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Reply to Alves et al. (2022) Discussion on "Stratigraphic record of continental breakup, offshore NW Australia" by Reeve et al. (2022)

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We welcome the Comment of Alves et al. (2022) as an opportunity to further discuss the stratigraphic record of continental break-up, offshore NW Australia. We here summarise Reeve et al. (2022), before discussing themes raised by Alves et al. (2022), specifically classification of our analysed stratigraphic succession as a 'Breakup Sequence' (as originally defined by Soares et al., 2012) and how we can interpret the processes driving unconformity development during continental breakup, particularly offshore NW Australia.

Summary of Reeve et al. (2022)

We used a dense 165,000 km^2 grid of 2D seismic reflection surveys, 12 3D seismic volumes, and 165 boreholes from across parts of the Exmouth Plateau, Exmouth Sub-basin, Carnarvon Terrace, and Barrow Sub-basin to examine the stratigraphic record of continental breakup offshore NW Australia. We specifically analysed the geological and geophysical expression and distribution of three Early Cretaceous unconformities, as well as the sedimentology and architecture of the related stratigraphic succession. These unconformities, located in the proximal domain of the NW Australian rifted margin (see Peron-Pinvidic et al., 2019), have previously been linked to continental breakup between Australia and Greater India (e.g., Arditto, 1993; Romine and Durrant, 1996; Tindale et al., 1998; Marshall and Lang, 2013; Gard et al., 2016; Paumard et al., 2018).

To assess the timing of unconformity development relative to recognised tectonic and geodynamic events, we recalibrated the age of dinoflagellate zones recorded within strata bounding the unconformities using calcareous nannofossil occurrences (see methodology in Gard et al., 2016). Critically, calcareous nannofossils, although not commonly preserved in Early Cretaceous sequences in our study boreholes, are well-calibrated to the global chronostratigraphic timescale and magnetic chrons (Gard et al., 2016). Our recalibration thus allowed us to use the abundant dinoflagellate microfossils found within the 165 studied boreholes, along with an assessment of sediment reworking and interpretation of seismic-stratigraphic relationships, to tie unconformity development to magnetic chrons in the adjacent continent-ocean transition zone (COTZ) and oceanic crust. From these findings, we suggested that the three unconformities may have formed in response to: (1) localisation of magma-assisted rifting, linked to COTZ development and/or seafloor spreading, between 134.98–133.74 Ma (Intra-Valanginian Unconformity); (2) generation of magmatic crust in COTZs between ~134–133 Ma (Top Valanginian Unconformity); and (3) full continental lithospheric breakup between ~132.5–131 Ma (Intra-Hauterivian Unconformity) (Reeve et al., 2022). Note that contrary to the claim made by Alves et al. (2022) (pXXX), we did not suggest that the end of the syn-rift phase was defined by the formation of a single unconformity. Instead, we recognised that breakup was "*represented by multiple unconformities [and inherently the surrounding strata] reflecting a complex history of uplift* *and subsidence during the transition from continental rifting to seafloor spreading*" (Reeve et al., 2022).

Breakup Unconformities and Breakup Sequences

Previous work on the evolution of continental margins has shown that breakup is "*marked by the deposition of a breakup sequence rather than a single stratigraphic surface [i.e. an unconformity]*" (Soares et al., 2012). We reiterate that we analysed a deepening-upwards (regressive) sedimentary succession (the deltaic Zeepaard Formation and overlying shoreface Birdrong Sandstone) containing three unconformities; we thus examined a Breakup Sequence (see Soares et al., 2012; Alves and Cunha, 2018; Alves et al., 2020), contrary to the assertion by Alves et al. (2022) that we did "*not provide a coherent stratigraphic analysis of continental breakup and its constituting sequences*" (pXXX). Of the three unconformities we mapped and classified as angular or simply disconformable, we acknowledge they could correspond to correlative conformities (i.e. surfaces that marks no deposition hiatus) away from our borehole constraints and/or in areas of little or no uplift (Alves et al., 2022). Critically, previous work (e.g., Soares et al., 2012; Alves and Cunha, 2018) and numerical modelling (e.g., Cloetingh et al., 1989; Kooi and Cloetingh, 1989; Kooi and Cloetingh, 1992) have shown that the geological characteristics of Breakup Sequences and their associated unconformities, in proximal margin settings such as our study area, can be broadly linked to spatial changes in uplift (and subsidence) during continental breakup. This lends confidence to our interpretation that the stratigraphic record we analysed *can* be tied to syn-breakup geodynamic processes.

Interpreting unconformity development during breakup

Alves et al. (2022) state that "*seismic-stratigraphic boundaries identified on the proximal margin…[like our study area]…cannot be tied to what are essentially protracted geodynamic processes happening near the loci of continental breakup*" (pXXX). We agree that reading the stratigraphic records of continental breakup is challenging and that the development of associated unconformities can be related to myriad local and regional processes (e.g., Soares et al., 2012; Gong et al., 2019; Monteleone et al., 2019; Peron-Pinvidic et al., 2019; Alves et al., 2020; Pérez-Gussinyé et al., 2020). However, it is important to note that the statement by Alves et al. (2022) at least partly emanates from analyses of the Iberia margin, where the proximal domain was situated >100–350 km from the locus of breakup (e.g., Soares et al., 2012; Alves and Cunha, 2018). It appears Alves et al. (2022) compare our study area to the Iberia-Newfoundland margin because, it seems, they consider the Exmouth Plateau to be a Type I margin, like the Iberian margin, as defined by the numerical models of Huismans and Beaumont (2011). Type I margins involve narrow regions of crustal thinning, conjugate margin asymmetry, rift flank uplift, exhumation of continental mantle, delayed formation of oceanic crust, and limited magmatism (Huismans and Beaumont, 2011). Critically, as Huismans and Beaumont (2011) themselves state, the Exmouth Plateau, NW Australia (i.e., our study area) is *not* a Type I margin; they instead define it as a Type II margin because it comprises a wide zone of thinned crust (e.g., Stagg et al., 2004), contains largely undeformed late syn-rift strata (e.g., Reeve et al., 2022), is not associated with mantle exhumation, involved some syn-rift magmatism (e.g., Symonds et al., 1998), is partly underlain by an area of magmatic underplating (e.g., Frey et al., 1998), and the progression from breakup to seafloor spreading was relatively quick (e.g., Reeve et al., 2021). Given the limited amount of syn-breakup faulting in our study area, which is a primary mechanism invoked in previous work to explain localised uplift (e.g., Pérez-Gussinyé et al., 2020), we thus suggest it feasible that unconformity development may be tied to regional geodynamic processes rather than purely local processes, such as fault-driven uplift.

Proposed continental breakup events offshore NW Australia

Based on the data presented in Reeve et al. (2022), previous studies, and their own work on other continental margins, Alves et al. (2022) offer their own interpretation of continental breakup offshore NW Australia, involving: (1) a phase of lithospheric breakup, implied mantle exhumation, and seafloor spreading along the Argo Abyssal Plain in the Oxfordian (~156 Ma), which produced a margin-wide Lithospheric Breakup Surface (i.e. an unconformity; Marshall and Lang, 2013); (2) formation of the Intra-Valanginian Unconformity in response to lithospheric breakup in the Cuvier Abyssal Plain, and the implied transition from continental rifting to mantle exhumation, and eventually seafloor spreading; (3) deposition of a conformable, net-regressive sedimentary sequence with no time gap at our proposed Top Valanginian Unconformity; and (4) full continental breakup only occurred in the Aptian (i.e. >10 Myr later than proposed by Reeve et al., 2022), with the Australian plate remaining pinned to Greater India and Antarctica until this time.

We agree with Alves et al. (2022) that lithospheric breakup in the Argo Abyssal Plain may also have instigated formation of a substantially older, margin-wide unconformity in the Oxfordian, although exploring this was beyond the scope of Reeve et al. (2022). Our interpretation that the Intra-Valanginian Unconformity formed due to localisation of magma-assisted rifting (Reeve et al., 2022) is also consistent with the suggestion of Alves et al. (2022) that it marks lithospheric breakup in the Cuvier Abyssal Plain. We acknowledge that the origin of Top Valanginian Unconformity is difficult to decipher and could be a local expression of faulting or some other process (Alves et al., 2022), although it could also represent generation of magmatic (not oceanic) crust in COTZs (Reeve et al., 2022). Yet we maintain it is plausible that the Intra-Hauterivian Unconformity (i.e. the top of the Breakup Sequence in the proximal margin domain), which coincided with the onset of seafloor spreading in the Gascoyne Abyssal Plain, marks full continental lithospheric rupture (Reeve et al., 2022). Here we note that Hauterivian and Barremian magnetic chrons within the oceanic crust of the Gascoyne Abyssal Plain and plate reconstructions support full lithospheric breakup of the NW Australian margin prior to the Aptian (e.g., Heine and Müller, 2005; Robb et al., 2005; Gibbons et al., 2012). Finally, we emphasise that our interpretations presented here and in Reeve et al. (2022) are hypotheses to be tested.

Concluding remarks

Variations in the style and diachroneity of continental breakup produce complex stratigraphic signatures. Although interpretations may differ, it is promising to see the overlap in ideas emanating from Reeve et al. (2022) and the discussion raised by Alves et al. (2022). We agree with Alves et al. (2022) that more work is required to test the hypotheses we advanced and to better understand the stratigraphic record of continental breakup offshore NW Australia, as well as other continental margins. For example, because biostratigraphic marker and magnetic chron ages are constantly being refined (e.g., Robb et al., 2005; Casellato and Erba, 2021), improving the resolution of these data provides a way to test our interpretations. Overall, we emphasise that our work supports a growing consensus "*that the integration of seismic reflection and well-calibrated biostratigraphic data is critical to reading rocks that record the processes driving continental breakup*" (Reeve et al., 2022). Critically, there is a vast array of geological, geophysical, and biostratigraphic data publically available from offshore NW Australia, and we strongly encourage its use.

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