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# Unravelling the Nature and Origin of Jurassic to Early Cretaceous Unconformities Offshore Southwest Britain

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## ABSTRACT

Jurassic and Early Cretaceous times were marked by significant changes in Earth's climate and tectonics, most notably the breakup of the supercontinent Pangaea, which led to the opening of the Atlantic Ocean. In Southwest Britain, one of the most prominent features of this time is the Base Cretaceous unconformity representing widespread erosion and non-deposition separating Cretaceous strata from underlying rocks. Despite its widespread presence in Southwest Britain, Iberia, Ireland and conjugate North Atlantic basins, the origin and nature of this unconformity remains enigmatic. To better understand its nature, seismic data was used to map the extent of the unconformities and to establish their relationships with onlapping Jurassic and Cretaceous stratigraphy. We reveal that the Base Cretaceous unconformity is a composite of at least three—Middle Jurassic, Late Jurassic to Early Cretaceous and Mid-Cretaceous—unconformities likely generated by erosion and non-deposition. The Mid-Cretaceous unconformity is often assumed to be responsible for the majority of erosion, but our findings suggest otherwise. Onlap patterns of the Lower Cretaceous Wealden Formation on truncated Jurassic units indicate that the Jurassic to Early Cretaceous unconformity was the most significant. Amplitudes of uplift across different basins in SW Britain are shown to be variable. The most substantial denudation occurred following Berriasian uplift, likely linked to shortening associated with North Atlantic opening. The Mid-Cretaceous unconformity is more subtle, primarily observed at basin margins and linked to the rift-drift transition of the Bay of Biscay. Subsidence histories differ across basins; some (e.g., Brittany Basin) can be explained by simple post-rift thermal cooling models, while others (e.g., Melville and South Celtic Sea Basins) require more complex explanations due to substantial missing stratigraphy, including reactivation of Variscan thrusts and sub-plate support. Our results emphasise that spatially and temporally distinct tectonic and denudation events can combine to generate large-scale composite unconformities.

## 1 | Introduction

Sedimentary basins offshore SW Britain, which are the primary focus of this study, include the Western Approaches Trough, South Celtic Sea, Bristol Channel, North Celtic Sea, Fastnet and Cockburn (Figure 1; van Hoorn 1987; Ziegler 1987; Kamerling 1979; Shannon 1991). The Western Approaches Trough consists of several ENE-WSW striking sedimentary sub-basins (Ziegler 1990). They comprise the Melville, Brittany, St Marys, Plymouth Bay and Southwest Channel basins (Ziegler 1987; Evans 1990; Harvey et al. 1994; Ruffell 1995). Most basin sediments were deposited in post-Variscan sinks that contain early Permian to Cenozoic stratigraphy (Evans 1990). All these basins share a major pre-late

**Summary**

- The Early Cretaceous denudation primarily occurred at the basin margins atop Variscan structures.
- Lower Cretaceous Wealden depositional patterns closely follow the Variscan structural trends.
- The Base Cretaceous Unconformity in SW Britain can be a composite of multiple unconformities from various eras.
- Major denudation is linked to Berriasian uplift and the opening of the North Atlantic.
- Simple stretching models are inadequate for explaining the subsidence histories of the Melville Basin.

Early Cretaceous angular unconformity that can be clearly seen on seismic reflection data. For instance, in the north Melville sub-basin, most of the Upper and Middle Jurassic sequence is not present, with only Lower Jurassic stratigraphy preserved in synclines (Chapman 1989; Hillis 1988). In the southwest of the Melville Basin, seismic evidence suggests the unconformity cuts down to Variscan basement (Husein et al. 2023). Denudation linked to Jurassic–Cretaceous events has been associated with the scarcity of hydrocarbon discoveries in the area. The direct erosion of source rocks and a reduced overburden may have disrupted the burial and maturation processes, resulting in immature source rocks. This, combined with the timing of hydrocarbon generation relative to migration pathways, has significantly increased the risk of unsuccessful hydrocarbon migration (Evans 1990; Husein et al. 2023). Additionally, tilting from fault movements appears to have breached many existing hydrocarbon accumulations. Our study will reinterpret the Base Cretaceous Unconformity with newly available seismic reflection data. We seek to identify erosional trends and related structures to better constrain the geological history of the region, which would likely aid future basin and petroleum systems modelling. As part of our analysis, we backstrip stratigraphy to produce subsidence histories. We explore whether a simple history of rifting and cooling is adequate to explain the observations or if more complex processes are required.

Several authors have described the nature of the unconformity and attempted to constrain the age of associated uplift and denudation using seismological observations and well data (Ziegler 1987; Hillis 1988; Chapman 1989; Ruffell 1992; McMahon 1995; McMahon and Underhill 1995). Other authors have estimated erosion associated with the unconformity from basin modelling and compaction analysis parameterised with vitrinite reflectance and sonic velocity data Deronzier et al. (1994); McMahon (1995); Menpes (1997). Numerous explanations have been published regarding the cause of the Jurassic to Early Cretaceous unconformities. Chapman (1989) argued that during Jurassic to Early Cretaceous times a major thermal doming event caused uplift and inverted the basin, with the latest Jurassic sequences are possibly deposited syntectonically with the doming episode. Ziegler (1987) linked the opening of the North Atlantic and rifting in the Bay of Biscay to the uplift in the region. Ziegler (1987) and Smith (1995) assume that the Aptian–Albian unconformity is the largest in the region. In addition to the Western Approaches Trough, the composite Jurassic–Cretaceous unconformity can be traced on seismic data into neighbouring basins such as Little Sole, Cockburn, South Celtic Sea, North Celtic Sea and Wessex (Ruffell 1995; Smith 1995; Evans 1990; Hillis 1988). Similarly, on the conjugate Atlantic margin, the structural highs in the West Orphan Basin appear to have eroded Jurassic stratigraphy Peace et al. (2022).

Notwithstanding this previous work, the spatial extent and timing of uplift events that resulted in the unconformities remain uncertain and their ages remain poorly understood. Establishing the geological history of this region is complicated by erosion of most of the mid-Lower Jurassic to Lower Cretaceous stratigraphy in the Western Approaches, thus limiting the observations available for interpretation. A further complicating issue is that over most of the study area, the unconformities merge into a single composite unconformity. We examine whether distinguishing erosive events can be aided by detailed seismic facies analysis and from comparison of the unconformities across the region. To address these challenges, this study employs a detailed seismic facies analysis and regional comparisons of unconformities using a comprehensive seismic and well dataset, including the reprocessed 2016 Western Approaches seismic data. This approach aims to constrain the age, distribution and intensity of Jurassic to Early Cretaceous uplift events.

## 2 | Geodynamic Setting, Palaeogeography and Basin Formation

This section examines existing geological and geophysical evidence that constrains the evolution of key basins in offshore SW Britain, including the North Celtic Sea, South Celtic Sea, Melville, Wessex, Brittany and South-West Channel basins (Figure 1). We examine evidence for spatial variability in the amplitude of denudation and how it may relate to several unconformities: the Mid-Jurassic, Base Cretaceous, Mid Cretaceous unconformities. We first assess published Variscan to Triassic geological histories and explore how they may relate to the formation of the basins and the younger unconformities. Published Jurassic and Cretaceous plate reconstructions, major tectonic activity and associated uncertainties are then reviewed with a view to relating them to the formation of the unconformities.

### 2.1 | Variscan, Permian and Triassic

Seismic data, gravity, magnetic surveys and onshore observations reveal that the structural framework of SW Britain is dominated by north-westwards-verging Variscan thrusts (Boillot and Lefort 1974; Gardiner and Sheridan 1981; Shackleton 1984; Cheadle et al. 1987; Le Gall 1990; Lefort and Max 1992; Busby and Smith 2001; Leveridge and Hartley 2006). In the Western Approaches, these thrusts dip ~20°–30° SSE and strike ~60°–70° N (Hillis and Chapman 1992).

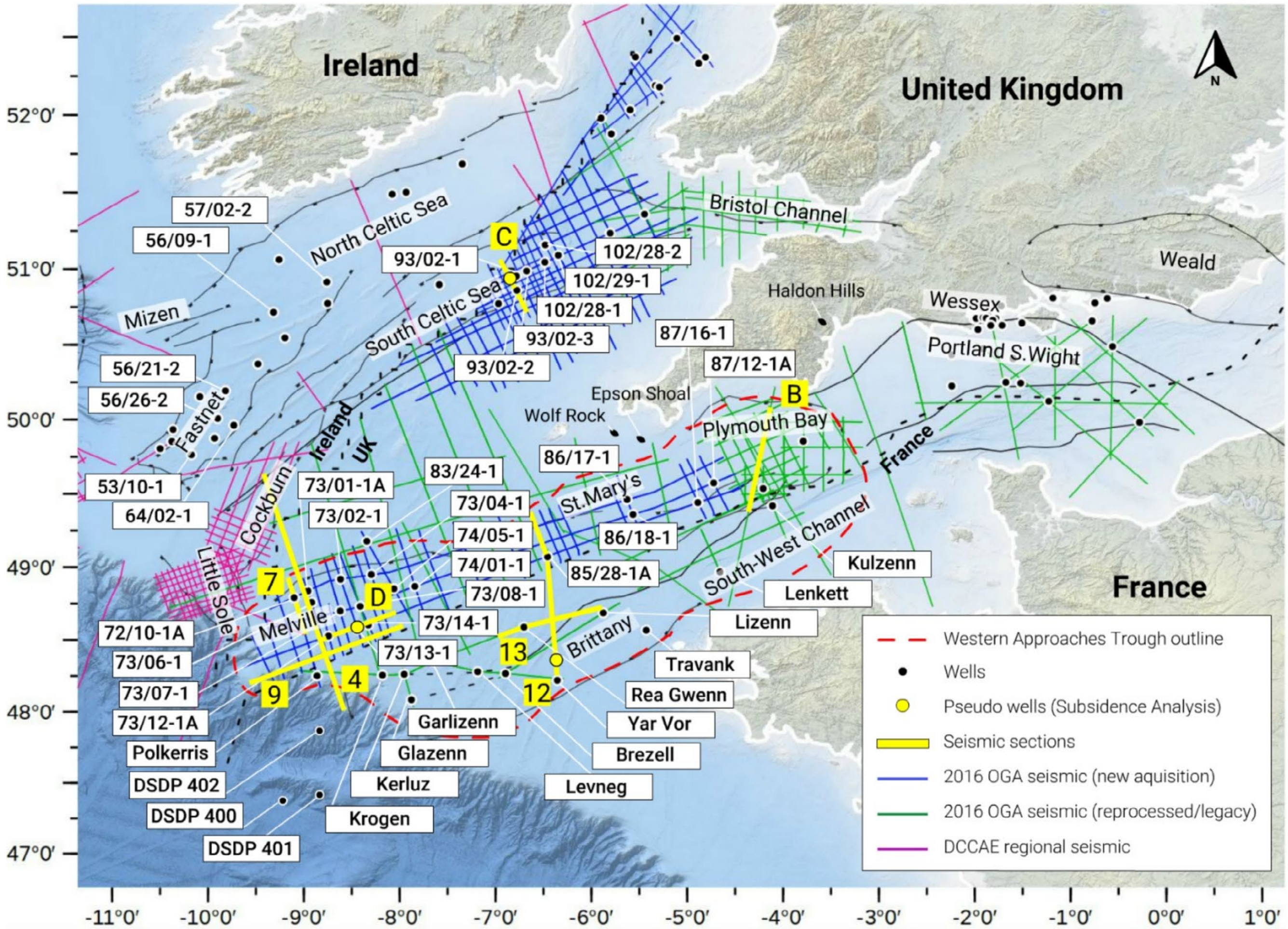


**FIGURE 1** | Study area. Key wells described in the text are labelled and yellow lines highlight seismic data shown in subsequent figures. Bathymetry and Topography from European Marine Observation and Data Network (EMODnet). UK Oil and Gas Authority (OGA). Irish Department of Communications, Climate Action, and Environment (DCCAE). Sections B, C and D referenced in the map can be found in the Supporting Information.

Permo-Triassic rift systems show strike directions similar to the Variscan thrusts, suggesting that these structures were reactivated during post-orogenic extension. Associated dextral strike-slip faults, likely representing lateral ramps reactivated under later tectonic stresses, have been identified in surrounding basins, including Brittany, Normandy and SW Britain (Coward and Smallwood 1984; Ziegler 1982; Holloway and Chadwick 1986; Coward 1993). It is likely that the faults formed because of dextral shearing due to a change in regional stresses (Ziegler 1982; Holloway and Chadwick 1986; Coward 1993). However, these structures remain unmapped in parts of the Western Approaches and the Brittany basins, leaving their influence on Jurassic–Cretaceous denudation events unclear.

Seismic reflection data indicate that Permo-Triassic clastic units thin to the north of the Melville Basin, likely due to crustal thickening caused by nappe stacking above the Melville thrust (Chapman 1989). To the south of the Western Approaches, thickened Permo-Triassic deposits mark the transition from compressional to extensional tectonics in the region (Ziegler 1982).

During the Late Triassic, thick successions were deposited in the Melville, St. Mary's, Celtic Sea and Wessex basins (Robinson et al. 1981; van Hoorn 1987; Evans 1990; Shannon 1991; Underhill and Stoneley 1998). Upper Triassic stratigraphy includes up to 1 km of Carnian Halite in the Melville and South Celtic Sea basins, indicating marine influx (Evans 1990; Husein et al. 2023). Similar salt units are observed in the Celtic Sea, Wessex, Portland South Wight, Aquitaine, Parentis and Northern Iberia basins (Biteau et al. 2006; McKie 2017; Figure 2). The presence of Carnian salt in the north Iberian basins and in eastern France indicates a significant marine influx and a possible connection to the Tethys Ocean through the Biscay fracture zone (Husein et al. 2023). These observations suggest that tectonic activity in the Bay of Biscay may have initiated during this period. However, it remains uncertain whether this activity influenced Jurassic sedimentation patterns.

## 2.2 | Jurassic

### 2.2.1 | Early Jurassic

The end of the Triassic saw widespread changes to marine conditions across SW Britain. This led to the conformable deposition of Jurassic marine shales and limestones (Haq et al. 1987;

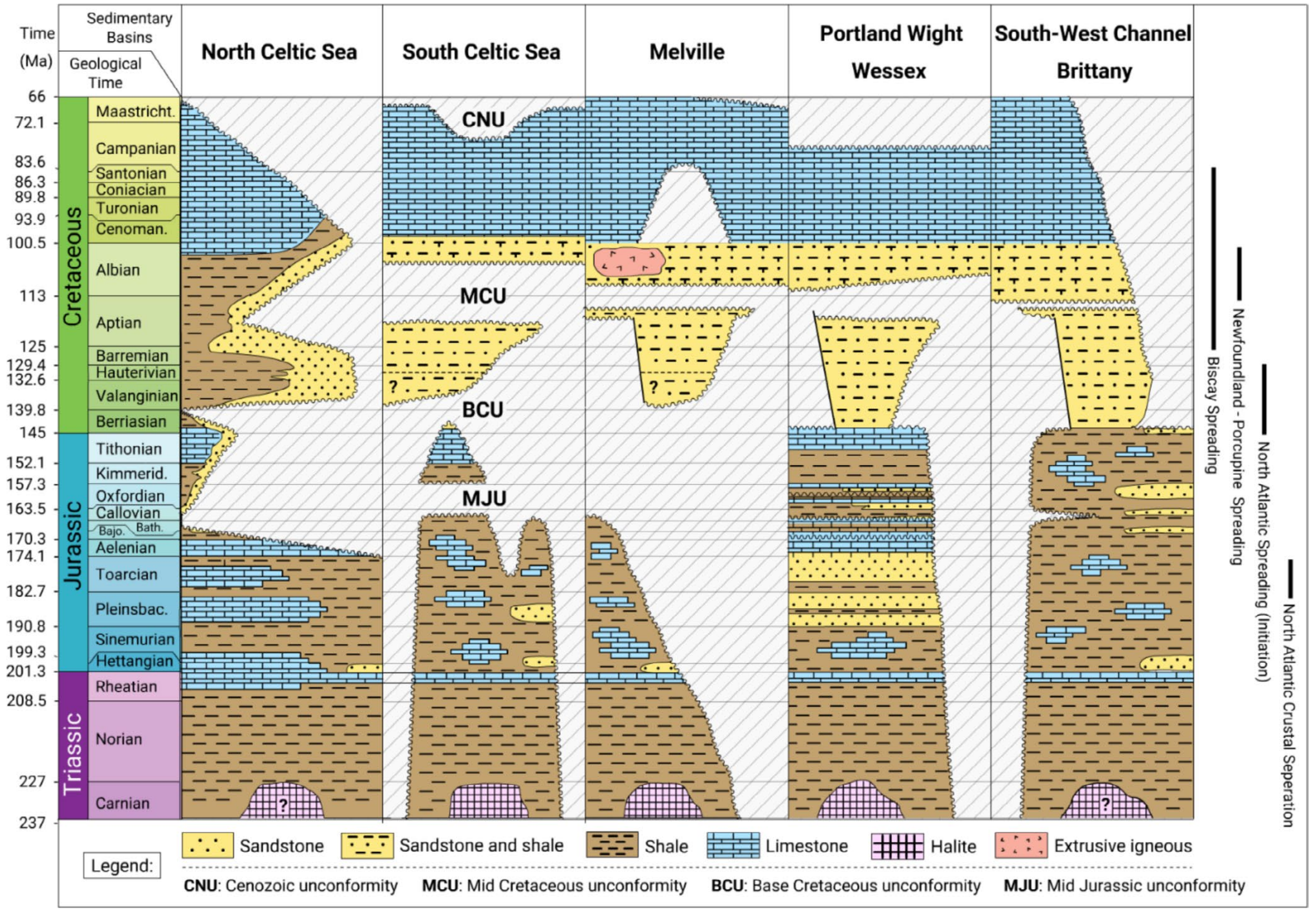


**FIGURE 2** | Generalised composite chronostratigraphic chart showing Triassic to Cretaceous stratigraphy of the North Celtic Sea (modified from Hartley 1995), South Celtic Sea (modified from van Hoorn 1987), Melville (modified from Husein et al. 2023), Wessex (modified from Underhill and Stoneley 1998, Cox and Sumbler 2002 and Barton et al. 2011), Brittany and South-West Channel basins (modified from Evans 1990 and Ruffell 1995). Column on the right of figure shows a summary of the age and duration of relevant North Atlantic tectonic events (Montadert et al. 1979; Srivastava et al. 1988; Pinheiro et al. 1992; Driscoll et al. 1995; Tugend et al. 2014).

Hillis 1988). Triassic to Early Jurassic rifting in the Western Approaches Trough was part of a larger northeast-trending rift system spanning Iberia, the western European margin and the eastern Canadian shelf (Masson and Miles 1986). The deposition of Rhaetian limestone, a regionally persistent seismic marker, marks the onset of the marine transgression and aids in identifying the top of the Upper Triassic succession (Figure 2; Bennet et al. 1985; Evans 1990).

Thick Jurassic marine units were deposited in the South Celtic Sea and Britanny basins, while in the northwestern Western Approaches Basin, the youngest Jurassic deposits are Hettangian and Sinemurian (Evans 1990). These units are characterised by continuous parallel seismic reflections and an absence of syn-depositional fault growth, suggesting tectonic quiescence (Hillis 1988; Hillis and Chapman 1992). However, poor legacy seismic imaging quality introduces uncertainty in the interpretation. In contrast, the Wessex Basin records thicker Lower Jurassic units along E-W striking faults, suggestive of deposition in a rift setting (Hawkes et al. 1998).

In the Plymouth Bay Basin, Lower to Middle Jurassic units are preserved in faulted sections, reflecting erosion or non-deposition on the adjacent basin highs (Evans 1990). The Lias Formation in the Brittany Basin consists of dark-coloured shales and calcareous claystones rich in terrestrial and marine organic matter (Ruffell 1995). The Lias in the Brittany Basin contains a total organic carbon content of up to 4% in Rea Gwenn and 3% in Travank within the Sinemurian section. These organic-rich units likely developed in tectonically isolated anoxic parts of the basin and are considered important hydrocarbon source rocks (Allen and Allen 2013; Ruffell 1995).

Hettangian sandstone units have been identified in the Melville, Britanny and Channel basins, with key occurrences recorded in wells 73/01-1A, Brezel and Lennket, respectively (Ruffell 1995; Evans 1990). The sandstone unit in the Melville Basin is interpreted as a localised deposit, as it cannot be traced into other wells (Evans 1990). The source of the sand, however, remains unproven and warrants further investigation. Similarly aged sandstone units have been documented in the Celtic Sea, Fastnet and the Melville basins (Robinson et al. 1981; van Hoorn 1987; Shannon 1991) and may represent shelf ridge systems, as suggested by Kessler and Sachs (1995).

Pliensbachian sands, part of the Dyrham Formation, were deposited in the Wessex Basin during a regressive cycle that led to shallow marine sedimentation (Hesselbo and Jenkyns 2010). Equivalent sandstones are present in the South Celtic Sea Basin but are absent in the Western Approaches Trough, likely due to tectonic or depositional variability (van Hoorn 1987; Evans 1990; Underhill and Stoneley 1998; British Geological Survey geological map index 327 2005).

#### 2.2.2 | Middle Jurassic

Middle Jurassic sedimentation in the North and South Celtic Sea basins was largely uniform, with minor local variations (van Hoorn 1987; Shannon 1991; Copestake et al. 2018). These deposits indicate tectonic quiescence during this period, when lithospheric evolution was primarily controlled by post-rift thermal subsidence following earlier extensional activity (Shannon 1991).

Stratigraphic observations from seismic and well data reveal episodes of uplift and erosion during the Bathonian to Oxfordian in the North Celtic, South Celtic and Bristol Channel basins (van Hoorn 1987; Millson 1987; Figure 2). These erosional events are synchronous with the onset of full ocean spreading in the North Atlantic at ~180 Ma (Ziegler 1989). In the Melville Basin, erosion of Middle and Upper Jurassic stratigraphy has been linked to Jurassic to Cretaceous uplift and subsequent denudation (Hillis 1988). However, to our knowledge, no seismic observations have been published clearly showing intra-Jurassic truncations in the Western Approaches, and hence evidence to support the presence of a mid-Jurassic unconformity there is weak. Seismic data suggest that preserved Middle or Upper Jurassic sediments are most likely located in a syncline in the north-west Melville Basin (Husein et al. 2023).

In the Brittany Basin, boreholes and seismic data show that Middle Jurassic stratigraphy transitions from mudstones into limestones near structural highs, reflecting localised depositional changes to shallower facies influenced by proximity to these highs (Evans 1990).

In the Wessex Basin, several minor unconformities can be observed within the Bajocian Inferior Oolite (Figure 2; Cox and Sumbler 2002). During the Bathonian, sandstone deposition reflects shifting depositional environments, possibly linked to relative sea-level fluctuations or tectonic activity. In the early Callovian, a minor stratigraphic hiatus is marked by a transition from the limestone-dominated Cornbrash Formation to the mudstone-rich Kellaways Formation (Figure 2; Barton et al. 2011). These unconformities and associated facies changes may have regional correlations with similar features in other basins across Southwest Britain. In western Iberia, the Lusitanian Basin experienced a late Callovian to early Oxfordian hiatus in sedimentation, attributed to tectonic inversion (Kullberg et al. 2013). High sedimentation rates, up to 270 m/Myr, coupled with the initiation of diapirism at the end of the Oxfordian, suggest the onset of transtentional rifting (Wilson et al. 1989).

Evidence of a temporary cessation of marine deposition in the North Celtic Sea Basin is provided by the deposition of an early Callovian to late Bathonian terrestrial red-bed unit. This unit uncomformably overlies Lower and Middle Jurassic sediments, marking an interruption of Jurassic marine deposition (Millson 1987). Further west, seismic imagery shows a pre-late Oxfordian unconformity that truncates Middle Jurassic sediments, indicating localised erosion events (Evans 1990).

#### 2.2.3 | Late Jurassic

During the Late Jurassic to Early Cretaceous, Atlantic Ocean-floor spreading extended northwards beyond the Newfoundland–Azores–Gibraltar fracture zone (NAGFZ; Ziegler 1989; Figure 3). Magnetic anomalies offshore SW Iberia in the Tagus Basin Abyssal Plain have been interpreted as evidence of an initial attempt at the northward propagation of the North Atlantic beyond the NAGFZ (Merino et al. 2021; Mauffret et al. 1989; Figure 3). However, due to inconclusive and low-resolution magnetic data, the possibility of sea floor spreading in the Tagus Basin Abyssal Plain remains uncertain (Figure 3). Spreading initiating in the Tagus Basin has been estimated to range from the Tithonian to the Valanginian–Hauterivian (Srivastava et al. 1988; Mauffret et al. 1989; Pinheiro et al. 1992). High Late Jurassic sedimentation rates in the neighbouring Lusitanian Basin suggest rifting during this period (McMahon 1995; Figure 3).

Spreading in the Tagus Basin was aborted and localised along the main North Atlantic axis during the Late Hauterivian (Verhoef and Srivastava 1989) or Barremian (Tucholke et al. 1989). Before oceanic crustal separation, crustal thinning resulted in syn-rift crustal extension of 50–70 km north of the NAGFZ (Skogseid et al. 2000). Combined data from gravity, magnetics, seismic profiles, well data and plate kinematic models indicate south to north progression of North Atlantic spreading (Tankard and Balkwill 1989; Verhoef and Srivastava 1989; Boillot et al. 1989; Nirrengarten et al. 2017). Magnetic anomalies suggest active oceanic spreading between the Canadian Grand banks and Iberia, as well as in the Biscay Fracture Zone (Montadert et al. 1979; Boillot 1984; Rosenbaum et al. 2002; Driscoll et al. 1995; Tugend et al. 2014; Figure 3). These observations and models suggest that the ocean-continent boundary in this region was established by the Mid Albian (~105–110 Ma; Rosenbaum et al. 2002; Nirrengarten et al. 2017).

During rifting of the continental margin and the formation of the proto-North Atlantic, Upper Jurassic sediments were deposited across the region (Montadert et al. 1979). Much of the Upper Jurassic succession in the Western Approaches Basin and along the margins of the Celtic Sea basin has been eroded (Evans 1990; Figure 2). In the North Celtic Sea Basin, preserved Upper Jurassic units consist of interbedded fluvial, marginal-marine and calcareous sediments (Evans 1990). These units reach a minimum thickness of 90 m in the eastern South Celtic Sea Basin, with thicker successions extending into the Bristol Channel Basin (Kamerling 1979; van Hoorn 1987; Figure 2).

In the Wessex Basin, during the mid-Oxfordian, two unconformities are observed within the Corallian Group: one located beneath the Clavellata Formation and the other beneath the Sandsfoot Grit Member. The Oxfordian succession contains several sand-rich units, possibly indicating increased siliciclastic input linked to a regional tectonic event (Figure 2; Barton et al. 2011).

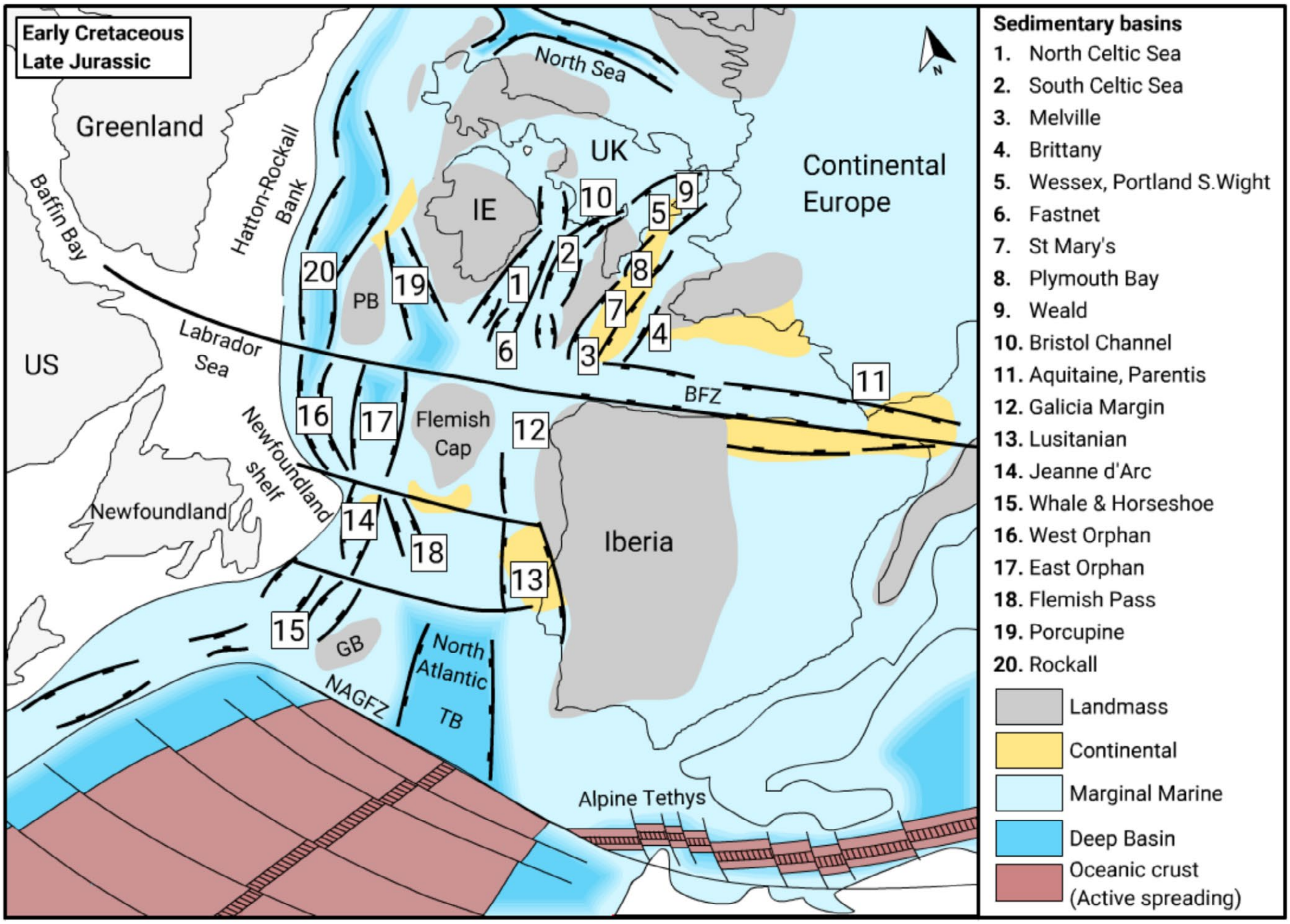


**FIGURE 3** | Early Cretaceous to Late Jurassic boundary plate tectonic reconstruction for the North Atlantic. Sedimentary basins in this study and conjugate basins are numbered. BFZ, Biscay Fracture Zone; GB, Grand Banks; NAGFZ, Newfoundland-Azores-Gibraltar Fracture Zone; PB, Porcupine Bank; TB, Tagus Basin. Plate framework modified from Skogseid (2010). Structural framework and gross depositional environments modified from Hawkes et al. (1998) and McMahon (1995).

The Brittany and Southwest Channel basins exhibit more continuous sedimentation from the Upper Jurassic into the Early Cretaceous. The Brittany Basin's continued subsidence contrasts with the widespread erosion observed in the neighbouring regions. In the Southwest Channel Basin, well Lennket-1 encountered over 800 m of Oxfordian to Portlandian shallow marine to brackish-water siltstones (Evans 1990; Figure 1). Marine rocks of the Oxford Clay and Kimmeridge Clay, present in the Wessex and Portland Wight basins of southern England, are absent from the Brittany Basin (Ruffell 1995).

## 2.3 | Cretaceous

### 2.3.1 | Early Cretaceous

Uplift and erosion across SW Britain provide evidence that the Late Jurassic tectonic events continued into Early Cretaceous times (van Hoorn 1987; Evans 1990; Shannon 1991). Lower Cretaceous stratigraphy was deposited during a period of active spreading in the Bay of Biscay, between the Aptian and Albian (Evans 1990).

The Early Cretaceous successions record a transition from marine to continental sedimentation, observed as locally preserved Wealden fluvial and lacustrine units (Evans 1990; Figure 2). Several localised Wealden depocenters in SW Britain exceed 1 km in thickness, particularly in the Brittany and North Celtic Sea basins (Menpes 1997; Byrne 2020). Overlying these units, the Upper Greensand and Gault formations represent the return to shallow marine deposition (Evans 1990; Menpes 1997). The formations consist of clastic and calcareous rocks in St. Mary's, Melville, Brittany, Fastnet, North and South Celtic Sea basins, as well as along the Armorican margin (Evans 1990; Hillis 1988; Figure 1). Aptian–Albian basalts and tuffaceous rocks have also been encountered in several wells in the Melville Basin, highlighting volcanic activity during this time (Hillis 1988).

In Brittany and the Southwest channel basins, the Jurassic and Lower Cretaceous units are deposited without significant interruption (Evans 1990; Ruffell 1992; Deronzier et al. 1994; Figure 2). Onshore in the Wessex Basin, the Wealden units are deposited on a regional unconformity and separated from the Upper Greensand and Gault Clay by a set of Aptian–Albian unconformities (Underhill and Stoneley 1998). These unconformities have a progressive westerly subcrop, indicating increased erosion towards the Cornubian Massif. In the Haldon Hills southwest of Exeter (Figure 1), Upper Greensand rests on the Permian stratigraphy (British Geological Survey Newton Abbot Sheet 339 1995), indicating a widespread deposition closer to the Cornubian Massif. However, the extent of Lower Cretaceous deposition across the Cornubian Massif and the scale of denudation related to the Mid-Cretaceous unconformity remain uncertain (Figure 3).

The sporadic distribution of the Lower Cretaceous Wealden Formation complicates the identification of unconformities. Where the Wealden is absent, seismic data reveal a composite BCU and MCU. This overlap makes it difficult to determine which unconformity is associated with the largest amplitude of denudation.

#### 2.3.2 | Late Cretaceous

Following crustal separation between Newfoundland and Iberia (Figure 3), seafloor spreading in the North Atlantic continued northwards to the Biscay Fracture Zone (Tappin et al. 1994). Magnetic anomalies in the Bay of Biscay indicate that spreading continued in until at least the Early Campanian (Klitgord and Schouten 1986). During this time, fault-controlled subsidence in the Western Approaches and Celtic Sea basins ceased, giving way to passive deposition for the rest of the Mesozoic (Petrie et al. 1989). High Late Cretaceous eustatic sea levels resulted in the deposition of hundreds of meters of chalk across the Celtic Sea, Western Approaches and Cornubian Platform (Tyson and Funnell 1987; Evans 1990).

In the South Celtic Sea Basin, chalk thickness reaches approximately 350 m. Halokinesis has led to localised accumulations of up to 844 m (as observed in well 93/2-1) on the flank of a salt wall (Kamerling 1979). In contrast, the Fastnet Basin exhibits thinner Upper Cretaceous stratigraphy, ranging from 120 to 160 m (Robinson et al. 1981). Thickness increases northwards, exceeding 820 m in the North Celtic Sea Basin (Colley et al. 1981). The decrease in thickness across the Fastnet Basin may be due to Albian to middle Campanian inversion (Colin et al. 1981; Robinson et al. 1981). Onshore, the nearest chalk outcrop occurs in in Devon, southern UK, where a 110 m-thick Cenomanian to Turonian section is preserved (Edmonds et al. 1975). Residual deposits of Santonian to Campanian-aged rocks extend as far west as the Haldon Hills in Devon (Figure 1; Selwood et al. 1984).

Early Cenomanian sandstones observed in the Cornubian Massif (Lott et al. 1980) and in well 86/18-1 in St. Mary's Basin suggest that significant areas remained subaerially exposed during this period. The extent to which the Cornubian Massif remained emergent throughout the Late Cretaceous remains uncertain (Tyson and Funnell 1987). These emergent areas may have influenced sedimentation patterns and contributed to the distribution of unconformities.

While previous studies have provided valuable insights, significant uncertainties persist regarding the tectonic history and the processes that formed the Cretaceous unconformities. To address these knowledge gaps, the remainder of this paper integrates new seismic observations with well data to reconstruct the stratigraphic and tectonic evolution of Southwestern Britain during the Jurassic–Early Cretaceous.

## 3 | Dataset and Methodology

The datasets used in this study were 2D seismic reflection and well data, and well reports from the UK Oil and Gas Authority (OGA) and the Irish Department of Communications, Climate Action and Environment (DCCAE). The seismic data cover more than 85,000 km$^2$ and include data from the Western Approaches Trough and neighbouring basins (Table 1). Most seismic data in the Western Approaches Basin consist of a 2016 survey (WG162D0001) with 87 lines with depths up to 9 s two-way time (TWT). In the Plymouth Bay Basin and the offshore Wessex Basin, 31 lines from surveys SH742D1014 and SH732D1015 were used to make observations of Variscan thrusts and Jurassic and Cretaceous deposition. In the Brittany and Southwest Channel basins, 10 lines from several surveys were used to include the French sector of the Western

**TABLE 1** | Summary of seismic reflection surveys used in the study.

| Basin coverage | Seismic survey name | Number of lines |
|---|---|---|
| Western Approaches Trough, South Celtic Sea & Haag Fras | WG162D0001 | 87 |
| Bristol Channel | WG842D0002, WG852D2001, WG922D0007 | 35 |
| Plymouth Bay & Offshore Wessex | SH742D1014, SH732D1015 | 31 |
| Brittany & Southwest Channel | 0839-CN01, 0354A-IR1A, 0447-81IR, 0839-CN01 | 10 |
| Little Sole | WA-5062 | 23 |
| Cockburn | HEX-82 | 12 |
| Cornubian Ridge, Haag Fras & Cockburn | WG722D0001 | 7 |
| English Channel, Western Approaches, South Celtic Sea & North Celtic Sea | BY752D1001 SWAT | 6 |

Approaches Trough. Various Irish seismic surveys and well data were used to interpret the unconformities and Lower Cretaceous units into neighbouring basins. The Little Sole Basin was interpreted using 23 lines from survey WA-5062. The neighbouring Cockburn Basin was interpreted using the HEX-82 and WG722D0001 surveys.

Seven lines from survey WG722D0001 were used to interpret the offshore basement high and Cornubian Ridge north of the Melville Basin. BY752D1001 SWAT seismic lines are deep seismic profiles reaching 15s TWT. The SWAT lines were augmented by lines from survey WG162D0001 to identify basin structures and potential Variscan thrust fault planes.

Well reports, well tops and checkshot data were unavailable in the Brittany Basin, and the interpretations relied on published well formation picks, well logs and lithology information from Ruffell (1995), Deronzier et al. (1994), Hillis (1988) and Menpes (1997).

Seismic data was tied to wells, and key seismic horizons were interpreted across the Western Approaches Trough, Cockburn, Little Sole, South Celtic Sea basins. The reflectors include top Variscan basement, top Permo-Triassic, top Upper Triassic, top Lower Jurassic, top Upper Jurassic, base Cretaceous unconformity, top Aptian (Wealden Fm. to Lower Greensand Fm.), Mid Cretaceous unconformity, top Albian (Upper Greensand Fm.), top chalk and the seabed. In this study, we distinguish between the Top Upper Jurassic horizon and the Base Cretaceous Unconformity (BCU) based on stratigraphic context. The term 'Top Upper Jurassic horizon' is used where the section remains conformable, and no truncation is observed, whereas the term 'Base Cretaceous Unconformity' is applied in areas where truncation or onlap of younger strata is evident. Seismic facies analysis included identifying onlaps and truncations on seismic data, which were used to establish histories of uplift and erosion, as well as changes in depositional environment. In the Little Sole and Cockburn basins, there is higher uncertainty on the interpretations due to the absence of well data. Permo-Triassic basement extensional faults, Jurassic and Early Cretaceous faults were first mapped on seismic data. Structures associated with the Variscan orogeny were tentatively mapped by interpreting fault planes using deep seismic profiles.

Isochron maps for the Wealden and Upper Greensand formations were constructed by gridding and interpolating interpreted seismic horizons. The isochron maps were computed using the mapped BCU, MCU and top Upper Greensand horizons. In areas that lack data, the isochron maps were interpolated to reflect regional trends and observations such as fault-controlled deposition. Gravity data was used to help interpret between the seismic lines and facilitate mapping trends and directions of structures. The isochron maps were combined with well lithology and existing biostratigraphic data to create a Gross Depositional Environment (GDE) map for the Wealden. The GDE map was used to assess remnant topography after Early Cretaceous uplift and structures associated with the creation of accommodation for the deposition of Wealden stratigraphy.

## 4 | Seismic and Stratigraphic Nature of the Unconformities

In this section, we analyse the seismic and stratigraphic characteristics of the Jurassic–Cretaceous unconformities. Using these observations, we interpret the tectonic structures that may have influenced the formation of these unconformities in the Melville, Cockburn and Brittany basins.

### 4.1 | Melville and Cockburn Basins

Seismic line 6 from WG722D0001 intersects both the eastern side of the Cockburn and Melville basins (Figures 1 and 4). The line best displays the main structural elements of the basins. The Melville Basin extends roughly 120 by 75km, and it is bounded to the north by a major basin bounding fault. The fault is an E-NE extensional fault that dips southwards. The Melville Basin Bounding Fault (MBBF) separates the Melville Basin from a basement high to the north (Figure 4). The fault is interpreted as a possible reactivated Variscan thrust, as it shares the same EW orientation as the Variscan structures identified by Hillis and Chapman (1992) on deep seismic profiles (BIRPS and ECORS 1986). The basement high constitutes the south-westerly extension of the onshore Cornubian Massif in SW Britain. In the Melville Basin, the stratigraphic units dip 2°–3° northwards until they are truncated updip by the BCU. The oldest stratigraphy truncated by the unconformity appears to be Permo-Triassic aged. Further west, the unconformity is observed on seismic data to truncate pre-Variscan rocks (Husein et al. 2023). The southern edge of the North Melville sub-basin marks the reappearance of the Jurassic section. The geometry of the Melville Mid-Basin Fault (MMBF) indicates that it is part of a wider fault zone with planar faults dipping south (Figure 4). South of the fault zone, Jurassic high amplitude seismic facies in the hanging wall are juxtaposed directly against Permo-Triassic units on the footwall. Jurassic units in the South Melville sub-basin are highly folded (Figure 4). The folds may be part of a positive flower structure. The possible presence of salt in the South Melville sub-basin could have created minor salt anticlines and diapers (Husein et al. 2023). The salt may have acted as a local detachment surface for faulting in the basin. The flower structure is truncated by the BCU, and most fault displacement appears to have terminated during the deposition of Lower Cretaceous stratigraphy (Figure 4).

North of the basin bounding fault is a basement high comprising of pre-Variscan rocks (Evans 1990; Figure 4). Early Carboniferous slates have been drilled in wells 83/24-1 and Cambrian amphibolite is recorded in well 73/02-1 (Figure 1). Seismic imagery indicates that the chaotic basement reflections are onlapped by sediments showing discontinuous seismic reflections with moderate amplitudes (Figure 4). The sediments are likely part of a series of thin half grabens of Permo-Triassic age. The sediments are also truncated by the BCU (Figure 4). Further east from the interpreted seismic line, seismic and gravity data suggest that the high becomes part of the Cornubian platform (Evans 1990). The Cornubian platform is likely composed of a succession of Devonian and Carboniferous rocks that were part of the Variscan orogeny (Figure 4). The Cornubian

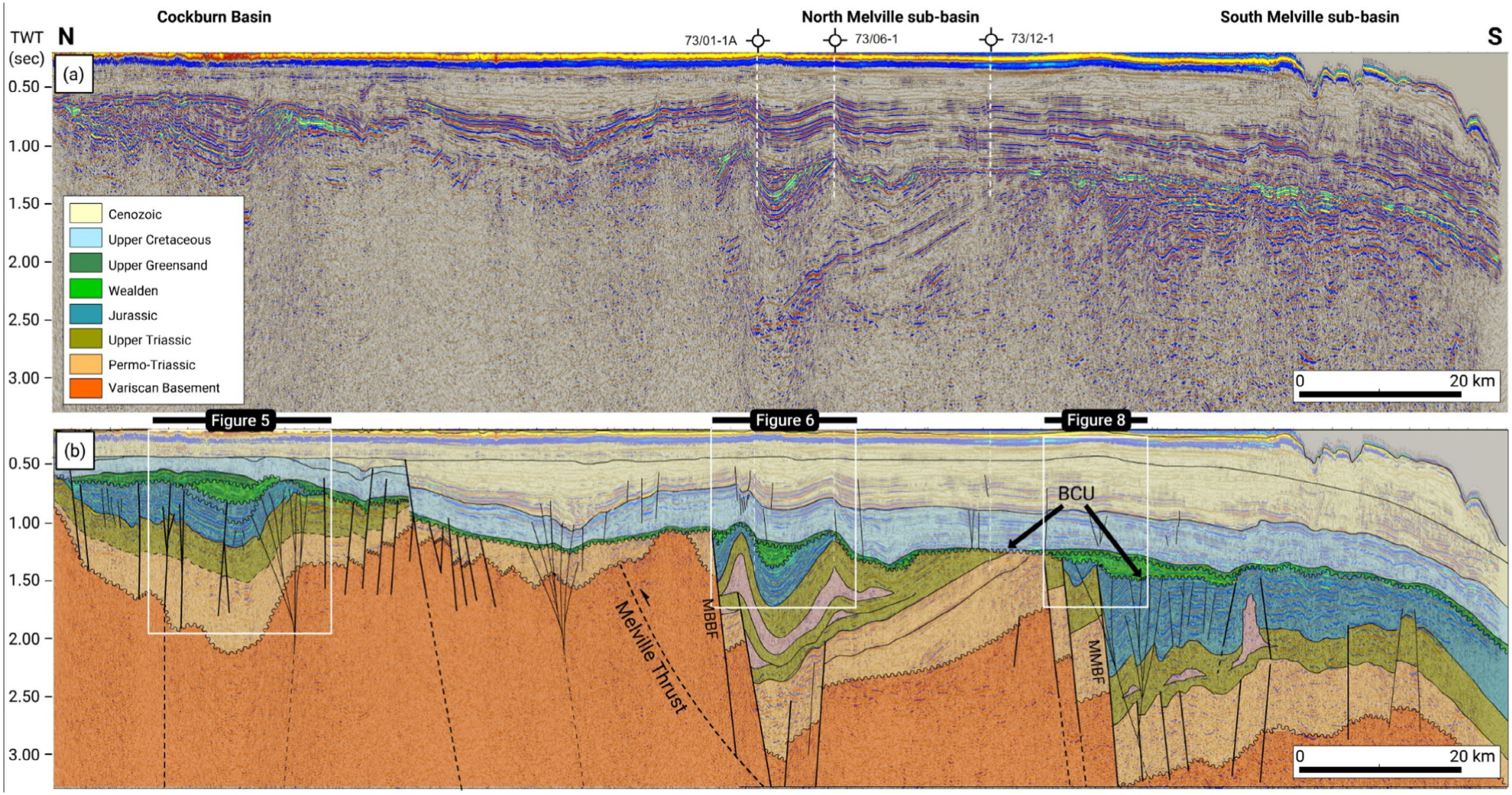


**FIGURE 4** | (a) Regional Seismic line WG722D0001-L6 in two-way time (TWT) from the Cockburn, North Melville and South Melville basins (see Figure 1 for location) and (b) interpretation. Wells 73/01-1A, 73/06-1 and 73/12-1 are projected onto the line. Note the regionally extensive Base Cretaceous unconformity across the three basins. Seismic data is presented using Positive Zero-Phase SEG (Society of Exploration Geophysicists) Display Polarity: Red = downward increase in acoustic impedance (positive amplitude response; peak), blue = downward decrease in acoustic impedance (negative amplitude response; trough).

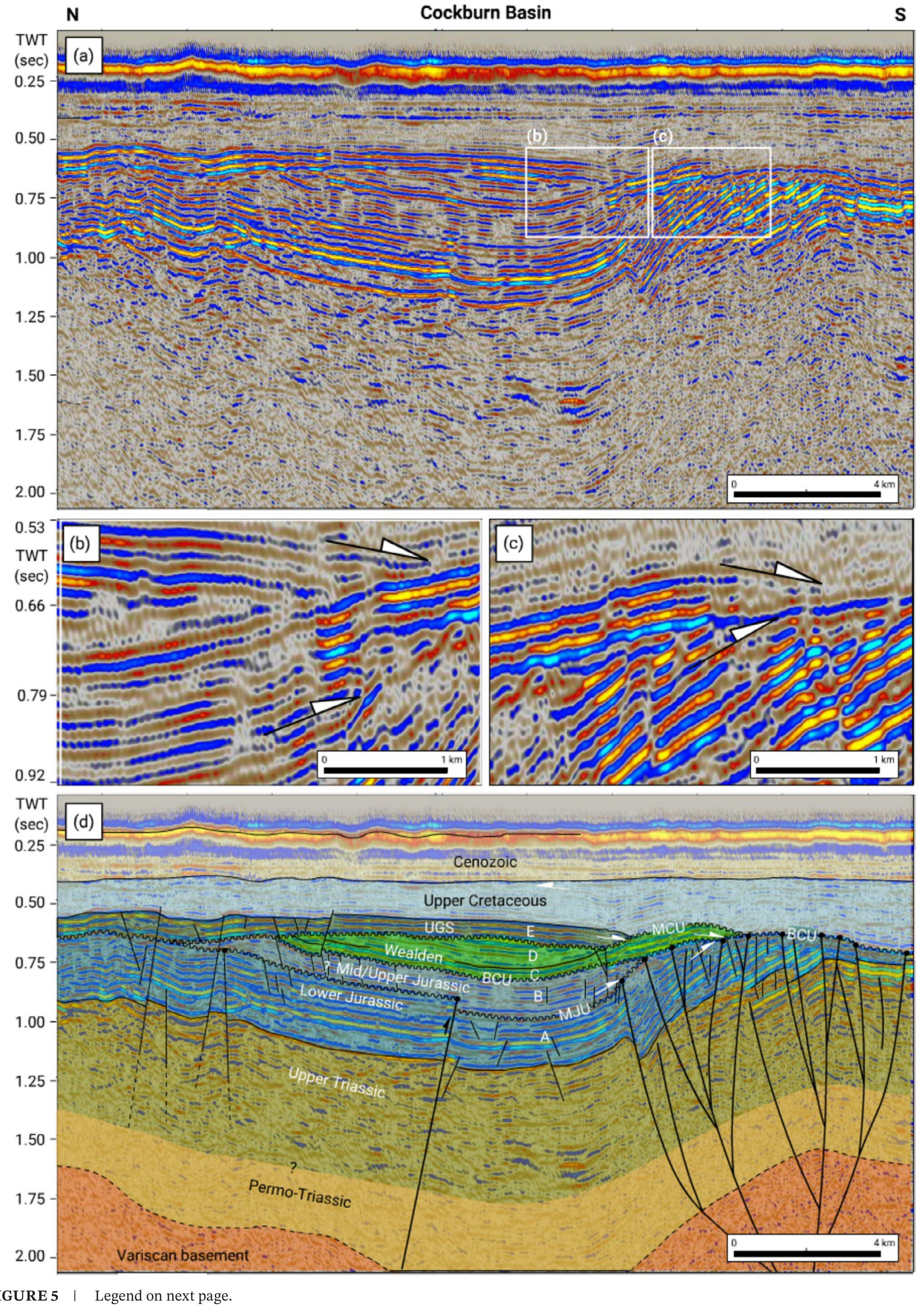


**FIGURE 5** | Legend on next page.

**FIGURE 5** | (a) Zoomed in seismic profile of the Cockburn Basin from Figure 4, (b) and (c) close up views of the truncation and onlap relationships, and (d) interpretation. The line highlights the complex nature of the composite BCU, where deeper in the syncline the MJU, BCU and MCU are interpreted separately. Seismic units A–E are identified based on seismic facies and onlapping relationships (shown with white arrows). Note most faults from the positive flower structure are truncated at the BCU. We suggest late Early Cretaceous to Cenozoic inversion created folds observed in the overlying stratigraphy.

platform has been intruded by granitic batholiths, and closer onshore, they are also observed to crop out on the Isles of Scilly (Evans 1990).

The Cockburn Basin is located between the Melville and Fastnet basins. The basin does not have any well data, and previous seismic interpretations were made by relying on regional unconformities and seismic facies correlation. The interpreted stratigraphy includes Triassic, Lower Jurassic, Lower Cretaceous, Upper Cretaceous and Cenozoic sediments. The Cockburn Basin sits on the Variscan basement and consists of a shallow basin reaching approximately 2.2 s TWT at its deepest. The deepest units have discontinuous low amplitude reflections, similar to Triassic seismic facies in the Melville Basin (Figure 4). On top of Triassic stratigraphy, angular Lower Jurassic reflections appear to be truncated by a regional unconformity that can be correlated to the BCU in the Melville Basin (Figure 4). The unconformity truncating Jurassic reflections can be traced northwards, where it becomes a possible paraconformity in basinal areas. Further to the north, a horizon equivalent to the unconformity is truncated by a second younger unconformity, possibly the mid-Cretaceous unconformity (Figure 4). A thick seismic package with low displacement faults is observed between the two unconformities; this package is equivalent to Early Cretaceous Wealden units as seen in the Melville Basin. A positive flower structure is seen to only affect Jurassic stratigraphy, where Jurassic rocks are eroded to the south. The basin is separated from a regional basement high by a large south-dipping normal fault with an average displacement of 0.5 s TWT (Figure 4).

#### 4.1.1 | Cockburn Basin

In the Cockburn Basin, an asymmetric anticline truncated by the BCU is clearly imaged in the seismic data. At the location of the anticline, the seismic unit A below the BCU is represented by a series of continuous high-amplitude reflections (Figure 5). The unit is interpreted as Lower Jurassic due to its visual similarities to this interval in the Western Approaches. The Lower Jurassic is onlapped by a second unit B consisting of moderate-amplitude discontinuous reflections (Figure 5). In the centre of the syncline, units A and B appear to be conformable. Towards the anticline, unit B onlaps onto A, and thus the interface between these units has been interpreted as an unconformity. The unconformity is likely the MJU due to location within the Jurassic unit. North of the section, units A and B are truncated by the BCU (Figure 5). Unit C is interpreted above unit B and consists of a set of continuous high-amplitude reflections. Unit C reflections are parallel to the reflections of unit B, but they onlap the BCU further south above the anticline (Figure 5). Thus, the interface between units B and C is interpreted as the BCU. Unit C is truncated by the MCU from the north. Unit D shows moderate-amplitude discontinuous reflections that are truncated by the MCU from both the north and the south. The seismic data from the Cockburn Basin exhibit the best evidence of the MCU clearly truncating reflections of the Wealden and the BCU. Further to the north, the MCU and the BCU merge into one composite unconformity (Figure 5). Above the MCU is unit E, a succession of continuous high-amplitude reflections that thin out to the north along the basin edge and downlap onto unit C. Further to the south on the section, unit E is not observed, which perhaps indicates a lack of deposition there. Above this succession, an Upper Cretaceous unit showing low-amplitude discontinuous reflections that exhibit folding is observed. The folds are truncated by a reflector close to the seabed at 0.4 s TWT (Figure 5).

The faults controlling the anticline likely converge between 2 and 3 s TWT (Figures 4 and 5). The Lower Jurassic reflections on the northern part of the anticline show the highest inward rotation towards the south, thus suggesting fault branching to the south. Based on fault convergence and rotations of the reflections, the structure is interpreted as a positive flower structure (Figure 5D). On the opposite side of the section, minor compressional displacement can be seen as a reverse fault truncating at the base of the MRU. Most of the faulting related to the flower structure ceases at the BCU. Seismic data deeper than 1.5 s TWT is noisy, and interpretations of Permo-Triassic and basement reflections are highly uncertain (Figure 5).

#### 4.1.2 | North Melville

Within the Jurassic syncline in the North Melville sub-basin, a stratigraphic unit with high-amplitude continuous reflections onlaps onto the Lower Jurassic high-amplitude interval (Figure 6). The interface between the two seismic units is interpreted as an unconformity. In the northern part of the syncline, at 1.3 s TWT deep, minor thrust faults are seen dipping towards the salt anticline in the north. The thrust faults could be linked to halokinises of the Upper Triassic salt. The unit is also truncated by an unconformity at its top (Figure 6). On top of the Jurassic stratigraphy, a few reflections of upper Lower Cretaceous sediments drape the entire basin (Figure 6). The upper Lower Cretaceous is penetrated by neighbouring wells 73/01-1A and 73/06-1 (Figure 1) and is equivalent to the Albian Upper Greensand Formation and Gault Clay Formation. The unit in the syncline can be interpreted as part of the Wealden Formation, with the BCU at its base and the MCU at the top. Alternatively, the unit could be a Middle or Upper Jurassic unit that has been deposited syntectonically during the Jurassic to Cretaceous uplift events or during halokinesis. The reflections in the entire package persist in amplitude and continuity, which could suggest laterally extensive Middle or Upper Jurassic marine deposition. Although uncertain, we suggest that the

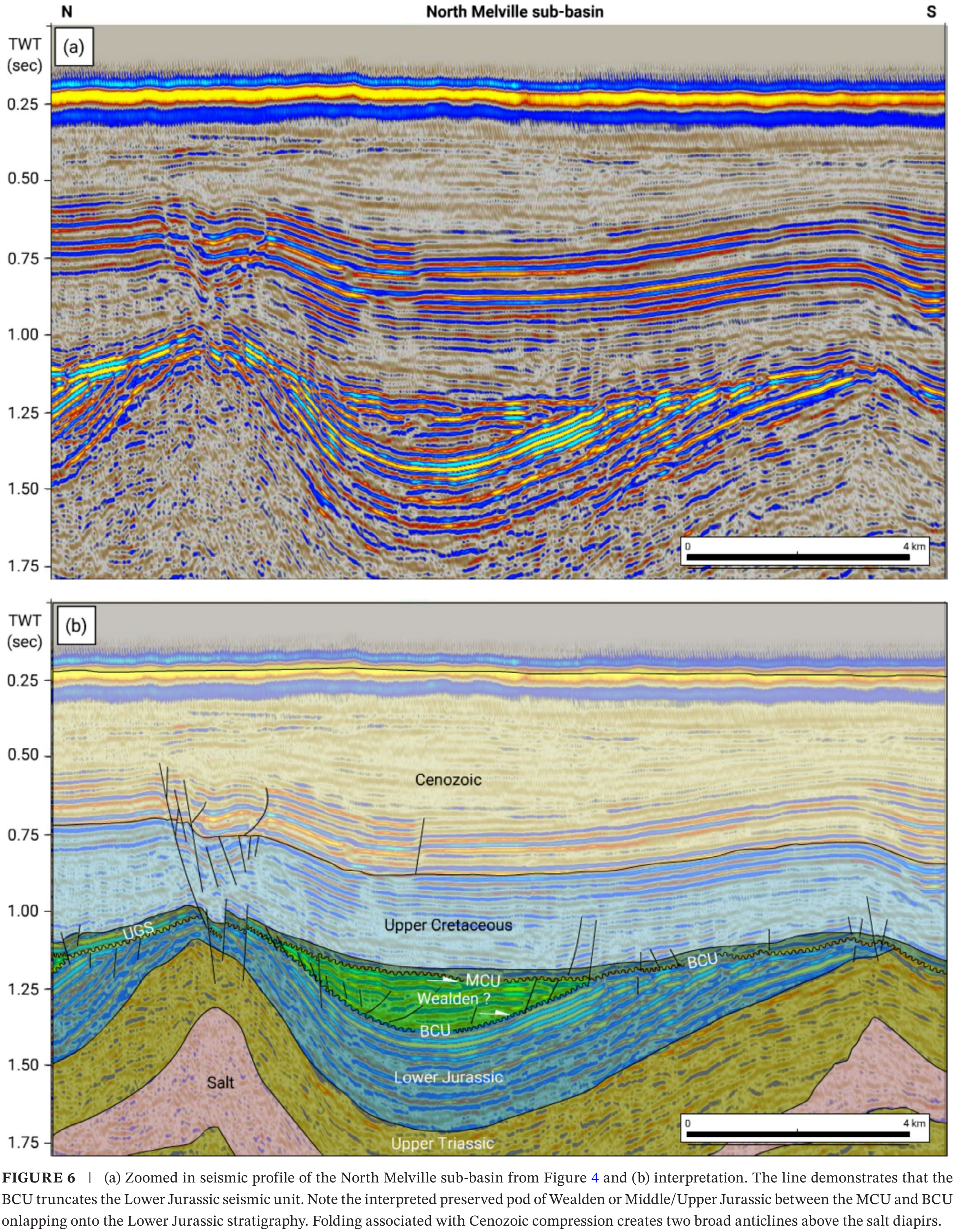


**FIGURE 6** | (a) Zoomed in seismic profile of the North Melville sub-basin from Figure 4 and (b) interpretation. The line demonstrates that the BCU truncates the Lower Jurassic seismic unit. Note the interpreted preserved pod of Wealden or Middle/Upper Jurassic between the MCU and BCU onlapping onto the Lower Jurassic stratigraphy. Folding associated with Cenozoic compression creates two broad anticlines above the salt diapirs.

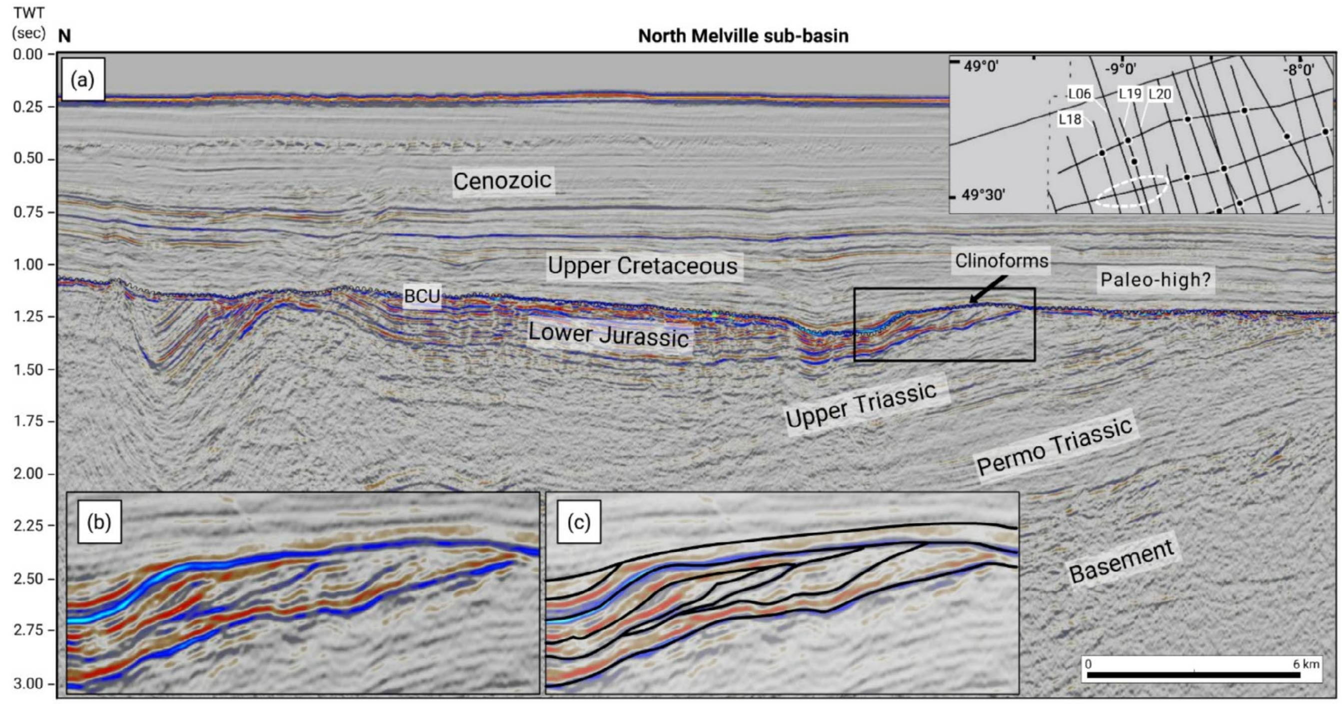


**FIGURE 7** | (a) Seismic line WG162D0001-L18 in two-way time (TWT) from the North Melville sub-basin (see Figure 1 for location) and interpretation. Note the Lower Jurassic high-amplitude-seismic facies develop into lower amplitude clinoforms towards the uplifted high in the north. Black box indicates location of inset shown in panel b and c. (b, c) Interpreted and uninterpreted Lower Jurassic clinoforms. Individual clinoforms are outlined in black. The insert location map highlights the locations of other seismic lines that exhibit similar seismic facies associated with the clinoforms. In the inset location map, the white dashed polygon indicates the approximate area of these observations.

Wealden interpretation is more plausible, due to the gross seismic similarity of the unit to one observed in the South Celtic Sea drilled by well 93/02-1 (Figure 1). Above the two salt anticlines, folding can be seen to continue until a near-seabed Cenozoic horizon at 0.45 s TWT (Figure 6). The folding is consistent with Cenozoic compression interpreted from stratigraphy in other parts of the basin. The reflections above the crest of the northern salt anticline show several extensional faults affecting Lower Jurassic to Cenozoic intervals. We suggest that the faults represent crestal collapse onto the salt body. The collapse features indicate that some of the folding above the salt diapirs is associated with halokinesis that continued into Cenozoic times.

In most of the Melville Basin, Lower Jurassic stratigraphy is typically manifest as continuous high amplitude seismic facies with minor variation (Figure 4). The seismic facies suggest a consistent depositional environment of marine shales and limestones. In contrast, on line L18, In the north Melville sub-basin, in the central uplifted part of the basin, Lower Jurassic stratigraphy is truncated at the BCU, followed by downcutting into Upper Triassic and Permo-Triassic stratigraphy to the south (Figure 7). At this location, seismic data show previously undescribed seismic facies: a partially eroded series of Jurassic clinoforms (Figure 7). The package forms from north to south, that is, from the direction of the uplifted block. The top of the clinoforms is increasingly truncated by the BCU proximal to the high (Figure 7). After depth converting the section using seismic stacking velocities and decompacting (Supporting Information Figure A), the clinoforms have apparent dip angles that range between 7° and 10°, which suggests they might be of clastic origin (Patruno et al. 2015). The height of the individual clinoforms ranges between 80 and 100 m. On seismic lines 06, L19, L20, similar facies of partially preserved clinoforms can be seen, giving the feature a width ranging between 18 and 30 km (Figure 7).

#### 4.1.3 | South Melville

In the South Melville sub-basin, south of the MMBF, the high amplitude Jurassic seismic facies reappear on the hanging wall blocks (Figure 8). The Jurassic stratigraphy is truncated by the BCU in both half grabens. North of the MMBF, the BCU truncates deeper Triassic stratigraphy. Above the BCU in the south Melville sub-basin, a stratigraphic unit is deposited both above Jurassic stratigraphy and appears over part of mapped Triassic stratigraphy. Further north, the unit pinches out on the Triassic high. The units show two distinct seismic facies, where the base is a series of continuous high amplitude reflections, followed by a unit with discontinuous low amplitude seismic facies. The low amplitude facies occur only in the southernmost hanging wall block in the section. The truncated and folded Lower Jurassic reflections indicate substantial uplift of this area. Moreover, there are no onlaps onto the Jurassic unit below the unconformity (Figure 8). The lack of onlaps indicates consistent widespread subsidence after erosion formed the BCU. The overlying unit is interpreted as the Early Cretaceous Wealden Formation, and thus the first Cretaceous sediments filling topography atop the BCU.

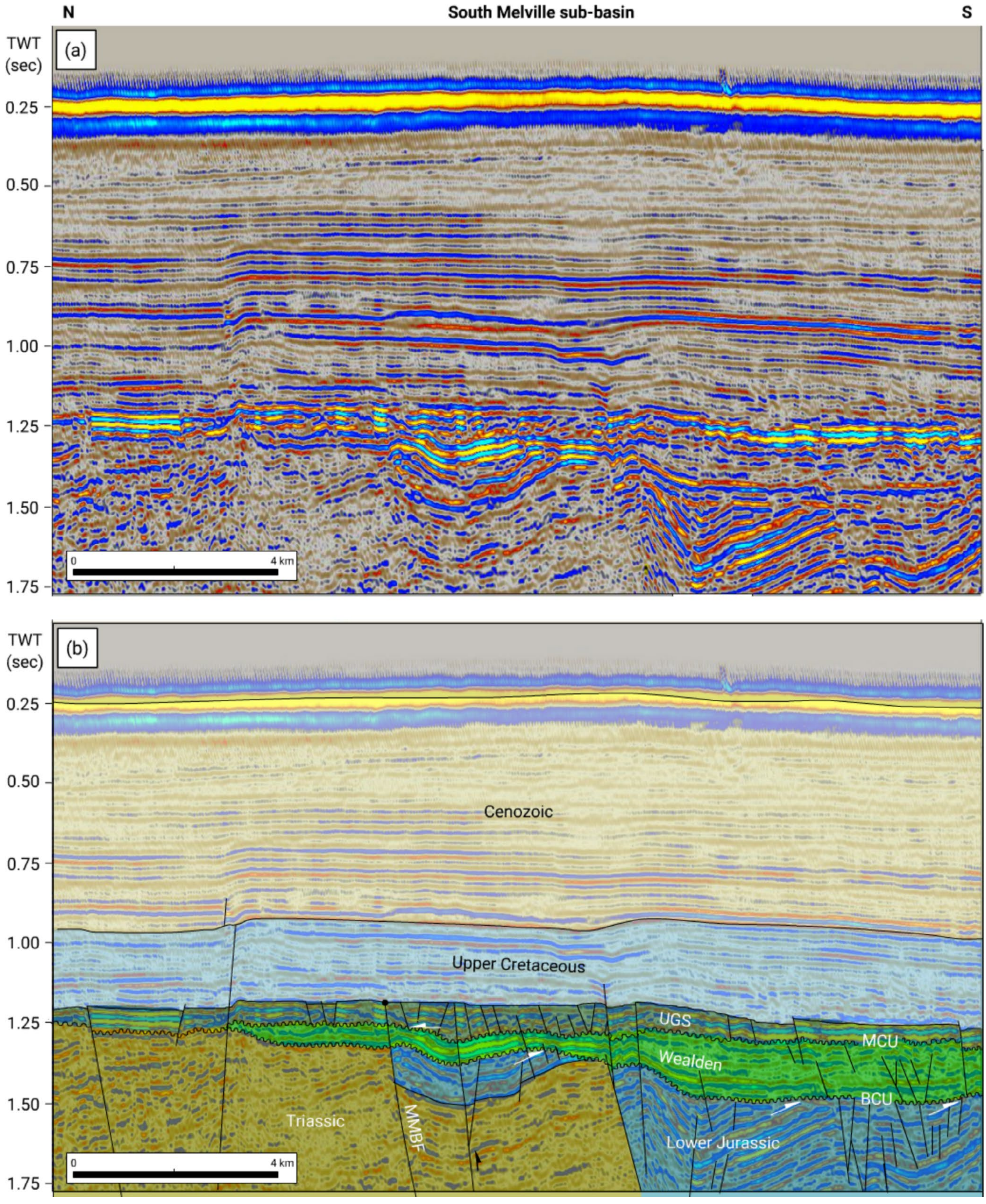


**FIGURE 8** | (a) Zoomed in seismic profile of the South Melville sub-basin from Figure 4 and (b) interpretation. The line shows the Base Cretaceous Unconformity (BCU) truncating Lower Jurassic units south of the Mid Melville Basin Fault (MMBF), and truncation of deeper Triassic units to the north. Note the thickening of the Wealden to the south. White arrows, onlap. Wealden and Upper Greensand (UGS) are broadly parallel, and erosion associated with the Mid Cretaceous Unconformity (MCU) appears to be minor.

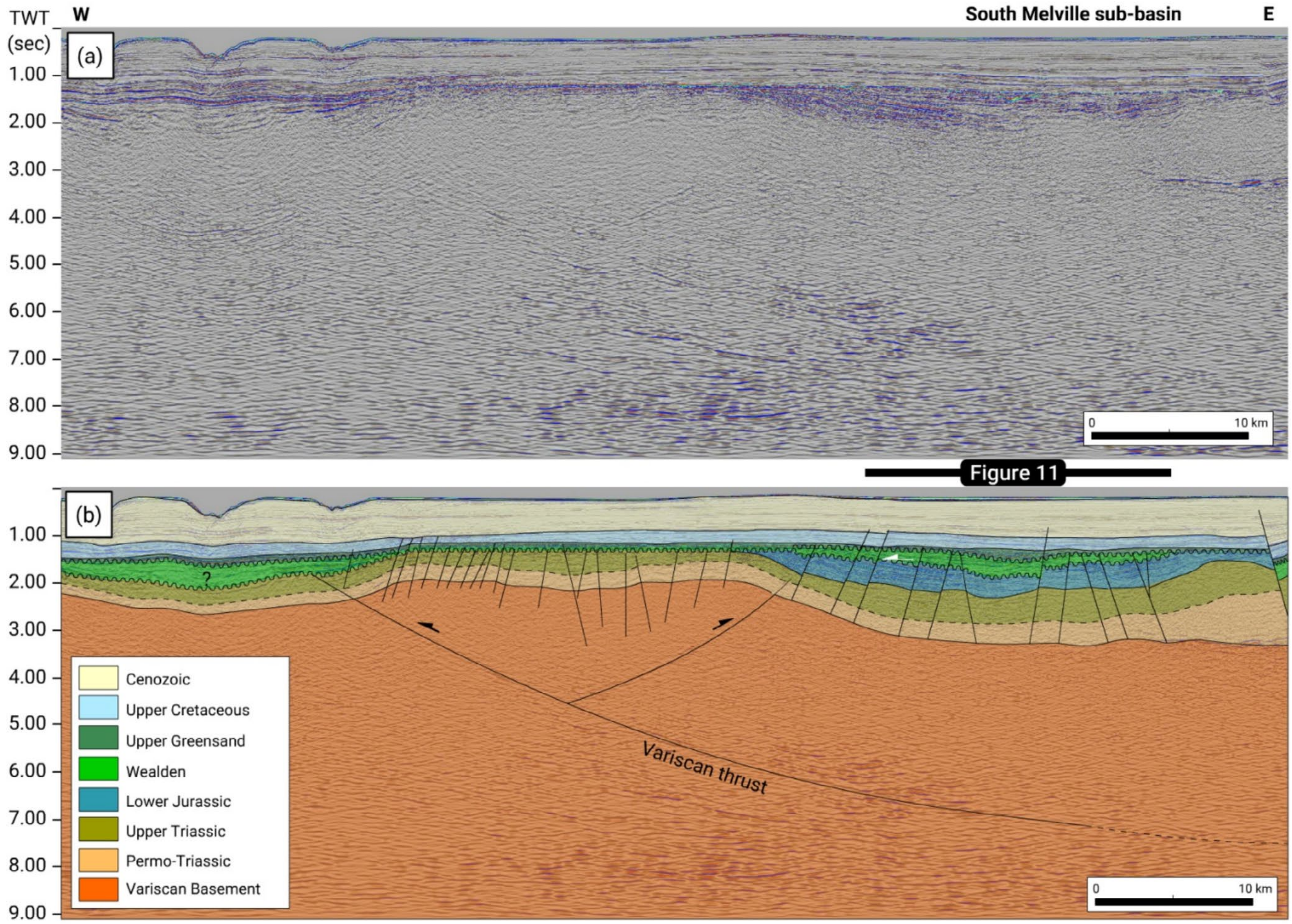


**FIGURE 9** | (a) Seismic line WG162D0001-L01 in two-way time (TWT) from the South Melville sub-basin (see Figure 1 for location) and (b) interpretation. Diffractions and fault planes are interpreted as a Variscan thrust and back thrust that reactivated, resulting in the erosional truncation of the Lower Jurassic units. Note the Wealden units onlap onto the Jurassic units closer to the uplifted block.

The discontinuous low-amplitude Wealden unit appears to gradually thicken southwards away from the fault (Figure 8). It is therefore likely that the unit onlaps onto the older lower units of the Wealden Formation. The lowermost continuous unit could represent Berriasian lacustrine facies as seen in the Wessex and St Mary's basins (Hawkes et al. 1998; Evans 1990; Figure 1). The Wealden is overlain by a stratigraphic unit that exhibits high-amplitude reflections (Figure 8). The reflections are highly faulted, with the faults constrained to within this package. Just south of MMBF, an onlap can be seen onto the Wealden unit (Figure 8). The onlap could indicate uplift of the high or renewed extension in the downthrown blocks. The MCU is interpreted based on the contrast in seismic facies and faulting patterns between the units surrounding the unconformity (Figure 8). The unit on top of the MCU is most likely the equivalent of the Upper Greensand formation and Gault Clay formation. They appear to thin out and possibly pinch out over the Permo-Triassic high just north of the MBF (Figure 8). Jurassic and older units are highly folded, with most of the associated faults being truncated at the BCU. Thickening of the Wealden formation and Upper Cretaceous chalk suggests the fault bounding the main Jurassic basin has been reactivated multiple times as a Cretaceous extensional fault. Upper Cretaceous stratigraphy along the same fault exhibits gentle folding, suggesting mild Late Cretaceous inversion.

In the Western part of the South Melville sub-basin, on E-W Seismic line L01, a broad 30 km wide uplifted area can be observed in the centre of the section (Figure 9). The high amplitude continuous Lower Jurassic reflections are truncated on the eastern side of the structure. Above the Lower Jurassic unit, a second unit of moderate amplitude continuous reflections can be seen onlapping onto Lower Jurassic stratigraphy. The unit's reflections are sub-parallel to the high amplitude Upper Greensand unit draping the entire basin. Furthermore, the only major unconformity seen on seismic imagery is below the package, indicating that it is most likely the Wealden Formation (Figure 9). In the west of the section, the centre of the syncline shows a major incision into the Wealden unit. The base of the incision is interpreted as the MCU, and the unit above as the Albian Upper Greensand Formation.

At ca. 7 s TWT deep, a set of diffractions can be seen with an apparent dip towards the south (Figure 9). The diffractions can be traced on seismic data to the western uplifted end of the structure. The diffractions are tentatively interpreted as a

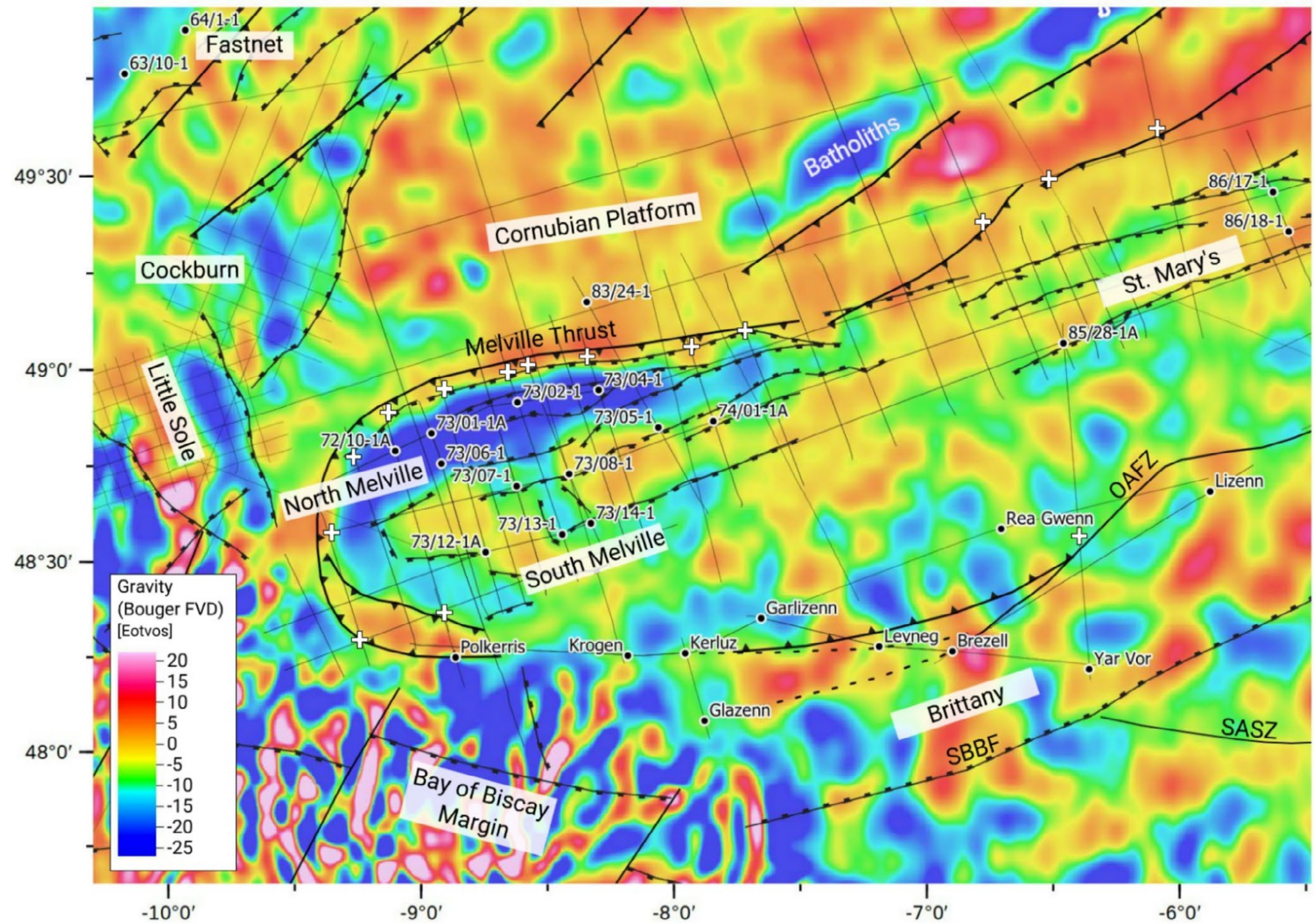


**FIGURE 10** | Interpretation of gravity (first vertical derivative) anomalies of the Western Approaches and neighbouring basins. Sedimentary basins and major features are annotated (white translucent boxes). Thick black curves, interpreted Variscan thrusts and Mesozoic faults; OAFZ, Ouessant–Alderney fault zone; SASZ, South Armorican Shear Zone; SBBF, Southern Basin Bounding Fault. Blue/Red, basin lows/highs. Note the discontinuous nature of the Variscan thrusts possibly caused by wrench faulting and lateral ramps. Thin black lines, seismic lines; annotated circles, wells; white crosses, seismic evidence for thrusts (see Figure 1).

deep-rooted low-angle thrust fault. Additionally, at ca. 3–4.2 s TWT deep, a shallow west-dipping reflection can be seen on the eastern edge of the uplifted structure (Figure 9). The reflection is interpreted as a possible back-thrust fault that is branched off the main thrust at approximately 4.7 s TWT. The thrust faults are the first observation of deep compressional structures observed on an E–W seismic line in the South Melville sub-basin. They are tentatively interpreted as reactivated Variscan structures that resulted in the erosion and truncation of the Lower Jurassic units (Figure 9). To understand the potential trends of the faults, we make use of regional gravity data.

The uplifted area bounded by the two thrust faults matches a NW–SE oriented positive gravity anomaly (Figure 10). In the southwest of the basin, the gravity anomaly strikes N–NE. At the northwestern limit of the Melville Basin, the high strikes E–NE. On seismic data, shallow south-dipping diffractions related to Variscan thrust faulting can be seen on most N–S lines in the Melville Basin lines (L03, L17, L18, L20, L22, L24, L26, L28 and L29). The diffractions typically terminate just north of the Melville basin bounding fault (Figure 10). Seismic evidence and gravity data support the interpretation of thrust fault trends around the basin. The geometry of the highs mapped using gravity data is interpreted as a curved thrust fault system that bends southwards around the Melville Basin.

The syncline north of the uplifted area contains the thickest successions of Lower Cretaceous sediments in the Melville Basin (Figure 11). The unit onlapping continuous amplitude Lower Jurassic reflections is interpreted as the Wealden Formation. The Wealden seismic facies show a combination of continuous moderate amplitude reflections with discontinuous low amplitude reflections. The difference in seismic facies could correspond to changing depositional environments from braided fluvial, meandering fluvial and lacustrine deposition (Sangree and Widmier 1979). The base unit of the Wealden Formation, as interpreted here, shows no reflectivity. It rapidly thickens towards the main fault. A similar package drilled by well 56/12-01 in the Fastnet Basin is dated as being Valanginian aged Rodriguez-Salgado et al. (2019); Figure (1). The base Wealden unit in the South Melville syncline could represent the first identification of the Valanginian in the

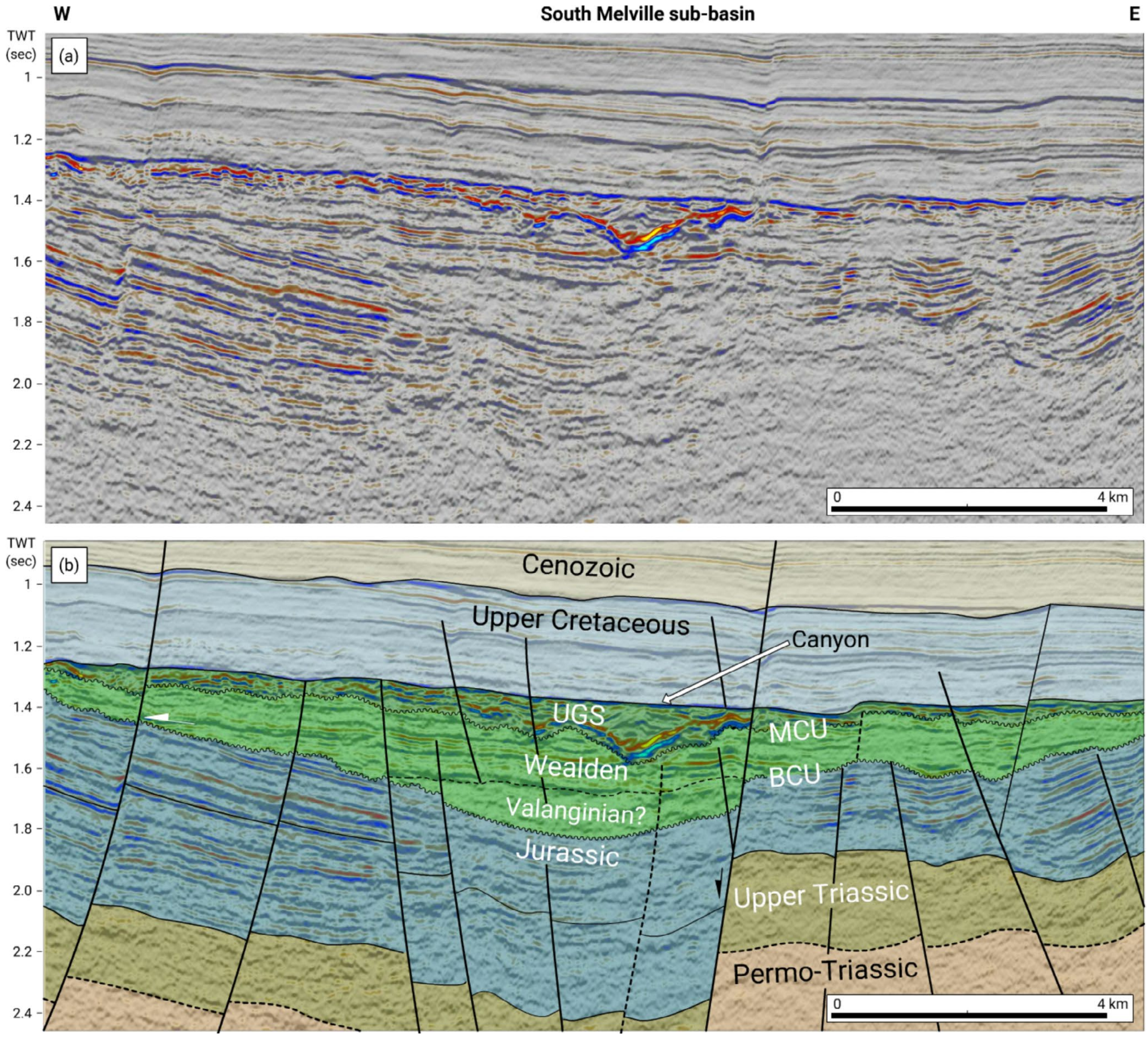


**FIGURE 11** | (a) Zoomed in seismic profile of the South Melville sub-basin from Figure 9 and (b) interpretation. The line established the thickening of Wealden on the Lower Jurassic in a SE-trending syncline in the South Melville sub-basin. A large shelf canyon system is interpreted as incising into the Wealden along the centre of the syncline. The base unit of the Wealden shows a package with transparent seismic facies interpreted as a possible Valanginian unit. BCU, Base Cretaceous Unconformity; MCU, Mid Cretaceous Unconformity.

Melville Basin (Figure 11). West of the section, the displacement along the faults in the Lower Jurassic is much higher in Cretaceous and Cenozoic times. The higher displacement indicates Middle to Late Jurassic extension had occurred. These observations and interpretations indicate that Middle to Upper Jurassic units were likely deposited in the area and eroded. A large incisional feature is observed at the top of the Wealden unit. The incision is ~4 km in width and incises ~0.2 s TWT into the Wealden. It has multiple centres indicating a role for active faulting in determining foci of incision. This erosional feature is interpreted as being a major Early Cretaceous shelf canyon system transporting sediments from the North Melville and Cornubian platform into the Brittany Basin or the Bay of Biscay (Figures 1 and 10).

## 4.2 | Brittany Basin

South of the Melville Basin in the Brittany Basin, a 130 km N-S composite seismic line was chosen as it intersects the OAFZ (Figures 10 and 12). The location of the OAFZ marks the transition between a highly uplifted basin in the north and continuous Jurassic and Cretaceous deposition in the south. The seismic line intersects two wells, Yar Vor and 85/28-1A (Figure 1). The latter was drilled on a high on the UK side and penetrates Eocene to Permo-Triassic sediments. In the well the BCU is observed to separate Lower Cretaceous from Permo-Triassic sediments. The well confirms the absence of all Jurassic and most of the Upper Triassic units, which we interpret as a manifestation of erosion. The Permo-Triassic units north of the well show a

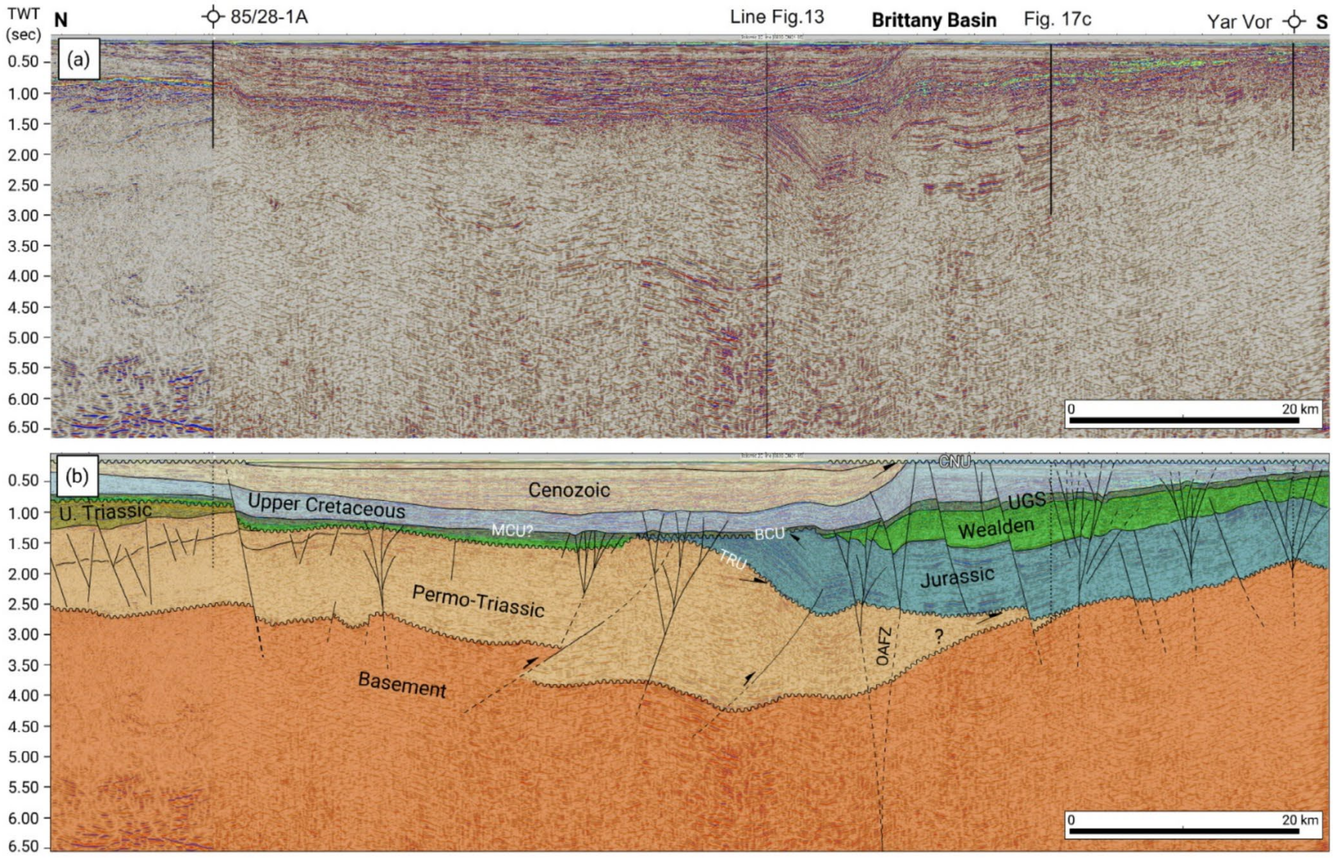


**FIGURE 12** | (a) Composite Seismic line WG162D0001-L35 and 0839.CN01-95 in two-way time (TWT) from the Southwestern Approaches to the Brittany Basin (see Figure 1 for location) and (b) interpretation. The line shows the transition between an uplifted basin in the north and continuous Jurassic and Cretaceous deposition in the south. Note the BCU truncates Jurassic and Permo-Triassic stratigraphy. The OAFZ displacement is mainly associated with Cenozoic uplift. Flower structures with minor displacement mostly terminate in the Lower Cretaceous to late Upper Cretaceous units. North-dipping thrust faults are interpreted as a cause for uplift and erosion of the Jurassic anticline. BCU, Base Cretaceous Unconformity; CNU, Cenozoic Unconformity; MCU, Mid Cretaceous Unconformity; OAFZ, Ouessant–Alderney fault zone; TRU, Triassic Unconformity.

set of normal faults, some of which pass through the BCU into Upper Cretaceous stratigraphy. On the southern end of the seismic line, well Yar Vor is used to guide interpretation; it appears to have been drilled on a Cenozoic positive flower structure. It intersects Cenozoic and pre-Permian stratigraphy (Figure 12). The area drilled by the well Yar Vor contains a complete succession of Cretaceous and Jurassic stratigraphy, which we suggest indicates that the area experienced minimal impact from Jurassic and Early Cretaceous denudation and thus perhaps uplift (Figure 12). The well also penetrates pre-Permian basement with no occurrence of Triassic or Permian sediments, suggesting a local Triassic unconformity, or that Triassic deposition is limited to the north of the area. Stratigraphic onlap is observed just south of the OAFZ, where Permo-Triassic horizons are truncated at the base of the Lower Jurassic. This evidence suggests the presence of a Triassic unconformity and limited deposition to the north.

The Jurassic seismic facies mainly show low amplitude and continuous reflections, with few laterally extensive horizons with higher amplitudes. The Lower Jurassic seismic facies increase in continuity and amplitude north of the OAFZ. The OAFZ is steep, with major vertical displacement that likely resulted in the uplift of the southern part of the section. Just north of the fault zone, the Jurassic interval is truncated by a major unconformity, the BCU (Figure 12). Uplift created a large partially preserved fold with a wavelength of ~20 km (Figure 12). North of the OAFZ, Jurassic stratigraphy shows minimal structuration, and the beds dip gently northwards.

Below the Jurassic fold, at 3.5 s TWT deep, the last continuous high-amplitude reflector is interpreted as the top basement. The basement reflector exhibits a fold of a similar wavelength to the Jurassic anticline above. The downward rotation of the reflections of the Jurassic and Basement anticlines to the south could indicate the presence of a north-dipping thrust fault. Furthermore, just north of the basement anticline, the basement reflections abruptly reappear at 3 s TWT. Similarly, on top of both sides of the basement, a unit showing low-amplitude discontinuous seismic facies can be seen (Figure 12). Separating the two units is a north-dipping area of no seismic reflectivity, indicating a potential shallow-dipping fault plane (Figure 12). This evidence implies a possible second thrust fault dipping to the north. East of the line, on seismic lines SWAT 8 and 9, a set of north-dipping deep reflections can be seen on the southern boundary of the Plymouth Bay Basin (Supporting Information Figure B). It is possible that these reflections represent part of the Variscan thrust system connected to thrusts observed in the Brittany Basin. Further east on SWAT 10, similar deep reflections can be seen at a depth of ~7 s but have an opposite direction of dip (i.e., towards the south), similar to the Variscan-related south-dipping English Channel monocline.

At well Yar Vor, 731 m of the Lower Cretaceous Wealden unit was recorded. Seismic data indicate that the unit thickens southwards into a graben structure and then thins further north (Figure 12). Estimated displacement along the normal faults increases with depth; this observation indicates that the deposition of the Wealden is controlled by extension along the normal faults. Three kilometres south of the OAFZ, the Wealden Formation appears to pinch out or be partially eroded by the MCU. The formation conformably overlies Upper Jurassic stratigraphy south of the OAFZ. Further north, the Wealden Formation reappears as a thinner sedimentary unit over Triassic sediments, separated by the BCU.

Above the Wealden, wells 85/28-1A and Yar Vor recorded up to 110 m and 118 m Late Aptian–Albian sediments, respectively. On seismic data, the Aptian–Albian appears as a series of high amplitude reflections above the BCU. The unit can be seen to slightly thicken in the downthrown fault block just south of well 85/28-1A. Late Aptian–Albian stratigraphy also thickens south of the OAFZ, following the depositional trend of the Wealden Formation.

Upper Cretaceous Chalk thickens gradually ~13 km north of the OAFZ, just above the truncated Jurassic anticline. The chalk is thickest south of the OAFZ, where it is truncated by an unconformity near the seabed. The unconformity also truncates the chalk and part of the Cenozoic stratigraphy observed in the north of the section. The Cenozoic units show layers thinning towards the OAFZ, suggesting syntectonic deposition (Figure 12).

Short wavelength clusters of folding affecting Upper Cretaceous and older stratigraphy can be seen in multiple areas surrounding the OAFZ (Figure 12). The highest intensity folding appears to have affected Aptian–Albian units. Lower in the section, the folds seem to be created by a set of converging faults that form fault anticlines as part of larger flower structures. The flower structures are observed regularly at intervals of ~10–20 km. In the northern part of the basin, the short wavelength folding stops at the base of the Upper Cretaceous interval, indicating a possible association with the events causing the MCU. The remaining flower structures show longer wavelength folding that continues into Cenozoic stratigraphy. The folding of younger stratigraphy and the broader nature of fold structures could indicate that the faults are associated with a separate uplift event. Alternatively, the faults could have been reactivated in Cenozoic times as part of the movement along the OAFZ.

To investigate the seismic facies within Jurassic stratigraphy, we make use of an EW section transecting the Jurassic anticline (Figure 13). On line 0839.CN01-44-44A, well Rea Gwen is drilled on an anticline structure subcropping the BCU. The well encountered 120 m of Early Cretaceous Upper Green Sand, 345 m of Lower Jurassic followed by 350 m of Upper Triassic stratigraphy (Menpes 1997). The Lower Jurassic seismic facies are high amplitude and continuous reflections, similar to the seismic facies observed in the Melville and Cockburn basins (Figures 5, 6 and 13). On the section, the Lower Jurassic stratigraphy is truncated by the BCU (Figure 13). Folding is absent in the Early Cretaceous to Cenozoic section. Down the eastern flank of the anticline, lower amplitude continuous reflections onlap the anticline (Figure 13). Further east, this package can be tied to the Middle or Late Jurassic unit interpreted on the intersecting N-S line. Onlapping stratigraphy suggests that uplift has occurred after the deposition of Lower Jurassic stratigraphy. As there is no well control in the area, it is uncertain if the onlapping stratigraphy belongs to the Middle or Upper Jurassic units. The units were later eroded by the events that created the BCU, indicating that a second phase of uplift has occurred. As seen in the N-S line (Figure 12), the amplitudes of the Lower Jurassic seismic reflections diminish in intensity towards the OAFZ, suggesting a possible facies change.

## 5 | Early Cretaceous Lithologies and Sediment Distribution

Biostratigraphic well data in the Western Approaches Trough often do not conclusively differentiate between Cretaceous Aptian and Albian units (OGA well biostratigraphy reports). In this study, the Aptian stratigraphy is relatively thin and is included as part of the Wealden Formation, which represents the latest phase of syn-rift deposition, characterised by predominantly terrestrial and marginal-marine facies (Figure 14). The transition from Aptian to Albian is marked by an increase in marine influence, evidenced by higher calcareous content and glauconite minerals (Evans 1990). Because the volcanics are interbedded with tuffaceous Albian shales, they are interpreted as Albian units following the MCU (Figure 15). The widespread Albian Gault and Upper Greensand Formations represent the post-rift phase, deposited during a time of expanded marine conditions.

To understand the structures involved in Jurassic to Cretaceous uplift events, we map the distribution, lithology and thickness of Cretaceous sediments deposited after the BCU and MCU. The quality of the seismic data does not merit interpreting the different Jurassic units and facies consistently around the basin; thus, individual structures influencing the MJU will not be interpreted separately.

### 5.1 | Early Cretaceous Wealden and Lower Greensand—(Hauterivian to Aptian)

In the northern part of the Western Approaches Trough, west of the Plymouth Bay Basin, the earliest Cretaceous sediments can be found in well 87/12-1A as a unit of sandstones and mudstones (Figure 1). Based on microfossil assemblages, the units are dated as Berriasian and were likely deposited in fresh to brackish waters.

In the Melville Basin, well 73/7-1 encountered 97.5 m of Hauterivian to Barremian sandstones, Aptian claystones and marls. The Aptian is unconformably overlain by Albian basalts. Well 73/5-1 encountered 36.5 m of Barremian and Aptian claystones interbedded with sandstone, covered by 39 m of Aptian to Early Albian sandstones. The units appear to be conformably overlain by Albian sediments.

In the neighbouring St. Mary's Basin, well 85/28-1A encountered 27.4 m of Barremian to Early Aptian sandstones interbedded with carbonaceous claystones. Further east, well 86/18-1 encountered 22.5 m of interbedded units of Barremian sandstone and 110 m of Aptian–Albian sandstones, siltstone and claystones. The sediments show continuous deposition to the Early Cenomanian with no presence of the Mid-Cretaceous unconformity. Neighbouring well 86/17-1 encountered 73 m of undifferentiated Aptian to Albian sandstones and claystones.

In the southern part of the Western Approaches trough, in the Brittany and Southwest Channel basins, several wells drilled through Wealden-equivalent rocks with thicknesses reaching 1160 m in well Lenkett and 1365 m in Glazenn (Menpes 1997). Wells Rea-Gwenn and Garlizenn, drilled in areas just north of the OAFZ, did not encounter any Wealden units before encountering the BCU.

In the South Celtic Sea, Lower Cretaceous lithologies and seismic facies are similar in wells 120/28-2, 102/29-1, 102/28-1, 93/023, 93/02-1 (Figure 1). The wells are re-interpreted based on the biostratigraphy of well 102/28-1, where the first unit above the BCU consists of Aptian to Barremian Wealden sediments with reworked Barremian to Berriasian rocks. A 278 m thick unit of undifferentiated Wealden sediments is encountered in well 93/02-1. That they pinch out before reaching well 93/02-3 suggests that they could be older Hauterivian to Berriasian rocks. Well 103/18-1 encountered 271 m of undifferentiated Lower Cretaceous sediments in a syncline. The sediments are possibly the same age as the Wealden units in well 93/02-1.

On the continental slope, Deep Sea Drilling Program well DSDP-402 drilled through 133 m of Aptian calcareous and carbonaceous mudstones, limestones and marly limestones (Figure 1). The unit's biostratigraphic assemblages indicate deposition in relatively shallow waters. Well DSDP-400 was drilled on a buried rotated fault block in 4399 m of water depth; it encountered Calcareous mudstones deposited in bathyal conditions (Figure 1). Well 401 was drilled on top of a tilted fault block, just at the break of the slope. It encountered late Aptian to Barriasian limestones and carbonate talus with biostratigraphy indicating a nearshore environment.

Further north, in the North Celtic Sea Basin, the Wealden units are widespread, with thicknesses of 1244 and 1415 m encountered in wells 56/9-1 and 57/2-2, respectively (Figure 1). Wealden deposition continued into the Fastnet Basin where > 500 m thick units of Wealden are encountered in wells 63/10-1, 56/26-2, 56/21/2. The Wealden is mostly deposited in the basinal areas and thins out towards basin margins, and it is completely absent (and hence interpreted as having been eroded) in well 64/2-1.

In the Western Approaches Trough, the largest Wealden sediment accumulations appear to be restricted to south of the OAFZ (Figure 14). On seismic data, the unit thickens away from the OAFZ and is thickest in the centre of the basin. In the Brittany Basin, the units reach thicknesses of up to 1 s TWT. They pinch out north of the OAFZ. The seismic data cannot be used to confirm if the units are truncated by the MCU or thin out to the basin edge. The Wealden unit was deposited in a basin that strikes NE and is 30–40 km wide and follows the geometry of the OAFZ. The southern basin bounding fault (SBBF) is not resolved on seismic data in the Brittany Basin but can be seen on seismic lines SWAT 7 and 8 as the stratigraphy onlaps the Armorican massif. The position of the basin bounding fault is adapted from Ziegler (1987) and modified based on the gravity lineaments observed in the area (Figure 10). On seismic data, the area surrounding wells Glazenn and Kerluz shows similar Cenozoic uplift trends as the OAFZ. Thus, it is unclear if the OAFZ continues to the south or north, or if uplift should be attributed to a second fault parallel to the OAFZ.

On the Western side, in the Little Sole Basin, a unit subcropping the BCU shows rapid stratigraphic growth eastwards to a N-S fault plane. The unit reaches up to 1.1 s TWT thickness adjacent to the fault (Figure 14), and it onlaps underlying continuous high amplitude reflections (Figure 14). The reflections are interpreted as Jurassic units based on the similarity to the Jurassic facies in the Melville Basin. In the South Melville sub-basin, the Wealden is observed to be deposited in a syncline parallel to the south Melville high, adjacent to the MMBF (Figure 2). To the north on the Melville Basin, Wealden deposition is mostly absent and locally restricted to fault block footwalls. In St. Mary's Basin, an area of possible thickened Lower Cretaceous sediments appears north of well 86/17-1 (Figure 1). The unit is 0.2 s TWT thick and is deposited in an E–NE graben that opens to a wider area of deposition in the east. The localised Cretaceous basin appears to truncate to the north and east. In the Cockburn Basin, the Wealden appears to be mostly preserved in basinal synclines (Figures 4 and 5).

In the South Celtic Sea Basin, a pod of Wealden is preserved in the western part of the basin (Figure 14). The pod is at least 20 km long (E-NE) and 7 km wide, likely extending into the Irish sector. Well 93/02-1 drilled into the syncline encountered 278 m of Wealden sediments (Figure 1). Further to the east of the basin, an E-W orientated pod of Wealden is 50 km long and 30 km wide. The thickness of Wealden units in the synclines is approximately 0.3 s TWT. Further east into the Bristol Channel Basin, a seismic unit is seen onlapping the Sticklepath-Lustleigh fault zone (Figure 14). The Sticklepath-Lustleigh fault is likely a Variscan strike-slip fault zone (Holloway and Chadwick 1986). The basin is referred to as the Stanley Bank Basin and has five shallow British Geological Survey (BGS) boreholes that encountered Cenozoic rocks (Tappin et al. 1994). The seismic unit interpreted as Lower Cretaceous Wealden extends from approximately 0.15–0.45 s TWT, deeper than the boreholes that sampled it.

It is likely that the Lower Cretaceous units received sediments from the elevated areas such as the Cornubian massif and offshore Cornubian Platfrom, Armorican massif, areas immediately north of the Variscan front. Contributions to sediment supply would have come from elevated areas in the Melville Basin and possibly local highs along the English Channel.

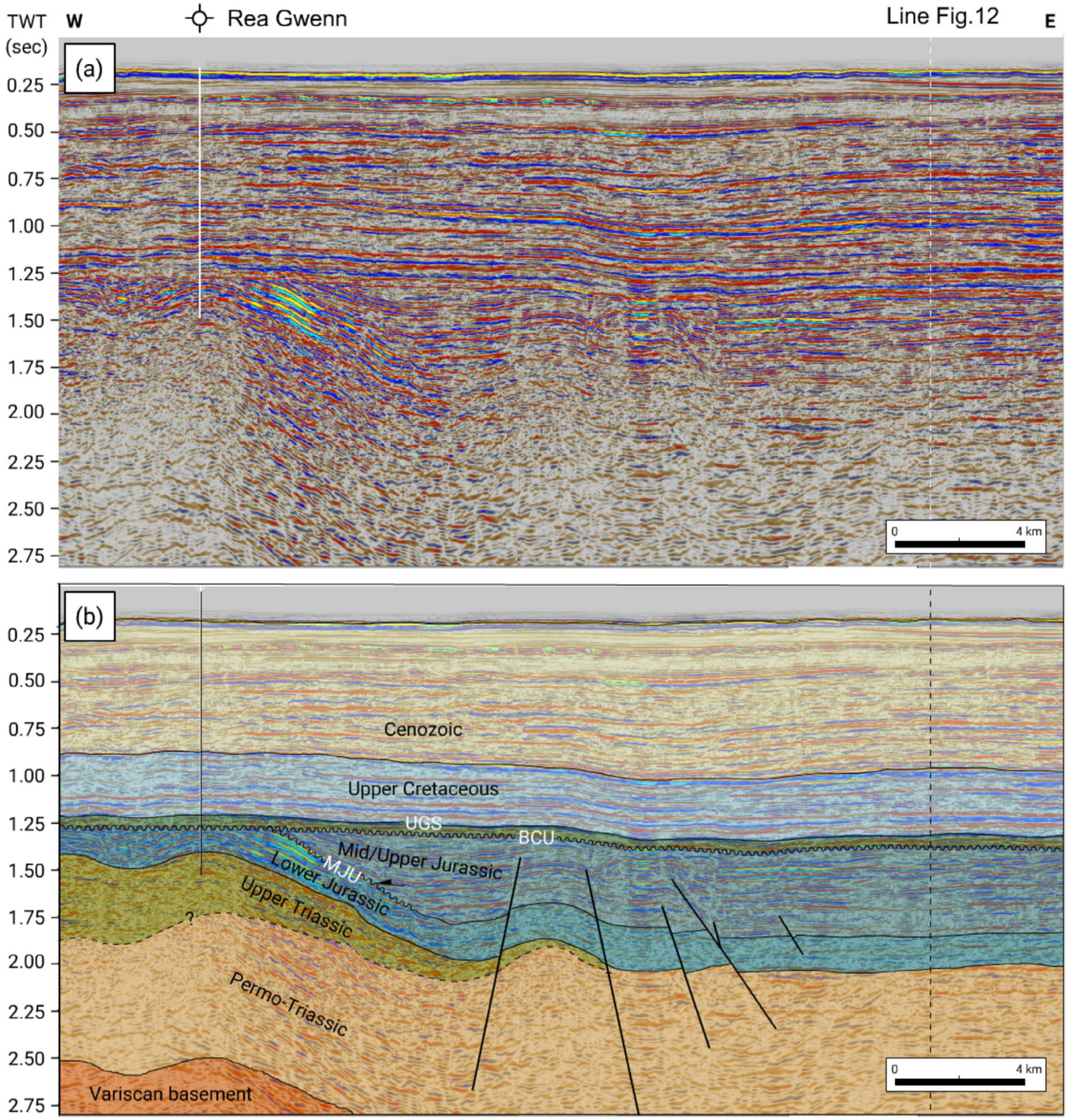


**FIGURE 13** | (a) Seismic line 0839.CN01-44-44A in two-way time (TWT) of the northern edge of the Brittany Basin (see Figure 1 for location) and (b) interpretation. The line shows Mid or Upper Jurassic units onlapping onto the Lower Jurassic at the Mid-Jurassic unconformity. The Middle/Upper Jurassic stratigraphy is truncated at the top by a younger Base Cretaceous Unconformity (BCU). UGS, Upper Greensand.

## 5.2 | Early Cretaceous Upper Greensand—(Albian)

All the wells drilled in the Melville, St. Mary's and west Plymouth Bay basins encountered late Early Cretaceous sediments Albian sediments with thicknesses ranging from 11.5 m in well 73/06-1 to 106 m in well 73/07-1. Generating an isochron map for the Albian unit is made difficult due to the widespread thin nature of the unit. Instead, the Albian facies transition is best described through well data from the Melville Basin (Figure 15).

The lithologies encountered are dominantly clastic units of intercalated calcareous claystones and sandstones. In the Melville Basin, sandstones are more dominant towards the base of the Aptian–Albian unit (Figure 15). Nine wells in the western part of the Melville Basin encountered extrusive volcanics (72/10-1A, 73/01-1A, 73/02-1, 73/06-1, 73/07-1, 73/08-1, 73/12-1, 73/13-1, 73/14-1). In well 73/02-1, the basalts have been described to have macrofossil fragments of echinoids and bryozoans, as well as black hyaline patches with conchoidal fracture and calcite

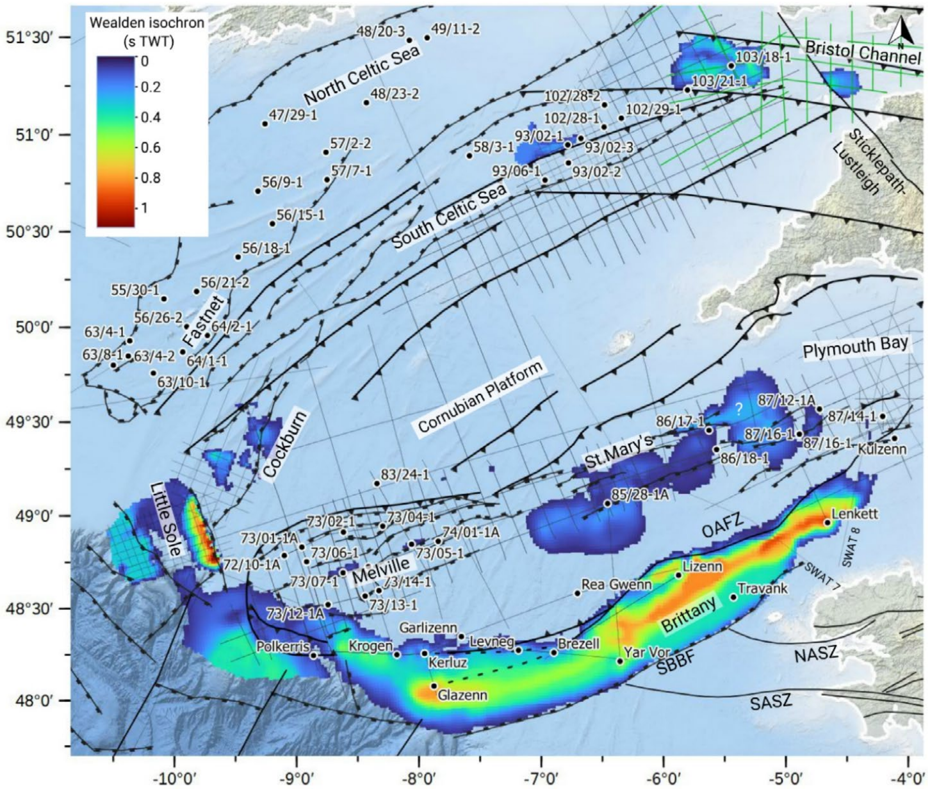


**FIGURE 14** | Isochron map of the Lower Cretaceous Wealden in SW Britain. Thickest units are interpreted in the Brittany and Little Sole basins. Minor accumulations of Wealden are present in St. Mary's, Cockburn, South Celtic Sea and Bristol Channel basins. Note how most of the interpreted pods of Wealden terminate at interpreted Variscan thrusts and associated strike-slip faults.

inclusions. The fossils and hyaline patches reflect a submarine origin for the volcanics. In well 74/01-1A at the far east of the basin, the volcanics are absent and dominant lithologies include sandstones, shales and an increase in carbonates. The sandstones and shales encountered in the zones around the basaltic intervals contain volcaniclastic debris and tuffs. Well 73/01-A, drilled on the flank of a salt anticline, encountered a volcanic unit that was devoid of marine flora or fauna and could indicate a localised terrestrial depositional setting. The absence of flora and fauna and the presence of ash suggest the volcanoes occasionally reached sea level. The abundance of vitrinite and humic material, such as in well 72/10-1A, indicates nearshore environments receiving terrestrial input. Further evidence of proximity to shore exists in well 73/02-1 where woody fragments and pyrite are found. It is difficult to correlate individual units in the Lower Cretaceous due to the variability of lithologies and the inconclusive biostratigraphic data in many wells in the Western Approaches.

Southwest of the Melville Basin, at the northern margins of the Bay of Biscay, DSDP wells 400 and 402 drilled into Albian rocks. This unit contained calcareous sediments deposited as turbidites and pelagic sediments. On the nearby platform high, DSDP well 401 encountered platform carbonates, dominated by pellet grainstones and packstones. In the Brittany Basin, well Lizenn encountered 205 m of siltstones containing traces of lignite and glauconite (Evans 1990); Albian sandstones were intersected by well Rea Gwenn (Deronzier et al. 1994) and undifferentiated late Early Cretaceous rocks were observed in Krogen-1B, Glazenn, Garlizenn and Brezel (Menpes 1997; Figure 1). Albian stratigraphy was eroded, perhaps as a consequence of Cenozoic uplift in Levneg and Lennket. Albian stratigraphy is completely absent in the Kulzenn well in the South-West Channel Basin. Upper Cretaceous Chalk is encountered on top of the BCU in Kulzenn, suggested that Albian sediments might have been deposited in this location (Deronzier et al. 1994).

## 6 | Discussion

In the previous sections, we examined stratigraphy across southwestern Britain to identify evidence of erosion in seismic and well data. In this section, we explore the implications of those observations and associated interpretations for understanding the structural and tectonic processes that influenced the distribution of Jurassic and Cretaceous unconformities. Following that, we synthesise the history of Early Jurassic, Mid to Late Jurassic, and Cretaceous tectonic and erosional events, including an assessment of potential ages for the unconformities. Subsequently, we backstrip stratigraphy to estimate the subsidence histories of the Brittany, South Celtic Sea and Melville basins, selected for their varying degrees of missing (strictly, *unobserved*) Jurassic and Cretaceous stratigraphy. Lastly, we speculate on the causes of the observed patterns of subsidence and uplift, proposing additional work that could help generate a more complete understanding of the geological history of southwestern Britain.

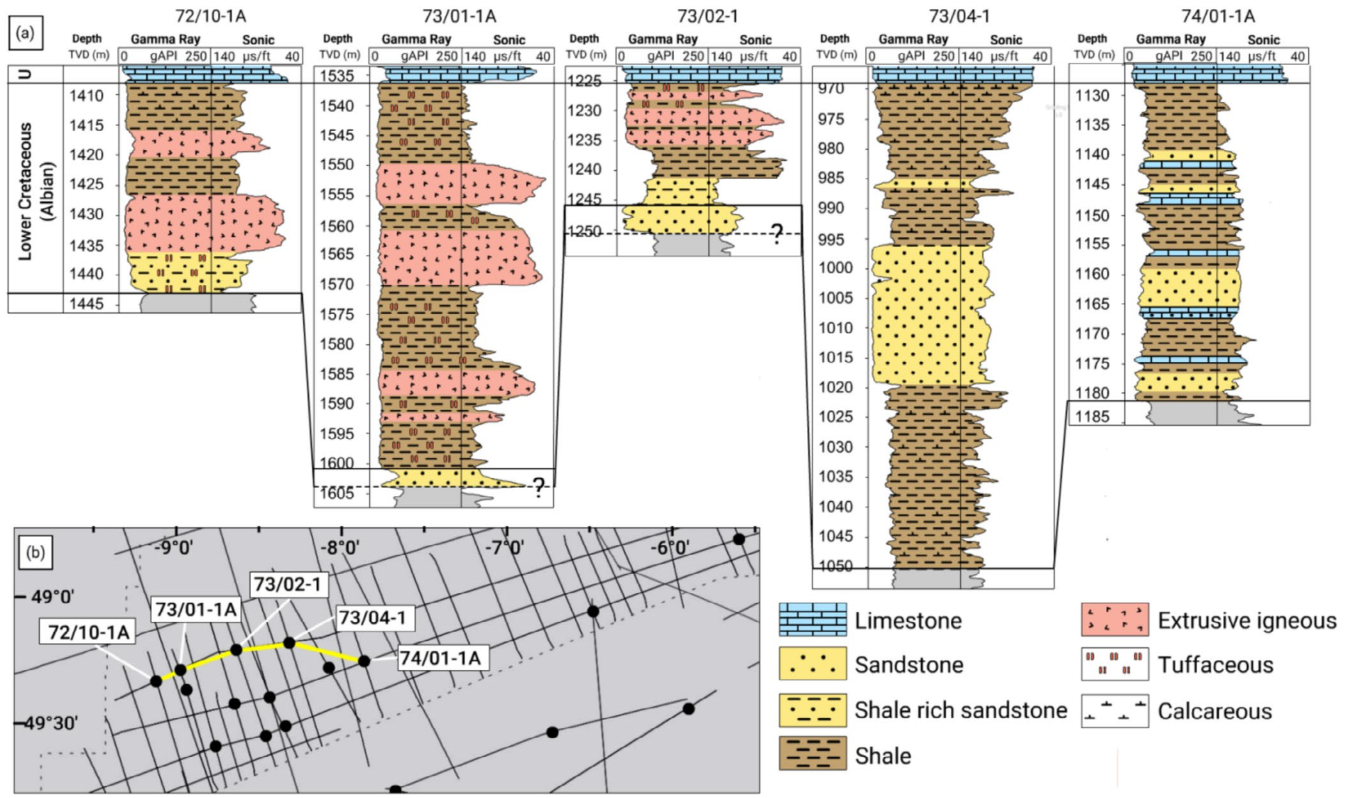


**FIGURE 15** | (a) Stratigraphic cross section and location map (b), showing gamma and sonic logs of the Lower Cretaceous Albian unit. The succession shows basaltic volcanism in the west Melville Basin associated with tuffaceous claystones and sandstones grading into Calcareous-rich clastics with interbedded limestones. Note the base sandstone unit in wells 73/01-1A and 73-02-1 could be parts of the Wealden or Lower Greensand Formations. The lithologies become more calcareous towards the top of the section.

### 6.1 | Structural Control and Variscan Inheritance

This study, along with the previous work summarised in the introductory part of this paper, highlights the significance of structural inheritance from reactivated Variscan thrust systems in influencing the development of post-Carboniferous basins (Figures 9, 10 and 12; Hillis 1988; Chapman 1989; Evans 1990; Ruffell 1995). Based on our analysis of seismic data, it is evident that the Wealden sediments were the initial deposits following Late Jurassic to Early Cretaceous uplift, displaying progressive onlapping onto older stratigraphy (Figures 2 and 11). Later in this section, we examine the Wealden depositional patterns to extract insights into the active structures during uplift events.

Seismic and magnetic data indicate that the strike of Variscan thrusts curves around the western edge of the North Melville Basin and is southeastward in the South Melville sub-basin (Figures 9, 10 and 12). The north-dipping thrusts identified in the Brittany Basin share the same trend as those beneath the South Melville sub-basin, which we tentatively interpret as an indication that Variscan compressional structures played a role in determining the geometry of the younger, extensional, sedimentary basins (Figures 10 and 14). In the Southwestern part of the Western Approaches and Brittany, the deposition of Jurassic sediments was apparently unaffected by the OAFZ, with depositional thicknesses comparable on both sides of the fault. Similarly, Early Cretaceous deposition of Wealden units appears to have continued just north of the OAFZ (Figure 12). Thus, we suggest that the OAFZ is a Cenozoic feature that could have formed parallel to (and south of) the identified Variscan thrusts (Figure 12). Further east, the Variscan fault system may link with thrusts interpreted on seismic lines SWAT 8 and 9 in the southern boundary of the Plymouth Bay Basin (Supporting Information Figure A).

### 6.2 | Early Jurassic Localised Denudation

A straightforward interpretation of the angular truncations observed within Jurassic stratigraphy in the North Melville, South Melville, Brittany and Cockburn basins is that Lower Jurassic sediments were deposited everywhere and mostly eroded by a large uplift event that generated the BCU. However, subtle evidence on seismic data reveals a more complex history of Early Jurassic evolution in the Melville Basin. For instance, in the North Melville Basin, the depth converted and decompacted clinoforms observed on seismic line L18 suggest possible clastic deposition (Figure 7). The evidence of clastic clinoforms in a limestone-dominated Lias suggests a localised marine–terrestrial transition and nearby terrestrial source of the sediment. The height, gradient and sigmoidal shape of the clinoforms suggest they could be large sand-prone and subaqueous delta-scale clinoforms (Patruno and Helland-Hansen 2018; Patruno et al. 2015). Well 73/1-1A north of the observed clinoforms encountered 15 m of Hettangian sandstone at 1999 m depth (Figure 1). The sand

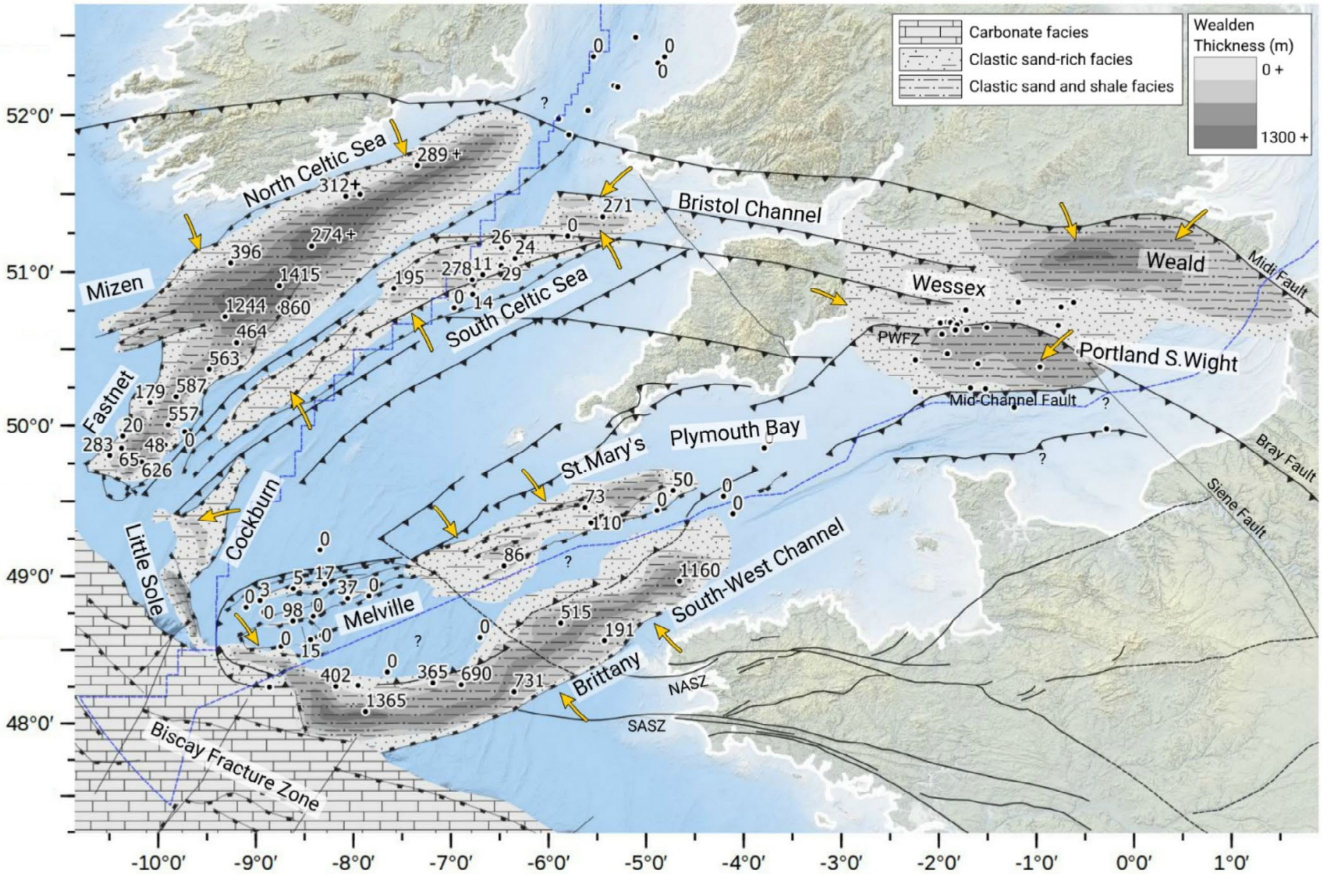


**FIGURE 16** | Thickness map of the Wealden unit in SW Britain. Wells are labelled with the thickness of Wealden encountered. Yellow arrows show the dominant sediment influx into the Wealden depocenters. The Main Variscan framework in Celtic Sea and Onshore UK is adapted from Le Gall (1990), the position of the Mid Channel faults is adapted from Boillot and Lefort (1974). Wealden thickness in the Wessex and Portland S.Wight Basin is from Hawkes et al. (1998). North Celtic Sea and Fastnet Wealden thickness map generated based on wells and data from Byrne (2020), Rodríguez-Salgado et al. (2019) and Ziegler (1990). NASZ, North Armorican Shear Zone; PWFZ, Portland Wight Fracture Zone; SASZ, South Armorican Shear Zone.

unit encountered in well 73/1-1A could be sourced from the described delta system in the south (Figure 7). The presence of the clinoforms dipping north from the central Melville Basin challenges the concept of Lower Jurassic deposition everywhere with minimal variations in thickness (cf. Evans 1990; Ruffell 1995; Chapman 1989). The thinning of Jurassic stratigraphy on the large erosional truncation observed in the Melville Basin could be explained by the area becoming a Late Triassic–Early Jurassic topographic high. An alternative explanation is that Early Jurassic stratigraphy was deposited in a rift setting where differential movements along major basin faults created localised basin highs. We suggest that minor Early Jurassic rifting is more plausible because similar thickness variations of Lias stratigraphy are seen along faults in the Wessex Basin (Hawkes et al. 1998; Figure 1).

### 6.3 | Mid to Late Jurassic Denudation

The Mid-Jurassic unconformity is evident in North Atlantic basins as a Bajocian to Oxfordian unconformity in the Jean d'Arc, Orphan, Lusitanian, Fastnet and North Celtic Sea basins (McMahon 1995; Sinclair and Riley 1995; Figure 3). Middle Jurassic sediments are mostly absent in the Melville, St. Mary's and Fastnet basins and on the Cornubian Platform. The lack of Jurassic stratigraphy makes identifying the Mid-Jurassic unconformity difficult as it merges with the BCU to create a composite unconformity (Figure 4). Evidence of MJU can be seen south in the Brittany Basin, where the complete Jurassic succession is preserved. A few kilometres east of well Rea Gwen (Figure 13), we interpreted Middle or Upper Jurassic seismic reflections onlapping Lower Jurassic reflections. This onlapping indicates that an uplift event occurred between Late Early Jurassic and Late Middle Jurassic times. This timing is consistent with the age of the Bajocian to Oxfordian unconformity observed in neighbouring basins (Figure 2). Therefore, we suggest that the unconformity is likely to be the MJU. Furthermore, the Middle to Upper Jurassic reflections are again truncated by a second unconformity: the BCU. The presence of erosional truncations indicates that a second uplift event occurred that resulted in erosion of the Middle or Upper Jurassic reflections. We suggest that this truncation was generated as a consequence of Late Jurassic–Early Cretaceous uplift.

In the North Melville Basin, the Wealden unit onlapping the Lower Jurassic reflections on both sides of the syncline is subparallel to Lower Jurassic stratigraphy in the centre of the syncline and exhibits no obvious erosive features (Figure 6). Given all the Mid and Late Jurassic–Early Cretaceous uplift events that occurred in neighbouring areas, we anticipate finding erosional features on the top Lias reflections. Thus, we suggest that rather than being subject to erosion, certain areas of the Melville Basin and SW Britain experienced low sedimentation rates during the Mid to Late Jurassic rates. In the Cockburn Basin, the parallel Jurassic reflections and absence of onlap onto older Jurassic stratigraphy suggest continuous deposition from Early to Mid or Late Jurassic times (Figure 5). Observations of the interiors of the two synclines preserved in the Melville and Cockburn basins reveal that during Middle Jurassic times, not all areas of these basins experienced uplift and denudation.

Several wells in the Brittany Basin, such as Krogen, Levneg, Yarvor and Lenkett (Figure 14), exhibit an uninterrupted Jurassic succession with continuous deposition. In contrast, wells Brezel, Linzen and Travank show a minor unconformity in the lowermost Upper Jurassic stratigraphy (Figure 14). The Kerluz and Glazen wells did not reach Jurassic rocks, but seismic facies suggest the presence of Jurassic units in the area. Galizenn and Rea Gwenn, drilled north of the Variscan thrusts, are the only two wells in the area that lack Middle or Upper Jurassic stratigraphy. The Variscan Thrusts seem to serve as a major structural boundary, distinguishing wells in the uplifted areas from those in regions experiencing continuous subsidence. Seismic imaging of the deeper Variscan faults is inconsistent in Brittany and the South Melville Basin; thus, the OAFZ served as a seismic reference in delineating the trend of Variscan faults. The OAFZ is interpreted to have formed as a large strike-slip fault directly south of the Variscan thrusts. Seismic data indicated that the OAFZ does not impact Jurassic to Lower Cretaceous deposition, suggesting it is a Cenozoic tectonic feature (Figure 12).

### 6.4 | Cretaceous Denudation

The Lower Cretaceous Wealden sediments delimited by the BCU and MCU provide insights into the history of denudation. By analysing their distribution and onlap onto older stratigraphy (Figures 2, 5, 6, 8 and 11), we can identify the structures involved. In SW Britain, Wealden deposition occurs in two distinct basin types: syncline sag-like basins (e.g., North Celtic Sea, South Celtic Sea, Fastnet, Cockburn, Brittany and SW Channel and Weald basins; Figure 16) and smaller half-graben basins exhibiting growth on major normal faults (e.g., Little Sole, Mizen, Stanley Bank and Portland South Wight; Figure 16). Our observations suggest the larger sag-like basins may have developed through the reactivation of low-angle Variscan thrusts.

In the South Melville Basin, a distinct separation between the MCU and BCU enables us to differentiate between the events responsible for erosion (Figure 8). The Wealden units deposited in hanging wall blocks are deposited parallel to the Cenozoic units above, while below the BCU, a clear angular truncation separates the Jurassic reflections (Figure 8). The Upper Greensand unit is also parallel to the Wealden units below the MCU. The highly folded and truncated Jurassic stratigraphy underlying the Wealden indicates that a Late Jurassic–Early Cretaceous shortening event caused most of the basin uplift and denudation, with Mid Cretaceous events playing a minor role. The new evidence established in this study challenges previous claims that the Mid Cretaceous Unconformity is the most significant erosive event in this region (cf. Ziegler 1987; Smith 1995).

In the South Celtic Sea, the Wealden pod is confined to three main Variscan thrusts without evidence of a significant Mid-Cretaceous Unconformity (Figure 16). In the western depocenter, Wealden facies onlap onto Middle Jurassic facies, progressively filling the syncline and merging into a composite BCU-MCU unconformity at the flanks (Figure 16; Supporting Information Figure C). In the eastern depocenter, clastic-dominated Wealden seismic facies lack clear seismic reflections, making it difficult to establish seismic facies and truncations. Moving eastward to the Bristol Channel Basin, Wealden stratigraphy is interpreted along the Sticklepath lineament, identified as a dextral late Variscan strike-slip fault (Holloway and Chadwick 1986). In the Brittany Basin, Wealden units thicken significantly into the basin centre and pinch out close to the interpreted thrusts (Figure 16). The Wealden deposition in Brittany appears to be analogous to the Weald Basin onshore SE UK, with sediments thickening in the central part and thinning towards the edges (Hawkes et al. 1998).

In Brittany, seismic data do not clearly reveal the geometry of the MCU. Thus, it is unclear whether Wealden deposition simply thins out northwards towards uplifted areas. While in basins to the north, such as the North Celtic Sea and Cockburn basins, the BCU is an angular unconformity at the basin margins (Ziegler 1990; Byrne 2020). The overlying Wealden is also clearly Truncated by the MCU (Rodríguez-Salgado et al. 2023; Figure 5). In the North Melville Basin, the tops of the Lower Jurassic clinoforms are truncated, suggesting erosion associated with either the MCU or Late Jurassic–Early Cretaceous events. The thinning of Albian units on top of the high suggests mid-Cretaceous uplift and erosion.

North of the South Melville sub-basin thrusts, thickened Wealden sediments form in a syncline, potentially serving as a pathway into a local Wealden depocenter in the Brittany Basin, where Glazenn drilled 1365 m of Wealden units. The eastern Brittany Basin and South West Channel Basin exhibit thick Wealden units likely sourced from the nearby Armorican and Cornubian Massifs, as well as possibly locally elevated highs around the English Channel monocline. An isolated depocenter in the St. Mary's Basin may have been connected to the Brittany Basin or remained a separate pod for some time, experiencing deposition similar to the nearby Purbeckian fresh to brackish water sediments seen in well 87/12-1A.

The Little Sole Basin, a narrow 15 km basin on the shelf edge, uniquely exhibits a non-Variscan trend, aligning sub-parallel to the shelf (Figure 16). By reconstructing the shelf to the Late Jurassic–Early Cretaceous boundary, the Little Sole Basin aligns parallel to the Biscay Fracture Zone (Figures 3 and 16), suggesting an association with rifting along the Bay of Biscay. An alternative interpretation could involve the reactivation of an unresolved Variscan fault.

The depositional patterns of the Lower Cretaceous Wealden units in sag basins and half grabens exclusively adjacent to Variscan features imply that reactivation along the thrusts is the likely factor for creating accommodation. We propose that most of the interpreted denudation resulted from Late Jurassic to Early Cretaceous uplift, with the highest amplitude uplift occurring in locations of older Variscan thrusts and associated strike-slip faults.

### 6.5 | Age of the Jurassic–Early Cretaceous and Mid Cretaceous Uplift Events

The earliest biostratigraphically dated Wealden rocks found in the Melville and St. Mary's basins are Barremian to Hauterivian aged (132.6–125 Ma; Figure 16; Well 73/07-1, 86/181 Biostratigraphy reports). In the Brittany Basin, Valanginian rocks, dating from 139.8 to 132.6 Ma, are interpreted in wells Lizenn and Brezell (Hillis 1988). Fastnet Basin's well 56/12-1 also reveals Valanginian rocks with a high stratigraphic growth rate (Rodríguez-Salgado et al. 2019). A unit displaying a similar growth pattern appears in the South Melville Basin (Figure 11), lacking seismic reflectivity, indicating possible early syn-rift alluvial fill (cf. Rodríguez-Salgado et al. 2019). The progressive onlap of the Wealden unit onto Lower Jurassic stratigraphy indicates rifting throughout the Early Cretaceous (Figures 4, 6 and 11). Nonetheless, the exact age of the Lower Cretaceous units is uncertain as they are undrilled where they exhibit the onlap. However, in Western Iberia and its Atlantic conjugate margin in the Grand Banks, lithological changes and abrupt increases in vitrinite reflectance measurements suggest two major Late Jurassic–Early Cretaceous uplift events (McMahon 1995). A Mid–Late Berriasian (~127 Ma) event is interpreted as having generated the largest uplift, and a second, minor Mid–Late Kimmeridgian (~154 Ma) event is suggested (McMahon 1995). Valanginian growth units in the Fastnet Basin (Rodríguez-Salgado et al. 2019) and the unit showing chaotic reflectivity in the Melville Basin (Figure 11) provide evidence for possible initial fill after the Late Jurassic and Early Cretaceous uplift. As Berriasian stratigraphy is mostly absent in the study area wells, it is possible that the highest amplitude Jurassic–Early Cretaceous uplift occurred during the Mid–Late Berriasian to Valanginian (~127–132.6 Ma).

In SW Britain, most wells reveal a Late Aptian to Early Albian (~113 Ma) intra-Cretaceous unconformity (Figures 4 and 15). Associated with this unconformity is extrusive submarine and terrestrial pyroclastic volcanism, concentrated in the western part of the Melville Basin. This volcanic activity coincided with the deposition of marine sandstone and claystones of the Upper Greensand formation (Figure 15). K/Ar dating of volcanic sills in the Melville Basin (well 73/7-1: 105.7 ± 7 Ma), Fastnet Basin (well 56/18–1: 113 ± 5 Ma), and Wolf Rock and Epson Shoal (112 ± 2 Ma; Figure 1) supports an Aptian–Albian age (well 73/7-1 and 56/18-1 reports, Harrison et al. 1977). The age of the MCU is best constrained where well and outcrop observations are available. In the Weald Basin of Southern England (Figure 16), Ruffell (1992) interpreted part of the Aptian under the MCU, with the nutfieldiensis transgression separating the unconformity from the lower Aptian (Casey 1961; Bridges and Stride 1982). The Late Aptian Sandgate Formation and the Aptian–Albian Folkestone Formation onlap the MCU, forming a composite unconformity later transgressed by the Albian Gault and Upper Greensand Formations. Additionally, during the late Aptian along the Western Iberian margin, substantial influxes of coarse-grained clastic sediments suggest potential denudation (Pinheiro et al. 1996). Radiometric dating, biostratigraphy and rock petrology collectively suggest a late Aptian to Early Albian age for the unconformity.

### 6.6 | Subsidence Analysis

In this section, we assess mechanisms that might be responsible for generating the stratigraphic observations and unconformities in southwest Britain. We first backstrip stratigraphy from the Brittany, South Celtic Sea and Melville basins to quantify their subsidence histories. These basins were chosen for analysis because they incorporate stratigraphy from across the region, and the observations presented earlier in this paper indicate that they have clearly experienced different amounts of denudation. We then discuss plausible mechanisms for generating the observed denudation with the aid of the contextual subsidence histories. To establish a history of vertical motions in SW Britain, we compare and discuss the tectonic subsidence of three basins (Figure 17; cf. Watts and Steckler 1979). First, a pseudo-well in the Brittany Basin, where Jurassic to Cretaceous deposition remains hitherto uninterrupted, was backstripped (Figures 1 and 12). Secondly, in the South Celtic Sea Basin, we analyse a pseudo-well located in a syncline with thick Middle Jurassic units (Figure 1; Supporting Information Figure C). Thirdly, In the Melville Basin, we backstrip stratigraphy recorded in well 73/13-1, which contains a 3 km Permo-Triassic section and intersects truncated Lower Jurassic reflections mapped with seismic data (Figure 1; Supporting Information Figure D).

The raw burial curves show rapid subsidence followed by a phase of subsidence at much reduced rates (Figure 17). The raw burial curves were decompacted following Athy's (1930) approach, such that we assume the porosity of the lithologies varies according to $\Phi(z) = \Phi_1 + (\Phi_0 - \Phi_1)e^{-kz}$ (Athy 1930, Supporting Information Spreadsheet E). The decompacted curves were water-loaded, assuming Airy isostasy prevails. Paleo-water depth uncertainties, which tend to be $< 200$ m in these basins, are included in the analysis and shown on Figure 17. The water-loaded subsidence curves were compared to theoretical subsidence curves generated assuming instantaneous stretching (McKenzie 1978; Fowler 1990). They were generated by systematically varying stretching factors from 1 to 2 (Supporting Information Spreadsheet E).

In the Brittany Basin, present-day sediment thicknesses correspond to a tectonic subsidence of ~2.1 km. Early Jurassic to Late Early Cretaceous rifting is assumed (Deronzier et al. 1994; Figure 12). Theoretical subsidence with a stretching factor of 1.52 incorporating Jurassic and Cretaceous rifting yields a low residual misfit to observed subsidence. In comparison to the South Celtic Sea, the Brittany Basin preserves up to 1.5 km of additional Upper Jurassic and 1.7 km of Lower Cretaceous deposition (Figure 17c). In the South Celtic Sea, most of the Upper Jurassic stratigraphy is eroded. Assuming Early Jurassic to Middle Jurassic rifting, the calculated stretching factor for the unrestored Jurassic syn-rift is 1.22 (Figure 17b). A larger stretching factor is likely, given the middle Jurassic is observed to be truncated on seismic (Supporting Information Figure C). In the Melville Basin, the best-fitting theoretical subsidence curve has a stretching factor of 1.6, calculated assuming Permian rifting (Figure 17a). The thermal subsidence profile produced by the Permian syn-rift period alone does align with the observed tectonic subsidence of the basin. Even with no additional subsidence from Jurassic and Cretaceous syn-rift, the tectonic subsidence requires an additional 2.8 km of Jurassic sediments to match the thermal subsidence of the Permian syn-rift. We interpret these results as being consistent with denudation of Jurassic and Cretaceous stratigraphy being greater in the Melville Basin than in the Brittany and South Celtic Sea basins.

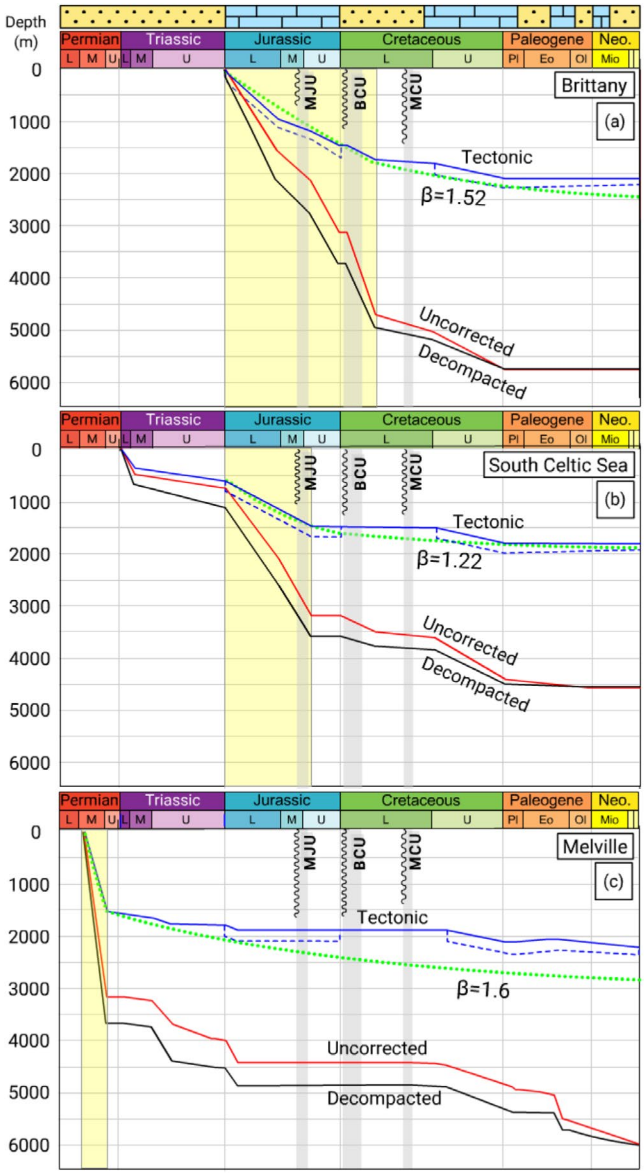


**FIGURE 17** | Subsidence plots for the Melville Basin (a), South Celtic Sea Basin (b) and the Brittany Basin (c). For location see Figure 1. Assumed syn-rift period shown in yellow. Generalised lithologies for the geological time periods shown at the top of the chart. Theoretical post-rift subsidence for the stretching factor that best fits subsidence during the inferred syn-rift period is shown by the dotted green curve.

## 6.7 | Origins of the Unconformities: Uplift Mechanisms

We now examine potential mechanisms for generating Late Jurassic to Early Cretaceous uplift of SW Britain. First, while lithospheric flexure can cause substantial uplift (Allen and Allen 2013), the subsidence curves display a characteristic concave-up trend typical of rifting (Figure 17). The apparent prevalence of tensional stresses during the opening of the North Atlantic, coupled with the absence of an obvious nearby lithospheric load, diminishes the likelihood of flexure-related uplift (Mauffret et al. 1989; Merino et al. 2021). We also suggest that glacio-eustasy is unlikely to have played an important role in generating observed denudation since Early Berriasian and Mid-Valanginian sea level drop appears to have led to widespread terrestrial conditions in NW Europe (Haq 2014). Moreover, biostratigraphy in wells across SW Britain indicates that paleo-water depths were small (< 200 m) at this time (Figure 17).

Rift flank uplift due to the initiation of seafloor spreading may have resulted in the denudation that generated the observed unconformities (e.g., Braun and Beaumont 1989). However, the observed erosion cannot be solely attributed to footwall uplift as basin centres also show signs of erosion (Figures 4 and 12). Such significant vertical motions could perhaps result from sub-plate support (Underhill and Partington 1993; Hoggard et al. 2016; Fernandes and Roberts 2021). Regional warping of the rift zone due to melt accumulation within or at the base of the lithosphere (underplating) prior to potential seafloor spreading in the Tagus Basin could also play a role (Keen et al. 1987; Figure 3). Early Cretaceous magmatism, including dolerite sills with K/Ar apparent ages of 125 ± 4 Ma (Barremian) in the Fastnet Basin (Well 56/18-1 report) and Lower Cretaceous volcanic plugs offshore Cornwall (Harrison et al. 1977), is also suggestive of support from the convecting mantle. However, inconclusive dating, with some samples with K-Ar ages of 113 ± 5 Ma (Aptian-Albian; Well 56/18-1 report) and 112 ± 12 Ma (Aptian-Albian; Harrison et al. 1977), indicates that more work needs to be done to understand the history of magmatism here.

Late Jurassic to Early Cretaceous erosional patterns and uplift observed or inferred in the study area are spatially variable, with different amounts of missing stratigraphic sections impacting different parts of basins. Specifically, we observe an increase in missing stratigraphic sections towards reactivated Variscan faults, basin bounding faults and strike-slip flower structures (Figures 4, 9 and 12). The spatial variability of missing stratigraphic sections, and their apparent control by structural elements, suggests tectonic shortening as the primary cause of uplift.

The younger Mid-Cretaceous Aptian–Albian events, coinciding with the northward propagation of the North Atlantic, featured significant E–W rifting between Newfoundland, Porcupine Bank and the Porcupine Basin (Skogseid 2010; Figure 3). This rifting extended southwestward into the East and West Orphan Basin (McMahon 1995; Skogseid 2010; Figure 3). Concurrently, the Bay of Biscay experienced N–S rifting, leading to oceanic crust formation around 110 Ma

**TABLE 2** | Summary of unconformities in Jurassic to Cretaceous stratigraphy, including their regional extent, proposed mechanisms and associated regional events. References are provided for the example areas with observed evidence: Jean d'Arc, Orphan and Lusitanian basins (McMahon 1995; Sinclair and Riley 1995); North Celtic Sea Basin (van Hoorn 1987; Millson 1987; Copestake et al. 2018); Fastnet Basin (Copestake et al. 2018; Rodríguez-Salgado et al. 2019).

| Age | Event | Example area(s) with observed evidence | Proposed mechanism in area of study | Regional events |
|---|---|---|---|---|
| Early Jurassic | Early Jurassic Unconformity (Inferred) | North Melville sub-basin (Figure 7) | Minor Early Jurassic rifting, differential movements along major basin faults created localised basin highs | Opening of North Atlantic |
| Mid-Jurassic (Bajocian-Oxfordian) | Mid-Jurassic Unconformity (MJU) | Jean d'Arc, Orphan, Lusitanian, Fastnet, North Celtic Sea and Cockburn basins (Figure 5); northern Brittany Basin (Figure 13) | Regional uplift due to tectonic shortening, focused on reactivated Variscan thrusts | |
| Late Jurassic (Oxfordian) | Late Jurassic Unconformity (Inferred) | Jean d'Arc, Orphan and North Celtic Sea basins | | |
| Early Cretaceous (Berriasian-Valanginian) | Base Cretaceous Unconformity (BCU) | Melville Basin (Figures 4, 6, 8, 9 and 11); South Celtic Sea Basin (Supporting Information Figure C); southern North Celtic Sea, Bristol Channel and north Brittany basins (Figure 13); Little Sole and Cockburn basins (Figures 4 and 5) | | |
| Mid Cretaceous (Aptian-Albian) | Mid Cretaceous Unconformity (MCU) | South Celtic Sea and Melville basins (Figures 4, 6, 8, 9 and 11), Cockburn Basin (Figure 5), Portland Wight, Wessex and Brittany basins | Regional uplift, broadly distributed unconformity, possible sub-plate support and volcanism | Opening of Bay of Biscay (rift to drift transition) |

(Montadert et al. 1979; Boillot 1984; Rosenbaum et al. 2002; Figure 3). The MCU's impact is evident in most of the basins in SW Britain, manifesting as erosion in basin centres and edges (Figures 5, 6, 8 and 11). The presence of volcanics (Figure 15) and interpreted widespread regional uplift during the opening of the Bay of Biscay suggests potential sub-plate support as a driving mechanism for the uplift.

Our research has unveiled that the BCU is mainly a composite unconformity formed by various events from the Mid-Jurassic to the Late Jurassic and Mid-Barriasian to Valanginian periods. Significantly, the most substantial erosion happened during the Mid-Berriasian to Valanginian event, which aligns with mapped Variscan structures and Wealden depositional trends, suggesting uplift likely due to shortening. However, in some parts of the basin, non-deposition rather than erosion may have contributed to the unconformity, indicating depositional hiatuses. In contrast, the MCU appears connected to volcanism and widespread regional erosion, suggesting a potential role of sub-plate support.

We suggest that backstripping stratigraphy across all sub-basins in this area will provide insights into their commonalities and their unique subsidence histories. Paleothermometry and quantifying over-compaction may help quantify the extent of Jurassic and Cretaceous sections removed by denudation (e.g., from vitrinite reflectance; seismic and sonic velocities; Smith et al. 1994; Corcoran and Clayton 2001; Mackay and White 2006). Lastly, calculating strain-rate histories for the basins could help to identify the geological processes that drove the vertical motions of offshore Southwest Britain.

## 7 | Conclusions

This study of Jurassic and Early Cretaceous stratigraphy in the sedimentary basins of Southwest Britain provides insights into the spatio-temporal evolution of the history of Permian to Recent lithospheric vertical motions. Seismic interpretation and subsidence analysis indicate that different basins in Southwest Britain had different histories of stretching and cooling. A simple model of Early Jurassic instantaneous rifting and post-rift cooling is consistent with the calculated subsidence history of the Brittany Basin, for instance. However, such simple stretching models are inadequate for explaining the subsidence histories of the Melville and South Celtic Sea basins.

The hitherto enigmatic Base Cretaceous Unconformity (BCU) and Mid Cretaceous Unconformity (MCU) indicate that there is substantial missing stratigraphy in these basins, which we suggest explains why simple rift-cooling models are inappropriate. We mapped stratigraphy throughout these basins using seismic reflection data that, as far as we are aware, have not been published before and legacy well data. This work shows that the BCU is a composite of multiple unconformities. Early Cretaceous denudation appears to have primarily occurred at the margins of basins across SW Britain, atop Variscan structures. Variations in interpreted denudation and seismic onlap suggest a connection to reactivated Variscan thrusts and transfer faults during Callovian–Oxfordian and Berriasian times. The majority of denudation that generated the composite BCU is attributed to erosion following Berriasian uplift, which we tentatively relate to shortening associated with the opening of the North Atlantic Ocean. In contrast, the shallower Aptian–Albian MCU is identified as a more subtle and broadly distributed unconformity. These observations combined with observed patterns of magmatism suggest that sub-plate support may have played a role in generating the vertical motions that resulted in the denudation that formed the MCU. We note that the MCU was probably generated at broadly the same time as the Bay of Biscay transitioned from rift to drift.

To illustrate the regional distribution, timing and mechanisms associated with these unconformities, Table 2 provides an overview of their key characteristics, including examples of affected areas where seismic evidence of truncation, onlap or erosional surfaces is observed, proposed mechanisms and broader regional events. These findings suggest that stratigraphy in sedimentary basins across SW Britain indicates a history of rifting followed by thermal sag interrupted by relatively short-lived mid-Jurassic and, dominantly, early Cretaceous phases of shortening and perhaps more widespread mid-Cretaceous sub-plate support.

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### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are openly available in UK National Data Repository at https://ndr.nstauthority.co.uk/.

### Peer Review

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section.