (Figure 8a). The top of the intrusion is truncated by sub-recent raised alluvial boulder terraces.

The freshest material is mid- to dark grey and comprises an impure gypsiferous matrix containing a significant amount of silt and sand-grade quartz and carbonate material grading up into numerous pebbles and cobbles (Figure 8b). Csontos et al. (2010a, b) noted the possible presence of halite from a taste test; this was not identified during the course of this investigation. There is a pervasive network of sparry and fibrous gypsum and anhydrite veins that vary from less than 1 mm to 5 cm thick (Figure 8d, e). These veins are usually deflected around clasts, although they occasionally cut through them. Elemental sulphur occurs as small yellow masses or veinlets and some outcrops may have a sulphurous smell when broken open. Crystalline epidote forms thin veins in the finer-grained gypsiferous matrix and on the surfaces of, or along fractures in clasts.

The edges of the gypsiferous bodies are marked by a deeply weathered halo up to 5 m thick (Figure 8b, c). The halo has a texture similar to that of the fresher material, but is pink-orange in colour, is less well cemented and contains the weathered remnants of gypsum/anhydrite veining. The transition from the fresher parts of the bodies is comparatively abrupt. The long axes of clasts have a steep sub-
Figure 8: Photographs of the gypsum intrusions. (a) Gypsiferous intrusion, top of Wadi Hawasina (point 9 on Figure 5). The gypsiferous intrusion (G) forms irregular patches on the road-cut cliff and the pink material on the slope to the right. The cliff comprises Al Jil Formation member 3 cherts, with Al Jil Formation member 1 limestones and shales to the right of the gypsum. (b) Fresh road-cut gypsum (grey) passing up into deeply weathered gypsum (pink) intruded into contorted shales and cherts of the Lower Matbat Formation. Col between Wadi Ad Dil and Wadi Qurta (point 8 on Figure 5). Figure for scale. (c) Vertical and horizontal boundaries between weathered gypsum intrusion and the Lower Matbat Formation. Location as photograph (b). (d) Anastomosing gypsum veining in fresh gypsiferous material with numerous pebbles and cobbles. Hammer for scale. (e) Close-up of impure gypsum matrix with numerous pebbles and cobbles of limestone and gypsum veins. (f) Well-rounded quartzite clast embedded in impure gypsum matrix. Scale bar is 5 cm.
parallel alignment close to the edges of the gypsiferous bodies, but show no evidence of bedding, clear preferred orientation or size-distribution in the middle of exposures of the bodies. The outer edges of the gypsiferous bodies are sharp and cut folds and faults within the Hamrat Duru Group host rock, clearly indicating the intrusions post-date emplacement of the Hawasina thrust sheets. The weathered tops of the intrusions are truncated by sub-recent cemented regolith.

Clasts in the Gypsiferous Intrusions

The clasts are mostly matrix-supported, and are pebble to cobble grade. They are generally no more than 15 cm in diameter, but rare examples may exceed 30 cm. Clasts from the weathered halo are typically iron-stained reddish purple. There are four broad types of clasts.

**Type 1: Hard, Fine-grained Sandstones and Siltstones**
The most abundant type comprises smooth, hard medium to dark grey fine-grained structureless or laminated feldspathic litharenites, quartzites with carbonate grains and siltstones. Clasts are frequently irregular in shape, but with smoothed faces and rounded corners. In thin section they are typically moderately to poorly-sorted (Figure 9a–d). Grains are mainly sub-angular to sub-rounded quartz with carbonate or secondary sericite or carbonate. Lithic fragments can comprise up to 20% of grains and mainly comprise micro-crystalline quartz and quartz-mica schist. There are also rarer grains of fine-grained carbonates, corroded and partly replaced detrital calcite, and mud-flakes. Secondary pyrite is common. Grain boundaries are frequently corroded and replaced by rhombic or interlocking calcite. Gypsum veining is also seen and, in rare cases, grains may be wholly or partly replaced by gypsum.

**Type 2: Limestones and Chert**
Clasts of limestone and chert are comparatively rare. Most clasts are no more than 5 cm long. They are sub-angular with smoothed edges. The limestones are mid to dark grey and, in thin section, are structureless or laminated and consist of microcrystalline calcite in which float circular or elongate quartz bodies up to 75 µm in diameter rimmed with slightly coarser crystalline calcite (Figure 9e).

**Type 3: Well-rounded Fissile Sandstones**
The third clast group comprises very well-rounded white or pale greenish-grey pebbles or cobbles of fine- to medium-grained sandstones some of which have a well-developed cleavage. These fissile sandstones contain abundant quartz and varying amounts of feldspar and micro-crystalline quartz, fine-grained schist, locally abundant pyrite and other opaque minerals and small amounts of mica flakes (Figures 9f–h). Carbonate lithic fragments are more common than in the Type 1 sandstones. The cleavage in the Type 3 fissile sandstones is a product of thin, sub-parallel bands of layer silicates. Diagenetic clay minerals including kaolin are also developed in the pressure shadows between quartz grains and lithic fragments. In common with the Type 1 hard dark sandstones, many samples show considerable amounts of secondary calcite as interlocking rhombs along grain boundaries and replacing the edges of quartz and carbonate grains.

**Type 4: Vein Quartz**
The fourth group of clasts comprise vein quartz. These are comparatively rare, reach 12 cm in diameter and are well-rounded and very smooth (Figure 8f). They are light milky-grey in colour and semi-translucent. Broken surfaces show they consist of interlocking quartz crystals up to 2 cm long.

**Other Clasts**
There are also rare, almost pure quartzites, made up of well-rounded quartz grains, where not sutured and corroded along grain boundaries.

The clasts of Type 1 hard, fine-grained comparatively immature sandstone are similar in composition to the sandstones of the Triassic Lower Member of the Al Jil Formation (Cooper, 1986). More mature quartzites and carbonate grains show a closer similarity with the Lower Jurassic sandstones of the Matbat Formation (Cooper, 1986). The Al Jil and Matbat formations may thus be a source for the Type 1 sandstone clasts. The Hamrat Duru Group also contains abundant cherts and limestones,
Figure 9: Photomicrographs of clasts from the gypsiferous bodies. Scale bars 0.5 mm.
(a) (plane polarised light ppl) and (b) (crossed polars xp) Type 1 hard dark sandstone class: quartz-rich with diagenetic rhombic calcite between, and corroding grain margins. (c) (ppl) and (d) (xp) Type 1 hard dark sandstone class: immature, quartz, lithic fragments, twinned plagioclase and opaque minerals with diagenetic rhombic calcite between, and corroding grain margins. (e) (ppl) Type 2 microcrystalline calcite with matrix-supported elongate and circular quartz and rhombic opaque minerals, similar to radiolarian lime-mudstones from the Hamrat Duru Group. (f) (xp) Type 3 fissile sandstone fine grained with a strong parallel fabric picked out by layer silicates. (g) (ppl) and (h) (xp) Type 3 fissile sandstone class: immature and comparatively poorly-sorted sandstone with lithic fragments (mainly microcrystalline quartz and schist), quartz and feldspar. Cleavage is defined by fine-grained layer silicate bands.
including radiolarian-bearing micrites, which are very similar in appearance to those seen as clasts in the gypsiferous intrusions. Cherts are also common within parts of the Hamrat Duru Group. This suggests the Type 1 and 2 clasts are likely to have been derived from the local Hamrat Duru Group country rock.

The high degree of rounding seen on the Type 3 fissile sandstones and Type 4 vein quartz clasts contrasts with the sub-angular or sub-rounded Type 1 and 2 clast suite. This suggests the rounding may not be a product of chemical or physical processes linked to their incorporation into the gypsiferous bodies. Instead, the fissile sandstones and quartz clasts may have undergone an earlier cycle of weathering and transport, and thus may be derived from an older conglomeratic rock. Pebbles of slatey phyllites and metamorphosed immature sandstone have been found in just one, thin geographically localised pebble conglomerate bed from the base of the sandstone turbidite unit of the Lower Member of the Al Jil Formation of the Hamrat Duru Group (Figure 4, Cooper, 1986, 1990). While no petrological comparison has been undertaken, the well-rounded cobbles of Type 3 white and pale fissile sandstone are generally much larger and their local abundance within the gypsum bodies suggests it is very unlikely these clasts could have been reworked from such a limited source within the Al Jil Formation. The Type 4 vein quartz pebbles and cobbles observed in the gypsum matrix have no analogue anywhere within the Hamrat Duru Group or wider Hawasina Complex.

**GRAVITY INVESTIGATION OF THE HAWASINA WINDOW GYPSUM INTRUSIONS**

Gravity measurements were acquired in February 2009 at 125 stations using a Scintrex CG5 gravimeter. The meter had a reading resolution of ± 0.001 mGal. Twenty gravity readings were repeated. These readings resulted in a repeatability of less than 0.01 mGal. The gravity stations were spaced approximately 1,000 m apart reducing to around 250 m close to the gypsum outcrops. Measurements along the main roads and trails provided generally good coverage. Gravity stations in inaccessible or difficult terrain were reached on foot. Wherever possible, station locations were selected to minimize the local terrain effects. Two profiles are presented here. Profile I runs southwest to northeast and Profile II from northwest to southeast direction across the Hawasina Window (Figure 10).

A base station was established at the centre of the survey area to monitor the drift of the gravimeter and the effects of Earth-tides, and was visited every 3–5 hours. Care was taken to minimize measurement errors and any ambiguous measurements were double-checked. Latitude, longitude, and elevation were recorded at each station using a hand held GPS (Global Positioning System) with 3 m accuracy.

**Gravity Data Processing and Modeling**

The gravity data were corrected for drift, tide, elevation, latitude and terrain. The drift was assumed to be linear between consecutive base station readings and was subtracted from the observed value. The effect of latitude was corrected using the 1967 International Gravity Formula (Mittermayer, 1969). The data were reduced to simple Bouguer anomaly using an average density of 2,670 kg/m³. The Bouguer density was taken as the average value for all of the different types of rock outcropping in the region. The survey was tied to the Muscat International Airport (Oman) base station at Seeb (23° 35.00′N 58° 17.68′E; \( g = 978,921.955 \) mGal).

Terrain corrections based on Digital Elevation Model (DEM) (Figure 11a) data with a 10 m resolution derived from ALOS PALSAR data (Ali et al., 2012) were calculated to obtain the Complete Bouguer anomaly, which corrects for gravitational irregularities due to variations in terrain (Figures 11b and 12). The local terrain corrections were based on near zone (0–30 m from the station), intermediate zone (30–135 m) and far zone (> 135 m) contributions. In the near zone, the effects of four sloping triangular sections, which describe a surface between the gravity station and the elevation at each diagonal corner were summed. In the intermediate zone, the terrain was calculated for each point using the flat topped square prism approach of (Nagy, 1966). In the far zone, the terrain was derived based on the annular ring segment approximation to a square prism as described by (Kane, 1962).
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We caution that the terrain corrections are based on relatively low resolution DEM data. As a result, some errors may occur in the final terrain corrections. For example, 10 m DEM data may not be sampled finely enough to accurately derive the near-zone terrain corrections over Hawasina Window where the topographic relief can be high. However, taking into account the quality of the gravity and positioning measurements, the overall accuracy of the complete Bouguer anomalies are estimated to be about 0.2 mGal.

It appears that the regional gravity field of the two profiles is insignificant. Manghnani and Coleman (1981) reported a gravity profile across the Semail Ophiolite in the central Oman Mountains that crosses the Hawasina Window. The regional gradient of the profile was estimated to be -0.8 mGal/km in a NE-SW direction. The Hawasina Window portion of the profile has an even lower gradient. Furthermore, the lengths of the gravity profiles are relatively small, not exceeding 26 km. Therefore, we infer that the regional gravity anomaly along the profiles to be a linear trend with a low gradient. Such a regional anomaly does not have significant variations and its removal will not significantly influence the negative amplitude and the shape of the observed anomaly. Therefore, the regional gravity field was not removed from the gravity profiles.

**Gravity Modelling with Geological and Geophysical Constraints**

Two projected gravity profiles (SW-NE and SE-NW, Figure 10) were modelled using 2.5-D forward modelling to assist in the interpretation of the subsurface geology of the area and geometry of salt intrusions. Profile I is a southwest to northeast trending 26 km-long profile that crosses the Hawasina...
Figure 11: (a) DEM data used to calculate the terrain corrections. (b) Calculated terrain corrections showing higher anomaly over Hawasina Window. White circles indicate the gravity stations. Stars locate the main gypsum outcrops.
Window. Profile II is 21 km-long and runs along the Hawasina Window and is roughly perpendicular to Profile I. The modelling of the subsurface structures was constrained using several sources of geological and geophysical data. Outcrop geology and cross sections (Figures 5 and 6) provided the control for the outcrop widths, formation boundaries and the average dips of exposed rocks. Furthermore, the depth to the Permian–Mesozoic shelf carbonates, Palaeozoic, Ara salt, crystalline basement were estimated from regional studies in central Oman Mountains (e.g. Shelton, 1990; Ravaut et al., 1997; Al-Lazki et al., 2002; Peters et al., 2003; Reuning et al., 2009). Additionally, the densities of the Hamrat Duru Group and distal Hawasina sedimentary rocks were obtained from the analysis of hand specimens collected from exposed rock units in and around the survey area. The shelf carbonates, Sumeini Group, Palaeozoic sediments and basement were assigned a density of 2,700 kg/m$^3$, 2,700 kg/m$^3$ 2,750 kg/m$^3$ and 2,800 kg/m$^3$, respectively (Manghnani and Coleman, 1981; Ali et al., 2008, 2009; Searle and Ali, 2009).

The density values for the formations are based on the laboratory measurements on the rock samples collected in the field, and the densities from the literature as listed in Table 1. The Hamrat Duru Group consists of limestone turbidites, shales, radiolarian cherts, silicified limestones and quartz-rich sandstone turbidites. The density of these rocks varies from 2,420 to 2,600 kg/m$^3$. A density of 2,200 kg/m$^3$ was assumed for a salt body at depth of ca. 6–8 km, and density of 2,300 kg/m$^3$ for the gypsiferous intrusions at the surface.

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<tr>
<th>Unit</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semail Ophiolite</td>
<td>2.90</td>
</tr>
<tr>
<td>Serpentinite</td>
<td>2.55</td>
</tr>
<tr>
<td>Haybi Complex</td>
<td>2.80</td>
</tr>
<tr>
<td>Hamrat Duru Group</td>
<td></td>
</tr>
<tr>
<td>Nayid, Sidr and Guwayza Fms</td>
<td>2.42</td>
</tr>
<tr>
<td>Matbat and Al Jil Fms</td>
<td>2.50</td>
</tr>
<tr>
<td>Sumeini Group</td>
<td>2.70</td>
</tr>
<tr>
<td>Permian-Mesozoic Shelf Carbonates</td>
<td>2.70</td>
</tr>
<tr>
<td>Palaeozoic</td>
<td>2.75</td>
</tr>
<tr>
<td>Ara salt</td>
<td>2.20</td>
</tr>
<tr>
<td>Gypsiferous body</td>
<td>2.30</td>
</tr>
<tr>
<td>Pre-Ara sediments</td>
<td>2.75</td>
</tr>
<tr>
<td>Basement</td>
<td>2.80</td>
</tr>
</tbody>
</table>

The structural geometry of the models was iteratively modified to derive a good match between the calculated and observed Bouguer anomalies. The formation densities were assumed to remain constant along the profiles. The parameters that were varied to arrive at the final models were shape and thickness of the individual units.

**Gravity Interpretation**

We recognise that the gravity data coverage over the Hawasina Window is limited. Nevertheless, the following interpretations are derived from the data. The Bouguer anomaly values are negative, ranging from -78 to -30 mGal. The thick Mesozoic and Palaeozoic sediments in the area as well as the occurrence of salt basin beneath the Hawasina Window can explain the negative anomalies.

**Simple Bouguer Anomaly**

The simple Bouguer anomaly (Chapin, 1996) profiles over the Hawasina Window (Figure 12) generally increase from south to north. Profile I shows relatively high Bouguer gravity anomaly to the southwest. The high gravity anomaly is caused by the denser rocks (Semail Ophiolite, shelf
carbonates and Haybi Complex) outcropping to the southwest of the profile. The Bouguer anomaly decreases sharply reaching values of -73 mGal from 6–7 km of the start of the profile due to the relatively low-density rocks of Hamrat Duru Group. The gravity gradually increases to the northeast due to the occurrence of Haybi Complex, shelf carbonate and Semail Ophiolite.

Profile II broadly follows the line of the central Hawasina Window anticline. Hence, the Bouguer gravity anomaly remains nearly the same over the whole window. To the northwest the Bouguer gravity anomaly gradually increases. This is consistent with a model whereby the Sumeini Group thickens (> 2 km) and Hamrat Duru Group thins to the northwest towards Jabal Rais. The profiles also show local gravity changes, which are largely an artefact of the use of a simple Bouguer slab approach, which does not properly account for the gravity effects of the (non-slab-like) local topography. Without first removing this effect by applying proper terrain corrections, it is difficult to interpret the simple Bouguer anomaly profile.

**Complete Bouguer Anomaly**

The Complete Bouguer gravity anomaly profiles were obtained by combining the simple Bouguer anomaly with the terrain corrections. The Complete Bouguer gravity anomaly profiles show several dispersed low-gravity weak anomalies (Figures 12b and 12d). Hence, the Complete Bouguer gravity profiles reveal a considerably clearer and better-defined image of local gravitational anomalies. The most striking features are the low-gravity anomalies of up to 4 mGal, which are associated with the gypsiferous intrusions.

**Hawasina Window Gravity Model**

The final subsurface gravity models, integrating gravity data with surface mapping are presented in Figures 13 and 14. A good match between the observed and calculated gravity anomalies is observed, suggesting an uplifted basement underlying the Hawasina Window. In this model, deep-level evaporites of the Ediacaran–lower Cambrian Ara Group are assumed to be a thin source of the gypsum intrusions. However, the observed gravity lows are insufficient to account for the intrusions through large-scale salt diapirism. The gravity anomalies associated with salt diapirism are generally 12 mGal or higher (Ali et al., 2014), whereas in the Hawasina Window the gravity anomalies correlated with gypsiferous intrusions are much less. Therefore, the inference is that the superficial gypsum intrusions are linked to deep-rooted faults.

**STRONTIUM ISOTOPE ANALYSIS**

Samples of gypsum and anhydrite have been analysed for their \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios, with the aim of narrowing down the possible age of the original material in the intrusions by comparison with reference curves (Veizer et al., 1999; McArthur et al., 2001, 2012; McArthur and Howarth, 2004). Two samples from the Hawasina Window have been analysed. Seven samples came from Jabal Qumayrah, where there are more extensive gypsiferous intrusions of gypsum and anhydrite (Cooper et al., 2013). Eighteen samples were collected from gypsiferous outcrops associated with the Jabal Majayiz, Qarat Kibrit and Qarn Alam salt domes in the Ghaba Salt Basin in south central Oman (Figure 1). The Ghaba Salt Basin outcrops have also suffered deep weathering and display the same hard granular morphology that characterises outcrops in the Jabal Qumayrah area. The age of the Ghaba Salt Basin salt domes is known to be Ediacaran–early Cambrian (Ara Group, ca. 547–538 Ma, Amthor et al., 2003; Peters et al., 2003; Allen, 2007; Reuning et al., 2009; Forbes et al., 2010). Comparing the measured \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios from samples in this area with the expected ratios derived from the reference curves can thus provide a control on the degree of variation in strontium isotope ratios from later diagenetic and weathering processes.

In each case, standard procedures were used so that only evaporites were dissolved. The sample was ground by hand to a powder and between 0.0250–0.0280 µg was put into a 2 ml centrifuge tube. Two ml of ultrapure MQ (milliQ) water was added and the mixture left overnight. The product was then centrifuged, transferred to labelled beakers for digestion with 7M nitric acid and strontium separated using standard column chemistry separation methods before measuring the \(^{87}\text{Sr}/^{86}\text{Sr}\) ratio using
Figure 12: (a) Elevation and terrain corrections for Profile I. (b) Simple Bouguer anomaly (BA) and complete Bouguer anomaly (CBA) profiles of Profile I showing gradual increase to the northeast. (c) Elevation and terrain corrections for Profile II. (d) Simple Bouguer anomaly (BA) and complete Bouguer anomaly (CBA) profiles of Profile II showing gradual increase to the northwest.
thermal ionisation mass-spectrometry. The results are summarised in Table 2 and plotted on Figure 15, which superimposes the results on the LOWESS (Locally Weighted Scatterplot Smoothed) curve from McArthur et al. (2012) for strontium from the Precambrian to present-day.

The results indicate that $^{87}$Sr/$^{86}$Sr ratios for the Hawasina Window and Jabal Qumayrah samples cluster closely between 0.708508 and 0.708629. One sample from Jabal Qumayrah, from the more intensely weathered, brown gypsum-rich surface crust, shows a lower $^{87}$Sr/$^{86}$Sr ratio (0.708120, JQ2 in Table 2), which may reflect recent weathering effects. Excluding JQ2, these results are consistent with the LOWESS curve for minerals deposited in equilibrium with the prevailing seawater from the Precambrian/Cambrian Boundary, intervals in the Ordovician and Silurian, and the Miocene (McArthur et al., 2012, Figure 15).

The results from gypsum and anhydrite deposits collected from the salt domes in the Ghaba Salt Basin are also shown on Figure 15 and range between 0.708232 and 0.708759. Notwithstanding the observed degree of weathering, these results are consistent with the LOWESS curve for the period...
during which the Ara Group evaporites were deposited. They are also compatible with the findings of Schröder et al. (2001), who recorded $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.70836 to 0.70854 in evaporites recovered from well cores in the Ara Group. Burns et al. (1994) reported a slightly higher ratio for the Ara Group (0.70918), which is at the upper end of the LOWESS curve for the Cambrian. These results suggest the mobilisation of evaporites during halokinesis and weathering has not altered their original $^{87}\text{Sr}/^{86}\text{Sr}$ ratios to a significant extent and, by extension, that the values from the Hawasina Window and Jabal Qumayrah areas may provide an indication of their relative ages. The clustering of the $^{87}\text{Sr}/^{86}\text{Sr}$ results also suggests later diagenetic and weathering effects have had little impact on overprinting and substitution, which would otherwise be expected to lead to greater variability in the ratios. This suggests the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios indicate a marine origin, although no attempt has been made to strip back the possible impact of deposition in a modified environment. Stein et al. (2000) and El-Tabakh et al. (2004) have shown that evaporatic rocks may have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios different from the seawater from which they were derived if, for example, they were deposited in restricted basins fed by rivers containing terrestrial strontium with an isotope signature different to that of the prevailing seawater ratio.

Figure 14: Gravity model of Profile II (for location see Figure 10). The chart compares the observed complete Bouguer anomaly and calculated gravity anomaly values using the model shown in the lower part of the diagram. The model extends beyond gravity residual endpoints to avoid edge effects.
Table 2

\( ^{87}\text{Sr}/^{86}\text{Sr} \) isotope ratios derived from samples from the Jabal Qumayrah area, Hawasina Window and Ghaba Salt Basin.

<table>
<thead>
<tr>
<th>Sample reference</th>
<th>Norm Ratio</th>
<th>Error 2( \text{sem} ) (%)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/106A</td>
<td>0.708629</td>
<td>0.0013</td>
<td>Jabal Qumayrah</td>
</tr>
<tr>
<td>5/106B</td>
<td>0.708533</td>
<td>0.0013</td>
<td>Jabal Qumayrah</td>
</tr>
<tr>
<td>5/106C</td>
<td>0.708508</td>
<td>0.0013</td>
<td>Jabal Qumayrah</td>
</tr>
<tr>
<td>5/106D</td>
<td>0.708527</td>
<td>0.0012</td>
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<tr>
<td>5/106F1</td>
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<tr>
<td>5/106F2</td>
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</tr>
<tr>
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</tr>
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</tr>
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</tr>
<tr>
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</tr>
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<td>OM11 5/5C</td>
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<td>OM11 5/11C</td>
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<td>1.06241E-05</td>
</tr>
</tbody>
</table>

Notes: \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratios normalised to \( ^{86}\text{Sr}/^{88}\text{Sr} = 0.1194. \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratios normalised to NBS-987 \( ^{87}\text{Sr}/^{86}\text{Sr} = 0.710235. \) Estimated external precision (2\( \text{sem} \)) based on analysis of the NBS987 standard over period of analysis = 0.0025% (+/-0.000018).

5 analyses of the EN-1 standard in the period of analysis yielded an average value of \( ^{87}\text{Sr}/^{86}\text{Sr} = 0.709163 \)

COMPARISON WITH OTHER GYPSUM BODIES IN THE OMAN MOUNTAINS: JABAL QUMAYRAH

The only other gysiferous intrusions identified within the area of the Oman Mountains are at Jabal Qumayrah, 75 km to the WNW of the Hawasina Window (Cooper et al., 2012, 2013) and immediately to the west of Jabal Sumeini, 150 km to the NNW. The Jabal Sumeini outcrops are small and have not been studied in detail.

The Jabal Qumayrah outcrops are located in the core of anticlinally folded and thrust Jurassic and Cretaceous Sumeini Group slope sediments that breached the previously-emplaced Hawasina, Haybi and Semail Ophiolite thrust sheets during the final stages of Late Cretaceous ophiolite obduction.
Like the Hawasina Window intrusions, the Jabal Qumayrah outcrops occur in structurally low thrust sheets, but the main area of exposure is very different from the Hawasina Window outcrops. It is considerably larger, with an irregularly-shaped central body, up to 600 m x 500 m, from which discontinuous pods of gypsum extend to the NW and south for up to 4 km. The boundaries of the central body are mostly faulted, but are locally intrusive. The gypsiferous bodies comprise a gypsum-rich weathered crust that conceals white granular anhydrite with small amounts of halite and native sulphur. The bodies contain abundant clasts, but unlike those of the Hawasina Window, the largest form rafts that are over 100 m long and 50 m thick. All appear to be derived from the Mesozoic Sumeini Group country rock and are interpreted as blocks which were ingested by the gypsum as it intruded into the Sumeini Group. The surface expression of the central Jabal Qumayrah intrusion shows a strong fault control, and its size, structure and gravity signature indicates the presence of an underlying salt diapir of which the outcrops represent the deeply weathered cap-rock (Cooper et al., 2012; 2013). The gypsiferous pods that radiate from the central area, all clasts in the gypsiferous matrix appear to have been derived from the local country rock.

Based on the known and potential stratigraphic and geographical distribution of evaporites in the Jabal Qumayrah region, Cooper et al. (2013) suggested the most likely source for the gypsum and anhydrite in Jabal Qumayrah was the Ediacaran–lower Cambrian Ara Group evaporites.

DISCUSSION

Implications from the Clast Assemblage in the Hawasina Window

The clasts within the gypsum bodies are interpreted to have been derived from two distinct sources, the local Hamrat Duru Group and the basement to the Hajar Supergroup.
The Hamrat Duru Group that forms the country rock to the intrusions comprises shales, limestones turbidites and conglomerates, sandstones and cherts. The abundant sub-angular to sub-rounded hard grey sandstone clasts are, in their petrographic characteristics, very similar to the Triassic sandstones of the Hamrat Duru Group. The rarer limestone and chert clasts are also similar to those seen in the Hamrat Duru Group. The comparative over-abundance of the sandstone clasts in the gypsum bodies when compared with the Hamrat Duru Group suggests a local source from Al Jil Formation beds along the fault up which the gypsum intruded and limited transport during emplacement.

The origin of the abundant pebbles and cobbles of the fissile felspathic litharenite sandstone and vein quartz is less clear. Their smooth surfaces and high degree of rounding suggests a previous period of reworking. Reworked, basement-derived clasts are extremely rare in conglomerates in the Hamrat Duru Group, and these cannot account for the relative abundance in the gypsum intrusions. They have no analogy in the late Permian to Cretaceous Hajar Supergroup, which comprises a sequence of predominantly shelf carbonates some 2.5 km thick, the nearest exposures of which are just 15 km along strike to the SW. This suggests that these clast types were derived from a deeper-level basement source that pre-dates the Hajar Supergroup shelf sediments and the Hawasina basin assemblage.

Conglomerates pre-dating the Hajar Supergroup that contain basement-derived clasts are mainly developed in the Proterozoic and Permian–Carboniferous. Possible analogies for the fissile sandstones have been reported from the fluvio-glacial deposits of the Cryogenian Abu Mahara Group (Allen, 2007) and the early Permian glaciogenic Al Khlata Formation (Levell et al., 1988; Angiolini et al., 2003, Martin et al., 2012; Heward and Penney, 2014). Neither can be considered to be a source with any certainty, as both contain a diverse clast assemblage not limited to those seen in the gypsiferous intrusions. The Abu Mahara Group also pre-dates the oldest known salt deposits of the Ediacaran–early Cambrian Ara Group, which may make it a less likely potential source. The Al Khlata Formation is not seen in the sediments exposed in the core of the Al Jabal Al-Akhdar anticline immediately to the SE of the Hawasina Window, though it is known from the Saih Hatat area of the Oman Mountains (Heward and Penney, 2014).

**Age and Source of the Hawasina Window Gypsum**

No direct age data have been obtained during these investigations from the highly weathered and recrystallised gypsiferous matrix material in either the Hawasina Window or Jabal Qumayrah intrusions. Strontium isotope data from this study intersect with the LOWESS curve (McArthur et
al., 2001, 2012) for the Neoproterozoic–Cambrian, intervals within the Ordovician and Silurian, and Miocene. There is no evidence for the deposition of evaporites in Oman during the Ordovician or Silurian. The sample base is small, but it points towards a source in the Neoproterozoic–Cambrian or Miocene stratigraphy, in which evaporites were deposited in the Ara Group and Fars Group respectively.

Ara Group: A Possible Ediacaran–Cambrian Source

The strontium isotope data, together with the assemblage of clasts in the gypsum intrusions of the Hawasina Window, suggest the gypsum was derived from stratigraphic levels beneath the Permian Neo-Tethyan sequences. We tentatively suggest a source from evaporites within the Ediacaran–lower Cambrian Ara Group, even though significant evaporite levels are not exposed in age-equivalent rocks in the pre-Permian basement where it is exposed in the windows through the allochthon in Al Jabal Al-Akhdar less than 50 km to the SE of the Hawasina Window. The age-equivalent rocks comprise pelagic re-sedimented carbonates, cherts, fine-grained turbidites and volcanoclastics of the Fara Formation (Allen, 2007; Rieu et al., 2007).

The Ara Group of the upper part of the Huqf Supergroup is a thick sequence of cyclic halite, anhydrite and limestones that developed in a complex series of NE-trending basins to the SE of the Oman Mountains (Fahud, Ghaba and South Oman salt basins) and to the north (Hormuz Salt Basin, Figure 1). The Fahud and Ghaba salt basins have been traced in the subsurface to the mountain front and may extend also beneath the allochthon to the east and south of Al Jabal Al-Akhdar and Saih Hatat, respectively (Mount et al., 1998). Gravity investigations by Ali et al. (2014) suggest that the Hormuz evaporites extend much further south and west into the United Arab Emirates and the Rub‘ Al-Khali Basin than previously suspected. They inferred that the Hormuz and Ara (Fahud and Ghaba) salt basins may have been connected, with structural highs in the basement influencing the location of evaporites deposition.

The salt in the South Oman and Ghaba salt basins has undergone significant halokinesis and salt domes locally pierce the surface in the Ghaba Salt Basin (Heward, 1990; Mattes and Conway-Morris, 1990; Peters et al., 2003; Reuning et al., 2009; Schoenherr et al., 2010). The Ara Group evaporites in the Fahud Salt Basin, which are the closest to the Hawasina Window, appear to be insufficiently thick and not to have been stressed enough for diapirs to form. The absence of evaporites from the equivalent stratigraphic interval where exposed in the Al Jabal Al-Akhdar area does not preclude the development of an Ara Group salt basin to the NW of the Al Jabal Al-Akhdar area, either as a NE extension to the Fahud Salt Basin or a smaller, separate entity. Cooper et al. (2013) came to a similar conclusion in relation to the gypsum bodies in Jabal Qumayrah. It is notable that Ara Group evaporites have not been exploited as a detachment horizon in either the Fahud Salt Basin or where identified by Mount et al. (1998) beneath the Hawasina Complex and Semi-All Ophiolite to the SW of Saih Hatat, notwithstanding the high levels of deformation and shortening immediately to the NE, in particular in Saih Hatat. This may offer further circumstantial evidence for the development of smaller and laterally more discontinuous salt basin development towards, and into what is now the area of the Oman Mountains.

Tertiary Evaporites: An Unlikely Source

The strontium isotope values are also consistent with a Miocene source for the gypsum. Evaporite minerals, in particular gypsum, are found in the Tertiary sequences in the interior of the Arabian platform to the west of the Oman Mountains, mainly in the Early Eocene Rus Formation and the Oligocene–Miocene Fars Group. However, they are not developed in the exposed Tertiary rocks along the western edge of the Oman Mountains, which comprise a thick sequence of limestones and marls in which gypsum is mostly absent (Nolan et al., 1990; Le Métour et al., 1991). Where gypsum is present, for example in the Fars Group at Jabal Hafit, it mainly occurs as isolated crystals and there is nothing to suggest these could represent remnants of thick deposits that became mobile. The context, thickness, and non-bedded form of the gypsiferous deposits in the Hawasina Window, together with the lack of intervening lithologies and scattered clasts within the gypsum is also very different to the Fars where seen, for example, in outcrops around Al Huwaisah or quarries in Al Wusta in central Oman.
Furthermore, both the Al Jabal Al-Akhdar area and, by implication, its NW extension in the Hawasina Window, and the Jabal Qumayrah areas were undergoing major uplift during the Oligocene–Miocene (Mount et al., 1998; Cooper et al., 2013). There is no evidence of in situ deposition of evaporites within the Oman Mountains area at this time. Even if there were local deposits, regional geological constraints render it inconceivable that the Qumayrah and Hawasina Window areas have been thrust over Miocene sediments from which the gypsum could have been subsequently mobilised. It is thus unlikely that the gypsum in the intrusions could have been derived from a Miocene or other Tertiary source.

Csontos et al. (2010b) reported strontium and sulphur isotope values from gypsum in the Hawasina Window and Jabal Qumayrah that fell within the interval of Miocene evaporites in the Middle East. They also concluded that the Qumayrah and Hawasina Window areas could not have been thrust over Miocene sediments and discounted a Miocene source. They suggested a Late Cretaceous age for the evaporites based on adjustments to the sulphur isotope values for sulphate reduction, and their observation that the Jabal Qumayrah evaporites appeared to be deposited at the Late Cretaceous top of the Sumeini Group. However, structural and gravity investigations by Cooper et al. (2013) in the Jabal Qumayrah area indicate that the significantly larger gypsiferous bodies in that area have an intrusive, and not a sedimentary relationship with the Sumeini Group country rock in which they are now exposed. They inferred the gypsiferous bodies represent the deeply weathered top of a salt body whose final emplacement into higher structural levels of the allochthonous Hawasina units was fault controlled. The Late Cretaceous palaeogeography also militates against the deposition of evaporites during this period. The closing Hawasina Ocean was undergoing NE-directed subduction beneath the Semail Ophiolite and a foredeep developed along the Oman sector of the edge of the Arabian Plate as a precursor to ophiolite obduction. There is no evidence for the general development of evaporites in sedimentary sequences from this time (Glennie et al., 1974; Robertson, 1987a, b).

### Other Evaporite Intervals Discounted

Other major evaporite intervals are developed in the Oman/southern Gulf region in the Permian Khuff Formation, the Middle Triassic Jilh Formation, and Late Jurassic Arab and Hith formations (Ziegler, 2001). These formations mainly consist of anhydrite, are not associated with halokinesis and do not extend into the Oman Mountains (Sharland et al., 2001). Khuff equivalents in the Oman Mountains comprise open-marine carbonate platform facies of the Bih and Hagil formations, and the Saiq Formation and lower part of the Mahil Formation respectively, which are linked to early rifting in the Hawasina Ocean segment of Neo-Tethys (Lee, 1990; Rabu et al., 1993; Maurer et al., 2009).

Similarly, the equivalent of the Jilh Formation evaporites is represented by the generally shallow-marine upper part of the Mahil Formation and terrigenous clastics in the Musandam Peninsula (Glennie et al., 1974; Ziegler, 2001). The Late Jurassic intra-basin evaporitic Arab and Hith formations pass eastwards into more open-marine facies, with the Hith Formation being broadly synchronous with the deeper-water Rayda Formation of the Oman Mountains to the southeast (Pratt and Smewing, 1990; Rabu et al., 1993). It is thus unlikely that the Hawasina Window evaporites are associated with these units. Finally, it is not impossible that geographically limited, as yet unknown evaporite basins may have developed locally along the NE edge of the Oman margin in the Permian during early Neo-Tethyan rifting. However, there is no evidence of such basins in the exposed stratigraphy, which suggests such a source is unlikely. The LOWESS curve of $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios for rocks of these periods does not intersect with measured ratios from the Hawasina Window and Jabal Qumayrah intrusions. Indeed, the Permian also marks a major low point in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for marine-derived minerals, in contrast to the high values recorded in the measured gypsum samples.

### Emplacement of Gypsiferous Bodies in the Hawasina Window

A model (Figure 17) for the emplacement of the gypsiferous bodies in the Hawasina Window needs to take into account four key features: (1) the localised extent of the bodies, (2) their linear distribution along fault lines, (3) the absence of major gravity anomalies, and (4) the age of the gypsum, based on strontium isotope data.
The orientation of the surface exposures of the gypsiferous bodies as elongate pods aligned along
faults points towards a primary fault-control for the distribution and emplacement of these bodies. The localised distribution and small negative gravity anomalies over the bodies probably reflect a comparatively small and localised sub-surface extent for these gypsiferous pods. The anomalies are too small to suggest the outcrops represent the top of a major diapir system or larger subsurface accumulations as implied by Csontos et al. (2010a). Ages derived from strontium isotope ratios imply an infra-Cambrian source beneath the Neo-Tethyan Permian–Mesozoic shelf carbonates and Palaeozoic sedimentary succession. This means the gypsum has penetrated about 4.5 km thickness of sedimentary cover, by comparison with exposed successions around Al Jabal Al-Akhdar, before intrusion into the lower levels of the allochthonous Hawasina complex.

Figure 17: Simplified cartoon to illustrate one possible origin of the gypsiferous intrusions in the Hawasina Window. The distribution of deeper-level structures is schematic. (a) Ediacaran–early Cambrian: Ara Group evaporite basins extend across southern and eastern Oman separated by highs. The basin beneath the Hawasina Window may be an extension of the Fahud Salt Basin to the west. (b) Early Cretaceous: The Permian–Mesozoic Neo-Tethyan carbonate platform extends across the eastern and central Arabian Plate. Normal faulting at the base of the platform succession developed during the Permian rifting phase. (c) Present-day: The Hawasina and Haybi complexes and the Semail Ophiolite have been emplaced onto the platform during Late Cretaceous obduction. Compression during the Oligocene folds and uplifts the Hawasina Window. Gypsum is brought up along high-angle deep-rooted faults, possibly reversing movement on earlier rift-related normal faults. Similar fault movements account for large-scale post-Eocene folding along the western edge of the northern Oman Mountains.

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The Wadi Ad Dil-Wadi Qurta tributary faults are essentially vertical and form a significant NNW-SSE down-to-the-SW trending lineament in the south-central Hawasina Window. They cut, and must thus post-date folding and thrusting within the Lower Hamrat Duru Group Thrust Sheet. They lie on line extending NNW to the southern end of the long axis of the Jabal Rais ‘pop-up’ structure. We suggest that these faults are deep rooted, which is consistent with the gravity data, and that a major fault underlies this part of the Hawasina Window. This fault then acted as a conduit through which the gypsiferous material could have risen from depth, not by simple diapirism, but through a primarily tectonic mechanism. Similar-sized finger-like gypsiferous bodies located along fault planes have been identified elsewhere, notably in the East Prebetic Fold Belt of southern Spain (De Ruig, 1995; Roca et al., 2006) where they have been attributed to diapiric fault-plane injection or squeezed diapirs (Roca et al., 2006). In that mechanism, diapirism was initiated during a period of extension, before compression and faulting resulted in squeezing and necking of the diapirs to form secondary bodies with finger-like geometries isolated from the source rocks. The area of the Hawasina Window has undergone a complex structural evolution with major phases of margin extension during the rifting stages of the Hawasina Ocean, and compression during ophiolite obduction and the Oligocene–Miocene (Nolan et al., 1990; Mount et al., 1998) uplift of the Al Jabal Al-Akhder anticline. We suggest that the Hawasina Window gypsum bodies may be broadly analogous to the Spanish example, with final emplacement of the gypsiferous bodies into the folded and thrust Hamrat Duru Group sediments. The emplacement took place during a post-obduction compressional phase associated with reversed movement along deep-seated rift-related faults which formed the conduit for entrained gypsum deposits.

These faults also appear to have been exploited by the hydrothermal activity that resulted in the development of sinters in Wadi Ad Dil to the north of the area of gypsiferous intrusions (Figure 5). Related fluid movement may also be responsible for the remobilisation of gypsum to produce the dense vein network in the gypsum bodies, kaolinsisation within some of the sandstone clasts and epidote crystals and veins. Elemental sulphur crystals are also associated with both sinter and gypsum deposits, suggesting bacterially-driven sulphate reduction of gypsum to hydrogen sulphite, followed by re-oxidation to form native sulphur (Jones et al., 1956; Feely and Kulp, 1957). The hydrocarbons necessary for this process are present, for example in fetid limestones in the Sumeini and Hamrat Duru groups, and a similar process can account for sulphur development in Jabal Qumayrah (Cooper et al., 2013). This process continues to the present-day in the Hawasina Window at Jabal Rastun, where fresh sulphur crystals are seen around hydrothermal vents.

The absence of gypsum exposed along other fault planes suggests it is a comparatively local phenomenon within the Hawasina Window, although the full extent of the gypsum bodies may be masked by their recessive weathering.

CONCLUSIONS

The gypsiferous-rich intrusions of the south-central Hawasina Window have no in situ origin within the allochthonous Hamrat Duru Group host rocks as these were deposited as Permian–Mesozoic deep-ocean sediments in the Hawasina Ocean segment of Neo-Tethys. Similarly, there is no clear source rock in the structurally underlying Permian and Mesozoic Neo-Tethyan carbonate platform sediments. These contain no abundant gypsiferous units where exposed in the north (Musandam Pensinsula) or southeast (Al Jabal Al-Akhder and Saih Hatat). We propose that the gypsum in the Hawasina Window intrusions has an origin in the Ediacaran–lower Cambrian Ara Group evaporites. This is also consistent with strontium isotope data. Gravity investigations indicate that the Hawasina Window is not underlain by a major salt diapir and the intrusion of the gypsiferous bodies is not a primary product of halokinesis. Instead, it is proposed that the gypsiferous bodies were mobilised at a late stage along major faults at deep burial depths through the Palaeozoic–Mesozoic basement and carbonate platform, following the Late Campanian conclusion of nappe emplacement and folding linked to the obduction of the Semail Ophiolite. The gypsum transported rounded clasts apparently derived from pre-Permian conglomerate beds, but many of the incorporated clasts were derived from stratigraphic levels in the Hamrat Duru Group close to the present-day outcrops.
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Figure 5: Geological map of the south-central Hawasina Window showing the main lithological and structural units and the location of the gypsum intrusions. Inset (bottom left) shows the distribution of the main thrust sheets. Note that areas shown as Haybi Complex locally include interleaved thrust slices of Hamrat Duru Group lithologies, which are not mapped separately at this scale. Numbers locate features described in the text or figure captions.