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Basement highs: Definitions, characterisation and origins

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Abstract

A glossary of commonly used terms related to the geometric forms and geological settings of basement highs is presented to assist cross-disciplinary understanding, qualifying prefixes for the term *basement* are discussed and a scheme for characterising basement highs is presented. This scheme is designed to standardise, and to add rigour to, description of basement highs. It will thereby enhance basement high comparisons and assist understanding of basement highs across technical disciplines. The scheme enables systematic characterisation of: the geometry of a basement high; the lithologic units and structures in, above and around it; timings; tectonics and origins of the basement high and play elements relating to resource prospectivity. Use of this scheme is demonstrated using the southern Rona Ridge (West of Shetland, UK Continental Shelf). The tectonic, isostatic, erosional and stratigraphic processes that form basement highs are also discussed, and examples in proven petroleum systems are presented.

KEYWORDS

basement highs, basement plays, characterisation, geometries, origins

1 | INTRODUCTION

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

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younger rocks or sediments. Basement highs occur across a wide range of scales and in wide variety of tectonic settings. Basement highs generally, however, typically share various common characteristics. They are commonly unconformably overlain by younger rock units, often with condensed depositional sequences. They are typically fringed by younger rocks or sediments and are commonly bounded on at least one side by a fault system. Also, basement highs generally show evidence of either uplift or relatively less subsidence than the surrounding younger sediments or rocks. Basement highs may occur within or adjacent to basins.

A petroleum play is a group of fields and prospects having a chance for charge, reservoir and trap and belonging to a geologically related stratigraphic unit (e.g. Royal Dutch Shell, 2013). A mineral play is a group of geologically related mineral deposits and prospects within a chronostratigraphically bound unit (Banks, Walter, et al., 2019). Several questions about basement highs should be answered to model the evolution of a basin or the prospectivity of a petroleum or mineral play, including the following. What type of *basement* is being characterised? What effects did the basement high have on the extent and quality of play elements? Can the basement high be a reservoir? Can a commodity occur within, adjacent to or above the basement high? How did the basement high evolve and how did this evolution relate to petroleum or mineral commodity generation, migration pathways and entrapment? What information is needed to improve the model? Answering these questions requires careful analysis and description of the basement high.

Modifying a classic quotation about petroleum in basement reservoirs by Landes et al. (1960), resources in basement highs are not geological "accidents" but are accumulations that obey all the rules of sourcing, migration and entrapment, so basement highs should be examined with the same professional skill and zeal that is applied to deposits in the surrounding sedimentary rocks. The study therefore does the following:

1. A glossary of topographic and structural terms related to basement high geometries and geological settings is presented. This is designed to help geoscientists better communicate and integrate these terms across technical disciplines.
2. The various uses of *basement* are summarised, and it is recommended that qualifying prefixes are used to explain what is meant by the term.
3. A characterisation scheme is presented with the aim of standardising the description of basement highs, which should then make it easier to compare different basement highs. Use of this scheme is demonstrated with the southern Rona Ridge (UK Continental Shelf).
4. Different origins of basement highs are listed because this can be helpful in evaluating petroleum source, migration, reservoir and trap.

Highlights

- A glossary of commonly used geometric terms related basement highs is presented
- Qualifying prefixes for the term *basement* are discussed, such as "acoustic basement"
- A scheme for characterising basement highs for use in the oil industry is presented
- Tectonic, isostatic, erosional and stratigraphic processes that form basement highs are discussed

We focus on basement highs that range from petroleum field to regional scales (i.e. more than circa 100 km^2). Although this study concentrates on the relationships between basement highs and petroleum systems, the characterisation scheme can readily be modified for use on basement highs that host mineral deposits, groundwater aquifers or geothermal reservoirs. This study is, therefore, aimed at geoscientists in petroleum, minerals, groundwater and geothermal resource industries. Those geoscientists can include geophysicists, seismic interpreters, basin and reservoir modellers, petroleum geologists, sedimentologists, hydrologists and structural geologists.

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 highs 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.

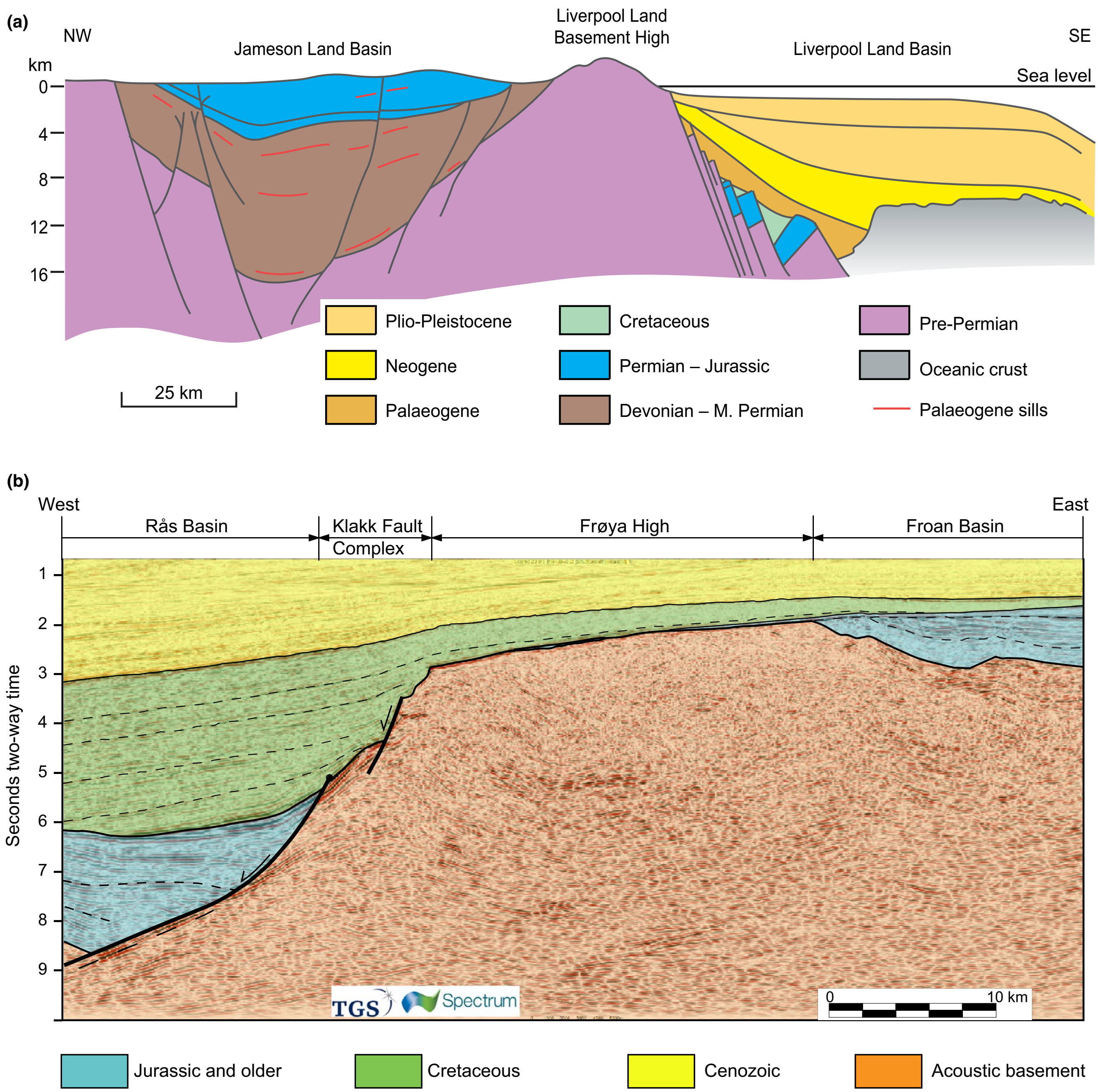


FIGURE 1 Examples of basement highs. (a) The subaerial Liverpool Land Basement High is a volume of pre-Permian "basement" rock (naturally fractured crystalline basement) that is significantly higher than the surrounding areas of basement rocks. The section is based on field data onshore and seismic data offshore (Banks, Bernstein, et al., 2019; Figure 2a). The basement rocks are buried below the Jameson Land Basin onshore, and by the Liverpool Land Basin on the western North Atlantic margin. (b) Interpreted seismic section across the Frøya High, offshore Mid-Norway, which is a submarine basement high covered by younger sedimentary rocks and sediments (modified from Muñoz-Barrera, Henstra, Kristensen, Gawthorpe, & Rotevatn, in review; Figure 5c). The Frøya High is bounded to the west by the Klakk Fault complex, which separates the basement high from the Rås Basin, with the Froan Basin unconformably overlying basement rocks to the east

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 *ridge* may become a *horst* when faults are resolved by better seismic data. Similarly, a *horst* may be better defined as an *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 *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 (Hajnorouzi, 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; Stočes & White, 1935)	Sirikit Field, Thailand (Morley, Ionnikoff, Pinyochon, & Seusutthiya, 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)

TABLE 1 (Continued)

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 & Briedis, 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	Frøya 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 some or all of the rocks of the same age in the surrounding areas. A platform can be a basement high and vice versa. Both can be an *intrabasin high*	Horda Platform, northern North Sea (Whipp, Jackson, Gawthorpe, Dreyer, & Quinn, 2014)	Reemst and Cloething (2000)
Ridge	A relatively long, narrow feature with relatively steep sides (that may be defined by faults), and that is topographically or bathymetrically higher than the surrounding areas. A ridge controlled by faults would be a *horst*	Lomonosov Ridge, Arctic Ocean (Moore, Grantz, Pitman, & Brown, 2011)	Fjeldskaar, Helset, Johansen, Grunnaleite, and Horstad (2008)
Spur	An area that is topographically or bathymetrically high compared with most of the surrounding area, and that projects from a larger *high*. They are typically wedge shaped in map view	Tampen Spur (Rønnevik, Bosch, & Bandlien, 1975)	Horstad, Larter, and Mills (1995)
Structural high	Topographic or bathymetric high caused by faulting and/or folding. This term is more generic (higher uncertainty) than such terms as *anticline* or *horst*	Doonerak Structural High, Central Brooks Range, Alaska (Dutro, Brosge, Lanphere, & Reiser, 1976)	Van Hoorn (1987)
Terrace	A relatively long, narrow gently dipping surface between a *high* and a *basin*	Halten Terrace, Norway (Borge, 2002)	Wilkinson, Lonergan, Fairs, and Herrington (1998)
Thermal subsidence/ uplift	Vertical movements related to thermal contraction or extension of the Earth's crust respectively	Bohai Basin, China (Allen, Macdonald, Zhao, Vincent, & Brouet-Menzies, 1997)	McKenzie (1978), Roberts and Yielding (1991)

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.

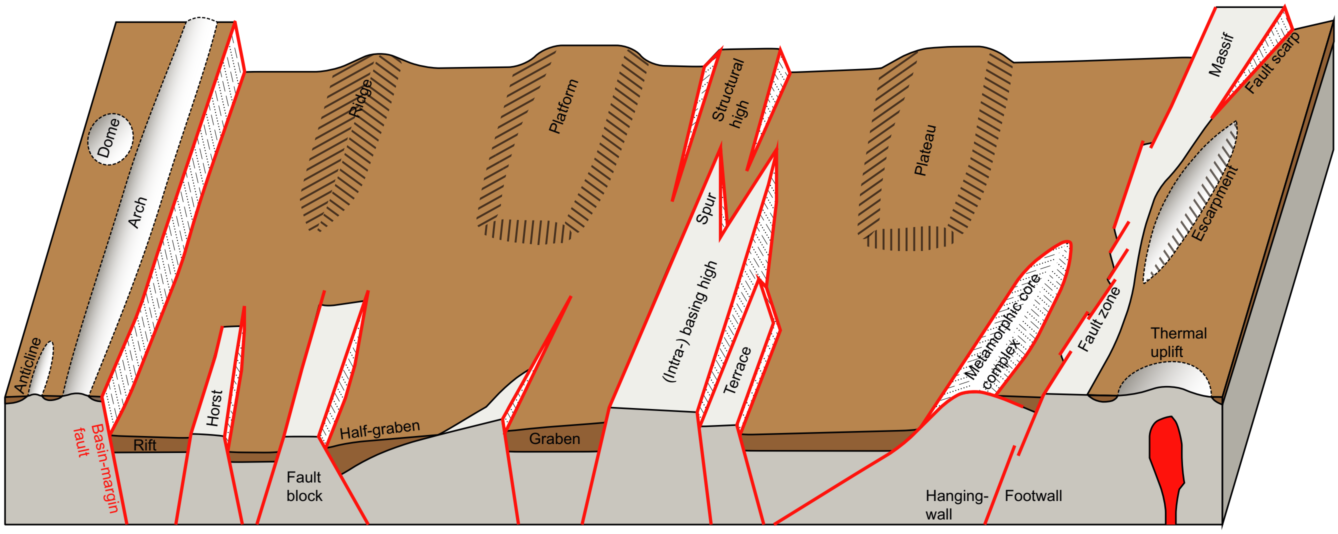


FIGURE 2 Schematic illustration of topographic and structural features related to basement highs, as defined in Table 1

TABLE 2 Examples of basement highs across a range of sizes, with islands for relative scale

Area (km^2)	Basement high example	Island example
>1,000,000	Fennoscandian Shield (Lahtinen, 2012)	Australia
100,000–1,000,000	Massif Central, France (Faure, Lardeaux, & Ledru, 2009)	Madagascar
10,000–100,000	Grampian and Northern Highlands terranes, Scotland-Ireland (Bluck, Gibbons, & Ingham, 1992)	Ireland
1,000–10,000	Rona Ridge (Larsen, Rasmussen, & Hjelm, 2010), Utsira High (Lundmark, Sæther, & Sørlie, 2013), Liverpool Land basement High (Banks, Bernstein, et al., 2019)	Cyprus
100–1,000	The central horst that hosts the Bach Ho oil field, Vietnam (Hung & Le, 2004)	Malta
10–100	Suban gas field, Indonesia (Hennings et al., 2012; Mohede, Malick, & Tyberoe, 2014)	Jersey
<10	Precambrian inliers, Charnwood Forest area, Leicestershire, UK (Carney, 2000)	Alderney

4 | CHARACTERISATION SCHEME FOR BASEMENT HIGHS

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).

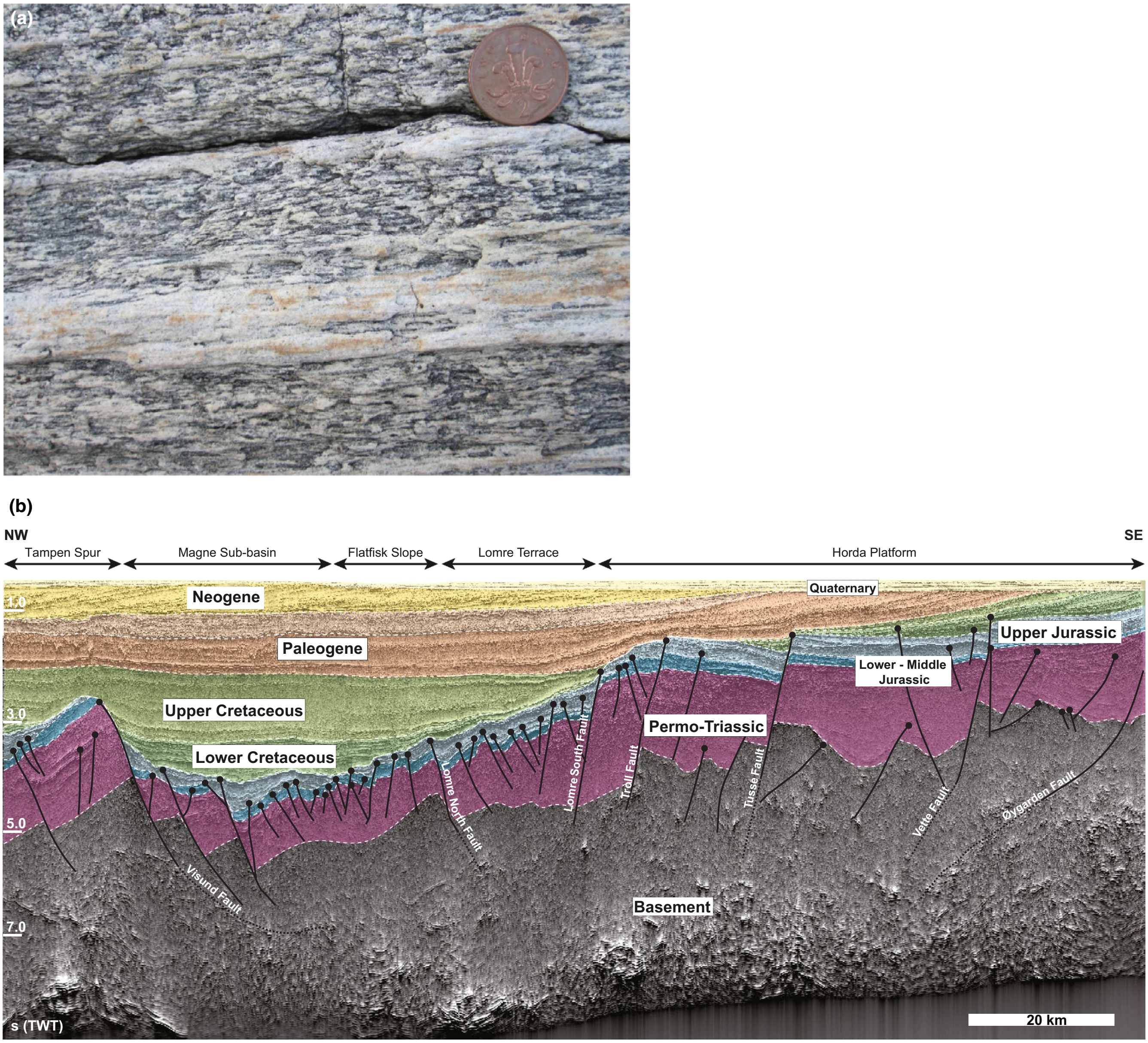


FIGURE 3 Examples of different ways in which *basement* may be considered. (a) Field photograph showing what a field geologist may think of as *basement* (view downwards). Caledonian gneiss (e.g. Putnis, Jamtveit, & Austrheim, 2018) exposed at Grønevika, Det norske Arboretet, Hjellestad, Bergen, Norway (60°15′19.49″N, 5°16′28.24″E). The rock would be considered as basement because of its crystalline lithologies, ages, metamorphism and low porosity. (b) What seismic interpreter may think of as *basement*. Interpreted seismic section between the Tampen Spur and Horda Platform, Northern North Sea, offshore Norway (from Tillmans, Gawthorpe, Rotevatn, & Jackson, in review). In this case, basement is defined in terms of the acoustic signature on seismic data

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

TABLE 3 Examples of suitable prefixes for the term *basement*

Analysis type	Recommended prefix for *basement*	Basis for definition	References
Geology	Precambrian[a]	Precambrian rocks are commonly referred to as *basement* because fossils are very rarely preserved, or because they underlie Phanerozoic sedimentary rocks	Kauffman and Steidtmann (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[b]	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)

[a]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).

[b]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).

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.

TABLE 4 Proposed basement high characterisation template, illustrated using the southern Rona Ridge

Analysis type	Characterisation	Example: southern Rona Ridge	Certainty (high, low, moderate no information)
A Basic description (Figures 4-6)	Basement high name	Rona Ridge[a]	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[a]. 60°16′23.4″N 3°37′57.8″W. Water depth ~160 m[2]	High
	Name(s) of license block(s)	P1368 Central. P2308. P2294. P1368 South. P1368 North. P1368 Southwest[b]	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[a]. Separating the Faroe-Shetland Basin from the West Shetland and East Solan basins[a]	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)[b]	High
	Recognition criteria (data used to identify the basement high, such as fieldwork, seismic data and gravity data)	2D and 3D reflection seismic[b]	High
	Other available data (e.g. geophysical, bathymetry, air photograph, satellite imagery, lithology)	Offset seismic and well data, regional geological analysis[a]	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[3]	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[d]	Moderate
	Depth or altitude of the base (depth where it joins the regional basement level)	~4,500 m[e]	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[f]	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[a,g]	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[a,g]	High

(Continues)

TABLE 4 (Continued)

Analysis type	Characterisation	Example: southern Rona Ridge	Certainty (high, low, moderate no information)
4. Structures (Figures 5 and 6)	Structures defining the margins of the basement high (e.g. faults or unconformities that bound the basement high)	Some flanks are normal faults[a], others are unconformities[a]	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[a,g,h]	High
	Structures in the rocks surrounding the basement high	Normal faults in a rift system[a]	Moderate
	Structures above the basement high (compaction folds, faults, etc.)	Normal faults[a]	Moderate
5. Timing of events (Figure 7)	Age(s) of the basement rocks (known or inferred)	~2.74 Ga pluton emplacement[f]	High
	Basement high deformation event(s) (known or inferred)	Archaean: pluton cooling and jointing[f]	Moderate
		Proterozoic: Laxfordian contraction[g]	Moderate
		Palaeozoic Caledonian Orogeny: fault reactivation[g]	Moderate
		Palaeozoic Variscan reactivation: brittle deformation[g]	Moderate
		Permo-Triassic: regional ENE-WSW extension[g]	Moderate
		Cretaceous Atlantic rifting: NE-SW extension[g]	Moderate
		Palaeocene-Eocene Alpine Orogeny: no deformation recorded[g]	Moderate
		Tertiary uplift: relaxation of pre-existing fracture network[g]	Low
	Age of relative uplift of the basement high (known or inferred)	Inferred Carboniferous-Jurassic exposure[g]	Moderate
	Ages of rocks around and above the basement high (known or inferred)	Jurassic[a]	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[g]	Moderate
6. Origins (Figure 7)	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 prospectivity (Fig. 8)	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[a]	High
	Seal (potential seal rocks within, above or around the basement high)	Top and lateral seal is provided by Upper Cretaceous mudstones[a]	High
	Reservoir (potential reservoir rocks within, above or around the basement high)	Fractured Lewisian tonalite (Archaean)[a,f,g]	High
	Fractured reservoir type	Type 1 naturally fractured reservoir (Nelson, 2001), with fractures providing porosity and permeability[h]	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[a]	High

(Continues)

TABLE 4 (Continued)

Analysis type	Characterisation	Example: southern Rona Ridge	Certainty (high, low, moderate no information)
	Charge (potential migration pathways within, above or around the basement high)	Oil mature charges probably from East Solan Basin. Late oil- to gas-mature fluids from Faroe-Shetland Basin. Migration through the basement high since Campanian[i]	High
	Timings (compatibility of ages of play and prospect elements)	All timings proven to be in desired sequence by the presence of petroleum	High
	Gross rock volume	No published information	No information
	Resources (known and produced reserves and contingent resources)	Lancaster Field: 523 MMbbl Best/2P + 2C[j]. Halifax Discovery: 1,235 Mmboe 2C Cont. Res. Whirlwind Discovery: 179 or 205 MMboe 2C Cont. Res. Lincoln Discovery: 604 MMboe 2C Cont. Res.[d]	High
	Hydrocarbon column height	Lancaster ~553m TVT (2C OWC)[j]	Moderate
	Fluid contact or free water level depths	Lancaster FWL 1,653 m TVDSS[j]. Height of oil–water transition not published	Moderate

Abbreviations: 2C, best estimate contingent resources; 2P, proved plus probable reserves; Best, best estimate; Cont. Res., contingent resources; CPR, competent person's report; FWL, free water level; Ga, billion years old; MMbbl, millions of barrels; MMboe, millions of barrels of oil equivalent; OWC, oil–water contact; TVDSS, total vertical depth subsea level; TVT, true vertical thickness.

[a]Trice (2014).

[b]Hurricane Energy (2019a).

[c]Estimated from Figure 5.

[d]RPS Energy Consultants (2017b).

[e]Spark Exploration (2019).

[f]Hurricane Energy (2019b).

[g]Hurricane Energy (2018).

[h]Belaidi et al. (2016).

[i]Nuzzo et al. (2018).

[j]RPS Energy Consultants (2017a).

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,

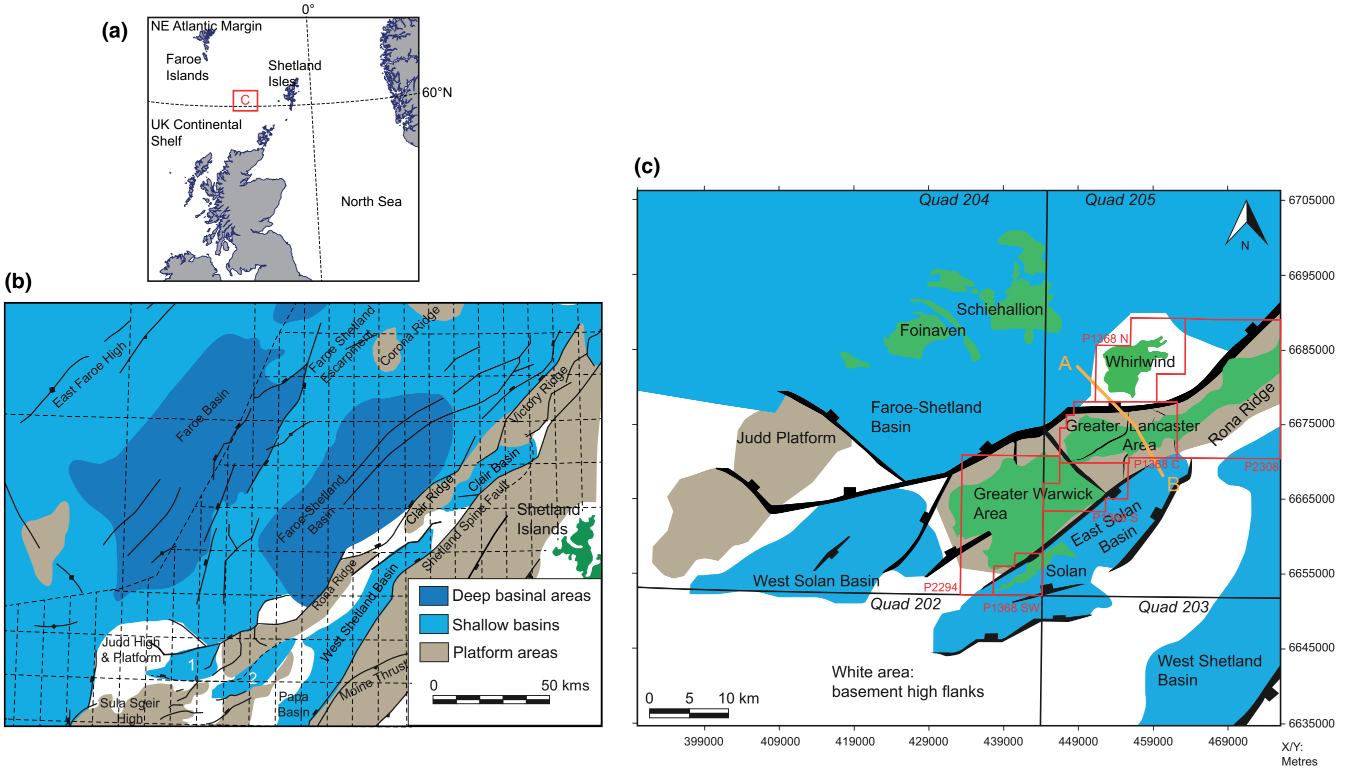


FIGURE 4 Basic description information to provide geographic and geological context to basement high characterisation, using the southern Rona Ridge example. (a) Location of Quadrants 202, 203, 204, 205, offshore, West of Shetland petroleum province and UK Continental Shelf. The location of (c) is shown by the red box. (b) Map of the West of Shetland basement highs and surrounding basins, showing the southern part of the Rona Ridge. 1 = West Solan Basin, 2 = East Solan Basin. (c) The southern part of the Rona Ridge and Judd Platform basement highs (grey), surrounding basement high flanks (white) and basins (blue), and ridge-bounding and ridge-segmenting normal faults. Green filled polygons = oil fields and discoveries, red unfilled polygons = southern Rona Ridge license blocks, grey unfilled polygons = other license blocks. Section A–B is shown in Figure 6a. Modified from Bonter and Singh (2017)

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

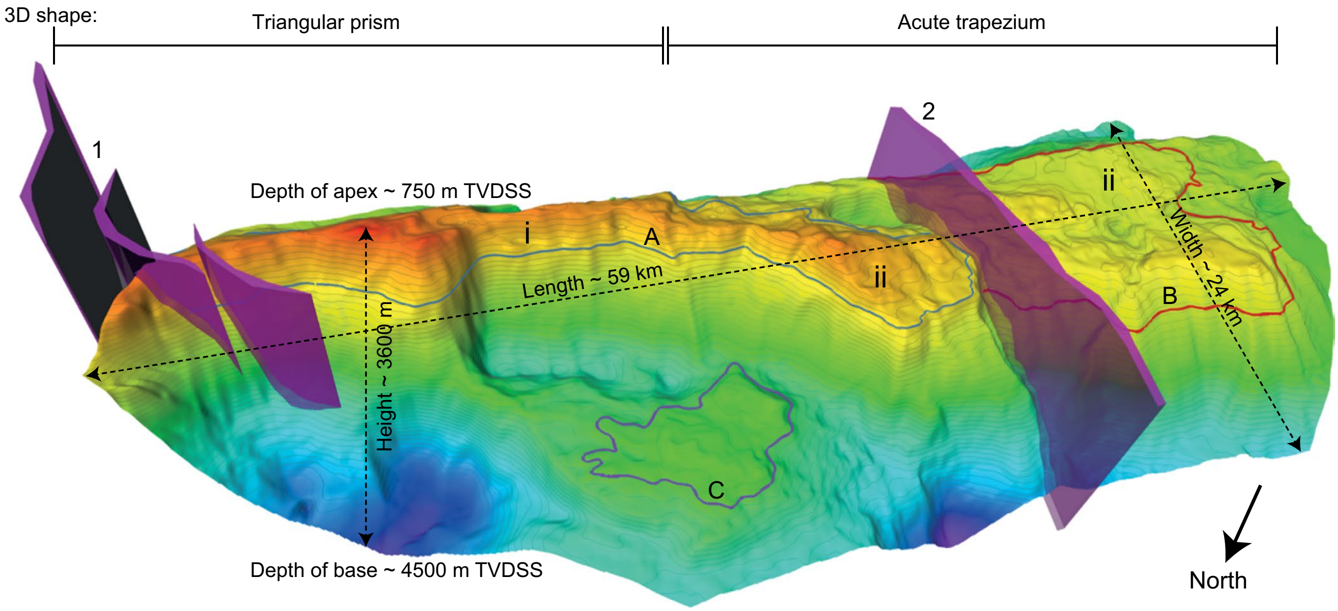


FIGURE 5 Example of geometric features of a basement high (Table 4, sections A and B), illustrated using the south Rona Ridge 3D Top Basement depth structure map (Hurricane Energy, 2019b; see Figure 4 for location). A = Lancaster Field oil–water contact at 1678 m true vertical depth sub-sea level (TVDSS; 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 km^2. 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

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 Mesozoic 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.

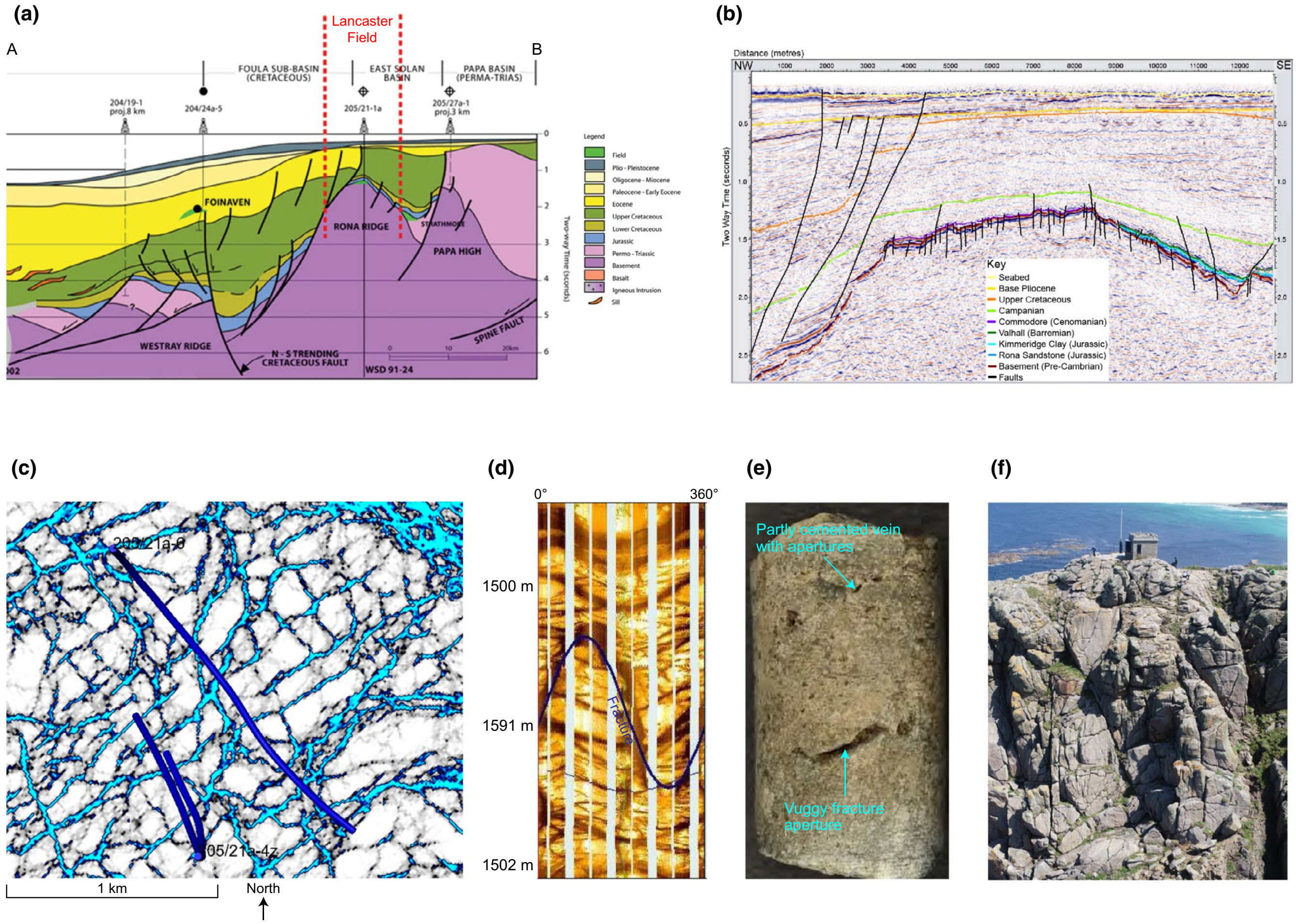


FIGURE 6 The variety of data types that can be used to analyse and illustrate the structures in, on and around a basement high, across a range of scales. (a) Basin-scale schematic cross-section across the West of Shetland region shows faults that define the western flanks of the Rona Ridge and Papa High. Lower displacement normal faults occur in, above and around these basement highs; major unconformities and faulting-relating folds (Hurricane Energy, 2015). The location is shown on Figure 4c. (b) Seismic interpretation of faults with displacements of up to kilometres that offset the Rona Ridge acoustic top Basement horizon and overlying formations. From Bonter (2014). (c) Well-connected network of faults with displacements of up to kilometre-scale (light blue, seismic discontinuities extracted by the Ant-Tracker Attribute) on the Lancaster Field seismic Top Basement surface. Dark blue lines are well trajectories. (d) Example of metre-scale fracture picked (blue sinusoidal line) on electrical image log data. Reproduced from Hurricane Energy (2015). (e) Centimetre-scale "microfracture" aperture on a sidewall core plug. Height of core plug is 45 mm. Figure 6c,e courtesy of Clare Slightam, Hurricane Energy. (f) Information can also be obtained about basement highs from outcrop analogues (Banks, 2019). Photograph taken from an unmanned aerial vehicle ("drone") of fractured granite at Sennen Cove, Cornwall, UK. The cliff is ~30 m high

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

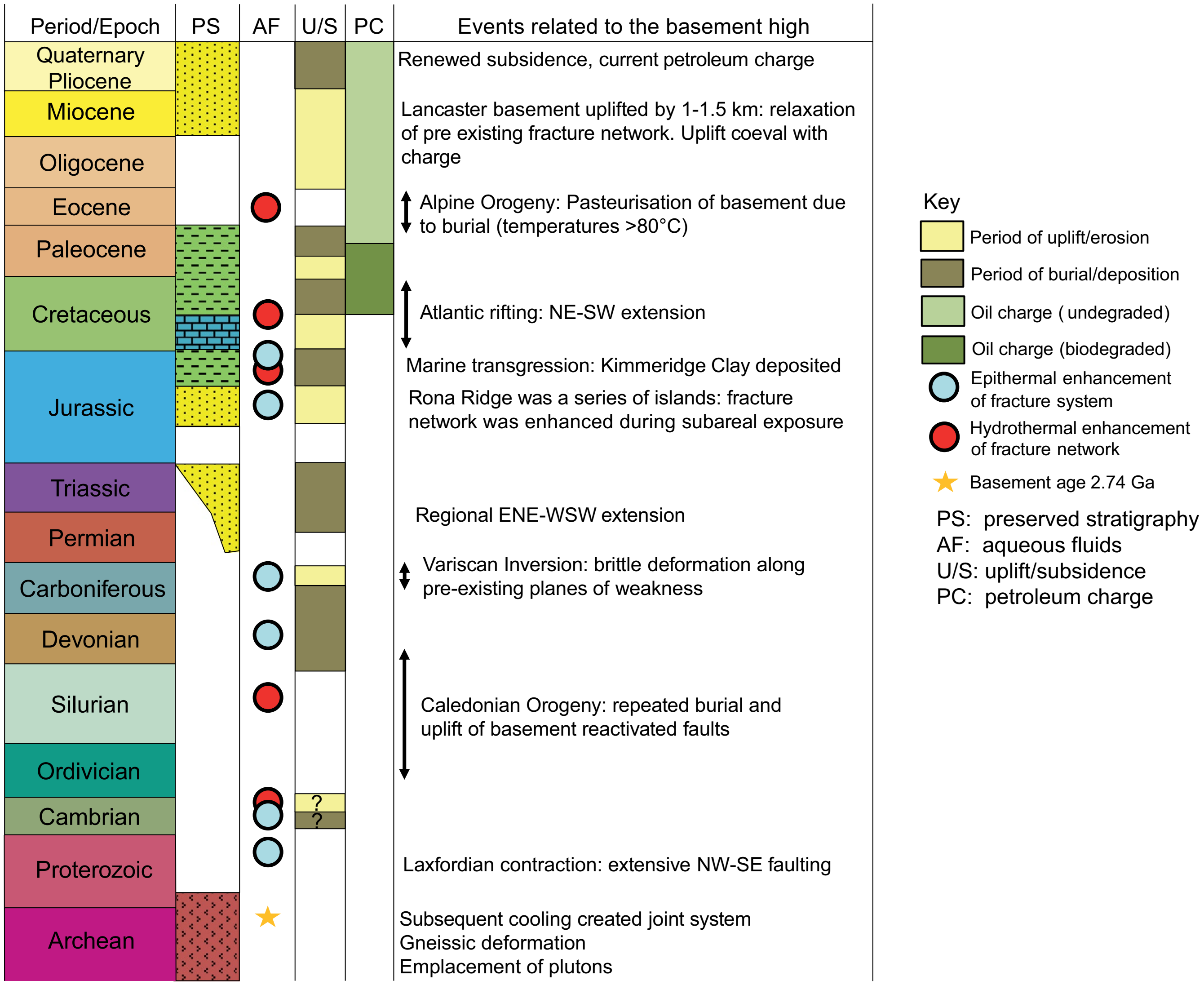


FIGURE 7 Example of the origins and timing of events related to a basement high illustrated using a tectonostratigraphic evolution chart, with fluid charge events and periods of uplift erosion and subsidence burial shown. This example shows how the Lancaster Field fractured crystalline basement reservoir (southern Rona Ridge) originated through several processes (Table 5) during its multi-event deformation history, and was consequently an uplifted, erosional, rotated faulted block that has most recently been affected by glacial rebound then subsidence. Note that the geological time axis is not to scale. Modified from Hurricane Energy (2018)

audited. 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 Sygnabere (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)

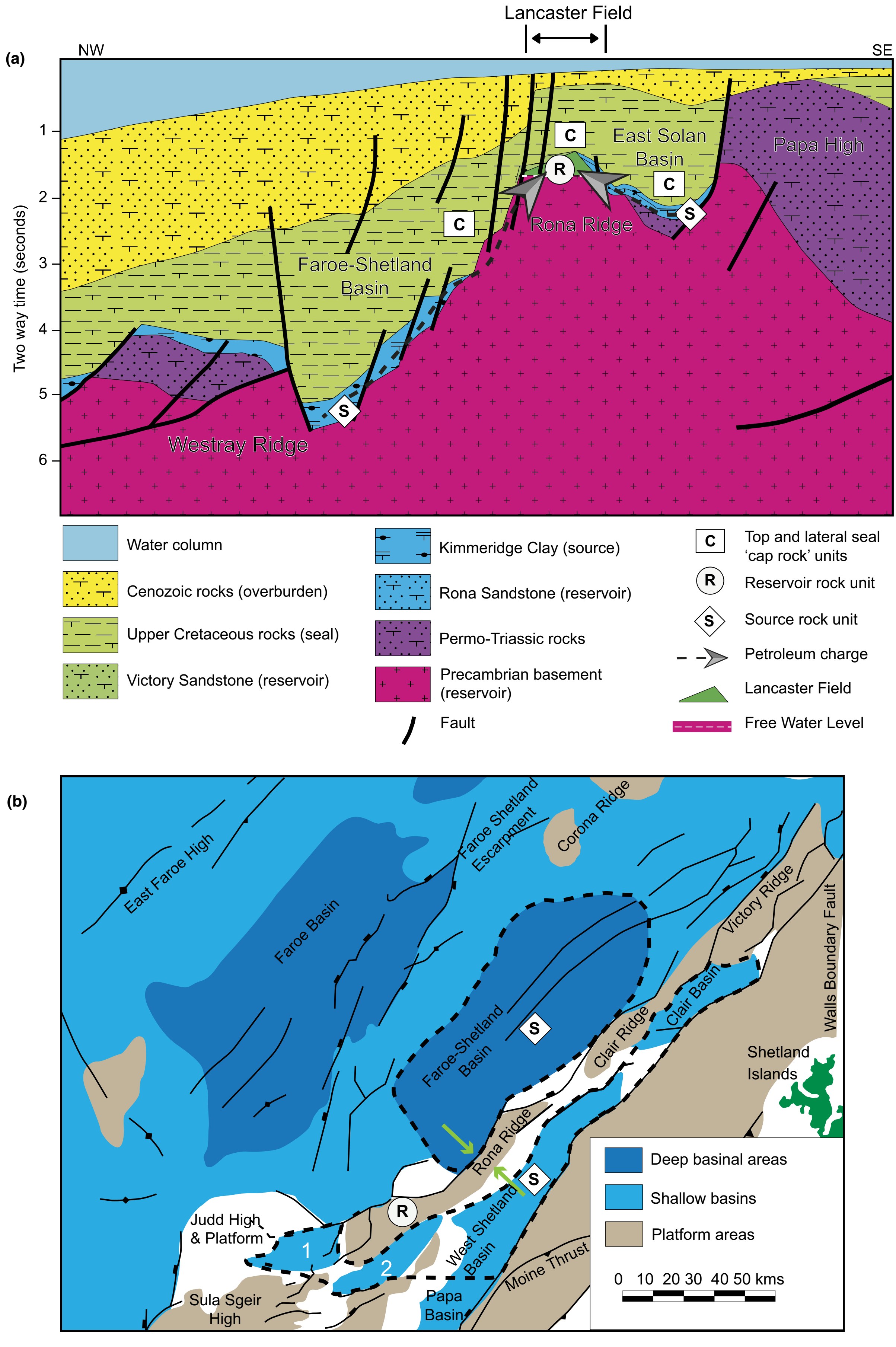
TABLE 5 (Continued)

Basement high type	Petroleum basin, province or field	Field example	Key reference	Effects on petroleum systems
Foreland bulge	Indus Basin	Lower Palaeozoic of central New York State	DeCelles and Giles (1996)	Supply sediments to foreland basins, influence faults and joints, focus for fluid flow
Buried bathymetric high or hill	Bach Ho oil field in the Cuu Long Basin (Vietnam). Note; also involves reverse faulting	Malvern Hills, UK (Butcher, 1962)	Cuong and Warren (2009)	Lateral and top seal for fluid reservoir
Basement arch	Western Canada Sedimentary Basin	Bighorn Arch (Wyoming)	Ross, Broome, and Miles (2004)	Subtle, long-lasting control on sediment thickness and fluid migration
Diapirs, thermal uplift and hotspot	Middle Jurassic of Central North Sea	Massif Central, Rhenish Massif	Ziegler and Dèzes (2007)	Increases geothermal gradient, provides sediments
Isostatic body	Santos Outer High, offshore Brazil	Alton and Askrigg blocks (Yorkshire, UK)	Buckley, Bosence, and Elders (2015)	Longstanding high controlling sediment supply and distribution
Glacial rebound	Norwegian Continental Shelf	Norway, Greenland, northern UK	Doré and Jensen (1996)	Supplies sediments, causes tilting of sequences and fluid contacts, compression and decompression of petroleum systems
Astrobleme	Chicxulub Impact Crater, Yucatan platform, Mexico	Meteor Crater (Arizona), Vredefort Crater (South Africa)	Donofrio (2002)	Related to sudden, intense deformation and sedimentation
Erosional basement high	Sarir Field, Sirte Basin (Libya)	Arizona (USA)	Ahlbrandt (2001)	Provide sediments and possible stratigraphic traps
Igneous basement high	Northern South Yellow Sea Basin	Western Scotland	Lee, Kwon, Yoon, Kim, and Yoo (2006)	Provide sediments, heat and possible traps

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


(a)
Lancaster Field
NW
SE
Two way time (seconds)
1
2
3
4
5
6
C
R
S
East Solan Basin
Papa High
Rona Ridge
Faroe-Shetland Basin
Westray Ridge
Water column
Cenozoic rocks (overburden)
Upper Cretaceous rocks (seal)
Victory Sandstone (reservoir)
Kimmeridge Clay (source)
Rona Sandstone (reservoir)
Permo-Triassic rocks
Precambrian basement (reservoir)
Fault
Top and lateral seal 'cap rock' units
Reservoir rock unit
Source rock unit
Petroleum charge
Lancaster Field
Free Water Level
(b)
East Faroe High
Faroe Basin
Faroe Shetland Escarpment
Corona Ridge
Victory Ridge
Walls Boundary Fault
Faroe-Shetland Basin
Clair Ridge
Clair Basin
Shetland Islands
Rona Ridge
West Shetland Basin
Judd High & Platform
Sula Sgeir High
Papa Basin
Moine Thrust
1
2
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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