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Natural fracture propping and earthquake-induced oil migration in fractured basement reservoirs

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ABSTRACT

The geological processes that create fluid storage capacity and connectivity in global fractured basement reservoirs are poorly understood compared to conventional hydrocarbon plays. Hosting potentially multibillion barrels of oil, the upfaulted Precambrian basement of the Rona Ridge, offshore west of Shetland, UK, gives key insights into how such reservoirs form. Oil presence is everywhere associated with sub-millimeter- to meter-thickness mineralized fracture systems cutting both basement and local preseal cover sequences. Mineral textures and fluid inclusion geothermometry suggest a low-temperature (90–220 °C), near-surface hydrothermal system, as does the preservation of clastic sediments in the same fractures. These fills act as permanent props holding fractures open, forming long-term fissures in the basement that permit oil ingress and storage. Calcite-fill U-Pb dating constrains the onset of mineralization and contemporaneous oil charge to the Late Cretaceous. The additional preservation of oil-stained injected sediment slurries and silica gels along basement faults suggests that rift-related seismogenic faulting initiated lateral oil migration from Jurassic source rocks into the adjacent upfaulted ridge. Subsidence below sea level in the latest Cretaceous sealed the ridge with shales, and buoyancy-driven migration of oil into the preexisting propped fracture systems continued long after the cessation of rifting. These new observations provide an explanation for the viability of sub-unconformity fractured basement reservoirs worldwide, and have wider implications for subsurface fluid migration processes generally.

INTRODUCTION

Fractured basement hydrocarbon reservoirs are recognized worldwide, but they are relatively poorly understood and underexploited (Trice, 2014). In such plays, oil migrates laterally from an organic-rich source rock into a subsurface paleohigh of fractured crystalline basement, forming a so-called "buried hill" trap (Biddle and Wielchowsky, 1994). The seal is provided by a blanketing sequence of clay-rich mudstone.

Given the very low matrix permeability of most crystalline basement rocks, oil and other associated fluids are transported and stored via well-connected fracture systems. The geological characteristics of these fracture systems are not well understood because they are poorly imaged in seismic reflection data, and core samples are sparse. Critically, the processes involved in fluid transport and storage are also uncertain, although it is often assumed that migration into the basement high is primarily a passive process driven by the relative buoyancy of hydrocarbons following maturation at the source (e.g., Trice, 2014).

We used geological observations, U-Pb calcite geochronology, and fluid inclusion geothermometry to explore the nature, age, trapping temperatures, and significance of widespread fracture fills (minerals, clastic sediment) associated with oil observed in basement cores along the ~200-km-long Rona Ridge, west of Shetland, UK. We argue that these fracture fills act as permanent natural props, which allowed gradual charging of the basement ridge with oil once it was sealed by shales following regional subsidence. We show that seismicity related to rifting may have initiated migration of oil from nearby organic-rich source rocks into the ridge. These findings have general implications for our understanding of the fluid storage capacity and connectivity of fracture systems developed below regional rift-related unconformities worldwide, including those related to hydrocarbon plays, aquifers, and geothermal systems.

Regional Setting

Significant oil discoveries have been made in basement rocks of the Rona Ridge, west of Shetland (Fig. 1A). The basement high that underlies the giant Clair Field (6–7 billion barrels stock tank oil in place) is associated with more conventional Devonian–Carboniferous sandstone reservoirs (Clair Group, Fig. 1B; Coney et al. 1993). Other assets, such as the Lancaster Field and associated discoveries in the southwest Rona Ridge, are hosted almost entirely within fractured basement (Trice, 2014; Belaidi et al., 2018; >18 billion barrels of oil initially in place).

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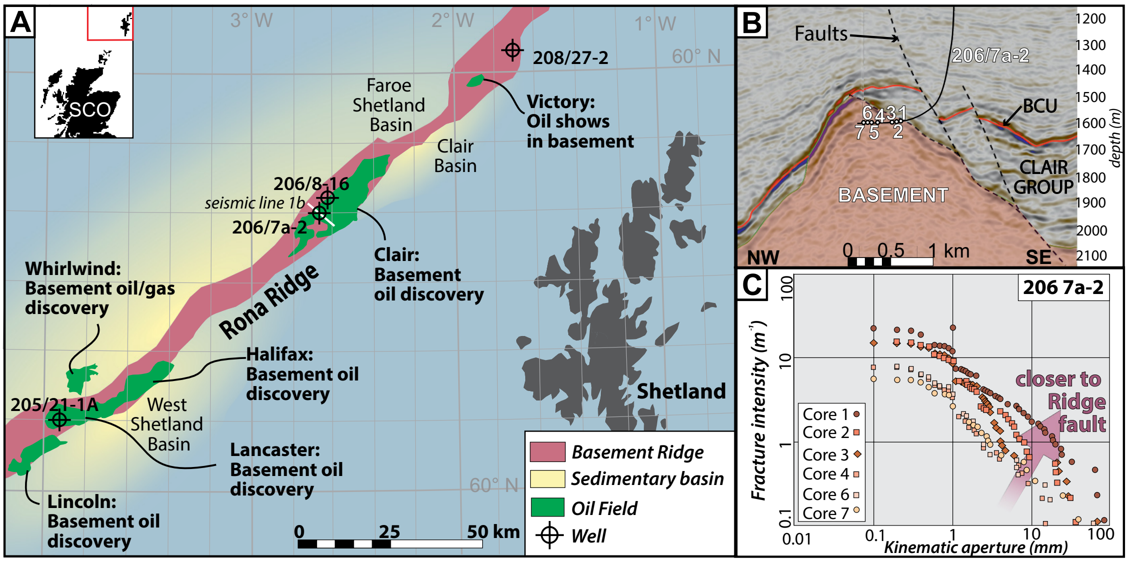

Figure 1. A: Simplified map showing location of Rona Ridge basement, oil fields, and wells referred to in this study (offshore Shetland, UK). SCO—Scotland. Mapped extent of the Clair Field includes the Devonian part of the reservoir (Clair Group). B: Northwest-southeast seismic reflection profile through the Clair Field (line of section shown in A) showing location of basement ridge, Clair Group, and base-Cretaceous unconformity (BCU; after Holdsworth et al., 2018). Position of 206/7a-2 well (drilled by Elf U.K. Ltd. in 1991) and associated cores shown in C are also shown. Note that the main Ridge fault here lies on the southeast side of the basement ridge; in other areas, such as Lancaster, equivalent structures lie on the northwest side (Trice, 2014); i.e., polarity of faulting changes along strike. C: Plot using approach of Ortega et al. (2006) showing how both fracture intensity (no. fractures/m) and kinematic aperture increase by almost an order of magnitude in the 206/7a-2 cores closer to Ridge fault. Slopes of distributions are consistently close to –1.

Geochemical studies of oils suggest a Late Jurassic Kimmeridge Clay source rock (Holmes et al., 1999; Finlay et al., 2011), thought to occur on the downfaulted flank of the ridge in the Faroe-Shetland Basin to the northwest (Ritchie et al., 2011). Basin modeling and radioisotopic dating of oils suggest that oil maturation in the region of Clair Field occurred at ca. 68 ± 13 Ma (Late Cretaceous; Finlay et al., 2011). The oil then migrated via fracture systems from its Jurassic source into the adjacent basement ridge and cover sequences such as the Devonian Clair Group.

The ~200-km-long, 15-km-wide Rona Ridge is composed of series of northeast-southwest–trending footwall blocks of Precambrian basement bounded by large Mesozoic normal faults with kilometer-scale offsets (Figs. 1A and 1B; Ritchie et al., 2011). Regional studies of basement cores west of Shetland have revealed variably deformed upper-amphibolite-facies granodioritic-dioritic plutons and orthogneisses that have yielded a narrow range of Neoarchean zircon ages (ca. 2.83–2.73 Ga; Holdsworth et al., 2018). These are broadly the same age as the Lewisian Complex in Scotland, and they form part of the larger Faroe-Shetland terrane located west of Shetland.

The basement ridge is immediately overlain by late Paleozoic–Mesozoic cover sequences, with many lateral thickness variations and local unconformities (Ritchie et al., 2011). This reflects the long-term persistence of the Rona Ridge as an emergent topographic high from Triassic to Cretaceous time. Regional subsidence and burial occurred in the Late Cretaceous, blanketing the ridge in deep-marine mudstones and forming a regional seal.

GEOLOGY OF OIL-BEARING FRACTURE SYSTEMS

Where oil is present, the main host fractures form the youngest and dominant set of brittle structures seen in basement cores, overprinting a variety of earlier ductile and brittle structures (see Holdsworth et al., 2018). Interpretation of seismic reflection profiles, well data, and oriented cores in Clair and Lancaster suggest a predominance of northeast-southwest fractures parallel to the trend of the ridge (Coney et al., 1993; Pless, 2012; Belaidi et al., 2018). The most continuous sample of these fractures comes from six 10-m-long core sections in the subhorizontal northwest-southeast 206/7a-2 well through the Clair Ridge (drilled by Elf U.K. Ltd. in 1991; Fig. 1B). In cores closest to the Ridge fault to the southeast, fracture intensities and kinematic apertures (thickness including fill; Ortega et al., 2006) are nearly an order of magnitude higher than in cores furthest away from the fault (Figs. 1B and 1C).

The oil-bearing fracture systems in both basement and well-cemented parts of the Devonian to Jurassic cover sequences all along the Rona Ridge show characteristic geological features (Fig. 2). Opening mode (tensile) fractures filled with minerals and/or clastic material dominate (Fig. 2A), and while most are millimeters to centimeters thick, examples up to several meters wide have been recognized (Fig. 2B). Fine- to coarse-grained mineral fills comprise quartz/cryptocrystalline silica-adularia-carbonate-pyrite veins and microbreccias ranging from <1 mm to decimeters in thickness (Figs. 2A and 2D). Quartz or cryptocrystalline silica fills and cements are only widely seen in basement-hosted fractures. Cockade-style (fracture fills in which individual clasts are completely surrounded by concentric layers of cement) mineralization textures, textural/compositional zoning, and the presence of mineral-lined vuggy (containing vugs, which are voids or large pores in a rock that are commonly lined with mineral precipitates) cavities up to many centimeters across are ubiquitous (Figs. 2A, 2C, and 2D). The same fracture systems also host distinctive clastic infillings of three kinds: chaotic breccias dominated by local wall-rock clasts (Fig. 2B); fine laminated siltstone-sandstone fills with delicate way-up criteria (e.g., graded bedding; Fig. 2A); and fine irregular networks of homogeneous siltstone thought to represent injected slurries (Fig. 2C). Where way-up indicators are preserved, they always young up toward the local top-basement unconformity surface. Clastic and mineral fills are texturally contemporaneous, with the former commonly partially cemented by calcite, quartz, or pyrite; geopetal structures are also preserved (Fig. 2A). Clastic fills are almost always heavily oil-stained, while calcite and quartz mineral fills and cements carry widespread oil inclusions; vuggy cavities are invariably occupied either by oil or oil-stained clastic material (Figs. 2A–2D). These observations suggest that mineralization and sediment ingress overlapped with oil migration.

Larger faults are less commonly well-preserved, but in one case, an oil-stained 1–2 mm layer of cryptocrystalline silica occurs along a slip plane with fine slurry-filled injections emanating out into the wall rocks (Figs. 2D–2G). This silica film is interpreted to be a natural gel generated during rapid seismogenic slip (see Kirkpatrick et al., 2013).

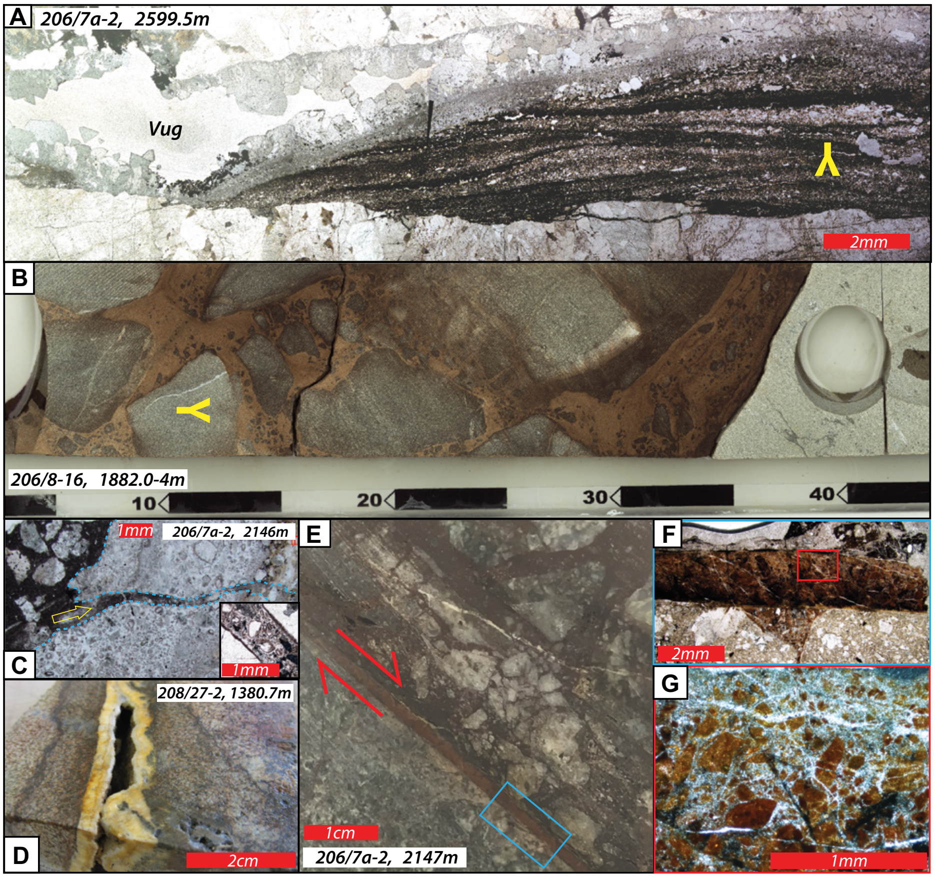

Figure 2. Geological characteristics of oil-filled fracture systems, with depths and wells indicated. A: Thin section of an oil-stained fracture partially filled by waterlain, laminated sandstone with fine-graded bedding and geopetal fill of quartz-calcite-pyrite; the large vug was originally filled with oil. B: Oil-stained meter-scale fissure fill in the Devonian Lower Clair Group with contorted bedding laminations and subrounded wall-rock clasts. C: Injected slurry of fine sediment with rounded clastic grains and bitumen clasts (inset), which can be traced back to larger sediment- and clast-filled cavity with oil stains. D: Large, previously oil-filled vug with lining of oil-stained calcite (brown) and later quartz (white), i.e., opposite relationship to that seen in A; note the oil stain in the surrounding basement gneiss. E–G: Oil-stained cryptocrystalline fill associated with the slip plane in brecciated basement gneisses from which fine slurry-like injections are seen to emanate. Yellow symbols in A and B are younging directions in fracture sediment fills. Locations of F and G are shown by the colored boxes in E and F, respectively.

The mineral fill textures are typical of low-temperature, near-surface hydrothermal systems, and they suggest that fractures remained open for protracted periods of time (e.g., Wright et al., 2009; Lander and Laubach, 2015). The ubiquitous presence of breccia, sandstone, and siltstone fills also indicates that the fractures formed open fissure systems connected to the surface, with material introduced downward by either gravity or flowing surface waters (e.g., Walker et al., 2011). The poorly cemented nature of these fills suggests that oil ingress began soon after fissure filling, ultimately flooding the fracture system and inhibiting further mineralization and cementation.

U-Pb GEOCHRONOLOGY AND FLUID INCLUSION STUDIES

Calcite U-Pb geochronology was conducted using in situ laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS; see the GSA Data Repository[1] for analytical protocols and data). Calcite from the Clair Field 206/7a-2 well locally postdates early laminated sediment and hydrothermal quartz, and it formed synchronous with pyrite (Figs. 1 and 2A); this calcite yielded a date of 89 ± 4 Ma (Fig. 3A). Calcite in the 208/27-2 well near the Victory Field (drilled by British National Oil Corporation in 1982) formed synchronous with local pyrite and predates local sediment fill and quartz (Figs. 1 and 2D); this calcite yielded a date of 71.9 ± 2.6 Ma (Fig. 3B).

Fluid inclusion assemblage studies were carried out on quartz and calcite fracture fills cutting basement, together with fracture-hosted calcite in Devonian cover rocks, to estimate the temperatures of mineral precipitation (see the Data Repository for details of samples, analytical methods, and data). Type 1 two-phase (liquid + vapor; L > V) aqueous inclusions dominate, and temperature of homogenization (T_H) salinity pairs define a distinct higher-temperature field (~215 °C) from quartz-hosted inclusions and a lower-temperature field (~<150 °C) defined by calcite inclusions (Fig. 3C). Importantly, the quartz and calcite here are hosted in the same basement fracture (see Fig. 2A). In this case, quartz precipitation predated, but overlapped with that of calcite, suggesting that two pulses of hydrothermal fluid migration occurred—one at higher temperature followed by one at lower temperature.

DISCUSSION

The Rona Ridge is representative of many sub-unconformity "buried hill" traps associated with fractured basement reservoirs (Biddle and Wielchowsky, 1994). The unaltered condition of the basement cores suggests that the Rona Ridge is little affected by deep subaerial weathering. However, analysis of seismic reflection data and cores from the Lancaster Field (Slightam, 2012; Belaidi et al., 2018) has revealed the presence of mineralized sediment–filled and breccia-filled fissures, several hundred meters deep, and up to several meters wide. These findings are consistent with the sediment- and mineral-filled fracture systems reported here all along the Rona Ridge at depths many hundreds of meters below local top basement.

Geological observations in active rifts (e.g., Iceland) and analogue modeling studies (e.g., van Gent et al., 2009) have shown that highly dilated, interconnected fissure systems can form in strong host rocks during extensional faulting as stresses become tensile in the uppermost crust. We suggest that the emergent Rona Ridge was affected by the contemporaneous and long-term development of near-surface (>0.5 km depth) open fissure systems that hosted hydrothermal mineralization from below and sediment ingress from above (Fig. 4A). The fluid inclusion data point to successive pulsing of hot and cold fluids in the basement, precipitating quartz- and calcite-rich fills, respectively. In the vein analyzed from well 206/7a-2, local quartz predated calcite, but in veins from other cores (e.g., 208/27-2; Fig. 2D), local quartz postdated calcite. From this, it is reasonable to infer alternating pulses of hot and cold fluid, with no consistent pattern on a regional scale.

Calcite U-Pb dating shows that the fissuring, mineralization, sediment filling, and initial ingress of oil occurred in the Late Cretaceous, presumably synchronous with active rifting (Figs. 4A and 4B). This fits well with hydrocarbon migration timing suggested by regional basin modeling (e.g., Lamers and Carmichael, 1999),

[1]GSA Data Repository item 2019254, U-Pb geochronology, fluid inclusion analyses, and data tables, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

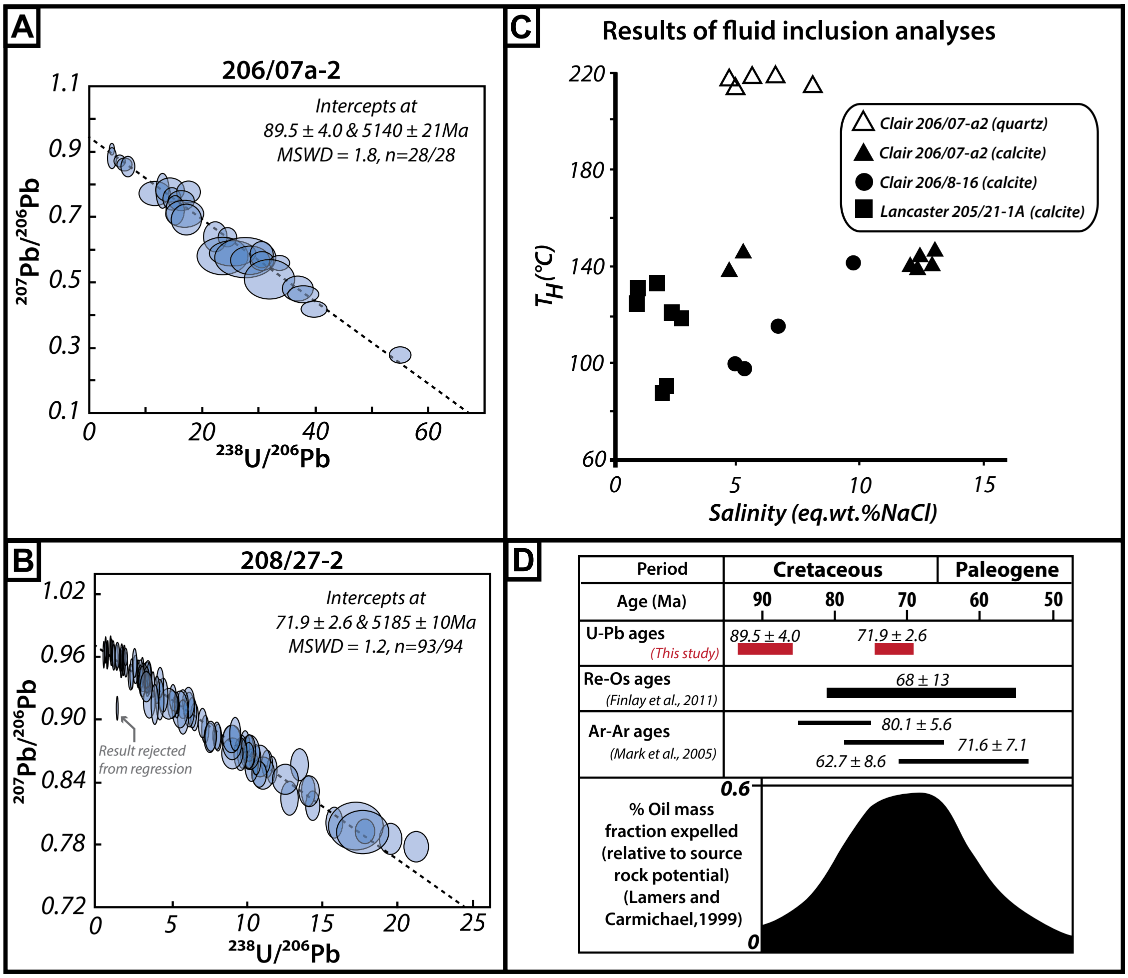

Figure 3. A,B: Tera-Wasserburg concordia plots showing $^{238}U/^{206}Pb$ versus $^{207}Pb/^{206}Pb$ for calcites from well 206/7a-2 (Clair Field, drilled by Elf U.K. Ltd. in 1991) and well 208/27-2 (near Victory Field, drilled by British National Oil Corporation in 1982), offshore Shetland, UK. Age uncertainties are quoted at 2σ. MSWD—mean square of weighted deviates. C: Homogenization temperature (T_H) versus salinity plot of fluid inclusion assemblages (FIA) from calcite and quartz in basement (well 206/7a-2) and Devonian Clair Group (well 206/8-16 drilled by BP in 2013) fracture fills. D: Summary of filling and oil migration times based on published papers and current study (after Finlay et al., 2011).

Re-Os dating of Faroe-Shetland Basin oil (Finlay et al., 2011), and Ar-Ar dating of adularia cements in the Victory Field (Fig. 3D; Mark et al., 2005). The ~25–20 m.y. spread in ages suggests a protracted period of activity, which also seems consistent with the fluid inclusion data and the observation that local mineralization sequences vary within and between wells.

The widespread preservation of vuggy textures and primary porosity, and the ubiquity of zoned, cockade-style textures, are indicative of fissure–mineral fill systems that remained open or partially open over long time periods (e.g., see Lander and Laubach, 2015). The presence of injected slurries originating from sediment-filled cavities (e.g., Fig. 2C) and the local preservation of fault-hosted, oil-stained silica gel along a basement-hosted shear fracture (Figs. 2E–2G) suggest a link between fissure formation and fluid—and by inference oil—migration related to active seismicity (Figs. 4A and 4B). Major hydrological changes are known to follow modern earthquakes (e.g., Wang and Manga, 2010). We infer a repeating cycle of interseismic dilatant fracturing and slow fluid ingress into strong basement host rocks (Fig. 4A; Muir-Wood and King, 1993) that alternated with rapid contraction of fluid- and sediment-filled voids during earthquakes and the upward transport of fluid through the basement (Fig. 4B).

Marine shales blanketed the Rona Ridge following its relatively rapid subsidence in the Late Cretaceous (Fig. 4C). It seems likely that once the naturally propped fissure systems had formed, upward migration of oil within the basement and up into local Devonian to Jurassic cover sequences below the regional seal was able to continue. There is little microstructural evidence for reactivation of oil-bearing fractures in the cores, although some calcite veins and cemented clastic fissure fills in the Lancaster Field preserve possible evidence for late dissolution prior to infilling with oil, likely during the Cenozoic (Belaidi et al., 2018). Thus, it appears that although seismicity may have triggered the onset of oil migration from source into the fractured basement ridge, later stages were likely buoyancy driven.

IMPLICATIONS AND CONCLUSIONS

Fissure formation and filling in consolidated rocks below regional unconformities have been recognized in a variety of settings (e.g., Montenat et al., 1991; Wright et al., 2009), but the potential economic significance remains largely unexplored. Our findings show that the development of tensile fissures in rheologically strong host rocks deformed close to the surface during tectonic extension presents an opportunity for the development of naturally propped networks of deeply penetrating, partially filled fissures. Following burial beneath a regional (or local) unconformity, these fracture systems are then potential sites for the accumulation and storage of hydrocarbons, geothermal fluids, or aquifer development. There is also evidence that active rift-related seismicity initiated hydrocarbon migration into the basement reservoir. This highlights the intriguing possibility that fracture dilation processes related to basement-hosted earthquakes could trigger migration episodes in global hydrocarbon basins.

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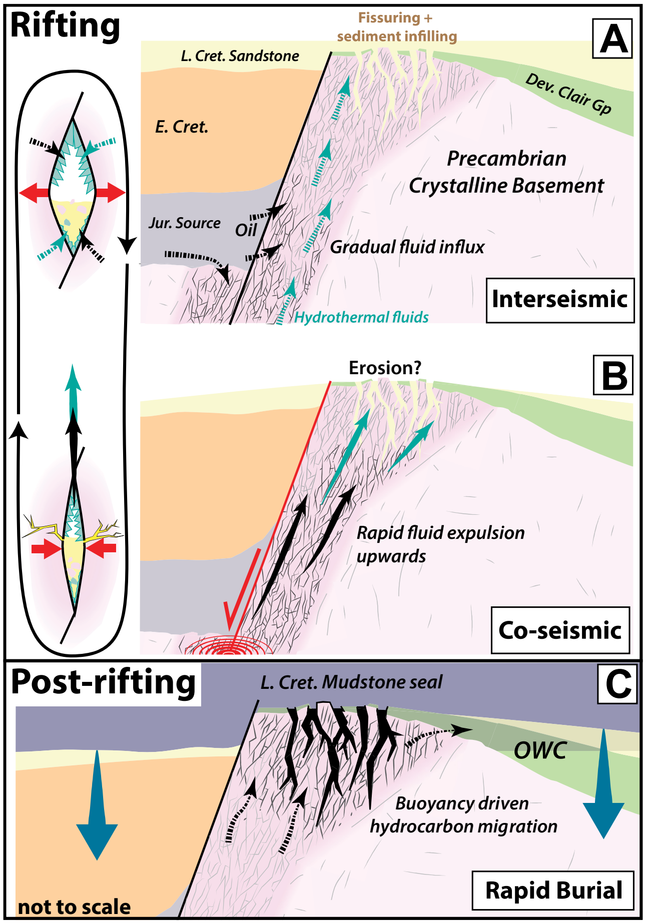

Figure 4. A–C: Simplified geological cross-section model to explain the development of Rona Ridge fractured basement play (not to scale), with distribution of various cover sequences drawn for illustrative purposes only. Fissure systems are hundreds of meters deep and at least several meters wide. Left: Repeated cycles of gradual opening of dilational fractures in basement during interseismic loading alternate with coseismic elastic collapse. This repeated cycle draws in fluids (hydrothermal, oil), leading to partial filling with mineral precipitates and/or deposition of sediment from the surface, followed by fluids being driven out during earthquakes and sediment-slurry injection into wall rocks. In effect, the basement ridge acts as an active fluid pump during rifting. Note that fractures are permanently propped open by their partial fills of sediment, wall-rock clasts, and minerals, and this facilitates later, buoyancy-driven migration of oil as the reservoir is charged from below. L. Cret.—Late Cretaceous; E.—Early; Jur.—Jurassic; Dev.—Devonian; Gp—Group; OWC—oil-water contact.

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