Radial clastic dykes formed by a salt diapir in the Dead Sea Rift, Israel

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ABSTRACT

Fanning structures radiating from a central perturbation are known in various geological environments, where different processes have produced similar geometry. The present contribution describes and analyses fanning clastic dykes in the Dead Sea Rift, a new example of diapir-related deformation. The dykes are opening-mode fractures exposed in lacustrine varved marl of the Lisan Formation, deposited 70–15 ka. They are arranged mainly in a radial and tangential geometry. The radial traces converge at the 'Black Hill' structural dome. The geometry of the fractures is consistent with stresses exerted by the rise of a salt diapir located underneath the Black Hill. The estimated extension of the radial fractures is in good agreement with the present topographic elevation of the hill. The absence of fractures in the overlying Holocene alluvium probably indicates that either the rise of the Black Hill salt diapir paused or is associated now with a different style of deformation.

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Introduction

Salt diapirs push overlying rocks upward, creating dome structures above them. For example, islands in the Gulf of Mexico and Persian Gulf are formed by emerging salt stocks (O'Brien, 1968), and ridges in the Great Kavir, Iran, expose more than 50 salt diapirs (Jackson *et al*., 1990). Salt diapirs form various types of oil traps, known in many oil provinces such as the North Sea and the Gulf of Mexico (Jenyon, 1986).

One motivation for this study is the potential of oil traps associated with salt along the Dead Sea Fault (Fig. 1). Asphalt seeps in the Dead Sea basin – which have been recorded since Biblical times (Genesis 14:10) – raised interest in the oil potential of the Dead Sea area as early as 1912 (Nissenbaum, 1991). Twenty exploration wells drilled since 1953 in this area have encountered hydrocarbons, but no commercial discovery has been made (Gardosh *et al*., 1997). Data on the detailed subsurface shape and structure of diapirs are essential for exploration. Rock formations penetrated by the salt may contain information about the shape and location of the intruding salt body. Numerical analyses predict extension features and thinning of the rocks overlying a salt diapir (Withjack and Scheiner, 1982; O'Brien and Lerch, 1987; Schultz-Ela *et al*., 1993). Experiments also show extension by normal faulting above and near rising diapirs, and thrusting away from them (Childs *et al*., 1993; Davison *et al*., 1993).

Different geological features of various scales and styles exhibit fanning patterns radiating from a central perturbation. Different mechanisms produce similar geometry. Examples include: (i) flexure and faulting of sedimentary host rocks during growth of igneous domes, Henry Mountains (Jackson and Pollard, 1990); (ii) giant dyke swarms such as the Mackenzie dykes in North America that radiate from plume centres (Ernst and Buchan, 1995; Ernst and Head, 1995); (iii) smaller radial dyke systems that propagated from central intrusions, e.g. Spanish Peak swarm (Johnson, 1970) and the Ramon dykes in Israel (Baer and Reches, 1991), radiating fracture-graben systems in Venus (Koenig and Pollard, 1998), radial fracture pattern caused by impact and indentation (Bahat, 1991; Lawn, 1993), columnar fractures in basalts growing radial to master fractures (DeGraff and Aydin, 1987), radial striations and hackles on fracture face (Bahat, 1991), radial thrust faults and fold axes associated with a diapir pinch-off (Jackson *et al*., 1998) or meteoritic impact (Shoemaker and Herkenhoff, 1984); and (iv) modelled radial microcracks at corners of inclusions of garnet (Whitney *et al*. 2000). The geometry of such structures elucidates the cause and location of the distortion, establishing regional palaeostress fields. We did not find any previous report on salt-related radial fracture sets.

The present contribution describes and analyses a well-exposed fracture system in the Ami'az Plateau, Dead Sea Rift, Israel, which provides a new example of diapir-related deformation.

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Geological setting

The 3- to 4-km-wide Ami'az Plateau (Fig. 1) is a downfaulted block in the western margin of the Dead Sea basin, which is a pull-apart graben within the active Dead Sea Transform Fault (Quennell, 1956; Garfunkel, 1981). The Ami'az block is bounded by the Mount Sedom salt diapir to the east and the major boundary fault of the Dead Sea basin on the west. The latter exposes Cretaceous platform carbonates overlain by sands of the Miocene Hazeva Formation. The Dead Sea graben was flooded several times (Fig. 2). The Sedom Salt deposited during the Neogene transgression is the earliest marine sediment in the Dead Sea depression (Zak, 1967; Agnon, 1983). The porous Hazeva sands overlain by the Sedom Salt may form oil traps. The Sedom Formation is overlain by the

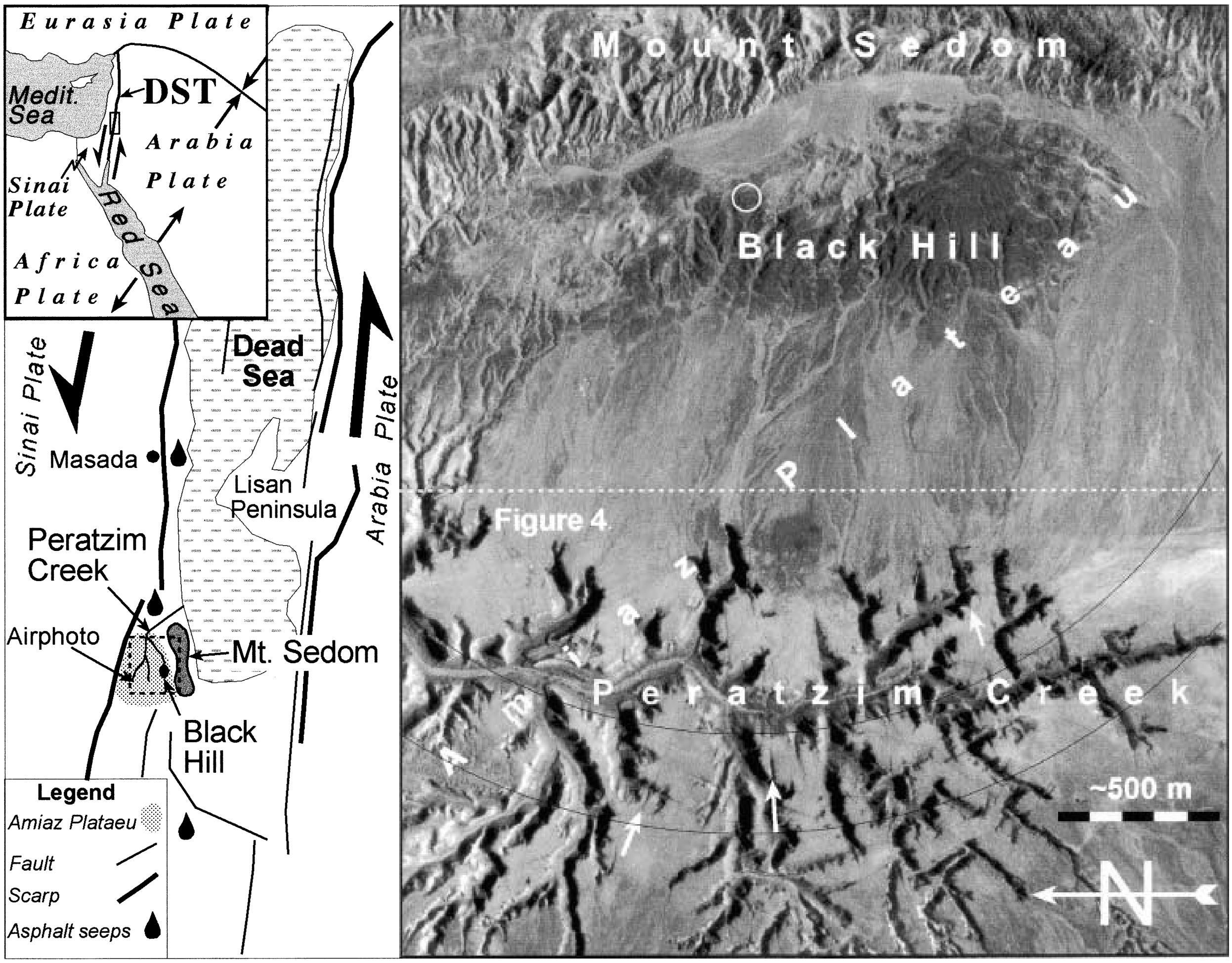

Fig. 1 Location maps and aerial photograph, showing the position of the Black Hill in the Ami'az Plateau west of Mt. Sedom. The Peratzim Creek exposes a radial and a tangential fracture system (clastic dykes) centred on the Black Hill. Arrows show examples of fractures. Extension is estimated (Table 1) along arcs centred at the white circle, which marks the centre of the elliptic fracture convergence zone, spanning approximately 1 km N–S and 2 km E–W.

Amora (Zak, 1967), Samra (Picard, 1943), and Lisan (Lartet, 1869) formations, all were deposited in Plio-Pleistocene lakes that preceded the modern Dead Sea. The Lisan Formation was deposited during the last glacial period, 70–18 ka (Kaufman, 1971; Kaufman *et al.*, 1992; Schramm *et al.*, 2000). In the study area it is partly covered by 0–2-m-thick alluvial sand and conglomerate shed off the cliffs and canyons in the plateau's margins.

The Mt. Sedom salt diapir has been emerging since the Pleistocene, piercing the overlying beds. The exposed part of the diapir was portrayed as a N–S-striking 'salt-wall' diapir by Zak (1967), who recognized the complexity of the subsurface shape. A combined structural and palaeomagnetic analysis showed that Mt. Sedom exposes a tight antiform (Weinberger *et al.*, 1997). Based on its structure and proximity to the Sedom diapir, Zak (1967) speculated that a dome structure known as the 'Black Hill' was also formed by the rise of an underlying salt diapir, perhaps a projection of the Sedom salt diapir.

Post-Lisan deformation in the Ami'az Plain

Clastic dykes were mapped in the Ami'az Plateau by tracing 1:4000-scale air photos and by an intensive field survey. The dykes, which are vertical fractures in the Samra and Lisan formations, are exposed as a consequence of a $\sim$ 50-m incision of the Peratzim canyons. They are typically up to 0.4-m wide and commonly filled with brown sand mixed with some fragments of the Lisan rocks (Fig. 3). The sand is similar to the alluvium that covers the Lisan Formation in part of the Ami'az Plateau. The contacts between the fracture fill and the overlying alluvium are sharp. In places, the fractures are rimmed by crystalline calcite, probably the product of transformation of aragonite (Katz *et al.*, 1972). No indication for shear movement was observed, layers are not offset across the fractures and intersecting fractures do not displace each other. Therefore, the fractures are considered to have formed in opening-mode.

The fracture map (Fig. 4) reveals that they comprise two main strike

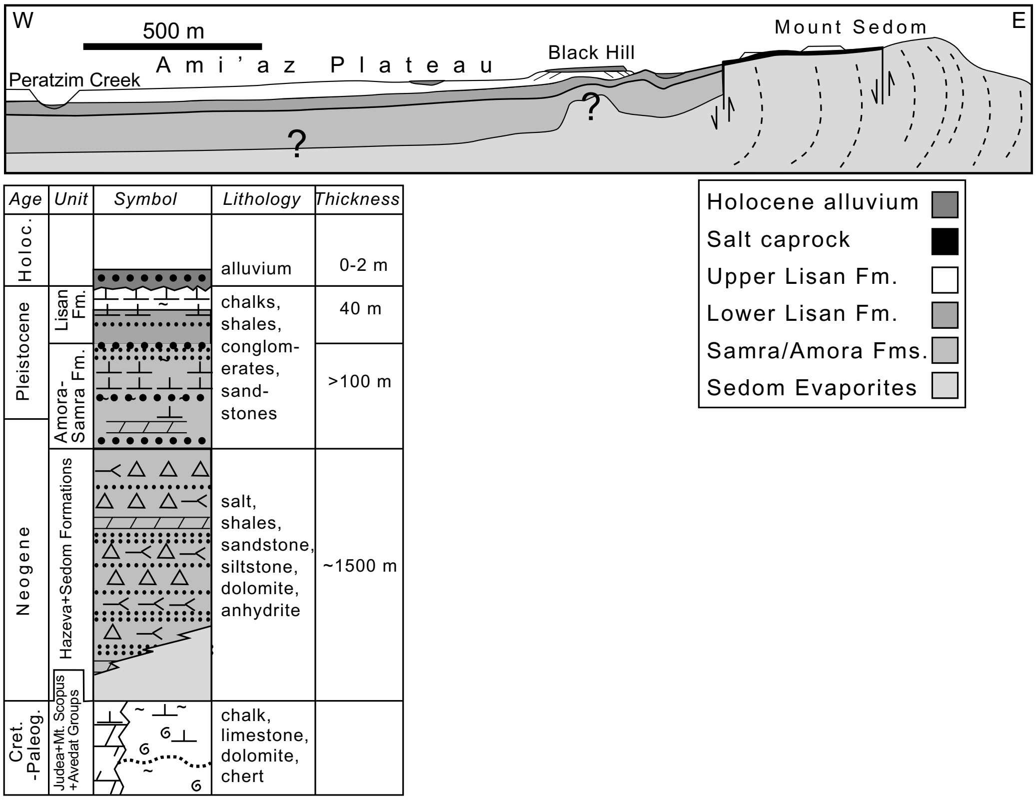

Fig. 2 Generalized stratigraphy in the Ami'az Plateau. An E–W section (modified from Zak, 1967) shows a postulated small salt diapir below the Black Hill west of Mt. Sedom. It is argued that the rise of such a diapir induced the formation of the radial and tangential fracture systems observed in the Ami'az Plateau. Horizontal and vertical scales are the same.

systems that intersect at approximately right angles. The radial system spans a sector of 60° between azimuth 060° and 120°. The tangential system spans over 90°, between 150° and 060°. Measurements made of 118 intersection angles of the radial and the tangential fractures are summarized in a histogram, showing that more than 80% of the angles are over 70° (Fig. 5).

The continuation of the radial set eastward converges at an elliptic area centred at the Black Hill. The Black Hill's flat summit is at −220 m bsl (below sea level), elevated some 50 m above the Ami'az Plateau. The Black Hill exposes pale layers, composed of clastics of fine-to-coarse calcarenite with some quartz and chert grains and several horizons of pebbles ranging from a few mm up to several cm as well as laminated gypsum layers. Westward dips of 45° are common and more moderate dips to the south-west and north-west occur in the southern and northern parts, respectively. The tilted beds are unconformably overlain by up to 1-m-thick alluvium comprising well-rounded pebbles to cobbles (up to 80 cm diameter) derived primarily from Cretaceous limestone, dolomite, and chert. The alluvium is nearly horizontal at the summit of the Black Hill but becomes progressively inclined toward the Ami'az Plateau. Dark patina on the alluvium dominates the surface and gives the hill its distinct dark appearance. Seismic lines also indicate that the young sedimentary fill in the Ami'az Plateau is deformed, probably as a result of diapirism and salt flow eastward (Gardosh *et al.*, 1997).

Kinematic association between the radial fracture system and the Black Hill salt diapir

It was hypothesized that the radial fractures formed as a result of a diapir rising beneath the Black Hill; this was tested by estimating the strain associated with these features. Because there are only 2–3 tangential dykes along any radius, their contribution to the strain is neglected. It was assumed that radial fractures formed when the extension near the surface caused by the rise of a salt diapir reached, or slightly exceeded, the tensile strength of the host rocks, which yielded in a brittle manner. Fracture widths may be used to estimate the amount of extension S in the rocks. An estimate was then made of the minimum amount of uplift at the Black Hill required to generate this strain. For a radial fracture system, this estimation is given by the ratio of the cumulative fracture widths δW along an arc centred at the inferred location of the system to the arc length L (Baragar *et al.*, 1996). S was calculated assuming that the centre of the uplift is at the Black Hill, where the radial fracture traces converge using:

$$S = \delta W/L. \qquad (1)$$

The strain is calculated for a limited range of arcs between 1.7 and 2.0 km

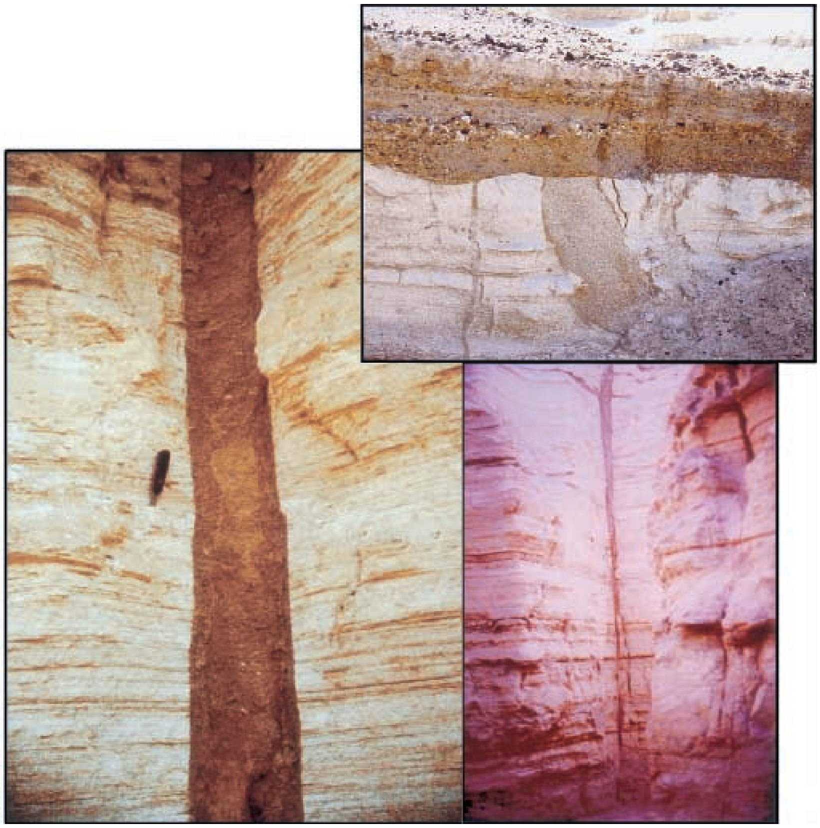

Fig. 3 (a) General view of a clastic dyke crossing the late Pleistocene lacustrine Lisan Formation. Note also the smaller fractures on both sides of the dyke. (b) A clastic dyke; white specs are Lisan intraclasts. Pocket-knife for scale is 9 cm long. (c) Upper termination of a fracture; Holocene alluvium is not affected by the fracture.

away from the centre of the convergence zone at the Black Hill (Fig. 1). In this area the mapped fracture arrays are not obscured by alluvium. The extensional strain is between 1.8×10^{-3} and 3.8×10^{-3} (Table 1), depending mainly on the fracture widths (minimum and maximum, respectively). For example, strain of 3.8×10^{-3} is calculated for 10 m of cumulative fracture maximum widths in $\sim$ 2700 m of arc, at a distance of $\sim$ 2000 m from the Black Hill. The strain provided by the topographic uplift is now estimated: the topographic slope a is of the order of the square root of the circumferential strain (Landau and Lifshitz, 1986; Baragar *et al.*, 1996; Fialko and Rubin, 1999):

$$a \sim \sqrt{s}. \qquad (2)$$

The strain calculated from the cumulative fracture widths provides a first-order approximation for maximum circumferential strain (Fialko and Rubin, 1999). Hence, the cumulative width of the radial fracture system requires a minimum uplift of the Black Hill on the order of 70 m (Table 1). Even if this estimate of the strain is off by one order of magnitude, the estimated uplift would be off by only a factor of 3. In spite of the large uncertainties associated with data, this rough estimate is in good agreement with the actual 50 m that the hill rises above the Ami'az plateau. Similar results were obtained for quantifying the amount of uplift following the geometric method of Baragar *et al.* (1996).

The clastic dykes demonstrate extensional deformation that is different from E–W extension manifested as N-striking normal faults near Masada, 25 km to the north (Marco and Agnon, 1995). The faults near Masada were syndepositional and their activity was associated with earthquakes. It is probable that the opening of the fractures here was also associated with earthquakes.

Uplift rates

The presented field observations and mechanical analyses suggest that a salt body – perhaps a projection of the Sedom salt diapir – is hidden underneath the Black Hill. The Sedom and Black Hill diapirs are not expected to rise at the same rate because of different overburden and buoyancy forces (Weinberger, 1992). Fifty metres of vertical elevation difference between the Black Hill and Ami'az Plateau give a Holocene mean rise rate of 3.5 mm yr^{-1} (Zak, 1967). Several indicators can be used to estimate the mean rise rate of Mt. Sedom diapir: (i) the Lisan Formation has been displaced by the diapir since the end of sedimentation about 20 ka; (ii) the present elevated salt table stopped forming about 15–20 kyr BP but is displaced along subvertical bedding planes about 80 m, implying a mean rate of 4–5 mm yr^{-1} (Zak and Freund, 1980); (iii) all the Mid-Holocene Dead Sea terraces north of Mt. Sedom are found at the same level, but in Mt. Sedom the same terrace is at least 30 m higher. Hence, the inferred mean diapir rise rate since the mid-Holocene is 6–9 mm yr^{-1} (Frumkin *et al.*, 1999). Preliminary results of an Interferometric Synthetic Aperture Radar (InSAR) study also show an uplift rate of 6–9 mm yr^{-1} at Mt. Sedom (Pe'eri *et al.*, 2001). All the estimates of the diapir mean rise rate range between 3 and 9 mm yr^{-1}, allowing for 60–180 m post-Lisan uplift (the last 18 kyr). The similar rise rates support a possible common source of the Mt. Sedom and the Black Hill salt. It is argued that the fractures cannot result from the rise of the Mount Sedom diapir because its elongate wall shape is incompatible with a central perturbation.

Time constraints

The fractures cross the entire section of the Lisan Formation, hence they post-date the drying of Lake Lisan about 18 ka (Schramm *et al.*, 2000). The sharp contacts between the fractures fill and the overlying, unfractured alluvium (Fig. 3) indicate that

Terra Nova, Vol **14**, No. 4, 288–294

Fig. 4 Map of fracture traces (yellow lines). Background aerial photograph by the Survey of Israel.

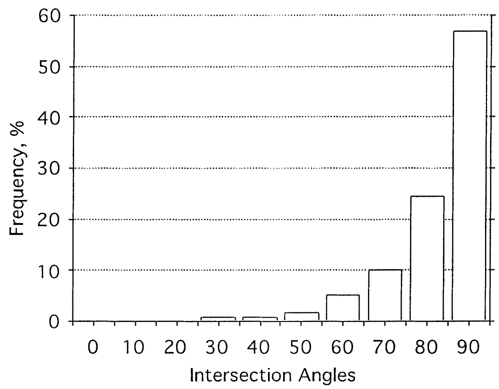

Fig. 5 Frequency of intersection angles of radial and tangential fracture systems. More than 80% of the intersections are at 70–90°.

the alluvium post-dates the fracturing. InSAR data show active rising of Mt. Sedom (Pe'eri *et al.*, 2001) and stability at the Ami'az Plateau. The Black Hill is between the two domains and its current movement is poorly constrained (Gideon Baer, pers. comm., Jan. 2002). Alluvium at the top of the Black Hill indicates some 50 m post-Lisan uplift there. Hence, either the Black Hill has stopped rising recently or deformation continues in a different style. The poor lithification of the Holocene alluvium cannot be ruled out as the cause for the lack of opening-mode fractures in this unit.

An interesting local geomorphic consequence of the fractures is apparent in the Peratzim Creek, a north-flowing drainage system incised into the Ami'az Plateau. Many of its tributaries follow the fractures (Fig. 4). This geometry of the drainage system, which is governed by the diapir-induced fractures, either post-dates or is contemporaneous with the rise of the Black Hill.

Conclusions

The array of radial opening-mode fractures accommodate on average 1.8×10^{-3}–3.8×10^{-3} extension in the Ami'az Plateau, Dead Sea Rift. The estimated extension is consistent with stresses exerted by 50 m rise of the Black Hill, where the extrapolated fracture traces converge. It is suggested that a salt diapir pushed the Black Hill upward and triggered fracturing around it. The topography of the Black Hill and the required uplift at the penetration zone based on fracture widths are in good agreement.

An intricate drainage system incised into the lacustrine Lisan Formation, the Peratzim Creek, follows the fracture traces. Fracturing post-dates the drying of Lake Lisan, about 18 ka, and pre-dates the overlying unfractured late Holocene alluvium. The absence of fractures in the alluvium indicates either a pause or cessation of rise or a transition to a different type of deformation.

Mapping presented herein provides independent support for previous speculations about a salt body beneath the Black Hill, and demonstrates how deformation analysis can constrain the location of hidden diapirs – potential hydrocarbon traps.

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Table 1 Calculated uplift of the Black Hill inferred from the radial fracture system. All distances are in metres. Two cases are presented: (i) individual fracture average width is 0.2 m; (ii) individual fracture maximum width is 0.4 m

Case study	Distance from centre	Arc length	No. of joints	Cumulative width average	Cumulative width max.	Strain average	Strain max.	Order of uplift average	Order of uplift max.
1	1725	2475	22	4.4	8.8	1.8×10^{-3}	3.5×10^{-3}	73	103
2	2075	2675	25	5.0	10.0	1.9×10^{-3}	3.8×10^{-3}	90	126

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