# A Tectonostratigraphic History of Orphan Basin, Offshore Newfoundland, Canada*

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## Abstract

Recent drilling along the eastern margin of Orphan Basin (Figure 1) and in the Flemish Pass, offshore Newfoundland, has spurred renewed interest in the economic potential of the region. Formation of Orphan Basin is linked to rifting and development of the North Atlantic Ocean, which began offshore Newfoundland as early as the Triassic and ended in the Early Cretaceous. The basin is positioned near a change in the spreading direction of the North Atlantic, with the onset of opening younging to the north. Plate reconstructions show a complicated interaction of small continental fragments in this region. An understanding of the evolution of the structurally and stratigraphically complex Orphan Basin has been primarily based on seismic data (e.g., Enachescu et al., 2005). Building on these detailed seismic studies, our approach incorporates well logs, core, cuttings, biostratigraphy, seismic data and subsidence history to understand tectonic drivers behind basin formation and the associated stratigraphic responses. Here we describe seven significant tectonostratigraphic events that define the formation and infilling of Orphan Basin.

## Discussion

Early rifting in Orphan Basin had begun by the Middle to Late Jurassic (possibly earlier), with Bajocian nearshore marine deposits preserved on Orphan Knoll and older Jurassic sediments imaged by seismic in the central and eastern portions of Orphan Basin. A second phase of rifting took place during the Tithonian and into the Early Cretaceous, with a shallow, restricted marine setting persisting across the East Orphan Basin area and into the Flemish Pass (Figure 1). The clastic sequences were predominated by shales formed under quiet waters with low oxygenation and little faunal content (Figure 2). Fluctuations in relative sea level during this time also resulted in sandy clastic fluvial and estuarine deposits accumulating in proximal settings. The depositional conditions resembled that of the Kimmeridgian in the Jeanne d'Arc Basin that incorporates the Egret Member (Sinclair, 1988)—a viable Late Jurassic source rock interval. Deformation of Jurassic and Lower Cretaceous sediments in Orphan Basin likely took place during two phases: Middle to Late Jurassic and the Latest Jurassic to Early Cretaceous. Supporting evidence for Middle-Late Jurassic deformation includes a prominent seismically imaged unconformity capping deposits that are everywhere deformed by faulting and warping. The Tithonian through Lower Cretaceous deposits appear generally conformable on seismic and in well data (Figure 2), but show localized deformation and associated uplift along the feature described by Enachescu et al. (2005) and others as the Central Orphan High (Figure 1).

The Lower Cretaceous sedimentary successions in Orphan Basin reflect a gradual deepening from nearshore-marine to shallow- or mid-shelf conditions as rifting propagated westward into western Orphan Basin. Shallow shelf conditions are recorded in the development of oolitic limestones at the Blue H-28 well (Figure 2) and various facies across the basin showing abundant bioturbation in a well-oxygenated setting. This rise in relative sea level was most likely a function of continued rifting and subsidence of basement blocks, which created accommodation space for Lower Cretaceous sediments that show pronounced accumulation against growth faults in West Orphan Basin (Figure 1). During basin filling in the Early Cretaceous, a drop in relative sea level in the Aptian resulted in sequence boundary development seen in both well and seismic data, with basement highs and the tops of basin fills truncated during subaerial exposure and erosion. This widespread unconformity extends south across the Grand Banks and likely reflects a large-scale tectonic event that, at this time, cannot be fully explained.

The mid to late Cretaceous is marked by resumed relative sea-level rise in the Albian and continued accumulation in deep sub-basins along both the western and eastern margins of Orphan Basin. Shallow, restricted marine shales are followed by progradational sandstones along the proximal margins of the basin, forming distinct coarsening upward parasequences (Figure 2). At this time, extensive thinning of the continental crust and perhaps development of serpentinized mantle (Figure 3; Welford et al., 2010) outboard of East Orphan Basin and the Orphan Knoll may be linked with subsidence and development of a major flooding surface expressed in proximal wells. Subsidence was, however, minimal in comparison to that of the latest Cretaceous and early Tertiary. Basin filling progressed until yet another relative sea level fall resulted in development of a Santonian-aged sequence boundary. This is distinguished by biostratigraphic markers from wells (Figure 2) and seismic evidence of an angular unconformity. Similar to the Aptian unconformity, the Santonian sequence boundary is also related to rifting with a comparatively subdued nature that reflects another relatively widespread tectonic event.

Following Santonian subaerial exposure and sequence boundary development along highs in Orphan Basin, lowstand progradation was recorded primarily within proximal wells. Progradation was succeeded by rapid subsidence of Orphan Basin beginning in the early to middle Maastrichtian as seen by transgressive surfaces of erosion in proximal wells (e.g., Linnet E-63 and Baie Verte J-57; Figure 2). The rate of subsidence was so rapid that little transgressive material was deposited and a maximum flooding event produced a prominent seismic reflector (“Base Tertiary”) across the basin (Figure 2). In the early to middle Paleocene, subsidence peaked at bathyal depths. This phase of rapid subsidence is somewhat later than would be predicted for a margin where transitional crust may have developed east of the basin during Albian-Santonian time, prior to Santonian sea-floor spreading by Anomaly 34 (Figure 3; Srivastava et al., 1988). Only minor faulting is observed within basin sediments during this time, suggesting that rifting had ended, and mantle upwelling/extension had moved away to the east and north. This would imply rapid post-rift thermal subsidence, which is not observed. We suggest that there are two possible mechanisms which might delay this subsidence: first, the mantle under the basin may still have been flowing in response to the development of transitional/oceanic crust to the east, even though the upper crust appears to have been passive; and second, based on evidence from seismic data, the basin remained coupled to the European continental plate to the north, across the incipient Charlie-Gibbs Fracture Zone (CGFZ), possibly until Maastrichtian time.

Along the northern limit of Orphan Basin, evidence of major crustal faulting explains the linear shelf edge that begins at 51 degrees N latitude. In this area, faulting appears to have taken place later than in Orphan Basin, but prior to development of the magnetic low that corresponds to Anomaly 34 south of the CGFZ (Figure 3). By analogy to the contiguous southern Labrador margin to the north, we think this is a non-volcanic margin, with a transitional zone against and outboard of the rifted continental crust. The age of the transitional zone may be Santonian to Maastrichtian, again by analogy to that in the southern Labrador margin (Chian et al., 1995). South of CGFZ however, Anomaly 34 marks the onset of the earliest oceanic crust (Figure 3; Srivastava et al., 1988). Until Maastrichtian time, continued continent-continent coupling may have prevented major subsidence over much of central Orphan basin while the western and eastern margins subsided more rapidly during Cretaceous time.

In the latest Cretaceous to Early Eocene, the area around the landward projection of the CGFZ in northern Orphan Basin experienced localized magmatism. Volcanic edifices are imaged on seismic and possess a strong magnetic signature. These volcanic highs appear to be sourced from depth where adjacent reflectors are abruptly truncated. These volcanic edifices postdate both the major crustal faulting in the area and development of the magnetic low that correlates to Anomaly 34 south of the CGFZ (Figure 3). Similar volcanism may occur on the conjugate margin of south Rockall Bank (Bull and Masson, 1996) and/or south Rockall Basin (Scrutton and Bentley, 1988). The major changes in plate motions at that time may have been responsible for the magmatism we observed along the northern edge of the Orphan Basin, where some of these changes may have been accommodated within the CGFZ.

During the remainder of the Tertiary, basin filling followed thermal subsidence and consequent creation of accommodation space. Prior to this time, the raised nature of the entire Orphan Basin had resulted in very subdued shelf/slope morphology. As basin filling commenced, various processes took place in different parts of the basin. Central Orphan remained relatively starved of sediment until the Miocene, whereas deposition in eastern Orphan Basin was predominated by mass transport complexes derived from sediments accumulated on the Sackville Spur. In the northern part of Orphan Basin, high sedimentation rates persisted during in the Eocene and Oligocene, but the area was sediment starved in the Neogene. The western margin of the basin saw the development of stepped shelf-slope morphology as eustatic sea level fluctuations formed of a number of sequence boundaries and correlative conformities.

## Conclusions

The evolution of Orphan Basin involves multiple tectonostratigraphic events that combined to influence the present day basin morphology and sedimentary fill. These events included: 1) Middle to Late Jurassic rifting, shallow marine deposition, and subsequent deformation; 2) Tithonian and Early Cretaceous rifting that propagated westward, with shallow marine to shelfal deposition; 3) development of the central Orphan High and deformation of Tithonian and Lower Cretaceous units around the time of Aptian sequence boundary development; 4) thinning of continental crust outside of Orphan Knoll and possible contemporaneous development of a major flooding surface in the Albian-Cenomanian; 5) Santonian sequence boundary development with late crustal faulting in northern Orphan Basin and north of the CGFZ, initiation of transitional crust with true oceanic crust development south of the CGFZ, and major subsidence of the basin in Maastrichtian-Paleocene time; 6) magmatism in northern Orphan Basin; and 7) Tertiary basin filling and shelf-slope development.

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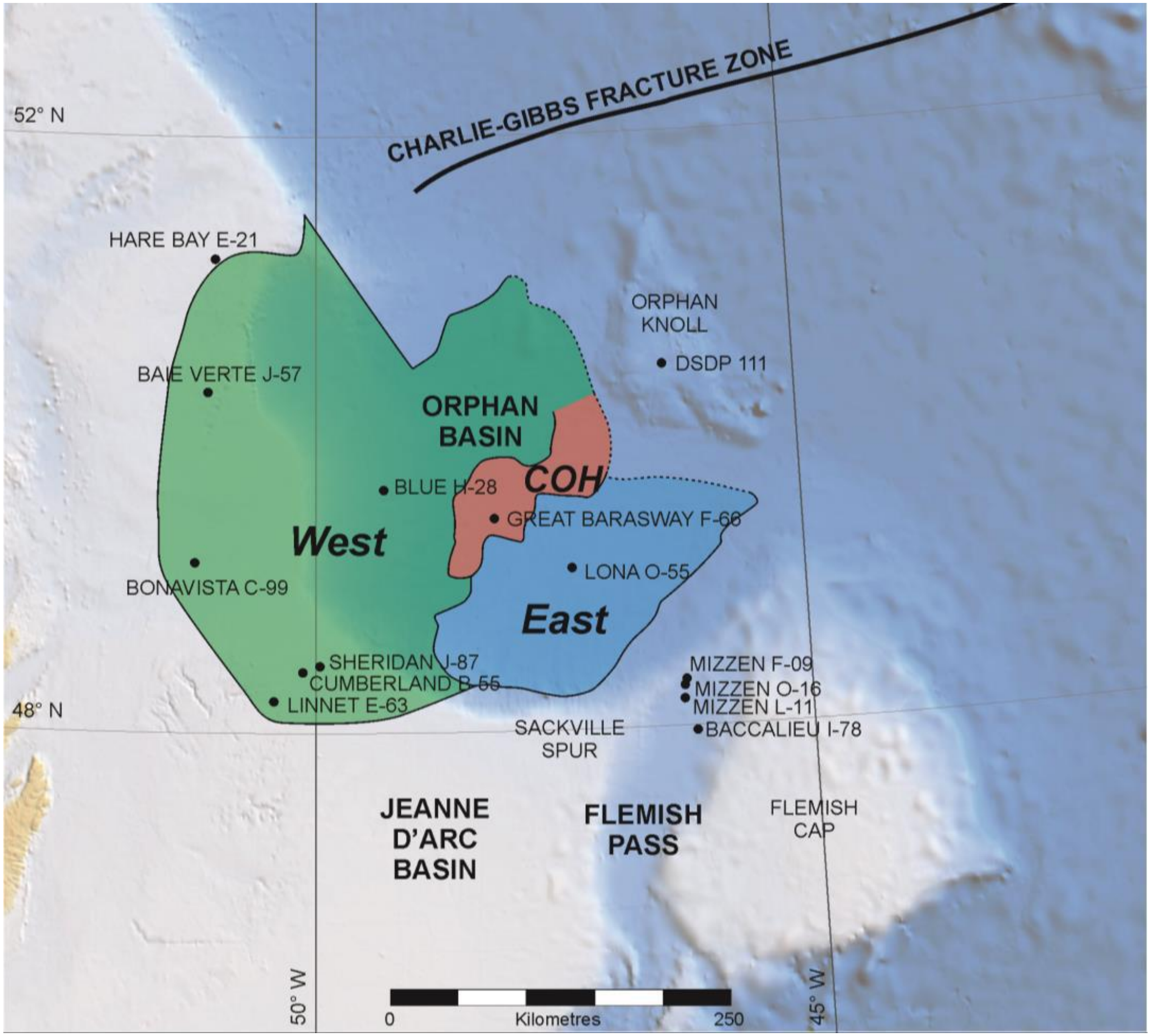

Figure 1. Bathymetric map of Orphan Basin showing well locations and the major bathymetric features. Orphan Basin is subdivided into West Orphan Basin, East Orphan Basin and the intervening Central Orphan High (COH).

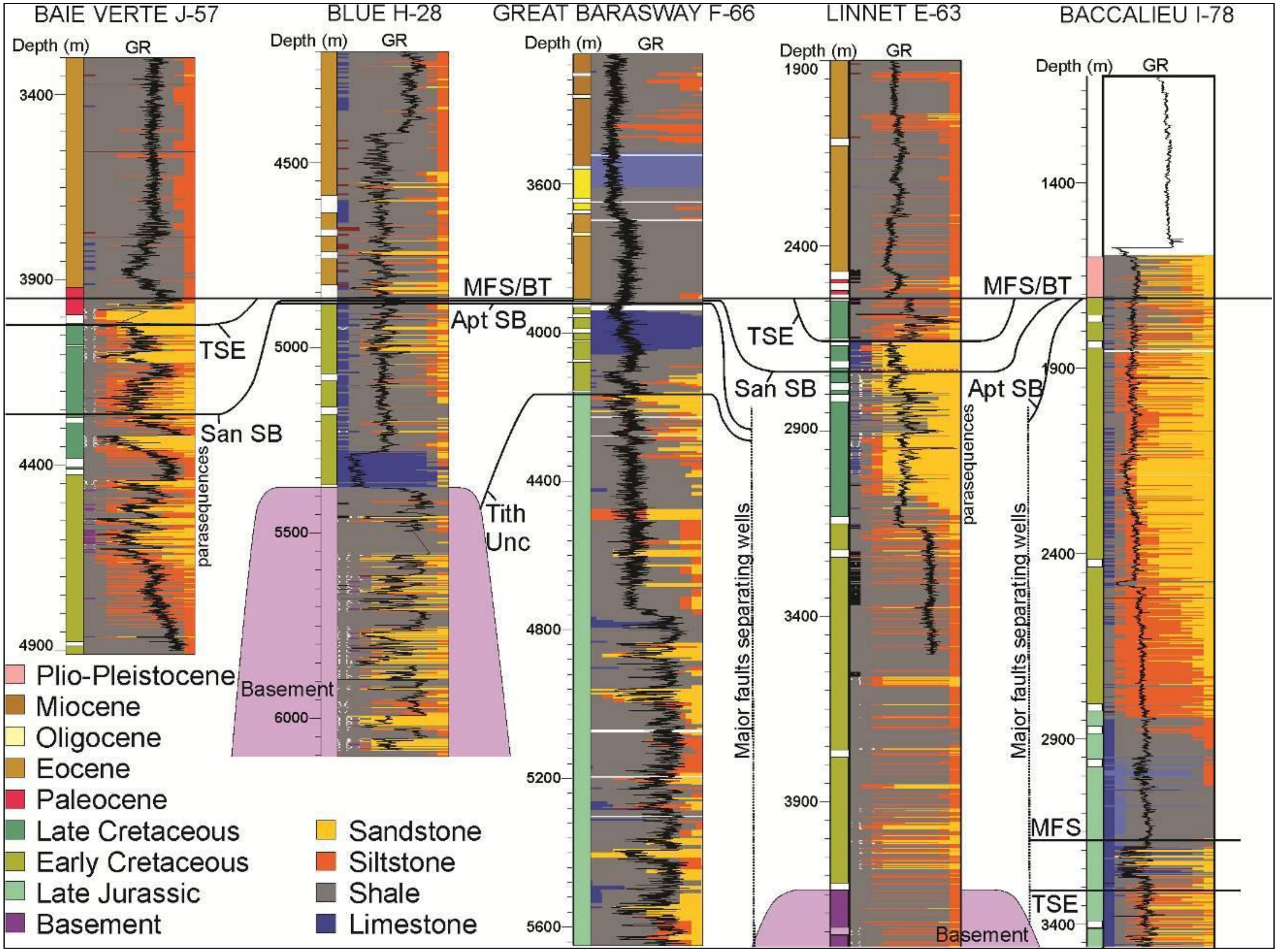

Figure 2. Cross section through Orphan Basin wells and the Baccalieu I-78 well of the Flemish Pass. Two major Cretaceous unconformities are present and account for much of the erosion that has taken place atop basement highs where the "Base Tertiary" surface overprints. In Great Barasway F-66, a Tithonian-Cretaceous unconformity is present; however, no unconformity was noted in the Baccalieu well. Apt SB= Aptian sequence boundary, BT= "Base Tertiary," GR= gamma ray, MFS= maximum flooding surface, San SB= Santonian sequence boundary, Tith Unc= Tithonian unconformity, TSE= transgressive surface of erosion.

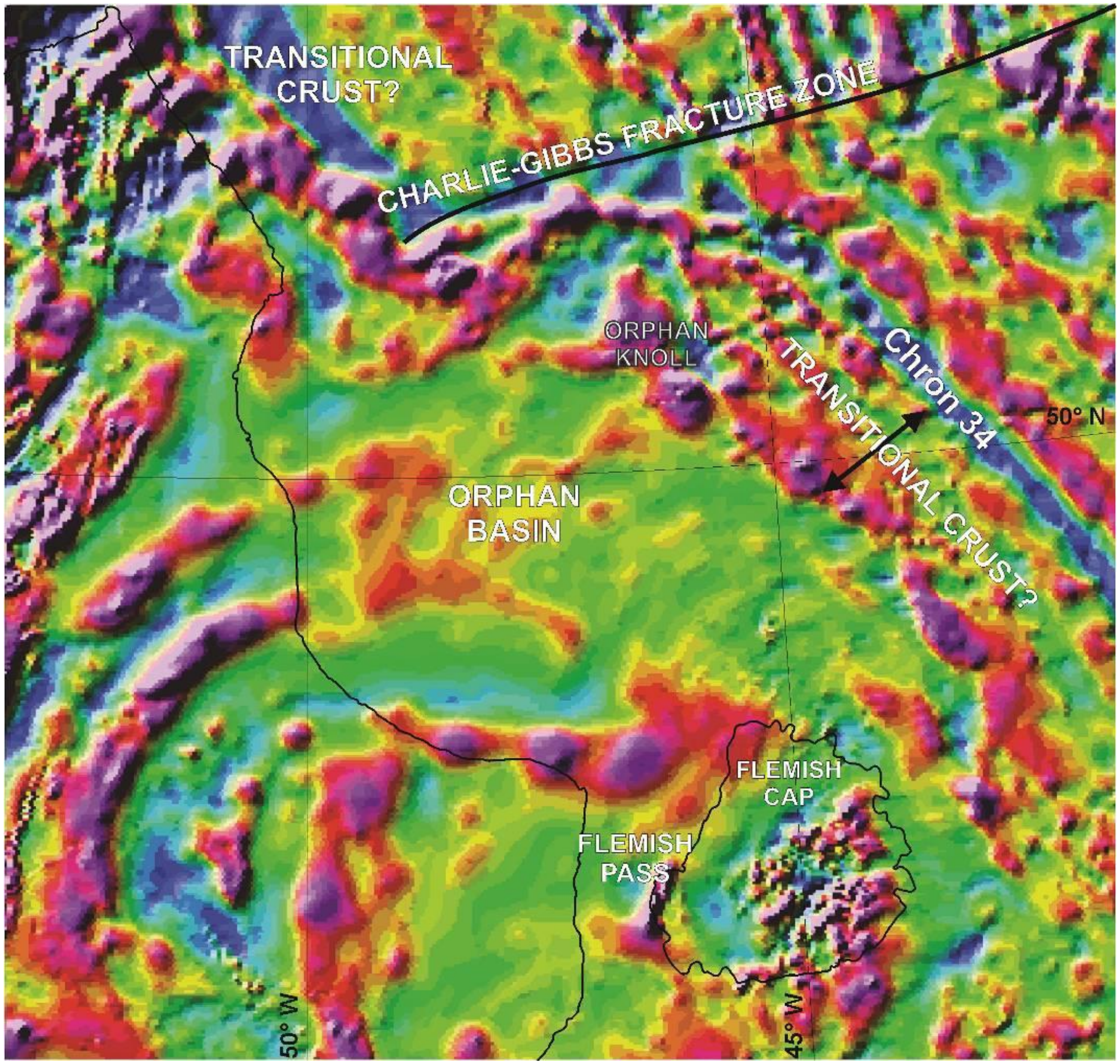

Figure 3. Magnetic map showing prominent anomalies in the Orphan Basin region and adjacent seafloor (after Oakey and Dehler, 2004). Red to purple colours reflect magnetic highs while greens and blues indicate magnetic lows. Also shown is the 400 m bathymetric contours that approximate the shelf edge and Chron 34.