Five buried crater structures imaged on reflection seismic data in Saudi Arabia

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ABSTRACT

Reflection seismic data acquired for hydrocarbon exploration in Saudi Arabia have revealed five buried crater structures ranging in diameter from 5 km to 34 km. These structures have little or no present-day surface expression and span a range of ages from Ordovician to Cenozoic. The Saqqar structure (29°35'N, 38°42'E) is 34 km in diameter and is formed in Devonian siliciclastics. The structure is partially eroded and is unconformably overlain by Upper Cretaceous and Paleogene strata up to 400 m thick. The Jalamid structure (31°27'N, 39°35'E) is 19 km in diameter at Lower Ordovician level and is infilled by Middle Ordovician sediments, at a present-day depth of 4,500 m. The Banat Baqar structure (29°07'N, 38°36'E) is 12 km in diameter at Middle Ordovician level and infilled by Upper Ordovician sediments, at a depth of 2,000 m. The Hamidan structure (20°36'N, 54°44'E) is 16 km in diameter at Paleogene level and is overlain by a thin veneer of Recent sediment. The Zaynan structure (20°23'N, 50°08'E) is 5 km in diameter and affects Triassic sediments at depth of 3,800 m, and is infilled by Jurassic strata. In addition to reflection seismic imaging, various amounts of gravity and magnetic data and drilled wells are available in or near these structures. Various models including impact cratering are discussed here for each structure. One structure (Saqqar) has yielded quartz grains with possible shock metamorphic features that, contingent on future work, may support a meteorite impact crater interpretation.

INTRODUCTION

During the course of exploration activities for hydrocarbons in the Phanerozoic sedimentary basins of Saudi Arabia, several circular subsurface structures have been identified on reflection seismic, gravity, and magnetic data (Figure 1). Some of these structures have also been penetrated by wells. These data have been collected over a long period of time, in some cases over forty years. This paper illustrates five of these structures for the first time and discusses their origin in light of available data and other published work. Three of the structures are in the Nafud Basin in the north of the Kingdom, and two in the Rub‘ Al-Khali Basin in the south. The chronostratigraphic context of these structures is shown in Figure 2.

REGIONAL GEOLOGICAL SETTING

Nafud Basin

The Nafud Basin in northwestern Saudi Arabia contains Neoproterozoic strata that locally thicken to 6 km in fault-bound basins and may be equivalent in age to the Huqf Supergroup of Oman (Allen, 2007; Amireh et al., 2008; Al-Husseini, 2011). This package is capped by the Lower Cambrian Angudan Unconformity. Thick siliciclastic shelfal sequences developed from the Cambrian through Devonian (Sharland et al., 2001). A suite of quartz diabase sills were intruded in the late Devonian. Samples from cored wells yielded K-Ar ages of 366 ± 18 Ma (Cocker, 1993). Carboniferous “Hercynian” tectonism had little expression in terms of discrete compressional structures in the Nafud Basin, but there are variable amounts of uplift and erosion on a structural wavelength of hundreds of kilometers (Faqira et al., 2009; Cantrell et al., in press).

The Paleozoic section is unconformably overlain by Upper Cretaceous strata that thicken eastwards into the Widyan Basin. Lamprophyric dykes were intruded during the Late Cretaceous, with K-Ar dates in the range 81 ± 4 Ma (Cocker, 1993). The Cretaceous section is overlain by Paleogene marine
strata. The Phanerozoic succession locally reaches 10 km in thickness (Figure 1). The dominant structural trend is a pervasive set of northwest-trending Cretaceous and younger faults, some of which bound the Wadi Sirhan and Umm Wual grabens. This trend is clear in exposed Paleozoic strata in the Nafud Basin and is less well developed east of the Wadi Sirhan Graben. The reactivation history of this fault trend is not well constrained due to the absence of post-Paleozoic cover in the western area where the trend is best developed.

**Rub’ Al-Khali Basin**

The Rub’ Al-Khali Basin occupies the south and southeast of Saudi Arabia. Intracontinental rifting occurred in Neoproterozoic to early Cambrian time, but the extent of Huqf Supergroup equivalents such as Hormuz salt into the Rub’ Al-Khali is poorly constrained (Husseini and Husseini, 1990; Allen, 2007; Smith, 2012). As in the Nafud Basin, a thick, relatively uniform siliciclast sequence was deposited from Cambrian to Devonian. The basin underwent local uplift and subsidence during the Carboniferous, but significantly less than the Al-Batin Arch to the northwest and the Oman-Hadramaut Arch to the southeast (Konert et al., 2001; Faqira et al., 2009).

The Rub’ Al-Khali Basin was a passive margin basin accumulating thick carbonate sequences from Middle Permian to Late Cretaceous time, on the southwest side of the Neo-Tethys Ocean (Guiraud et al., 2005; Blakey, 2008). Pulses of Late Cretaceous and Paleogene fault reactivation and inversion were synchronous with ophiolite obduction in Oman (Searle et al., 2004; Johnson et al., 2005; Ali et al., 2008). From the Oligocene onwards, continent-continent collision of the Arabian Plate along the Zagros thrust front resulted in further folding and faulting (Mouthereau et al., 2012). The Saudi Arabian basins were affected by glaciation in the late Neoproterozoic, Ordovician and Carboniferous (Allen, 2007; Craig et al., 2009; Le Heron et al., 2009).

**CHARACTERISTICS OF KILOMETER-SCALE CRATER STRUCTURES**

Due to the occurrence of volcanism and active basin hydrodynamics on Earth, many mechanisms can give rise to structures in sedimentary basins that are circular in plan-view (Stewart, 1999; 2003; Schmieder et al., 2013). Mechanisms that might cause kilometer-scale crater-like structures include igneous and sedimentary volcanism or subsurface material redistribution, salt diapirism, salt or carbonate dissolution, glacial activity (e.g. kettle holes) and impact of meteorites. Origin and type of circular geological structure can potentially be identified on the basis of geometric characteristics at the scale of reflection seismic data (Stewart, 2003; Table 1). The crater structures presented in this paper are described individually in light of available evidence and possible mechanisms. In view of at least one of the newly-identified structures possibly having sufficient evidence to be considered an impact crater, more detailed introduction to impact structures in Earth’s sedimentary basins follows.
Formal acceptance of a geological feature as an impact structure requires evidence of shock metamorphic structures or impact melts that are uniquely associated with impact dynamics (French and Koeberl, 2010). This requirement creates a category of candidate impact structures whose morphometry is well-constrained by remote sensing or reflection seismic imaging but have not yielded shock metamorphic evidence, and are therefore not formally accepted as impact structures. Depending on the impact “target” lithology, depth of erosion of impact structure, and available sampling, the required shock metamorphic evidence can be surprisingly rare, sometimes leading to protracted debate on the cratering mechanism (e.g. Buchner and Kenkmann, 2008; Salameh et al., 2008). To date, some 184 structures are accepted as impact features on Earth (Earth Impact Database, 2012) though many more candidate structures have been identified (Rajmon, 2010). In the Arabian Peninsula at the time of writing, two structures are formally accepted as resulting from meteorite impact - the Recent hundred-meter scale Wabar crater field in the Rub’ Al-Khali (Philby, 1933), and the Eocene 5.5 km diameter Jabal Waqf as Suwwan structure in Jordan (Salameh et al., 2008). Additional, candidate impact structures have been identified on the basis of reflection seismic imaging in Oman (Levell et al., 2002) and aerial imaging and fieldwork in Saudi Arabia (Garvin and Blodget, 1986; Gnos et al., 2011).

Impact craters in the size range relevant to this paper are classified as either simple or complex based on their size and morphology (Figure 3; Pike, 1988; Melosh, 1989). On Earth, “simple” craters are usually bowl-shaped and less than ca. 3 km in diameter, with uplifted rims and depth-to-diameter ratios of around 1:6. “Complex” craters have diameters larger than about 3 km and are characterized by a central uplift and terraced outer rim. Still larger impact structures form “peak-ring” and “multi-ring” basins. By analogy with

Figure 2: Chronostratigraphic summary of the Nafud and Rub’ Al-Khali basins showing stratigraphic position of the crater structures discussed in this paper. Vertical dashed lines show age uncertainty range for craters preserved below significant unconformities. Simplified after Sharland et al. (2001), Allen (2007), Al-Husseini (2011) and Mouthereau et al. (2012).
Table 1
General characteristics of circular structures in sedimentary basins, after Stewart (2003) and references therein. These are characteristics that can be identified from reflection seismic imaging and other remote sensing data and are compiled for assessment of structures where no direct sampling is available (e.g. undrilled buried structure)

| Family          | Member                        | Diameter (km) | Plan-view Shape (Circular vs. Other) | Maximum/Minimum Diameter ratio | Crater (vs. Dome) | Central Uplift or Peak Within Crater? | Overturned Peripheral Strata? | Inward-facing, Peripheral Extensional Fault(s)? | Depressurization Aspect Ratio | Genetic Requirement to Form Linked Arrays? | Related to Regional Trends? | Characteristic Specific Geologic Setting? | Related Structure in Deep Underlying Strata? | Restricted Stratigraphic Occurrence? |
|-----------------|-------------------------------|---------------|-------------------------------------|--------------------------------|-------------------|--------------------------------------|-------------------------------|-----------------------------------------------|-------------------------------|--------------------------------------------|-------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| Intrusions      | Salt diapir                   | 1–5           | Y 1                                  | N N                             | ~                 | ~                                    | 1–5+                          | N ~                             | N Y N                                        |                               |                               |                               |                               |                               |                               |
|                 | Mud or shale diapir           | 0.1–5         | Y 1                                  | N ~                             | ~                 | ~                                    | 1–5+                          | N ~                             | ~ Y N                                        |                               |                               |                               |                               |                               |                               |
|                 | Igneous diapir                | 1–10          | ~ 1+                                 | N ~                             | ~                 | ~                                    | 1–5+                          | N ~                             | N Y N                                        |                               |                               |                               |                               |                               |                               |
|                 | Igneous sill/laccolith        | 0.1–10+       | ~ 1+                                 | N N                             | N N               | 0.01–0.2                             | N ~                            | N Y N                                        |                               |                               |                               |                               |                               |                               |
|                 | Sand cone sheet               | 0.1–3         | Y 1                                  | N N                             | N N               | 0.1–0.2                              | N ~                            | ~ N Y N                                       |                               |                               |                               |                               |                               |                               |
| Pillows         | Salt                          | 1–10          | ~ 1+                                 | N N                             | N N               | 0.01–1                              | N ~                             | N N N                                        |                               |                               |                               |                               |                               |                               |
|                 | Sand                          | 1–10          | ~ 1+                                 | N N                             | N N               | 0.01–1                              | N ~                             | N N N                                        |                               |                               |                               |                               |                               |                               |
|                 | Mud or shale                  | 1–10          | ~ 1+                                 | N N                             | N N               | 0.01–1                              | N ~                             | N N N                                        |                               |                               |                               |                               |                               |                               |
| Volcanoes       | Igneous                       | 1–50          | Y 1                                  | N ~                             | N N               | 0.1–0.5                              | ~ ~                             | N Y N                                        |                               |                               |                               |                               |                               |                               |
|                 | Mud or shale                  | 1–5           | Y 1                                  | N ~                             | N N               | 0.1–0.5                              | N ~                             | N Y N                                        |                               |                               |                               |                               |                               |                               |
| Fluid expulsion | Diatreme or maar              | 0.01–10       | Y 1                                  | Y N                             | N ~               | ~ 2+                                 | N ~                            | N Y N                                        |                               |                               |                               |                               |                               |                               |
|                 | Phreatomagmatic explosion     | 0.01–1        | Y 1                                  | Y N                             | ~                 | ~ 0.01–2                             | N ~                            | ~ Y ~                                         |                               |                               |                               |                               |                               |                               |
|                 | Gas pocket                    | 0.01–0.7      | Y 1                                  | Y N                             | ~                 | ~ 0.01–0.2                           | Y ~                            | ~ Y ~                                         |                               |                               |                               |                               |                               |                               |
|                 | Freshwater rafting            | 0–17          | N ~                                  | Y N                             | ~                 | ~                                    | ~ N                            | N Y ~                                         |                               |                               |                               |                               |                               |                               |
| Withdrawal basin| Igneous (caldera)             | 2–50          | Y 1                                  | Y ~                             | N ~               | 0.5–1                                | N ~                            | N Y N                                        |                               |                               |                               |                               |                               |                               |
|                 | Sediment redistribution       | 0.01–10       | ~ 1+                                 | Y ~                             | N ~               | 0.1–1                                | N ~                            | N N N                                        |                               |                               |                               |                               |                               |                               |
|                 | Karst (carbonate & evaporite) | 0.01–1        | Y 1                                  | Y N                             | N N               | 0–10                                 | Y ~                            | ~ Y N                                         |                               |                               |                               |                               |                               |                               |
|                 | Salt deflation                | 2–15          | ~ 1+                                 | Y N                             | N ~               | 0.5–1                                | N ~                            | N N N                                        |                               |                               |                               |                               |                               |                               |
| Tectonic        | Pull-apart basins             | 0–40          | N 2–5                                | Y N                             | ~                 | 0–1                                  | ~ Y                            | N Y N                                        |                               |                               |                               |                               |                               |                               |
|                 | Drape fold (dome)             | 1–100         | Y 1+                                 | N N                             | N N               | 0.2–2                                | N ~                            | N Y N                                        |                               |                               |                               |                               |                               |                               |
|                 | Interference folds            | 0–100         | Y 1+                                 | N N                             | N N               | 0.2–2                                | N ~                            | N Y ~                                         |                               |                               |                               |                               |                               |                               |
|                 | Polygonal faults              | 0.3–2         | N 1                                  | N N                             | N N               | 0.5–3                                | Y ~                            | ~ Y N                                         |                               |                               |                               |                               |                               |                               |
| Bioherms        | Patch reefs and carbonate mounds | 0.01–5       | ~ 1+                                 | N N                             | N N               | 0.05–0.5                             | N ~                            | Y N N                                        |                               |                               |                               |                               |                               |                               |
| Glacial         | Kettle holes                  | 0.01–5        | Y 1+                                 | Y N                             | N ~               | 0.01–0.1                             | N N                            | Y N N                                        |                               |                               |                               |                               |                               |                               |
|                 | Drumlins                      | 0.1–2         | Y 2+                                 | N N                             | N N               | 0.01–0.1                             | N N                            | Y ~                                         |                               |                               |                               |                               |                               |                               |
| Impact craters  | Simple                        | 1–3           | Y 1                                  | Y N                             | ~                 | ~ 0.05–0.3                           | ~ N                            | N N N                                        |                               |                               |                               |                               |                               |                               |
|                 | Simple (very low angle impact)| 1–3           | Y >1                                 | Y N                             | ~                 | ~ 0.05–0.3                           | ~ N                            | N N N                                        |                               |                               |                               |                               |                               |                               |
|                 | Complex and Peak-ring basins  | 3–100+        | Y 1                                  | Y Y                             | ~                 | ~ 0.01–0.1                           | ~ N                            | N N N                                        |                               |                               |                               |                               |                               |                               |
observations of impact structure populations elsewhere in the solar system, the transition from complex craters to these large types of structure is likely to occur at diameters greater than 30 km on Earth (Baker et al., 2011). Complex craters have depth-to-diameter ratios in the range 1:10 to 1:100, due to the amount of crater floor rebound in the impact process (Wünnewmann and Ivanov, 2003; Collins et al., 2008; Senft and Stewart, 2009).

The relatively shallow aspect ratio of impact craters is a discriminating characteristic because many alternative crater-forming mechanisms form comparatively deep structures for a given diameter (Table 1). Shockwave deformation leads to pervasive damage of strata some distance beneath the crater floor. Beyond a depth of about 25% of crater diameter the impacted strata transition to being in-situ and intact at the scale of reflection seismic imaging (Senft and Stewart, 2007; 2009), which is another distinguishing characteristic if quality seismic imaging is available. Uplift, erosion and reburial can lead to partially preserved craters – or the crater itself may be completely eroded leaving only a damaged footprint (Figure 3).

Given the proportion of Earth covered in water and freshly deposited, unconsolidated sediments, many impacts on Earth will have occurred into “targets” with material properties quite different from those generally studied on extraterrestrial bodies and in shield areas of Earth. The mechanics and effects of “soft target” impacts are less well documented than impact structures in “hard targets” (Buchanan et al., 1998; Richardson et al., 2002; Dypvik and Jansa, 2003; Davison and Collins, 2007). So there may be additional features - or absent features - associated with impacts preserved in Earth’s sedimentary basins relative to impact into well-lithified or crystalline targets (e.g. Collins et al., 2008; Senft and Stewart, 2011).

FIVE SUBSURFACE CRATER STRUCTURES IN SAUDI ARABIA

Saqqar Structure

Saqqar is a ca. 34 km diameter circular structure in the Nafud Basin. The Saqqar structure is centered at 29°35’N, 38°42’E, an area of partially exposed solid geology and gentle topography at an elevation of 600–700 m (Figure 4). In this area, Devonian formations are unconformably overlain by the Maastrichtian Aruma Formation. Deformation at the Saqqar structure affects the Devonian
strata but not the overlying Upper Cretaceous and younger beds. A grid of 2-D reflection seismic lines with spacing in the range 5–10 km images a circular structure with an uplifted central high surrounded by a concentric, moat-like syncline, which is in turn bounded by a fault system (Figure 4). The structure is visible on eight of these seismic lines. The circular plan form of the bounding fault interpretation is based on a combination of reflection seismic imaging (e.g. Figure 5) and gravity data (Figure 4). The central high is imaged on seismic and has been drilled by several wells (Figure 5). One well is deep; the others are shallow wells drilled to depths less than 1,500 m. The general form of the central high is borne out by gravity data but there is no clear signature on aeromagnetic data (Figure 4). The rim syncline is ca. 150 millisecond TWT (ca. 300 m) deeper in the northwest flank of the structure relative to the southeast flank (Figure 4).

Devonian strata on the southern margin of this structure are exposed and were mapped in the field by Wallace et al. (2000) as the Ja’alat as Samra fault and fold system, where unusual deformation has affected the Tawil and Jauf formations, but not the overlying Maastrichtian Aruma Formation (Figure 4). Devonian regional dips rarely exceed 10° at present, so the occurrence of dips steeper than 40° is considered anomalous. The steep dips mapped at surface broadly coincide in location and trend with the margin of the circular structure mapped on seismic data (Figure 4).

A deep exploration well together with several shallower wells drilled in the central high revealed consistently steep dips (30–40°) in the Cambrian–Ordovician section and demonstrate that strata in the crest of the central uplift are currently at shallower structural levels than their regional elevations. Dipmeter data also indicate the presence of numerous faults, some of which were confirmed by log correlation and age dating. Several cores cut in the wells demonstrate steep dips – occasionally as high as 70° – and abundant unusual deformation features including pervasive, centimeter-scale faults with normal and reverse offsets (Figure 6a).

In general, Paleozoic subarkosic sandstones and shales in the Nafud Basin do not show deformation beyond the usual effects of physical and chemical compaction. Quartz grains in the sandstones display internal textures reflecting their origin; those derived from plutonic rocks (granites) are optically homogenous, while those derived from metamorphic rocks (e.g. gneisses) generally display penetrative deformation effects such as undulose extinction, boehm lamellae and annealing textures. Both types are typically found in sandstones. In contrast, thin sections from a bed of white sandstone that was penetrated in the Saqqar structure show indications of pervasive penetrative deformation. These include: (1) wavy or patchy extinction affecting nearly all quartz grains; (2) dense suturing and interpenetration of quartz grains, their texture resembling quartzite (Figure 6b); and (3) most quartz grains contain parallel regularly spaced planes that resemble cleavage (Figure 6c). In detail, the planes are faint, and usually outlined by trains of very small (< 1 μm) inclusions (Figure 6d). Individual quartz grains display up to 3 planar directions, although one generally prevails, and generally not parallel to the optical crystal directions. While many resemble planar deformation or “feather” features (c.f. French and Koeberl, 2010; Poelchau and Kenkmann, 2011), additional work is needed to characterize them and establish their origin. Nonetheless these penetrative deformation features are particularly unusual and together with the large-scale geometry of the Saqqar structure, may represent evidence of meteorite impact.

Evidence in support of alternative, non-impact models for the Saqqar structure is largely absent. There is no magnetic signature that might indicate a significant igneous intrusion associated with the structure, and there are no deep evaporites or carbonates to dissolve and create a collapse structure of this size. Dissolution processes do not cause overlying strata to rise above their regional elevations, yet such uplift is present in the Saqqar central high, constrained by reflection seismic and well data (Figures 4 and 5).

The large-scale geometry of the Saqqar structure is a good match with the general morphology of a complex impact crater, albeit deeply eroded (c.f. Figure 3). Based on the absence of distinctive crater-fill deposits on seismic data and cores, we interpret the level of pre-Late Cretaceous erosion to have reached close to, or deeper than the crater floor. Modeling of depth-to-diameter ratios of impact craters on Earth suggests a final crater depth of ca. 700 m for a diameter of 34 km (Wünnemann and Ivanov, 2003). This gives an estimate of the minimum amount of erosion implied
Buried crater structures, Saudi Arabia

Figure 4: Saqqar data and mapping. All maps are the same scale and cover the same area. North is up. The main subsurface circular bounding fault structure is shown on each map for reference. (a) Satellite image, small circular features are cultivated areas. (b) Subsurface data coverage, also showing the location of Figure 5 (purple highlighted seismic line). (c) Surface geology, simplified after Wallace et al. (2000). (d) Top Ordovician two-way-time (TWT) map based on the 2-D seismic grid and wells shown in (b). (e) Airborne Bouguer gravity. (f) Airborne magnetic signature reduced to pole.
Figure 5: (a) Reflection seismic data, (b) interpretation and (c) depth conversion of 2-D seismic line through the Saqqar structure. Horizontal scale is the same in all subfigures. Interpretation outside the Saqqar structure is constrained by a regional seismic grid that ties offset wells. The west end of the section is tied to a Proterozoic well penetration 75 km away. MSL – Mean Sea Level.
Figure 6: Core and thin section photos from the Qasim Formation in the Saqqar central uplift. (a) Core photograph showing highly faulted sandstone and shale beds with mixture of normal and reverse faults. (b) Thin section of sutured quartzite, crossed polars. Most grains display undulose and patchy extinction, and are sutured together. Grains x, y, and z are in optical continuity (single crystal). (c) Thin section of sutured quartzite, crossed polars. Some planar features highlighted in red, not including trails of aqueous fluid inclusions along curved fractures. (d) Close up of a single quartz grain showing faint planar lamellae spaced 5 μm apart. Several generations of fluid inclusions are present, most aligned along healed microfractures, and obscuring the planar features.
by the impact interpretation. The arrangement of a positive gravity anomaly restricted to the center of the structure (Figure 4e) is characteristic of impact craters larger than 30 km in diameter (Pilkington and Grieve, 1992).

An impact of this magnitude in a shallow-marine setting ought to generate a fine-grained layer of ejected material ranging from tens of centimeters in thickness at a radial distance of one hundred kilometers, thinning to millimeters at distances greater than five hundred kilometers (Collins et al., 2005). Therefore there is an opportunity to further test this interpretation at outcrop and in cored wells. Since no ejecta material has been found in nearby Devonian outcrops to date, the age of the Saqqar impact structure is poorly constrained to being between Late Devonian and Late Cretaceous.

Jalamid Structure

The Jalamid structure is a 19 km diameter feature located in the northern part of the Nafud Basin (31°27′N, 39°35′E), in an uplands area ca. 850 m above sea level. Surface geology consists of Paleogene sediments that dip gently to the west (Wallace et al., 2002). The Jalamid structure is buried 4 to 5 km below the present land surface. The structure is fully covered by 3-D reflection seismic data (Figure 7) and drilled by a number of wells – though only one well penetrates to the interpreted level of the crater. No gravity or magnetic anomaly is present in this area. Some minor igneous intrusions are imaged on seismic and penetrated in wells as meter-scale, isolated sills in the Silurian section. The intrusions have not been directly dated in this area.

Detailed mapping on 3-D reflection seismic data shows a well-defined crater structure at top middle Cambrian level (Burj Formation, Figure 7). This crater is 19 km in diameter and is characterized by a synclinal moat inboard of a crater-margin fault system, and a broad central high capped with a pronounced but poorly-imaged peak structure. In some orientations of cross-section, this poorly-imaged “peak” is discernible as a triangular (i.e. conical in 3-D), upwards-pointing feature. This peak is ca. 6 km in diameter at its base and is at least 400 milliseconds (ca. 800 m) in height. The overall crater structure is for the most part radially symmetrical, but in the north and northeast the crater margin has unusual monoclinal form with outward-facing extensional faults within the synclinal low (Figure 7). A set of folds emanates radially from the central peak and terminates in the synclinal moat (Figure 7). Some minor strike-slip faults trending WNW–ESE are visible in the Burj Formation outside the crater (Figure 7). The reactivation history of these faults is not well constrained, but mapping elsewhere in this 3-D survey indicates that a large part of their movement history is post-Silurian.

A representative seismic line intersecting the crater center provides constraint on crater age and reveals some enigmatic features (Figure 8). The seismic interpretation is constrained by several wells, the deepest of which is offset 5 km from the crater center and which penetrated top Lower Ordovician (top Saq Formation) with good log coverage, core recovery and biostratigraphy (well location shown in Figure 7). Pre-Ordovician stratigraphy is controlled by regional mapping tied to offset deep wells. Neoproterozoic strata below the crater and central uplifted regions are poorly imaged, and it is not possible to say from the available data whether there are any related deep structures. The crater and central uplifted region affect strata to at least the depth of top Neoproterozoic (Figure 8).

The crater and central uplifted area are truncated by Middle Ordovician strata (Hanadir Member), providing relatively good, Early Ordovician control on the age of the crater structure. The Hanadir Member thickens significantly to a maximum isopach thickness above the central uplifted area of ca. 700 m, compared with typical local thickness in the order of 200 m. This thickening begins 4 to 5 kilometers radially outboard of the crater margin fault system as mapped at top Lower Ordovician. Evidently a shallow basin formed with a radially-symmetric flexural component centered on the crater during or immediately after the cratering process.

An intriguing aspect of the Hanadir Member is that its upper surface is structured into a gentle dome, centered on the middle of the crater. This dome rises some 300 m above the regional top Hanadir surface and appears to be a precise inversion of the local basin of anomalously thick
Hanadir. The timing of this domal inversion is well-constrained to being late Silurian following a period of isopachous deposition of Upper Ordovician and lower Silurian strata (Figure 8). This indicates a gap of some 30 million years between infill of the supra-crater basin and the inversion, and 40 million years overall between crater formation and the inversion. Although igneous intrusives are present in this area, only minor igneous bodies are imaged in the vicinity of the crater. These intrude Silurian strata and are therefore significantly younger than the crater (Figure 8). The anomalously thick Middle Ordovician Hanadir Member was studied from cuttings and cores and yielded abundant microfossils. Although no igneous material was observed within the samples from the Hanadir Member, the microfossils were recorded as being anomalously dark in color, particularly towards the base of the formation. This is interpreted as an unusual thermal effect (Filatoff et al., 2000).

Figure 7: Mapping of the Jalamid structure from 3-D seismic reflection data. (a) Oblique view of top middle Cambrian (Burj Formation). (b) Combination display of top Middle Cambrian mapped surface and dip map (dark trends and pixels are calculated high dips). (c) Structural interpretation of top Middle Cambrian from (b).
Figure 8: (a) seismic section, (b) interpretation and (c) depth conversion of line through the Jalamid structure. The seismic section and interpretation are flattened on top Silurian to remove later regional tilt. The seismic section location is from a 3-D survey, location of line shown on Figure 7.
The lowest 50 m of the well cored and logged shallow-marine sandstones that contain burrows but are barren of age-diagnostic taxa. These sands are assigned to the Lower Ordovician (upper part of Saq Formation), which is consistent with regional maps (Figure 8). As interpreted, the Saq Formation represents the crater floor (Figure 8). The samples are described as well-compacted with syn-sedimentary deformation and strain assigned to drilling effects, but no features that might be interpreted as products of shock deformation were reported. Image logs show noticeable contrast in bedding organization between the lower parts of the Hanadir Member and the underlying Saq Formation (Figure 9). The Hanadir bedding is regular and shallow-dipping whereas it is difficult to pick out any coherent bedding in the Saq Formation (Figure 9).
It does not appear to be straightforward to identify a simple model for the complete evolution of the Jalamid structure. The Lower Ordovician crater could be a candidate impact structure, which would explain the crater and possibly the immediately overlying basin filled with Middle Ordovician – but impact cratering would not explain the upper Silurian dome. An alternative mechanism could involve sediment redistribution and intrusion, as proposed in relation to kilometer-scale crater and peak structures in the Silurian–Devonian Murzuq Basin of Libya (Moreau et al., 2012), which was along trend with the Nafud Basin at the time, albeit some 2,000 km distant (Guiraud et al., 2005; Faqira et al., 2009). Sediment redistribution has the attraction of potentially solving the crater and doming as a single process (sediment mobilization and movement from deep-level creates a withdrawal crater while intrusion or extrusion of that sediment at shallow-level creates a dome). But there are two problems with application of a sediment redistribution model to the Jalamid structure. Firstly, reflection seismic data indicate that the crater and dome episodes of tectonics are separated by tens of millions of years. Secondly, there is no evidence to-date on the seismic data or in well control of sedimentary intrusions at any level in the imaged stratigraphy (i.e. above Proterozoic). A composite model is offered here consisting of impact, followed some time later by sub-crater igneous intrusion.

We suggest that an impact occurred into the Lower Ordovician shallow-marine shelf, creating a crater with central peak structure, set in a shallow flexural basin that was infilled by the end of the Middle Ordovician. The layout of large-scale structural elements mapped within the Jalamid crater (Figure 7c) is a good match with internal structure of known impact craters (e.g. Abels, 2005; Kenkmann et al., 2005; Kenkmann and Poelchau, 2009). We then suggest that, in the late Silurian, an igneous laccolith intruded the Neoproterozoic below the crater, perhaps exploiting damage caused by the impact event. This laccolith deformed the late Neoproterozoic to late Silurian section into the dome seen today. Multi-kilometer-scale doming above laccolithic intrusion has been imaged on reflection seismic data elsewhere (e.g. fig 3b in Jackson, 2012). The intrusion would also explain thermal effects in the Middle Ordovician microfossils, and is consistent with the minor intrusions on 3-D seismic and in the well. At the time of writing, however, there is no unequivocal evidence for either the Early Ordovician impact event or large-scale late Silurian-aged igneous intrusion.

Banat Baqar Structure

The Banat Baqar structure is a 12 km diameter feature located in the Nafud Basin at 29°07′N, 37°36′E, 120 km southwest of the Saqqar structure. Local topography is at an elevation of ca. 750 m. Surface geology consists of Silurian–Devonian sediments that dip gently to the east, with patchy thin Quaternary cover. The Silurian–Devonian outcrop contains a pervasive set of NNW-trending faults with a spacing of 3–5 km (Figure 10). The Banat Baqar structure is buried ca. 2 km below the surface. The structure is imaged by a sparse grid of 2-D reflection seismic data. There are four lines in the vicinity, and the structure is imaged on two of them (Figure 10). Banat Baqar is undrilled; the nearest deep well is some 60 km distant, though the stratigraphic tie to this well via regional 2-D seismic is good. A positive Bouguer gravity anomaly is present (Figure 10).

Seismic image quality over Banat Baqar is reasonably good and shows a fault-bound low affecting Lower and Middle Ordovician strata (Figure 11). The faults are inward-facing on both seismic lines that image the structure. Plan-view mapping between the seismic lines is guided by the gravity map and indicates a circular (i.e. crater) form of the low and its bounding fault system (Figure 10). A central high is imaged within the crater on both seismic lines (Figure 11). The central high rises ca. 70 milliseconds (about 170 m) above the crater floor, but strata within it do not exceed their regional elevations (unlike Saqqar and Jalamid). The crater is entirely contained within the upper Cambrian to Upper Ordovician section. Lower Cambrian and Proterozoic strata provide clear, relatively unstructured markers below the crater (Figure 11). The crater was completely buried by the end Ordovician.

Like Jalamid, a dome structure later developed over the Banat Baqar crater. The Banat Baqar dome deforms the Silurian section on reflection seismic cross section (Figure 11). The dome is expressed at the present-day surface as a Silurian inlier (Figure 10). The timing of doming is not constrained
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more precisely than being post-Silurian, because the Silurian–Devonian contact is close to the surface in this area and no younger, undomed strata are preserved. This does however provide a minimum time interval between the cratering and doming processes of nearly 30 million years.

Reflection seismic imaging shows that there is volume loss from the cratered Lower Ordovician to upper Cambrian interval (Figure 11). Although the top Cambrian is poorly defined below the crater, offset well control demonstrates that the top Lower Ordovician to top lower Cambrian does not contain significant amounts of carbonates or evaporites. Therefore dissolution or salt withdrawal is unlikely. The seismic data also indicate an unusual, relatively bright reflector in the

Figure 10: Mapping of the Banat Baqar structure. All maps are to same scale, North is up. (a) False color satellite image (Enhanced Thematic Mapper). (b) Surface geology after Wallace et al. (2000). The Ghuwar and Samra members are within the Tawil Formation. Regional dip is to northeast. (c) Subsurface mapping at top Lower Ordovician (top Saq Formation). (d) Airborne Bouguer gravity.
Figure 11: (a) 2-D seismic section, (b) interpretation and (c) depth conversion of line through the Banat Baqar structure. Location of line shown on Figure 10.
upper Cambrian section below the crater (Figure 11). Since this reflector is imaged on both seismic lines that cross the crater, it is unlikely to be a geophysical artifact. The reflector has the same polarity as top middle Cambrian (Burj Limestone), and so can be interpreted as a “hard” seismic event. It has lower amplitude than the Burj reflector so the acoustic impedance contrast with the fine-grained siliciclastics of the lower Saq Formation is not as great. Nonetheless, this unusual reflector could be interpreted as an igneous intrusion, leading to a combined igneous intrusion plus sediment redistribution model for the crater (e.g. Underhill, 2009; Cigolini et al., 2012; Moreau et al., 2012). In such a cratering mechanism, the volume of material lost from below the crater (plus the volume of the igneous intrusion, which is added into the sub-crater volume), is balanced by redistribution of material to shallower structural levels – infilling the crater in this case. Some signs of large-scale sediment redistribution might be expected within the crater fill if this model is applicable, for instance constructional extrusive edifices or sills. Available seismic imaging indicates the Upper Ordovician crater fill to have a rather parallel-bedded, “quiescent” character. Parallel-bedded character of the crater fill does not rule out an intrusion and redistribution-cratering model, but it does challenge that model with a question concerning the depositional architecture of the supposedly redistributed sediment. There is no magnetic anomaly associated with Banat Baqar. An alternative model for the Banat Baqar crater is impact cratering. The general form and geometrical attributes (aspect ratio, lack of underlying structure) accord with impact crater characteristics. The positive gravity anomaly might be construed as evidence against impact, given that documented impact craters at this scale tend to be characterized by negative gravity anomalies (Pilkington and Grieve, 1992). However, the Jabal Waqf as Suwwan impact crater, some 225 km distant from Banat Baqar, displays a positive gravity anomaly (5 mGal), comparable with the 2 mGal positive anomaly at Banat Baqar (Abdelhamid, 2001; Wünnemann et al., 2011). A further challenge to the impact interpretation of both Banat Baqar and Jalamid is the similarity in their age. As currently mapped, these structures are separated by the duration of the Middle Ordovician, but this depends on accurate correlation of the rather thin Middle Ordovician sequence (i.e. Hanadir Member) from the Banat Baqar area to offset well control. Since this correlation could be in error, there is a chance the Banat Baqar and Jalamid structures are similar in age. Although impact crater pairs or “doublets” that result from the impact of binary asteroids are known in the terrestrial cratering record, the 320 km separation of Banat Baqar and Jalamid is greater than would be expected of doublet impact craters of this scale (Bottke and Melosh, 1996; Miljković et al., 2013). It could generally be said that uniqueness of occurrence is a factor in favor of impact interpretation (Table 1) and this would obviously be lessened if the ages of Banat Baqar and Jalamid converge. Irrespective of crater mechanism at Banat Baqar, the doming mechanism is also rather enigmatic, not least because it is similar in appearance and timing to the dome associated with Jalamid structure. As at Jalamid, the significant time period between formation of the crater and development of the dome suggests that the mechanisms of crater and dome development could be different, albeit with a link that causes the crater and dome to be coincident. The idea of Ordovician impact cratering followed by later updoming due to igneous laccolithic intrusion at depth is also tentatively offered for Banat Baqar.

Hamidan Structure

The Hamidan structure is a 16 km diameter feature located in the Rub’ Al-Khali Basin at 20°36’N, 54°44’E. Hamidan is at shallow structural level, apparently buried only by recent dunes and sabkha. Thin layers of Quaternary or Neogene strata might also overlie the structure but were not recorded in wells or reflection seismic data. Decameter-scale sand dunes and interdune sabkha define the local topography, at a general elevation of 75 m above sea level. The structure is imaged on three 2-D seismic lines (Figure 12). There are several wells in and around the structure, including a deep exploration well that drilled to the Cambrian at a depth of ca. 5 km. There is also airborne gravity and magnetic data coverage, both of which show pronounced anomalies that are circular in plan view (Figure 12). Satellite imagery details a low-lying area of sabkha with Recent evaporites overlying the structure. The structural map shown in Figure 12 was produced using potential field anomalies to guide structural interpretation in between the seismic lines, combined with well control.
Figure 12: Mapping of the Hamidan structure. (a) Enhanced Thematic Mapper image, blue hues indicate moisture content, dark blue is standing water. (b) Subsurface map of top Cretaceous (Top Aruma Formation) based on reflection seismic interpretation, wells and potential field anomalies. (c) Airborne Bouguer gravity. (d) Airborne magnetic anomaly reduced to pole.

The quality of reflection seismic imaging is poor on all three lines that cross the structure (Figure 13), evidently due to the unusual nature of near-surface strata. Strata buried immediately below the recent sediments appear to be structurally disrupted – broken, locally steeply dipping and chaotic, contributing to the poor reflection seismic signal. This contrasts with the regional seismic character which characteristically consists of monotonous, sub-horizontal reflectors with fair to good seismic image down to three seconds two-way time or more, even on old vintage data. Nonetheless the seismic data indicate that the Hamidan disturbed area is bounded by inward-facing extensional faults that penetrate into the Paleozoic strata (Figure 13). Poor imaging of the deep section on reflection seismic data means it is not possible to directly constrain the base of the structure and whether or not it is linked to deep stratigraphy or basement. Gravity and magnetic data show pronounced anomalies in this area (Figure 12). The gravity anomaly is a positive,
somewhat polygonal feature, and the magnetic anomaly is positive with a number of concentric circular ring features. The potential field anomalies are co-located and overlie the fault-bound disturbance seen on reflection seismic lines. Therefore it can be concluded that the anomalies on all data types are related to the same structural feature. The fidelity of the potential field anomalies suggests that the cause is at a relatively shallow structural level.

Wells in and near the structure include a deep exploration well that drilled to Cambrian level. This well is located within the zone of fault-bound structural disturbance and potential field anomalies (Figures 12 and 13). No dipmeter data are available for this deep well. The stratigraphy fits regional depths and isochore thicknesses of all main stratigraphic units from Cretaceous level to base of the well. This in turn indicates that the section has regionally consistent low dip (anomalously high dips would alter the depth isochores), and the good fit of formation tops with regional elevations indicates that there is no major structural disturbance in the deep strata that are poorly imaged on reflection seismic. The seismic interpretation and depth conversion shown in Figure 13 incorporate the formation tops in time and depth and inferred low dips. No igneous material, salt intrusion or any other stratigraphic anomaly was recorded in the pre-Cretaceous section of this well. There are stratigraphic anomalies, however, in the Paleogene to uppermost Cretaceous sections of all three wells located in the “disturbed zone” (Figures 12 and 13). In these wells, the lithology is reported as “mixed” and paleontology as “contaminated”, leading to irresolvable stratigraphy within the Paleogene section (Hennington et al., 1979). With increasing depth, the stratigraphy returns to conventional organization in the Cretaceous Aruma Formation at a depth of ca. 900 m. The two wells outside the disturbed zone have regular lithology and paleontology throughout, recording shallow-marine to evaporitic Dammam, Rus and Umm er Radhuma formations that are regionally consistent in character and depth (Figure 13).

So at Hamidan there is a fault-bound feature some 16 km in diameter with potential field anomalies and disturbed stratigraphy in the Paleogene and uppermost Cretaceous intervals. Although the character of this anomalous structure is not clearly imaged on reflection seismic data, deep well control suggests that the main structure is confined to the shallow Paleogene level, with inward-facing bounding faults extending down to Paleozoic level. Several alternative mechanisms could account for these observations. Dissolution collapse is relatively common at shallow stratigraphic levels in the Rub’ Al-Khali and adjacent areas (Bakiewicz et al., 1982; Edwards et al., 2012), often focused on the evaporitic Eocene Rus Formation, and zones of collapsed, seismically incoherent strata occur. However, the closest known examples of shallow-level dissolution are some 400 km distant from Hamidan, and they tend to be rather smaller in scale than the Hamidan structure. In-situ dissolution and brecciation in the Paleogene strata at Hamidan would however not account for the extensional faults that are observed to extend down to the Paleozoic and therefore this mechanism is unlikely to be the prime cause of the structure. Dissolution at Cretaceous or Jurassic level is conceivable, but a dissolution structure in the Mesozoic at this scale would be unprecedented in the basin, and the faults that penetrate the pre-Mesozoic section would still be unaccounted for.

An igneous intrusion could explain the potential field anomalies, and could perhaps explain the structural observations in a model of intrusion at depth, followed by withdrawal and caldera collapse combined with a pipe system feeding phreatomagmatic maar activity at the surface (e.g. Gorter and Glikson, 2002; Paillou et al., 2006). None of the wells recorded igneous material, nor are there any signs of igneous structures in the reflection seismic data, though igneous intrusions of Maastrichtian to Eocene age are described at outcrop several hundred kilometers further east in Oman (Gnos and Peters, 2003). Hamidan is considerably larger in diameter than known individual or coalesced maar structures (Begét et al., 1996; Jordan et al., 2013).

Salt tectonics is another possibility, perhaps a dome or intrusion of Ediacaran–Cambrian Hormuz salt that formed then collapsed in the Paleogene or Neogene. Hamidan is reasonably close to known salt structures in the Fahud and Ghaba basins of Oman. The Ghaba Basin salt structures include domes and diapirs of Ara Group evaporites, some of which have been active until present-day and which are exposed at the surface (Peters et al., 2003; Reuning et al., 2009). The distance
Figure 13: (a) 2-D seismic section, (b) interpretation and (c) depth conversion of line through the Hamidana structure. Location of line shown on Figure 12.
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from Hamidan to the nearest salt diapir at surface in Oman is 195 km (Qarn Sahmah), though unexposed salt structures may be somewhat closer (e.g. Al Kindi et al., 2011). Gravity anomalies are commonly associated with salt structures but are usually expected to be negative (Nettleton, 1962), as indeed is the case with the Ghaba Basin structures (Peters et al., 2003). However, the Hamidan gravity anomaly is positive (Figure 12), something only rarely associated with salt (e.g. Benassi et al., 2006). Of the structures described in this paper, Hamidan is closest to the known salt basins of Oman and the Arabian Gulf, but the occurrence at Hamidan of a salt intrusion at very shallow structural level would be unique in the Rub' Al-Khali. No evidence of salt diapirism was observed on the data available in Hamidan.

Another option to consider is that Hamidan is a meteorite impact structure. In an impact interpretation, the disturbed Paleogene section would be explained by crater floor and fill. The seismically imaged faults that extend to the Paleozoic would represent the faults and terraces that bound what would be a complex crater (c.f. Figure 3). There would be progressively less effect with depth below the crater, which fits the well data. The reflection seismic data are equivocal in this regard due to poor imaging at depth. The potential field anomalies are not straightforward to explain in the context of an impact model, though concentric gravity and magnetic anomalies are known from impact structures elsewhere (e.g. Pilkington and Grieve, 1992; Tsikalas et al., 1998). The positive gravity anomaly indicates that the material within and/or below the crater are denser than laterally equivalent strata. A possibility in the impact scenario is that locally enhanced hydrothermal activity in the crater vicinity (e.g. Osinski et al., 2001; Parnell et al., 2010) led to relatively lithified, denser strata. Although an impact crater interpretation is arguably the most compatible with the observations at Hamidan, it is unproven.

Zaynan Structure

The Zaynan structure is a 5 km diameter feature located in the Rub’ Al-Khali Basin at 20°23’N, 50°08’E. Local topography consists of decameter-scale sand dunes at a general elevation of 250 m. The structure is imaged on four 2-D seismic lines (Figure 14). The nearest well, which is 20 km distant, penetrated to Triassic level giving good local stratigraphic control (Figure 15). There is also airborne gravity and magnetic data coverage – neither show anomalies at this location.

The mapping shown in Figure 14 is based solely on 2-D seismic lines. The structure is consistent in character on each of these lines and is unlikely to be a geophysical artifact. On all four lines the structure has the form of an excavated depression in the upper layers of Triassic strata at a depth of ca. 3,800 m below the surface. A single 3-D “Mexican hat” geometry is a good fit to the seismically-imaged profiles through the structure (Figure 14). Unlike the other structures reviewed in this paper, the lateral margins of the Zaynan structure are not faulted at the resolution of the available reflection seismic data. The line closest to the interpreted center of the structure shows a broad central uplift.

The crater affects the Triassic Jilh and Sudair formations. The overlying Minjur Formation, which spans a considerable time interval from Late Triassic to Early Jurassic, is present in the offset well but is relatively thin. It is not clear with available seismic resolution whether the Minjur predates or

Figure 14: Zaynan structure mapping at top Triassic (Top Jilh Formation). The structural interpretation is based solely on the available 2-D reflection seismic grid (shown).
Figure 15: (a) 2-D seismic section, (b) interpretation and (c) depth conversion of line through Zaynan structure. Location of line shown on Figure 14.
postdates the crater. The geological setting ranges from shallow marine (Jilh, Sudair) to emergent (Minjur) (Ziegler, 2001). The crater fill is similar in seismic character to the Jurassic carbonates (Arab to Dhruma formations). Other features on the reflection seismic data support the carbonate crater-fill interpretation – a localized high in Triassic and uppermost Paleozoic reflectors below the crater and a subtle high at top Jurassic level above the crater (Figure 15). Since the Jurassic carbonates have high seismic velocities relative to the Triassic Sudair shales, the high below the crater can be explained by velocity pull-up. The crater is ca. 70 milliseconds TWT deep, which depth converts to 190 m using representative carbonate velocities. Substituting carbonate for shale velocities based on local well control results in a velocity pull-up in the range 10–20 milliseconds, depending on the velocities and thicknesses used, the same order of magnitude as the observed time-domain high below the crater. The overlying dome can be explained by differential compaction of a carbonate section within the crater relative to the surrounding Sudair shales.

There are a limited number of viable mechanisms to explain the Zaynan structure. It is not due to dissolution collapse or withdrawal of material from below because the reflection seismic data gives a clear image of continuous (though slightly pulled up) reflectors below the crater. Seismic lines in the regional 2-D seismic grid surrounding the crater demonstrate that there are no similar features in the vicinity, or elongate channel-like aspect to Zaynan itself that would indicate fluid current erosion processes as a potential cause. On the available reflection seismic lines there is no evidence for the presence of narrow, steep structures below the crater, so there appear to be no underlying feeder structures that might lead to this being a phreatomagmatic feature. Feeder structures could conceivably exist, however, in the gaps between the available seismic lines but there is no evidence for igneous activity in the area on reflection seismic or well data. The geometry and uniqueness of Zaynan crater is compatible with a meteorite impact origin. In an impact structure interpretation, a 5 km diameter crater formed in poorly lithified sediments would be expected to display some characteristics of “complex” impact craters (Figure 3, Table 1) which would provide an explanation for the observed uplifted central area.

CONCLUSIONS

Five large-scale, previously unpublished circular structures have been described from subsurface Phanerozoic basins of Saudi Arabia. Based on the observations and discussion presented here, all five of these features are considered candidate meteorite impact structures (Table 2). Well cuttings and cores were examined in search of impact metamorphic features such as impact melts, nested cone structures, and microscopic shock deformation features. One structure (Saqqar) has yielded grain-scale textures that could support an impact crater interpretation, though further work is required to definitively identify these textures.

The other four structures have been assessed on the basis of various combinations of reflection seismic imaging, well control and potential field data. In each of these four cases, there are other geological processes compatible with the observed data, usually involving postulated igneous activity. However, in no case has direct evidence in favor of a non-impact interpretation been found. Therefore, it is possible to argue for or against an impact interpretation in these examples. Two of the structures (Jalamid and Banat Baqar) have domal inversion of the crater, separated from the cratering event by several million years. These localized inversions are difficult to explain, but due to their spatial association must be linked in some way to the cratering process.

With the exception of Zaynan, the craters described here are larger than 10 km in diameter. The biggest (Saqqar) would be, if confirmed, among the 25 largest known impact structures on Earth. Bringing these examples together in a discussion of possible impact structures has not led to unambiguous interpretations in each case, but should serve as a focus for further data collection as opportunity arises that may lead to conclusive answers.
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ACKNOWLEDGEMENTS

The authors thank the Saudi Arabian Ministry of Petroleum and Mineral Resources and the Saudi Arabian Oil Company (Saudi Aramco) for granting permission to publish this paper. We also thank the staff of Saudi Aramco’s Core Laboratory for their help in core layout and sample preparation. This paper reflects the work of many colleagues at Saudi Aramco, particularly E. Muzaiyen, A.K. Norton, A. Wyllie and H.B. Xiao. The manuscript also benefitted from reviews invited by GeoArabia from G. Osinski, M. Schmieder and R. Stern.

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Table 2
Summary of the crater structures described in this paper

| General characteristics | Saqqar | Jalamid | Banat Baqar | Hamidan | Zaynan |
|-------------------------|--------|--------|-------------|---------|--------|
| Location                | 29°35'N, 38°42'E | 31°27'N, 39°35'E | 29°07'N, 37°36'E | 20°36'N, 54°44'E | 20°23'N, 50°08'E |
| Diameter (km)           | 34     | 19     | 12          | 16      | 5      |
| Age constraint (Ma)     | 70 - 410 | 470 - 480 | 450 - 470  | 0 - 50  | 180 - 230 |
| Depth of burial at present (m) | 400 | 4,500 | 2,000 | ~ 100 | 3,800 |
| Gravity anomaly (mGal)  | Positive (9) | No | Positive (2) | Positive (6) | No |
| Magnetic anomaly (nT)   | No     | No     | No          | Positive (5) | No |
| Preservation of crater  | Deeply eroded | Fully preserved | Fully preserved | Fully preserved | Fully preserved |
| Geological setting at time of formation | Unknown | Shallow marine | Shallow marine | Shallow marine | Shallow marine |

Available reflection seismic and wells

| Reflection seismic | 2-D (9 lines) | 3-D | 2-D (2 lines) | 2-D (3 lines) | 2-D (4 lines) |
|-------------------|---------------|-----|---------------|---------------|---------------|
| Wells             | 6             | 1   | 0             | 3             | 0             |

Shock metamorphism criteria

| Grain-scale planar fractures/deformation features ? | Possible | Unknown | Unknown | Unknown | Unknown |
| Outcrop-scale features e.g. shatter cones or impactites ? | Unknown | Unknown | Unknown | Unknown | Unknown |

Geometrical and Geological criteria

| Circular or elliptical (vs irregular) in plan view? | Polygonal | Circular | Circular | Circular | Circular |
| Max/min diameter ratio | 1.1 | 1 | 1 | 1 | 1 |
| Crater or dome form ? | Crater | Crater and later dome | Crater and later dome | Crater | Crater |
| Central uplift within crater? | Yes | Yes | Yes | Yes | Yes |
| Overturned peripheral strata? | Unknown | Unknown | Unknown | Unknown | Unknown |
| Inward-facing peripheral faults? | Yes | Yes | Yes | Yes | No |
| Depth/diameter aspect ratio of crater | Unknown | 0.01 | 0.03 | 0.02 | 0.04 |
| Adjacent or nearby structures with same form, scale & age? | No | Banat Baqar ? | Jalamid ? | No | No |
| Related to regional trends ? | No | No | No | No | No |
| Related structure in deep underlying strata ? | No | Unknown | No | Unknown | No |
| Salt in or near structure ? | No | No | No | No | No |
| Igneous material in or near structure ? | No | Yes | No | No | No |
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Manuscript submitted February 24, 2013;
Revised June 3, 2013;
Accepted June 10, 2013