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Bedout: a possible end-Permian impact crater offshore of northwestern Australia; Research Article

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The Bedout High, located on the northwestern continental margin ofAustralia, has emerged as a prime candidate for an end-Permian impact structure. Seismic imaging, gravity data, and the identification ofmelt rocks and impact breccias from drill cores located on top of Bedout are consistent with the presence of a buried impact crater. The impact breccias contain nearly pure silica glass (Si[O.sub.2]), fractured and shock-melted plagioclases, and spherulitic glass. The distribution of glass and shocked minerals over hundreds of meters of core material implies that a melt sheet is present. Available gravity and seismic data suggest that the Bedout High represents the central uplift of a crater similar in size to Chicxulub. A plagioclase separate from the Lagrange-1 exploration well has an Ar/Ar age of 250.1 [+ or -] 4.5 million years. The location, size, and age of the Bedout cratercan account for reported occurrences of impact debris in Permian-Triassic boundary sediments worldwide.

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The cause of the catastrophic mass extinction at the end of the Permian has been the focus of considerable debate. Becker et al. (1-3) and others (4-10) have presented evidence that a major impact was associated with the extinction of >90% of marine taxa. The evidence includes fullerenes with extraterrestrial helium and argon (1, 7), meteorite fragments (8), Fe-Ni-Si "metamorphosed grains" of probable meteoritic origin (5, 8, 9), Fe-Ni metals with impact spherules (6, 10), and shocked quartz (4).

Acceptance of the idea that an impact accompanied the Cretaceous-Tertiary (K-T) extinction increased dramatically with the discovery ofthe Chicxulub crater (11, 12). We searched for a Permian-Triassic (P-T) boundary impact crater in parts of the Southern Hemisphere that once comprised the supercontinent of Gondwana, because the impact evidence is most abundant in continents from this region (such as Australia and Antarctica). Gorter, based on the study of a single seismic line (13, 14), suggested that the Bedout ("Bedoo") High offshore of northwestern Australia might be the central uplift of a large end-Permian impact crater. In this paper, we describe the Bedout structure and present evidence from drill cores, additional seismic and gravity data, and Ar/Ar dating of plagioclases that Bedout is a large, buried, end-Permian impact crater and possibly the source of the P-T ejecta deposits distributed globally (Fig. 1 and fig. S1).

[FIGURE 1 OMITTED]

Geology of the Bedout structure. The Bedout High is part of the Roebuck basin, which forms the northwestern continental margin of Australia (Fig. 2). Existing studies of the structure include two regionalseismic surveys conducted by the Australian Geological Survey (AGSO)and the Japan National Oil Company (JNOC) (15) and two exploratory wells drilled 9 km apart on the top and flank of the Bedout High (Bedout-1 and Lagrange-1) that extend to depths of 3052 m (9986 feet) and 3273 m (10,738 feet), respectively (Fig. 3 and fig. S2). Both wells were drilled through ~3 km of marine and fluvial sediments consisting of carbonates with occasional interbeded siltstones and mudstones (Tertiary to Cretaceous) and sandstones interbeded with claystones, siltstones, and coal (Cretaceous to Triassic) before reaching a breccia [Late Permian (fig. S2) (16)]. Two of the 14 AGSO regional seismic lines cross over the Bedout High (Fig. 2). In addition, four wells penetrate Permian strata (two are shown in Fig. 2) offshore that help to identify seismic reflectors that define the Bedout structure and stratigraphy. In both the Lagrange-1 and Bedout-1 cores and cuttings, fluviatile and marine Keraudren (Middle to Late Triassic) sediments are deposited directly on top of the breccia [Late Permian (Fig. 4 and figs. S2 and S3)].

[FIGURES 2-4 OMITTED]

Presently, the Bedout High stands several kilometers above the surrounding basement (17). Deep crustal reflections and seismic refraction velocities also suggest that the Bedout High is underpinned by elevated middle and lower crust. Both core and cuttings cataloged as basalts and referred to as a "volcanic breccia" were recovered from the top of the High. This regional "volcanism" associated with rifting ofthe continental margin of Australia is classified as the "Bedout Movement" of P-T age (18, 19). Immediately after the formation of the Bedout High and termination of the Bedout Movement, there is a regionalangular unconformity at the top of the High, consistent with uplift and erosion at the end of the Permian (20). Coincident with the formation of the Bedout High is the rifting of the continental "Sibumasu sliver" off northeastern Gondwana (21). The resulting post-impact tectonism, uplift, faulting, and erosion during the Triassic and Jurassictime periods regionally overprinted the Bedout structure and deformed the original complex crater morphology.

The Bedout breccia. Both the Lagrange-1 and Bedout-1 exploration wells ended in what was inferred to be a volcanic breccia. Fifty-two meters--30 m of cuttings and 22 m of core--were collected from the breccia unit in Bedout-1, and 391 m of cuttings were sampled from the breccia trait in the Lagrange-1 drill hole. The Bedout core displays a series of centimeter-sized green clasts, some with variable banding and others that are poorly sorted (with chaotic dips of 30[degrees] to50[degrees] in hand specimens) (Fig. 4 and fig. S3) over the entire core length (20). Most of the clasts throughout the core are dark green and massive and appear glassy in hand specimens, but in thin section many are partially altered to fine-grained chlorite or a mixture of fine-grained plagioclase, carbonate, and Fe oxides. We identified unaltered glass and relic igneous mineral grains from the lowest section of the core, at 3044 m (9986 feet) (Figs. 5 to 8 and figs. S4 to S14). A section from higher in the core at 3041 m (9977 feet) also contains several large and highly fractured plagioclase phenocrysts (figs. S8 and S9). The basal 8 m of the core contains many small rock andmineral clasts in a predominately glassy matrix that has partially altered to chlorite. Brownish glass shows evidence of flow structure (fig. S10), and calcite is observed as veins and in cavities in several thin sections (figs. S11, S13, and S14). The mineral clasts are mostly single and multiple aggregates of plagioclase, and the lithic clasts are of glassy fragments. The complex mixtures and very different textures in the lower 8 m of the core are similar to the cores from inside the Chicxulub crater (22-25) (Fig. 4 and figs. S3, S9, and S10 to S14).

[FIGURE 5 OMITTED]

The clast from 3044 m (9986 feet) contains shocked minerals surrounded by a matrix that is almost entirely glass, except where it has been altered to chlorite. The samples include shock-melted plagioclasethat has been completely or partially converted to glass (Figs. 6 and 8), spherulitic glass (Fig. 7, A and B), and pure silica glass (Si[O.sub.2]) (Fig. 7C). Plagioclase encloses diaplectic glass (maskelynite) with a composition identical to that of the surrounding plagioclase anorthosite ([An.sub.50]) (Fig. 8, analyses 3 and 4 in table S1). We also identified magnesian iron titanium oxide [([Fe.sub..84], [Mg.sub..14]) Ti[O.sub.3]] grains that are stoichiomelfically ilmenite, heterogeneous silica glass, albite, sanidine, and a partially melted carbonate (CaC[O.sub.3]) clast with fragmented ooids (26, 27) (Figs. 5to 8 and figs. S4 to S7, A and B; table S1). Sanidine, identified optically and confirmed by microprobe analysis of a 10-[micro]m grain (analysis 5 in table S1), has 43% albite in solid solution without anysign of segregation (microperthite).

[FIGURES 6-8 OMITTED]

The Lagrange-1 cuttings consist of various types of partly crystalline and partly glassy rock of mostly basaltic composition (fig. S7).Some of the fragments are identical to those found in the Bedout core (figs. S11 to S15). One of these fragments, from 3255 m (10,679 feet), is shown in fig. S7, A and B. fig. S7A shows feldspar crystallites (laths) in "swallowtail" terminations, indicating rapid crystallization from the glassy matrix. The feldspar laths display heterogeneouscompositions and are mixtures of either pure albite (table S2, no. 1) or K-feldspar (table S2, no. 2) in their glassy matrix (table S2, no. 3), as seen in the backscattered image (fig. S7B) of one of the grains.

We interpret these textures, chemistry, mineralogy, and mixture ofdifferent fragments as indicating that the basal 8 m of Bedout- 1 isan impact melt breccia. The completely or partially melted and fractured plagioclase crystals and abundant glassy clasts are most diagnostic. The coexistence of titanium-rich silica glass in close proximity(within 1 mm) to titanium-poor but slightly aluminous silica glass (analyses 23 and 24 in table S1 and Fig. 7C) requires silicate liquid immiscibility that is not seen in terrestrial magmatic environments.

Partially melted and recrystallized carbonate lithic fragments (Fig. 5) and spherulitic glasses (partially altered to chlorite; Fig. 7Band analysis 22 in table S1), with a different chemical composition from the glassy matrix, are again features attributable to an impact-generated melt breccia. Magnesian-ilmenite (analysis 20 in table S1) found as microlites in the matrix is also an uncommon mineral in volcanic rocks. The glassy rock clasts can be attributed to the melting of target materials that contained Mg-rich sediments (such as dolomites) and common Fe-Yi oxides (such as magnetite, titanite "sphene," andfutile), which are found in crustal environments. Overall, the compositions of the minerals and glasses of the Bedout core are consistentwith a heterolithic impact breccia or melt-rich suevite, formed by impact-triggered heterogeneous melt formation and subsequent quenchingand crystallization. Such compositions are unknown and unlikely to exist in terrestrial volcanic agglomerates, lava flows, and intrusive pipes. Individually, some of these minerals may rarely occur in volcanic or plutonic rocks, but never in association with each other.

In particular, natural volcanic processes generate silicate melts up to but not exceeding about 78% silica. Taken as a whole, these features are most consistent with impact-generated melting. Volcanism associated with rifting does not produce melts (glasses) such as nos. 23 and 24 in table S1 (nor does any other endogenous magmatic process). The overall textures of these heterolithic fragments, especially the Bed out glasses, are similar to the features of the Sudbury Onapingbreccia and the melt breccias inside the Chicxulub crater (Fig. 4) (22-24, 28).

Ar/Ar dating of the Bedout core. We Undertook [sup.40]Ar/[sup.39]Ar age measurements on feldspar concentrates from the Bedout-1 core and Lagrange-1 impact breccia by step-heating and single-crystal fusionexperiments [(29) and supporting online material (SOM)]. [sup.40]Ar/[sup.39]Ar dates on six individual plagioclases from 3041 m (9977 feet) from the Bedout-1 core indicate ages that are much younger than the overlying Triassic sediments. Petrographic and microprobe examination of the Bedout core from 3044 and 3041 m (9986 and 9977 feet) revealed significant alteration in plagioclase grains and possibly extensive K addition (Figs. 6 to 8 and figs. S8 and S9), resulting in young [sup.40]Ar/[sup.39]Ar ages. Individual feldspar grains display heterogeneous chemical compositions due to alteration or disequilibrium in the sample cuttings (table S1 and fig. S7, A and B). The glassy matrix from 3044 m (9986 feet) had extremely low K (<0.1%) and proved unsuitable for [sup.40]Ar/[sup.39]Ar dating. A plagioclase separate at 3255 m (10,679 feet) from the Lagrange-1 cuttings, which displayed the least evidence of alteration or disequilibrium, has an [sup.40]Ar/[sup.39]Ar age of 250.2 million years (My), with a plateau portion between 8 and 90% gas release at 250.1 [+ or -] 4.5 million years ago (1[sigma] [+ or -] 1%), consistent with the previous K-Ar measurement on a plagioclase separate from Lagrange-1 [253 [+ or -] 5 My (30)] (Fig.9 and SOM). Similar problems in dating plagioclase separates were observed in the Yucatan-6 melt rocks from the Chicxulub crater (23).

[FIGURE 9 OMITTED]

Geophysical evidence. Confirmation that the Bedout High consists of an impact breccia and melt sheet led us to reinterpret some seismiclines provided by AGSO (18), including line S120-01 (Fig. 10), originally interpreted by Gorter

(13, 14). Our revised chronostratigraphy for line S120-01 includes the Lagrange-1 mad Bedout-1 stratigraphic sections, correlation with adjacent onshore seismic sections and wells(31), and the Ar-Ar and K-Ar dating of the melt breccia. The top of the Permian (blue line, Fig. 10) is conformable with the Bedout High,whereas Triassic sediments (light green line, Fig. 10) unconformablyonlap onto the structure (Fig. 10 and fig. S15). The revised seismicsection shows a broad uplifted core of basement (red line, Fig. 10) 40 to 60 km in diameter elevated a minimum of 6 to 9 km. The "pre-Permian" strata (Fig. 10), inferred only from seismic character correlations (16), are not well imaged in the seismic data and yet appear to show uplift with the basement core. Alternatively, because the deepermaterial has yet to be sampled and dated, these sequences could all be end-Permian crater-fill impact debris. We also detect a slight uplift of Permian and earlier strata at a radius of ~100 km from the center of the Bedout High, but it is not clear that this is a concentricfeature. A two-dimensional velocity model derived from ocean-bottom seismometer wide-angle reflection and refraction data collected alongthe S120-01 line (32) reveals a central uplift beneath the Bedout High, with some 6 to 7 km of vertical structural relief on midcrustal isovelocities. Although less well resolved, the data also suggest possible variations in Moho depth beneath Bedout (33). It is difficult toassess, however, whether this Moho topography is, like Chicxulub, the result of the dynamic effects of the crater- (and Bedout High-) forming process extending down to the base of the crust (33-35) or is the result of later rifting of the continental margin.

[FIGURE 10 OMITTED]

The Bedout structure was emergent in the Early to Middle Triassic and is probably deeply eroded. Onshore in the Canning Basin, much of the Permian and Early Triassic section is missing: over 0.5 to 1 km of section overall, and as much as 2 km on topographic highs (36). We do not know the depth of erosion at Bedout, but it is probable that the unconformity at the top of the Permian represents a missing section. The Lagrange-1 well extends for several hundred meters through theimpact melt breccia, but it is uncertain how much more of the High is actual impact melt breccia. The isostatic residual gravity model for the Bedout structure and the Bouguer gravity over Chicxulub both show a semicircular gravity low surrounding the expression for the central peak (Fig. 11). Unfortunately, the resolution of the offshore gravity data is not of sufficient quality to obtain a vertical derivative image, which is generally used to highlight the more subtle gradients, and assist in assessing the geomorphometric parameters, includingsize, of the Bedout structure. The outer edge of the gravity low hasa diameter of ~100 km and is similar in size to the better-resolved Chicxulub gravity low (Fig. 11).

[FIGURE 11 OMITTED]

Comparisons of the Bedout structure with other impact structures. As first noted by Gorter (13, 14), the geophysical expression of the Bedout High is similar to the central uplift in other large impact craters. Fracturing and brecciation, caused by the impact of large meteorites with the crust, produce a characteristic negative gravity anomaly surrounding a gravity high, a feature that led to the initial discovery of Chicxulub (12). Such an anomaly exists at Bedout (Fig. 11),but it is somewhat obscured by other complex crustal features derived from younger tectonic overprinting (from the Triassic and Jurassic). The gravity high in the center of large terrestrial craters is due to the central uplift elevating denser basement rocks. At Bedout, thegravity high is clearly associated with a structural high. The central uplift at Chicxulub is poorly imaged seismically, consists mostly of ~6 to 7 km of uplift of midcrustal isovelocities, and is ~40 to 60km in diameter (33). These dimensions compare well with the Bedout High, suggesting that Bedout may be about the same size as Chicxulub (~200 km in diameter). The slight uplift noted at a radius of ~100 km at Bedout may be a subtle expression of the outer rim, but this is speculative. If the Bedout High is a central uplift similar to the one at Chicxulub, then the erosion at Bedout could be extensive, because the top of the Chicxulub central uplift lies about 3.5 km below the crater floor (37).

The seismic profile across Bedout is similar to one across the 40-km-diameter Mjolnir crater (fig. S16) in the Barents Sea (38), exceptthat the Mjolnir central uplift is much smaller (1.5 to 2 km high and 8 km wide). Mjolnir has a central uplift that extends well above the pre-impact surface (horizon LIB, fig. S16) and is apparently the result of differential subsidence in the annular trough around the peakunder the load of post-impact sediments (39). Permian strata at Bedout are overlain by ~3 to 5 km of sediment, so it is possible that differential subsidence has altered the relief of the Bedout High since its initial formation.

Evidence for a P-T impact in Gondwana. A large impact crater at Bedout is consistent with the global distribution of impact ejecta in the P-T boundary and helps explain apparent anomalies in the observed patterns. Large (>200 [micro]m) impact ejecta fragments have, so far,only been found in the P-T boundary at sites relatively close to Bedout (Fig. 1). Meteorite fragments from the P-T boundary at Graphite Peak in Antarctica range in size from 50 to 400 [micro]m (8) (Fig. 1).We have found shocked quartz ranging from 150 to 550 [micro]m in size at Fraser Park, adjacent to the well-known site at Wybung Head in the Sydney Basin (4) (Fig. 12 and fig. S1, A and B) and grains up to 250 [micro]m at Graphite Peak, Antarctica (Fig. 1 and fig. S1). The shocked quartz at Fraser Park and Graphite Peak comprises ~1% of the quartz fraction, compared to ~50% at many K-T boundary sites (40). Retallack et al. (4) suggested that such a small amount of shocked quartzin the P-T boundary may indicate a minor impact, but we interpret the low percentage as a product of dilution by reworking of the ejecta in a continental depositional environment. The P-T boundary layer in the Sydney Basin and in Graphite Peak is a claystone breccia 10 to 20cm thick containing abundant rip-up clasts from the underlying soil (4), whereas the shocked quart-rich distal K-T boundary deposits are composed mostly of ejecta and are <1 cm thick (41).

[FIGURE 12 OMITTED]

When the maximum grain sizes of shocked quartz from Fraser Park and Graphite Peak are plotted with respect to distance from Bedout, they match well with the maximum sizes for shocked quartz in the K-T boundary and their distance from Chicxulub (Fig. 12). Pope (42) demonstrated that the global shocked quartz distribution in the K-T boundary is best explained by dispersal by stratospheric winds and the settling of the particles through the atmosphere. Such a dispersal mechanismis not efficient in latitudinal transport of debris and, therefore, an impact at Bedout would disperse shocked quartz mostly over the Southern Hemisphere. Thus, a large impact at Bedout is consistent with the size of the shocked quartz grains found in Australia and Antarctica and may also explain why such grains are not found further north.

Elsewhere, in China (Meishan) and Japan (Sasayama), Fe-Ni-Si metalnuggets, oxides, and spherules ~30 to 200 [micro]m in size are foundin the P-T boundary (5, 6, 8, 43). Similar-sized spherules with refractory grains (Mg-Ni-Fe oxides and Si-Ca-Al oxides) from the K-T boundary are attributed to formation in the Chicxulub vapor plume (44), and a similar vapor plume origin has been proposed for the P-T spherules (5, 8). These high-energy vapor plume products are dispersed much more widely than the elastic debris (shocked quartz) (42), thus the presence of vapor plume condensates in China and Japan without shockedquartz is consistent with an impact at Bedout. The apparent absence of P-T impact ejecta from sites far to the north of Gondwana, in whatis today North America, Europe, and most of Asia (formerly the Laurasia supercontinent), may also be a consequence of a far Southern Hemisphere impact at Bedout, but more work is needed to verify this hypothesis.

Discussion. We have presented geochemical, geochronological, biological, and petrological evidence that links the Bedout structure to end-Permian impact deposits worldwide (Fig. 1). The recognition of an impact breccia in the Bedout High emphasizes the difficulties in interpreting old impact structures that are subtle in their expression and do not retain the pristine characteristics of younger, well-preserved craters such as Chicxulub (12). Available drill cores have sampledonly the upper portion (~22 m of intact core at Bedout-1 and 391 m of cuttings at Lagrange-1) of the impact melt breccia and contain mostly highly shocked materials. The shock pressures recorded in the Bedout core were sufficient to produce maskelynite (28) (pressures of 35 to 45 GPa) and silica glass (>45 to 65 GPa). They were too high to preserve planar deformation features in quartz (<35 GPa) but sufficiently high to form stishovite (15 to 40 GPa) and perhaps hexagonal diamond (70 to 140 GPa) (45). Thus, other samples from the Bedout High mayproduce additional evidence of shock (stishovite, coesite, and diamond), assuming that suitable target rocks were present. Similarly, future analyses may isolate pristine mineral grains for radiometric dating and thus better constrain the end-Permian age and its hypothesizedassociation with the P-T boundary. Additional geophysical data, and perhaps coring, are needed to better determine the size of the structure.

The evidence for yet another impact event coincident (within the age uncertainty) with severe flood basalt volcanism raises the question of the relation of such catastrophes to each other and to mass extinction events (46). There has been increasing speculation that large bolide impacts have been responsible for processes such as continental flood basalt eruptions and mantle plumes (47, 48). Present models suggest that an impact may induce a volcanic outburst if the bolide strikes a preexisting hot spot. However, the probability of such an event occurring is extremely remote (49, 50). In the case of Chicxulub and now Bedout, the crater locations are opposite (rather than exactlyantipodal) (Fig. 1) to the position of the volcanic province (Deccanand Siberia respectively). Indeed, Melosh (49) has calculated that the amount of kinetic energy needed to create the volume of the Deccantraps (~500,000 [km.sup.3]) would require some 5 X [10.sup.23] J or twice the amount of kinetic energy generated by the Chicxulub impactor (10 km at 20 km/s).

Although it seems clear that an impact may not be the direct causeof the volume or flood basalts, it may still act as a "trigger" or the event. At both Siberia and Deccan, Ar-Ar dating has shown that volcanic rocks with mantle plume affinities predate the main pulse of the Deccan and Siberian traps (51, 52). Thus, the impact(s) and subsequent energy release might enhance the catastrophic eruption era preexisting mantle plume. New models may need to be considered to properly assess, identify, and confirm extraterrestrial impact events and to further understand the impact process and its relation to severe volcanism and mass extinctions in the geologic record.

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(25.) The Bedout-1 impact melt breccia is similar to the Yucatan-6(Fig. 4) melt breccia, with centimeter-sized clasts of fine-grained to glassy, typically altered, melt rock in a fine- to medium-grained melt rock matrix composed mainly of feldspars, chlorite, and carbonate, lf the Bedout impact melt breccia reflects the compositions of thetarget rocks, then one can assume that the upper part of the Bedout basement was dominated by more feldspar-rich rocks or basaltic volcanics (24). The difference between the Bedout-1 and Yucatan-6 impact melt breccias is that most of the clasts and the matrix in Bedout have been pervasively altered to chlorite.

(26.) The fossil ooid fragments and carbonate clast lack shock features but are intimately associated with the glassy (silicate) matrix, which is consistent with an impact origin. Similar observations have been made for the Haughton, Ries, and Chicxulub crater breccias. These textural features may be attributed to carbonate-silicate liquid immiscibility (27). The recognition of fossil ooids in the end-Permian-aged Bedout-1 impact melt breccia suggests that sedimentary (marine) target rocks were also present at the time of impact.

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(29.) We used the biotite standard GA1550, developed at the Australian National University Research School of Earth Sciences (RSES) in Canberra, Australia, the in-house standard for the past 35 years thatis now widely recognized as one of the best primary (meaning fundamentally calibrated) standards in the world. For the purpose of this study, the 98.5 My (biotite) standard age was used, which is good to better than 0.3% for determining the J-value neutron flux parameter of irradiation. All materials were inspected under a binocular microscope before irradiation. Notable brown

staining discolored most of the grains and is likely due to iron oxides. The concentrates were weighedand wrapped in aluminum foil Samples were then sealed in an outer aluminum canister. The inner packaging components consisted of a pure silica glass tube with a cadmium liner (0.2 mm thick) between the glass and outer canister. The fluence monitor biotite GA1550 (K/Ar age of98.5 [+ or -] 0.8 My) was packed in the canister at regular intervals. The canister was then irradiated for 4 days in the Heavy Ion Fusion Accelerator Reactor (HIFAR) reactor at Lucas Heights, New South Wales. The canister was inverted three times during the irradiation, to reduce the neutron fluence gradient across the container. After irradiation and a cooling-off period, samples and standards were repacked in aluminum foil. The biotite standard and plagioclase unknowns were loaded onto an extraction line connected to a VG 3600 gas source massspectrometer with a resolution of ~600. Samples were heated in a series of steps, with each sample subjected to approximately 15 steps, for a duration of 14 min for each step. Data were reduced using the Macintosh program Noble, developed at the RSES, Canberra, Australia. Correction factors to account for K-, C[-, and Ca-derived Ar isotopes are ([sup.36]Ar/[sup.37]Ar)Ca = 3.5 X [10.sup.-4] ([sup.39]Ar/[sup.37]Ar)Ca = 7.86 x [10.sup.-4] ([sup.40]Ar/[sup.39]Ar)K = 2.2 x [10.sup.-2], ([sup.38]Ar/[sup.39]Ar)K = 0.136, and ([sup.38]Ar)Cl/ ([sup.39]Ar)K = 8.0. Blanks and backgrounds were generally atmospheric and/or insignificant in terms of fraction of gas analyzed. Air standards were used to determine mass fractionation, which is known within about 0.3% and was assumed not to vary on the time scale of sample analysis.

(30.) Sample cuttings from the Lagrange-1 well (latitude 18[degrees]16'37.4"S, longitude 119[degrees]18'0.7.2"E) were provided by the British Petroleum Company (BP) to A. Webb of Amdel Petrology, Australia. The results were published in the BP company report (20) and are currently available upon request from Geoscience Australia in Canberraor the GSWA. K/Ar dating was performed on plagioclases handpicked byWebb from cuttings sampled in the lowest (10,215 feet) section of the Lagrange-1 exploration well. This sample was described as suitable for age dating, resulting in an age of 253 [+ or -] 5 My.

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(35.) Like Chicxulub, the refraction data show that the Moho is distorted beneath the Bedout High (33, 34). The rise of the Moho, however, is slightly offset from the central peak, suggesting that the material beneath the transient crater (~20 km of crust) was not just simply pushed down under the crater floor as observed for Chicxulub (34). The deeper crustal structure of Bedout is less well resolved (32); thus, its relation to the Bedout High and subsequent continental rifting needs further investigation.

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Supporting Online Material

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