Basement highs currently receive much attention from the petroleum industry because of recent reservoir discoveries in basement highs, such as on the Utsira High, Norwegian Continental Shelf (e.g. Olsen, Briedis, & Renshaw, 2017; Riber, Dypvik, & Sørlie, 2015) and the Rona Ridge, UK Continental Shelf (e.g. Trice, 2014). Petroleum is currently being produced from basement reservoirs, including from the Bach Ho “buried hill”, offshore SE Vietnam (e.g. Cuong & Warren, 2009) and the Zeit Bay field fractured basement, Egypt (El Sharawy, 2015). Although it is possible that basement rocks may form reservoirs that are not in basement highs, petroleum exploration of basement rocks has focussed on highs. Basement highs can be provenance for basinal sediments, influence sediment and petroleum migration pathways, form fluid traps (petroleum, potable water and geothermal water) and act as nucleation points for carbonate build-ups (e.g. Trice, 2014). Basement highs can also influence migration and precipitation of fracture-hosted mineralisation and base metal sulphides (e.g. Garbarino, Naitza, Tocco, Farci, & Rayner, 2003; Hitzman & Valenta, 2005). We use basement high to refer to an area in which the basement rocks are significantly higher than in the surrounding areas (Figure 1; e.g. Landes, Amoruso, Charlesworth, Heany, & Lesperance, 1960). We use the term significantly to mean the magnitude is sufficient to strongly influence the petroleum system.

Basement highs may or may not be: (a) above present-day sea level; (b) present-day topographic or bathymetric features; and (c) partly or completely covered by...
1. A glossary of geometric terms related to basement highs is presented.
2. Qualifying prefixes for the term basement are discussed, such as “acoustic basement”.
3. A scheme for characterising basement highs for use in the oil industry is presented.
4. Tectonic, isostatic, erosional and stratigraphic processes that form basement highs are discussed.

2. GLOSSARY OF TOPOGRAPHIC AND STRUCTURAL FEATURES RELATED TO BASEMENT HIGHS

A wide range of terms are used in both academic literature and the natural resources industries to describe topographic or structural features within and around basins (Table 1; Figure 2). Although some glossaries have been published that include terms relating to basement highs (e.g. Nystuen, 1989; Peacock, Knipe, & Sanderson, 2000), basement terms are commonly used loosely and interchangeably. Although Nystuen (1989) provides a useful classification scheme for many types of structures within and around basins, there is a need for more rigorous definitions of basement high terms to enable consistent characterisation. We, therefore, provide definitions of numerous terms that are commonly used to describe the forms and geological settings of basement highs (Table 1). These definitions are kept simple, nonrestrictive and generic to accommodate overlap and ambiguity of the literature’s engrained terms. We use the term significantly in these definitions to mean that the feature strongly influences the petroleum system.
We acknowledge two outstanding issues relating to the definitions given in Table 1 that should serve as discussion topics during case-specific basement high interpretations. Firstly, some definitions may need to change when the scale or resolution of observation changes. For example, a \textit{ridge} may become a \textit{horst} when faults are resolved by better seismic data. Similarly, a \textit{horst} may be better defined as an \textit{anticline} if it is established that fault throw is significantly smaller than the amplitude of the fold. Table 2 shows examples of basement highs across a wide range of sizes. Some basement high terms should be scale dependent. For example, it would not be useful to include every bump along a Top Basement seismic reflector as a \textit{basement high}.
### Table 1

List of topographic and structural terms commonly used to describe geometric forms and geological settings of basement highs, with definitions, and examples with known petroleum systems and key references. These terms are illustrated in Figure 2. *Regional* is used here to mean of a scale larger than a petroleum field.

| Term               | Definition                                                                                                                                                                                                 | Example                                                                                       | References                                                                                       |
|--------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| Anticline          | A fold that closes upward is an *antiform*, and it is an *anticline* if the folded layers retain their correct depositional sequence in the structure (Ramsay, 1967)                                           | Pishvar Anticline, Iran (Hajnouzzi, Pourkemani, & Maleki, 2016)                               | Agosta, Alessandroni, Tondi, and Aydin (2010)                                                |
| Arch               | Broad, open *anticline of regional size* (Nystuen, 1989)                                                                                                                                                       | Salakh Arch, Oman (Storti et al., 2015)                                                       | Pollastro, Jarvie, Hill, and Adams (2007)                                                     |
| Basement           | Commonly defined in the petroleum industry as igneous or metamorphic rocks (Landes et al., 1960). Qualifying terms are commonly used, such as *acoustic basement* (the area below which coherent seismic reflectors can be identified; Bruvoll et al., 2012) or economic basement (Ramm, Forsberg, & Jahren, 1997). See Section 3                                                                 | Wilmington Field, California, USA (Koning, 2003)                                             | Landes et al. (1960)                                                                         |
| Basement high      | An area in which the basement rocks are higher than in the surrounding areas (Landes et al., 1960)                                                                                                               | Utsira High (Fazlikhani, Fossen, Gawthorpe, Faleide, & Bell, 2017)                           | Grogan et al. (1999), Koning and Darmono (1984), P'an (1982)                                 |
| Basin              | Usually defined as an area of subsidence in which sediments are deposited. Subsidence is commonly controlled by normal faults (Gibbs, 1984). Pull-apart basins can be controlled by strike-slip faults (Rodgers, 1980), whereas foreland basins are controlled by thrust faults (DeCelles & Giles, 1996) | Permian Basin, USA (Kley, 2018)                                                               | Watson, Hayward, Parkinson, and Zhang (1987)                                                   |
| Basin high         | Topographic, bathymetric and/or geological feature in a sedimentary basin within which some or all of the rocks are higher than those of the same age in the surrounding areas. There is no requirement for basement to be involved, although basin highs are commonly also *basement highs*                                                                 | Central Basin High, Barmer Basin, Western Rajasthan, India (Naidu et al., 2017)               | Anders and Schlische (1994), Kane, Jackson, and Larsen (2010), Young, Gawthorpe, and Hardy (2001) |
| Basin-margin fault | A fault that marks the edge of, and typically controls, a basin (Roberts & Yielding, 1991). Synonymous with *border-fault system* (Schlische, 1992) and *boundary fault* (Morley, 1995)                                | Rønne Basin, Denmark (Neilsen, Petersen, Dybkjær, & Surlyk, 2010)                            | Leeder and Gawthorpe (1987)                                                                  |
| Dome               | *Anticline* with a regularly curved surface and a roughly circular or weakly elliptical outline in map view. They need not be bounded by faults, although some domes are fault bound, including *metamorphic core complexes* (Coney, 1980b). Some domes are created by diapirs (Marshak, Tinkham, Alkmim, Bruekner, & Bornhorst, 1997), so may not involve basement | Teapot Dome, Wyoming (Klusman, 2006)                                                          | Coney (1980a)                                                                               |
| Escarpment         | An elongate slope facing in one direction that separates two more gently sloping surfaces. They can be created by faulting and/or by erosion. An *escarpment* is, therefore, a steep face of a high rather than being a high itself. An escarpment can form the boundary between a high and a basin. See *fault scarp* | Sigsbee Escarpment, North Atlantic (Lee & George, 2004)                                        | Schlager and Camber (1986)                                                                  |
| Fault block        | Fault-bound volume of rock (Diller, 1886; Stöcès & White, 1935)                                                                                                                                               | Sirikit Field, Thailand (Morley, Ionnikoff, Pinyochon, & Seusuthiyi, 2007)                    | Jackson, Gawthorpe, Leppard, and Sharp (2006)                                                 |
| Fault scarp        | Defined by Leith (1923) as a landform caused at the Earth’s surface by fault movement or by later erosion along the fault that leaves one side of the fault plane standing higher than the other side. See *escarpment* | Ninian Field, North Sea (Underhill, Sawyer, & Hodgson, 1997)                                   | Stewart and Hancock (1991)                                                                  |

(Continues)
| Term                        | Definition                                                                                                                                                                                                 | Example                                                                                   | References                                      |
|-----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|------------------------------------------------|
| Fault zone                  | Defined by Hills (1940) as the zone of disturbed rocks between faulted blocks. Fault zone is commonly used for a system of related fault segments that interact and link, and are restricted to a relatively narrow band or volume (Nevin, 1931) | San Andreas Fault (Sylvester & Smith, 1976)                                                | Gibson (1994)                                  |
| Flexural uplift or subsidence | Buoyancy-induced vertical (isostatic) deformation that decreases in magnitude away from a fault (Egan, 1992) commonly modelled as an elastic response to fault slip (Roberts & Yielding, 1991) | Central Greece (Poulimenos & Doutsos, 1997)                                                | Weissel and Karner (1989)                      |
| Footwall uplift             | Uplift that occurs below a fault (in the footwall of a normal fault)                                                                                                                                          | Northern North Sea (Yielding, 1990)                                                        | Jackson and McKenzie (1983)                    |
| Growth fault                | A normal fault that is characterised by an increase in displacement down the dip of the fault, and by an increase in sediment thickness in the hanging-wall towards the fault plane, with older beds commonly having steeper dips than younger beds. This implies that the fault was active and cut the Earth’s surface during sedimentation | Offshore Louisiana (Losh, Eglinton, Schoell, & Wood, 1999)                                  | Ocamb (1961)                                   |
| Half-graben                 | Asymmetric area of subsidence controlled by hanging-wall subsidence above a controlling (basin-margin) fault (Barr, 1987). A half-graben typically contains a hanging-wall sedimentary wedge that thickens towards the growth fault, with older beds commonly having steeper dips than younger beds | Northern North Sea (McLeod, Underhill, Davies, & Dawers, 2002)                             | Roberts and Yielding (1991)                    |
| High                        | A general term for topographic, bathymetric and/or geological feature within which some or all of the rocks are higher than those of the same age in the surrounding areas (Blake et al., 1978). This may be used in preference to either basement high or basin high to avoid having to specify basement involvement, and without the need for the feature to be entirely within a basin | Utsira High (Wild & Briëd, 2010)                                                           | Dickinson (1979)                               |
| Horst                       | Elongate area of relative uplift mostly bounded by sub-parallel normal fault zones that dip away from the area of uplift (Reid, Davis, Lawson, & Ransome, 1913). Horsts are commonly bounded by grabens or half-grabens | Auk Field, central North Sea (Trewin, Fryberger, & Kreutz, 2003)                             | Dennis (1967)                                  |
| Intrabasinal high           | See basin high                                                                                                                                                                                              | Montepetra intrabasinal high, northern Apennines, Italy                                   | Conti, Fontana, Mecozzi, Panieri, and Pini (2010) |
| Massif                      | A high of regional size, and usually consists of crystalline rocks                                                                                                                                           | Froya High (Hinz, 1972)                                                                    | Ryan, Calder, Donohoe, and Naylor (1987)       |
| Metamorphic core complex    | A generally dome- or arch-like uplift of metamorphic or plutonic rocks overlain by tectonically detached and relatively unmetamorphosed cover rocks (Coney, 1980a; 1980b). The faults that cause exhumation may be normal faults (Crittenden, Coney, & Davis, 1980) or thrusts (Dallmeyer, Johansson, & Möller, 1992) | Rhodope metamorphic core complex, Greece (Dinter & Royden, 1993)                           | Dewey (1988)                                  |
| Plateau                     | An elevated tract of comparatively flat or level land; a tableland (Simpson, & Weiner, 1989). A positive geomorphological and/or structural feature dominated by a surface of even relief, typically higher than contemporaneous surrounding areas. A submarine plateau is below sea level. Such onshore plateaus as the Tibetan Plateau are surrounded by higher mountains | Exmouth Plateau, NE Australia (Velayatham, Holford, & Bunch, 2018)                          | Garzione et al. (2017)                        |

(Continues)
TABLE 1 (Continued)

| Term                      | Definition                                                                 | Example                                                                  | References                                       |
|---------------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------|-------------------------------------------------|
| Platform                  | A relatively flat or gently tilted area within which rocks are higher than   | Horda Platform, northern North Sea (Whipp, Jackson, Gawthorpe,             | Reemst and Cloething (2000)                      |
|                           | some or all of the rocks of the same age in the surrounding areas. A      | Dreyer, & Quinn, 2014)                                                    |                                                 |
|                           | platform can be a basement high and vice versa. Both can be an intrabasin  |                                                                            |                                                 |
|                           | high                                                                       |                                                                            |                                                 |
| Ridge                     | A relatively long, narrow feature with relatively steep sides (that      | Lomonosov Ridge, Arctic Ocean (Moore, Grantz, Pitman, & Brown, 2011)     | Fjeldskaar, Helset, J ohansen, Grunnaleite, and  |
|                           | may be defined by faults), and that is topographically or bathymetrically |                                                                            | Horstad (2008)                                  |
|                           | higher than the surrounding areas. A ridge controlled by faults would be   |                                                                            |                                                 |
|                           | a horst                                                                    |                                                                            |                                                 |
| Spur                      | An area that is topographically or bathymetrically high compared with     | Tampen Spur (Rønnevik, Bosch, & Bandlien, 1975)                           | Horstad, Larter, and Mills (1995)                |
|                           | most of the surrounding area, and that projects from a larger high. They  |                                                                            |                                                 |
|                           | are typically wedge shaped in map view                                      |                                                                            |                                                 |
| Structural high           | Topographic or bathymetric high caused by faulting and/or folding. This   | Doonerak Structural High, Central Brooks Range, Alaska (Dutro, Brosge,    | Van Hoorn (1987)                                |
|                           | term is more generic (higher uncertainty) than such terms as anticline or  | Lanphere, & Reiser, 1976)                                                 |                                                 |
|                           | horst                                                                       |                                                                            |                                                 |
| Terrace                   | A relatively long, narrow gently dipping surface between a high and a      | Halten Terrace, Norway (Borge, 2002)                                      | Wilkinson, Lonergan, Fairs, and Herrington (1998) |                                                 |
|                           | basin                                                                      |                                                                            |                                                 |
| Thermal subsidence/       | Vertical movements related to thermal contraction or extension of the      | Bohai Basin, China (Allen, Macdonald, Zhao, Vincent, & Brouet-Menzies,    | McKenzie (1978), Roberts and Yielding (1991)    |
| uplift/                   | Earth’s crust respectively                                                 |                                                                            |                                                 |
|                           |                                                                           |                                                                            |                                                 |

Secondly, some terms remain imprecise and have overlaps, and may need case-specific definition. For example, what should be the boundary between definitions of anticline, arch and dome? Should a fault-bound spur be called a horst? Such structures as domes, fault blocks, ridges and spurs can, for example, all be defined simply as basement highs until further data are available. Careful definition and explanation are important because nonexperts, or experts who have not previously worked on a particular basement high, can be confused or misled by imprecise terminology. Some basement highs will be a combination of various other types, such as a structure that is a combination of fault block and anticline. This suggests that the certainty of the interpretation should be qualified when assigning a geometric term to a particular basement high. We suggest indicating the level if certainty in the data and interpretation in the characterisation scheme presented in Section 4.

Despite these issues, Table 1 should add clarity to terms that are deeply engrained yet typically insufficiently defined in the literature.

3 TYPES AND DEFINITIONS OF BASEMENT

Basement is commonly used loosely in the geosciences, and different definitions for it are given across the literature in a range of contexts (Figure 3). Basement rock can mean a variety of things, depending on the region being discussed and the perspective of the geoscientist (Koning, 2003). A rigid definition of basement is not possible because of entrenchment of various basement terms in the literature, and because the term must be broad enough to cover a wide range of data types, locations and geological ideas (Koning, 2003). For example, some geoscientists use basement to refer to nonsedimentary rocks, regardless of age, if they are unconformably overlain by a sedimentary rock or sediment (e.g. Garbarino et al., 2003; Jordan & Allmendinger, 1986; Landes et al., 1960; Lu, Zhao, Wang, & Hao, 2008). In contrast, P’An (1990) gives a definition of basement that includes rocks with a sedimentary origin, providing they have little or no matrix porosity.

We recommend that, to avoid potential confusion and misunderstanding between geoscientists, the term basement should not be used by itself wherever possible, but use one or more prefixes that denote(s) the basis on which that basement type is defined. Table 3 shows examples of recommended prefixes for the range of basement types. Geoscientists should explain the basis of their basement prefix. The questions “what is the basement type?” and “how is top basement defined?” should be answered for each study, location and data type. Note that we use the general term basement high in this study because we are not discussing a particular basement type or implying how it was defined.
Here, we present a systematic scheme for characterising basement highs. The approach is similar to the scheme for characterising fracture networks presented by Peacock and Sanderson (2018) because it identifies distinct analysis types, and because it is structured such that characterisation of a basement high progresses from descriptive, to quantitative and to genetic. The characterisation scheme presented in Table 4 is demonstrated using the southern Rona Ridge, offshore UK. This example is used because it has a proven petroleum system and enough data are available in the public domain and peer-reviewed papers to enable a detailed characterisation by a third party.

We recommend that the scheme presented in Table 4 should be sequentially populated using all available data and interpretation types, which may include published literature, fieldwork, rock and fluid samples, gravity and magnetic data, seismic surveys and mineral production information. We also recommend that the analyst states their degree of certainty for each part of the scheme (i.e. high, moderate, low and no information) to indicate strength of models and gaps in knowledge, even if such statements are qualitative. It is important to properly reference credible publications that are available to the reader (see Santini, 2018). In our analysis of the Rona Ridge, however, we have at times had to use such sources such as company reports or presentations, some of which are only available online (e.g. Hurricane Energy, 2019a–c).
Although we have developed this characterisation scheme (Table 4) primarily for the petroleum industry, it requires only few modifications or additional criteria to be usable for other commodities (Section 4.7).

### 4.1 Basic description of a basement high

Characterisation of a basement high should commence by providing geographic information and the geological setting. This information should include what would be included, for example, in a field description of an outcrop or in a geological setting chapter of a thesis or report. This would include geographical details about the location of the basement high, the types of data available and observational information about the geology of the area. These fundamental descriptions for the southern Rona Ridge are shown in Table 4 (Section A) and Figure 4.

### 4.2 Geometry of a basement high

Geometric information about a basement high should enable readers to visualise its shape, and such information would also
aid calculation of gross rock volume and fluid column height. The geometry of a basement high can be characterised in terms of various attributes (Table 4, Section B), including the following:

4.2.1 | Size

This should include the area of a basement high in map view, or the long and short axes of the basement high. It may be difficult or ambiguous to define the exact size of a basement high, especially because the stated area covered depends upon the depth slice at which the area is displayed. Also, data coverage may not be consistent over the area of the basement high. Table 2 shows examples of basement highs across a range of scales.

4.2.2 | Shape

The shape of a basement high should be described or quantified at least in map view and in one cross-section, but ideally also in 3D. It is common in geology to assign a simple descriptive term to the outline geometries of features. Simple descriptive shapes that could be used to describe the map view (i.e. 2D) geometries of basement highs include circular, oval, triangular, square, rectangular, rhombic, etc. Simple descriptive shapes that could be used to describe the 3D geometries of basement highs include cuboid, wedge, flat-top dome, etc. The assigned shape could then be used in basement high volumetric calculations (e.g. Belaidi, Bonter, Slightam, & Trice, 2016). Note that many natural features tend to have fractal geometries (Mandelbrot, 1982), so shapes tend to become more elaborate as resolution increases.

| Analysis type | Recommended prefix for basement | Basis for definition | References |
|---------------|---------------------------------|----------------------|------------|
| Geology       | Precambrian<sup>a</sup>         | Precambrian rocks are commonly referred to as basement because fossils are very rarely preserved, or because they underlie Phanerozoic sedimentary rocks | Kauffman and Steidmann (1981), Salah and Alsharan (1998) |
| Structural    | Igneous and metamorphic rocks that are overlain by a deformed sedimentary cover, with deformation in the sedimentary typically uncoupled with deformation in the structural basement | Sylvester and Smith (1976), Vendeville, Ge, and Jackson (1995), McQuarrie (2004) |
| Orogenic<sup>b</sup> | Rocks deformed during an orogenic event that are subsequently partly or completely covered by younger sediments | Gessner, Collins, Ring, and Güngör (2004) |
| Weathered     | Regolith and saprock units above the fresh bedrock of an already defined basement type | Wright (1992) |
| Geophysics    | Gravity                          | Region of the subsurface showing a “strong” gravity response | Nunziata and Rapolla (1987) |
|               | Magnetic                         | Region of the subsurface showing a “strong” magnetic response. It may refer to either: (a) the rocks below a magnetic response; or (b) the rock unit causing the magnetic response | Behrendt and Wotorson (1970), Skilbrei et al. (2002), Treitel, Clement, and Kaul (1971) |
|               | Acoustic/seismic                  | Region of the subsurface showing a “strong” response to a passing seismic wave in the subsurface. Typically used for the region beneath the deepest coherent or continuous seismic reflector of a stratified sedimentary succession | Allaby (2013), Bruvoll et al. (2012), Cooper, Davey, and Cochrane (1987) |
| Fluid flow    | Porosity                         | Rocks with matrix porosity and permeability that is too low for them to store or produce an economically viable hydrocarbons | Hayes (1991) |
|               | Naturally fractured crystalline   | Igneous or metamorphic rocks that produce fluids from fractures | Trice (2014) |
| Industrial    | Economic                         | Typically used for the subsurface region beneath the rocks that contain commercial oil or gas, but we suggest it could be broadened to mean rocks below the depth at which economic mineral resources may be exploited | Burgess (1974), Selley (1978) |

<sup>a</sup>Other ages of rock have been used to describe basement, including, for example, Silurian (Himmerkus, Reischmann, & Kostopoulos, 2009) and even Miocene (Woodside, Mascle, Huguen, & Volkonskaia, 2000).

<sup>b</sup>The names of orogenic events are commonly used as prefixes to basement to describe the rocks deformed during that orogen. Examples include Caledonian basement (Ritzmann & Faleide, 2007) and Variscan basement (Maluski, Rajlich, & Matte, 1993).
| Analysis type | Characterisation                                                                 | Example: southern Rona Ridge | Certainty (high, low, moderate no information) |
|---------------|----------------------------------------------------------------------------------|-----------------------------|---------------------------------------------|
| A Basic description (Figures 4-6) | Basement high name                                                             | Rona Ridge<sup>a</sup> | High                                      |
|                | Name of the part of the basement high being evaluated                           | The southern Rona Ridge | High                                      |
|                | Location (onshore or offshore region, country, continent, latitude—longitude or UTM, water depth) | Quadrants 204, 205, offshore, West of Shetlands, UK sector, Europe<sup>a</sup>. 60°16′23.4″N 3°37′57.8″W. Water depth ~160 m<sup>2</sup> | High                                      |
|                | Name(s) of license block(s)                                                      | P1368 Central. P2308. P2294. P1368 South. P1368 North. P1368 Southwest<sup>b</sup> | High                                      |
|                | Present-day geological region (e.g. basin, mountain range or petroleum province name) | The West of Shetland petroleum province of the UK Continental Shelf<sup>a</sup>. Separating the Faroe-Shetland Basin from the West Shetland and East Solan basins<sup>e</sup> | High                                      |
|                | Present-day tectonic setting (e.g. rift system, passive margin, continental shelf, orogenic belt) | Passive continental shelf of the North East Atlantic Margin | High                                      |
|                | Exploration and production summary (associated hydrocarbon fields, discoveries or prospects, associated wells and fluid types intersected) | Greater Lancaster Area: Lancaster Field (light oil). Halifax Discovery (oil leg and gas cap). Greater Warwick area: Lincoln Discovery (oil) and Warwick Prospect. Whirlwind Discovery (light oil or gas condensate)<sup>b</sup> | High                                      |
|                | Recognition criteria (data used to identify the basement high, such as fieldwork, seismic data and gravity data) | 2D and 3D reflection seismic<sup>b</sup> | High                                      |
|                | Other available data (e.g. geophysical, bathymetry, air photograph, satellite imagery, lithology) | Offset seismic and well data, regional geological analysis<sup>d</sup> | High                                      |

2. Geometry of the basement high (Figure 5)  
| Size (area covered in map view, or lengths of long and short axes, to shallowest saddle of regional basement level) | ~2,500 km<sup>3</sup> | Moderate                                      |
| 2D shape (description of the shape in map view) | Straight-sinuous, rectangular wedge with lateral downthrown terraces | Moderate                                      |
| 3D shape (description of the shape in 3D) | Triangular prism to acute trapezium (southwards) | Moderate                                      |
| Depth or altitude of the crest relative to a datum level | Top Basement apex for Halifax Discovery at ~750 m TVDSS<sup>d</sup> | Moderate                                      |
| Depth or altitude of the base (depth where it joins the regional basement level) | ~4,500 m<sup>2</sup> | Low                                          |
| Height (distance between the depths or altitudes of the apex and the base of a basement high) | ~3,600 m | Low                                          |
| Topography of the upper surface (e.g. maximum and average dip, cross-sectional geometry) | Undulating | Moderate                                      |

3. Lithologies (Figure 7)  
| Basement lithologies (known or inferred) | Tonalite with minor granodiorite, quartz diorite and granite<sup>e</sup> | High                                          |
| Lithologies around the basement high (known or inferred lithologies in surrounding areas, including ages, thicknesses, facies, etc.) | Jurassic-Cretaceous organic-rich marine shales, Cretaceous and Tertiary mudstones and sandstones with minor carbonates<sup>a,g</sup> | High                                          |
| Lithologies overlying the basement high (known or inferred, their ages, thicknesses and facies) | Cretaceous and Tertiary mudstones and sandstones with minor carbonates. Jurassic-Cretaceous organic-rich marine shales<sup>a,g</sup> | High                                          |

(Continues)
| Analysis type       | Characterisation                                                                 | Example: southern Rona Ridge                                                                 | Certainty (high, low, moderate no information) |
|--------------------|----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|-----------------------------------------------|
| 4. Structures      | Structures defining the margins of the basement high (e.g. faults or unconformities that bound the basement high) | Some flanks are normal faults, others are unconformities                                   | Moderate                                      |
|                    | Structures within, and segmenting, the basement high (e.g. faults, folds, fracture systems) | Seismic-scale faults, fault zones, “large aperture fractures”, “shear fractures”, joints, “microfractures”, dolerite dykes, veins | High                                          |
|                    | Structures in the rocks surrounding the basement high                             | Normal faults in a rift system                                                             | Moderate                                      |
|                    | Structures above the basement high (compaction folds, faults, etc.)              | Normal faults                                                                            | Moderate                                      |
| 5. Timing of events | Age(s) of the basement rocks (known or inferred)                                  | ~2.74 Ga pluton emplacement                                                               | High                                          |
|                    | Basement high deformation event(s) (known or inferred)                           | Archaean: pluton cooling and jointing                                                     | Moderate                                      |
|                    |                                                                                   | Proterozoic: Laxfordian contraction                                                        | Moderate                                      |
|                    |                                                                                   | Palaeozoic Caledonian Orogeny: fault reactivation                                          | Moderate                                      |
|                    |                                                                                   | Palaeozoic Variscan reactivation: brittle deformation                                     | Moderate                                      |
|                    |                                                                                   | Permo-Triassic: regional ENE-WSW extension                                                  | Moderate                                      |
|                    |                                                                                   | Cretaceous Atlantic rifting: NE-SW extension                                               | Moderate                                      |
|                    |                                                                                   | Palaeocene-Eocene Alpine Orogeny: no deformation recorded                                  | Moderate                                      |
|                    |                                                                                   | Tertiary uplift: relaxation of pre-existing fracture network                               | Low                                           |
|                    | Age of relative uplift of the basement high (known or inferred)                   | Inferred Carboniferous-Jurassic exposure                                                   | Moderate                                      |
|                    | Ages of rocks around and above the basement high (known or inferred)              | Jurassic                                                                                   | High                                          |
|                    | Ages of structures in, around and above the basement high (known or inferred)      | Numerous possible ages of structures. Normal faults inferred active sometime between Upper Cretaceous and Base Pliocene | Moderate                                      |
| 6. Origins         | Origin of the basement high (processes that created the basement high; Table 5)   | Uplift of the flank of the Faroe-Shetland Basin during Mesozoic rifting                    | Moderate                                      |
| 7. Economic         | Source rocks and spatial relationship (potential source rocks above or around the basement high) | Late Jurassic Kimmeridge Clay Formation, Juxtaposed with and onlapping the basement high | High                                          |
| prospectivity      | Seal (potential seal rocks within, above or around the basement high)              | Top and lateral seal is provided by Upper Cretaceous mudstones                              | High                                          |
| (Fig. 8)           | Reservoir (potential reservoir rocks within, above or around the basement high)    | Fractured Lewisian tonalite (Archaean)                                                    | High                                          |
|                    | Fractured reservoir type                                                           | Type 1 naturally fractured reservoir (Nelson, 2001), with fractures providing porosity and permeability | High                                          |
|                    | Trap types (potential trap types within, above or around the basement high)        | Greater Lancaster Area and Greater Warwick Area are both combination stratigraphic-fault traps: three-way buried hill and one-way fault sealed. Whirlwind is a stratigraphic (buried hill) trap | High                                          |

(Continues)
4.2.3 | Depth or altitude of the crest

Information should be given about the shallowest point (apex) below mean sea level for the top of a submarine basement high, or the altitude of the highest point above mean sea level of a subaerial basement high.

4.2.4 | Depth or altitude of the base

Information is needed about the depth or height relative to mean sea level where the flank of a basement high becomes part of the regional basement elevation.

4.2.5 | Height

An estimate should be given of the vertical distance between the apex and the base of a basement high.

4.2.6 | Topography of the upper surface

The topography of the upper surface of a basement high should be described. This would include, for example, the maximum and average slope or the cross-sectional geometry (e.g., horizontal, planar sloping, undulating).

Table 4 (Section B) and Figure 5 give information about the geometric features of the southern Rona Ridge.

4.3 | Lithologies related to a basement high

This should include information about the known or inferred lithologies that comprise a basement high, which could be igneous, meta-igneous, meta-sedimentary and/or sedimentary. The description should also include the known or inferred lithologies around and above a basement high. For sediment or sedimentary rock units around or above a basement high, information should include such details as their ages, thicknesses,
depositional facies and hiatuses. Table 4 (Section C) shows information about the lithologies related to the southern Rona Ridge.

4.4 | Basement high structures

The structures within, around and above a basement high should be described, and this can be done using a variety of data types (Figure 6). Initial focus would be on structures that define the boundaries, flanks and segmentation of a basement high, including basin-bounding faults. Such description would help identify features that could have been major fluid flow conduits or barriers, or have formed traps. This description would also help for selecting appropriate analogues for a basement high. Structures within, around or above the basement high to be described include faults, fracture systems, folds, gravity-collapse structures and erosional features. Kinematic data, if available, should be presented as evidence of the displacement directions of faults. Figures 5 and 6, and Table 4 (Section D) show structures identified within, around and above the southern Rona Ridge.

4.5 | Timing of events

The absolute ages of rock units or deformation events (e.g. from sediment growth packages with constrained biostratigraphy or radiometric dating) in, around and above a basement high should be listed. The relative ages of rocks and structures (e.g. from seismic reflectors of known or inferred ages, and from cutting and abutting relationships of faults) should be stated if absolute age data are unavailable. It should be determined whether the basement high developed before, during or after deposition of the surrounding rocks. The sequence of events that have modified the basement high, including ages of relative uplift, needs to be determined. It may also be possible to comment on the style of relative uplift of a high. For example, a basement high may have risen relative to a fixed datum while the surrounding basins subsided, or a basement high may have undergone subsidence but at a
slower rate than the surrounding basins. Table 4 (Section E) and Figure 7 show information about the timing of events on and around the southern Rona Ridge.

4.6 Origins and tectonic settings

Basement highs can occur in a range of tectonic or erosional settings and can be caused by a range of processes. Description of any basement high should include an interpretation of its origin and originating tectonic processes (Table 5). A basement high may be the product of more than one geological process (i.e. a combination basement high). For example, a particular basement high might have formed as a horst, influenced both by isostatic behaviour of the basement rocks and by erosion. This aspect of basement high characterisation should be incorporated into basin evolution and play assessments because the process(es) that created a basement high may have influenced other geological processes, including those that control petroleum system and petroleum play elements. Table 4 (Section F) and Figure 7 show information about the tectonics of the southern Rona Ridge. We suggest that the Rona Ridge formed because of uplift of the flank of the Faroe-Shetland Basin, which is a Mesoic rift system.

4.7 Influences on prospectivity

This section of the characterisation scheme (Table 4, Section G) is designed primarily for the petroleum industry, although petroleum play elements can be easily modified for use as mineral play elements (Section 4.7; e.g. Banks, Walter, et al., 2019; McCuaig, Scarselli, O'Connor, Busuttil, & McCormack, 2018). For petroleum play analysis (e.g. Grant, Milton, & Thompson, 1996), information or prediction is needed about the influence of the basement high on migration pathways, reservoir, trap and seal elements, and the timings of each of these. As with analysis of other play types, basement high play characterisation should include probabilistic assessment of the uncertainty of the interpretation relating to each play element (e.g. Roy, 1979). Figure 8 shows these play components using the southern Rona Ridge.

If petroleum or other minerals have been discovered in or around a basement high, then its geometry, lithology, structures, origin and evolution (Sections 4.2–4.6) are crucial inputs to estimate possible gross rock volume and fluid column heights. Knowledge of lithologies, porosity-permeability ranges and fault-fracture systems in and around a basement high is also required to consider possible fluid leakage that could influence petroleum volumes. The depths of contacts between fluid types are also crucial information.

FIGURE 5 Example of geometric features of a basement high (Table 4, sections A and B), illustrated using the south Rona Ridge 3D Top Basement depth structure map (Hurricane Energy, 2019b; see Figure 4 for location). A = Lancaster Field oil–water contact at 1678 m true vertical depth sub-sea level (TVDSS; Hurricane Energy, 2019c). B = Lincoln oil discovery “oil down to” at 2,258 m TVDSS (Hurricane Energy, 2019c). C = Whirlwind Discovery “oil down to” at TVDSS (RPS Energy Consultants, 2017b). The depth of the apex is from RPS Energy Consultants (2017b) and the depth of the base is from Spark Exploration (2018). The basement high covers an area of ~1,200 km². It has an approximately trapezoid shape in map view shape (including the Whirlwind downthrown block). The topography of the upper surface can be described as an undulating wedge (area i) and an undulating planar slope (areas labelled ii). Structures segmenting the basement high include: 1 = Westray Fault Zone; 2 = Brynhild Fault Zone. Contour increment 100 m. 3D Top Basement depth structure map image courtesy of Clare Slightam, Hurricane Energy.

3D shape: Triangular prism Acute trapezium

Depth of apex ~ 750 m TVDSS

Depth of base ~ 4500 m TVDSS

North
The characterisation scheme shown in Table 4 is designed principally for evaluation of basement highs in the petroleum industry. It is, however, modifiable to basement high characterisation for other purposes and industries. For mineral exploration in and around basement highs, for example, mineral assemblages could be inserted into the exploration and production summary of Table 4, and deposit types could replace trap types. Basement high characterisation for groundwater, geothermal and contaminant transport evaluations could include such categories as climate, rainfall, surface drainage and subsurface fluid flow pathways.

5 | DISCUSSION: IMPLICATIONS FOR BASEMENT HIGH ANALYSIS

Characterising basement highs is an important aspect of basin and basement analysis, and petroleum, groundwater, geothermal and mineral resource evaluations. Researchers and economic geologists conducting screening assessments are likely to have little corporate data available to them, and so will be heavily reliant upon public domain and internet searches for basement high interpretations and schematic figures. Data sources will include peer-reviewed publications and corporate reports, some of which are independently
We have written this study to help clarify the basement high terminology and to suggest a thorough basement highs characterisation scheme. We suggest that the descriptions and illustrations of basement highs are commonly insufficient, and often fall short of what would be included in a routine description of, for example, a mountain range or a nonbasement petroleum reservoir. Even the terminology used can be vague or misleading. For example, although such terms as the Bach Ho Field “buried hill” (Cuong & Warren, 2009) and Zeit Bay “fractured basement” (El Sharawy, 2015) give some information about a basement petroleum field, these phrases can lack rigour. They do not enable readers to envisage the basement high, assess its prospectivity or use it as an analogue for another basement high. We hope this study will help geoscientists to more systematically describe and report their basement high information, and build 4D models of these structures.

6 | CONCLUSIONS

A glossary of terms to describe and define the geometries of basement highs is presented (Table 1), with the aims of clarifying the terminology and improving cross-disciplinary understanding. Basement has a broad range of meanings and uses in the geosciences, so we suggest that a qualifying prefix should be used, and succinct description of it be stated in reports and figures, to make it clear what type of basement is being described and how it was
**Table 5** Examples of different basement high types and originating tectonic settings or processes of basement highs with examples.

*Erosional basement highs* are formed when a landscape is eroded and younger sediments are deposited around and potentially over older basement rocks. Volcanic and intrusive igneous rocks could be considered as basement (e.g. lithologic basement, acoustic basement or economic basement types), even if younger than surrounding sedimentary units.

| Basement high type          | Petroleum basin, province or field | Field example | Key reference | Effects on petroleum systems |
|-----------------------------|------------------------------------|---------------|--------------|-----------------------------|
| Rotated fault block         | Northern North Sea                 | Sinai, Greece, Svalbard | Mandl (1987), Fossen, Hesthammer, Johansen, and Sylngabere (2003) | Provides sediments, creates half-grabens |
| Horst                       | Ninian Field (North Sea)           | Rio Grande Rift (New Mexico) | Tomasso, Underhill, Hodgkinson, and Young (2008) | High dividing two basins or sub-basins. Wider horsts can contain synclinal basins (Mack, Seager, & Leeder, 2003) |
| Rift flank                  | Norwegian Continental Shelf and South Atlantic | Yemen, East African Rift, west Africa | Anell, Thybo, and Artemieva (2009) | Provides sediments, directs sediment transport |
| Transfer zone               | Northern North Sea                 | Canyonlands (Utah) | Morley, Nelson, Patton, and Munn (1990) | Control sediment pathways, petroleum migration and traps |
| Metamorphic core complex    | Rechnitz Window and Styrian Basin (Austria) | Rechnitz Window (Eastern Alps), Cyclades (Greece) | Dunkl, Grasemann, and Frisch (1998) | Provide sediments, increase geothermal gradient |
| Transtensional regime       | Phitsanulok Basin (Thailand)       | Northumberland Basin (UK) | De Paola, Holdsworth, McCaffrey, and Barchi (2005) | Cause local uplift in regions otherwise dominated by extension |
| Strike-slip pop-up          | Turpan-Hami Basin (China), Salton Trough (California) | Spanish Central System, Salton Trough (California) | McClay and Bonora (2001) | Local highs providing sediments |
| Flower structure            | Western Sichuan Basin (central China) | Minas Fault Zone (Nova Scotia), Fife (Scotland) | Harding (1985) | Local highs providing sediments and traps |
| Thick-skinned fold-thrust system | Wind River Basin (Wyoming), Apennines (Italy) | Wind River Basin (Wyoming), Apennines (Italy) | Boyer and Elliott (1982) | Provide sediments and traps, create foreland basins, tilts porous sequences enabling long-distance fluid migration |
| Thrust pop-up               | Potwar (Pakistan)                  | Bude (SW England) | Jaswal, Lillie, and Lawrence (1997) | Provide traps |
| Reverse fault               | Bach Ho oil field in the Cuu Long Basin (Vietnam). Note: also a buried bathymetric high or hill | Somerset and Dorset (SW England), Wind River Canyon (Wyoming, USA) | Miller and Mitra (2011) | Creates traps, fluid conduit |
| Orogen interior             | Not applicable                     | Himalayas, Alps, Rocky Mountains | Price (2002) | Provides sediments and create foreland basins, but very low prospectivity within these regions |

(Continues)
defined (Table 3). We define *basement high* in this study to mean an area in which the basement rocks are significantly higher than in the surrounding areas, significantly being used to mean that they influence the petroleum system. Note that we use the general term *basement high* here because we are not specifying a particular basement type, dataset or identification criterion.

A scheme is presented to systematically and thoroughly characterise basement highs (Table 4). This includes description of the location and geometry of the basement high, related lithologies and structures, the tectonics and origins of the basement high, the timings of modifying events and the influence on commodity resources and prospectivity. Use of this scheme is demonstrated using the southern Rona Ridge (West of Shetland petroleum province, UK). The scheme can easily be modified for use in the mineral, geothermal and groundwater resource sectors. The characterisation scheme presented in Table 4 is, therefore, an expandable guide for describing basement highs systematically and consistently for different purposes across the geosciences.

**FIGURE 8** Example of the influence of a basement high on economic prospectivity, using the example of the southern Rona Ridge and Lancaster Field. (a) Geoseismic section used to show how a fractured basement high reservoir and trap can: (1) be charged by petroleum from onlapping source rock kitchens, (2) be sealed above and laterally and (3) have been a provenance for adjacent clastic reservoirs. Modified from Trice, Hiorth, and Holdsworth (2019). (b) Schematic illustration of the Rona Ridge petroleum source kitchens (Nuzzo et al., 2018) and schematic charge pathways into the Rona Ridge basement high. 1 = West Solan Basin, 2 = East Solan Basin
**Cenozoic rocks (overburden)**

**Upper Cretaceous rocks (seal)**

**Victory Sandstone (reservoir)**

**Kimmeridge Clay (source)**

**Rona Sandstone (reservoir)**

**Permo-Triassic rocks**

**Precambrian basement (reservoir)**

**Top and lateral seal ‘cap rock’ units**

**Reservoir rock unit**

**Source rock unit**

**Petroleum charge**

**Fault**

**Water column**

**Free Water Level**

**Lancaster Field**

**East Faro High**

**Faroe-Shetland Basin**

**Clair Ridge**

**Judd High**

**West Shetland Basin**

**Papa Basin**

**Sula Sgeir High**

**Shetland Islands**

**Walls Boundary Fault**

**Deep basinal areas**

**Shallow basins**

**Platform areas**

**0 10 20 30 40 50 kms**
A range of processes can create basement highs, as listed in Table 5. We suggest that knowledge of, and models for, the origins of basement highs is likely to improve understanding of other geological processes related to basement highs, and will improve understanding of their influence on commodity prospectivity. For example, knowledge of the processes that created and modified a basement high may enhance 4D understanding of the petroleum system affected by that basement high.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article because no new data were created or analysed in this study.

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