GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G52309.1

Manuscript received 12 April 2024
Revised manuscript received 15 June 2024
Manuscript accepted 2 July 2024

On the delayed expression of mantle inheritance–controlled strain localization during rifting

Frank Zwaan[1,2,3,*], Duncan Erratt[4], Gianreto Manatschal[4], Pauline Chenin[4], and Guido Schreurs[1]
[1]University of Bern, Institute of Geological Sciences, Baltzerstrasse 1+3, 3012 Bern, Switzerland
[2]GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[3]University of Fribourg, Department of Geosciences, Chemin du Musée 6, 1700 Fribourg, Switzerland
[4]Université de Strasbourg, Centre National de la Recherche Scientifique, Institut Terre et Environnement de Strasbourg, UMR 7063, 5 Rue René Descartes, 67084 Strasbourg, France

ABSTRACT

In this paper, we explore the relative impact mantle inheritance can have on the evolution of magma-poor rift systems during the early stages of rift localization. To this end, we revisit the tectonic history of the Mesozoic Northeast Atlantic and its North Sea subdomain, analyzing these observations through comparison with results from recent analogue tectonic modeling work. Our analysis suggests that initial broadly distributed rift basin formation may be controlled by crustal inheritance, whereas the subsequent localization of deformation along deeper mantle inheritance may have caused the overprinting of previous rift basin trends in the Northeast Atlantic. This overprinting became possible as soon as the thinning of the ductile crust during progressive rifting allowed for sufficient coupling between the mantle and the upper crust. Importantly, we suggest that no changes in plate motion direction due to large-scale reorganization of the plate tectonic system are needed for differently oriented basin trends overprinting each other to develop. With these insights, we propose an updated scenario for rift kinematics in the North Sea involving continuous E-W plate divergence and provide a framework to rethink the evolution of other rift systems around the world during their early stages of rift localization.

INTRODUCTION

It is well known that different types of inheritance (compositional, structural, thermal) from previous tectonic phases may localize deformation during (renewed) rifting (e.g., Manatschal et al., 2015; Schiffer et al., 2020). Extensive research has focused on the interplay between (stress-controlled) deformation and inheritance. However, this research mainly considered crustal inheritance (e.g., Phillips et al., 2016), whereas the impact of inheritance in the underlying lithospheric mantle has been mostly overlooked. Although some studies address the importance of mantle inheritance (e.g., Chenin and Beaumont, 2013; Chenin et al., 2019; Heron et al., 2019), well-defined constraints on the nature and role of mantle inheritance are lacking.

In this paper, we explore how mantle inheritance can impact the evolution of magma-poor rift systems during the early stages of rift localization. To this end, we revisit the Mesozoic tectonic history of the Northeast Atlantic and its North Sea subdomain and compare the evolution of the rift basins there to insights from recent analogue tectonic modeling work by Zwaan et al. (2022). By doing so, we show that mantle-controlled deformation may simply overprint previous rift basin trends that were controlled by an interplay between stress field and upper crustal inheritance. This overprinting can occur as soon as sufficient coupling between mantle and upper crust is achieved through the thinning of the ductile middle/lower crust, i.e., during the transition from “stretching” to “necking” that is a key moment in the evolution of magma-poor rift systems, representing a shift from broadly distributed to strongly localized thinning of the lithosphere, before the subsequent hyperextension and eventual breakup stages (e.g., Lavier and Manatschal, 2006).

This mechanism explains how differently oriented rift basins in the Northeast Atlantic are not necessarily formed as a result of changes in plate kinematics (i.e., plate motion direction) as was previously proposed, but can instead be due to the delayed impact of deformation along deep mantle features such as sutures that are differently oriented from any structures controlled by crustal inheritance. These insights provide a framework to rethink the early evolution of other rift systems around the world, since stress directions cannot be reliably deduced from strain patterns alone.

EARLY-STAGE RIFTING IN THE NORTHEAST ATLANTIC DOMAIN

We turn to the Northeast Atlantic domain at the end of the Jurassic for a general assessment of early-stage magma-poor rift development (Schiffer et al., 2020; Fig. 1). Although final breakup was magma-rich and linked to the Paleocene North Atlantic plume (Planke et al., 2000), the initial (Devonian–Late Jurassic/Earliest Cretaceous) rift evolution saw limited magmatism and can thus be studied in a magma-poor context without having to consider the significant impact that magmatism can have on rift kinematics (e.g., Buck, 2006).

By the end of the Jurassic, a broad zone of rifts and sedimentary basins, some dating back as far as Devonian times, had formed in the Northeast Atlantic. These basins often had different orientations but formed roughly within the former collision zones between Baltica, Avalonia, and Laurentia (Fig. 1). Late Jurassic basin formation concentrated along two corridors: a first one stretching from the future Atlantic domain into the North Sea, along the suture zones bordering Baltica, and a second corridor arriving from the Central Atlantic, where breakup was already attained, propagating toward Greenland and the Labrador Sea (Fig. 1,

---

Frank Zwaan https://orcid.org/0000-0001-8226-2132
*frank.zwaan@gfz-potsdam.de

CITATION: Zwaan, F., et al., 2024, On the delayed expression of mantle inheritance–controlled strain localization during rifting: Geology, v. XX, p. , https://doi.org/10.1130/G52309.1

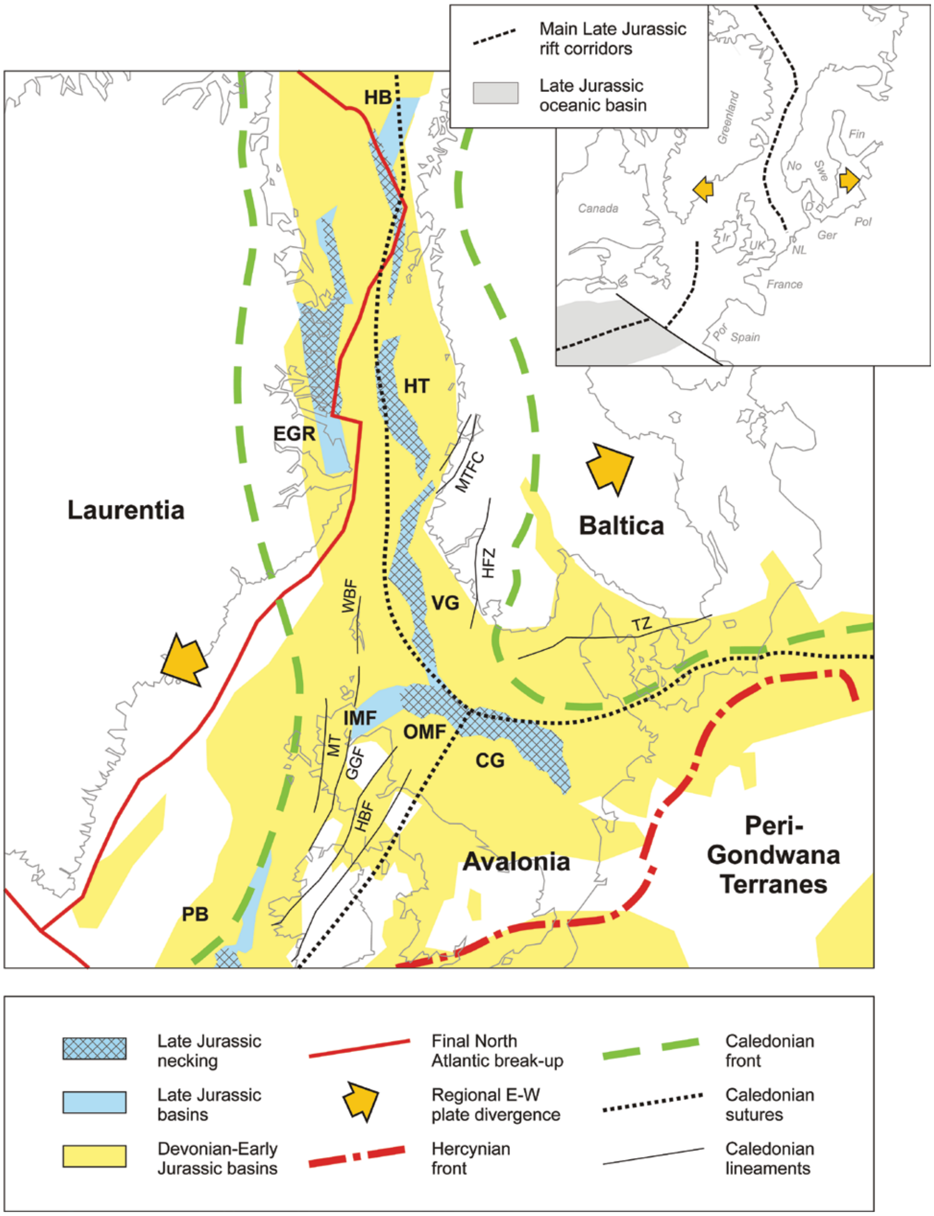

Figure 1. Distribution of rifts and sedimentary basins in the Northeast Atlantic domain in Late Jurassic times (145 Ma). CG—Central Graben; EGR—East Greenland Rift; HB—Hammerfest Basin; GGF—Great Glen Fault; HBF—Highland Boundary Fault; HFZ—Hardangerfjord Fault Zone; HT—Halten Terrace; IMF—Inner Moray Firth; MF—Moray Firth; MT—Moine thrust; MTFZ—Møre-Trøndelag Fault Zone; OMF—Outer Moray Firth; PB—Porcupine Basin; TZ—Tornquist Zone; VG—Viking Graben; WBF—Walls Boundary Fault. Modified after Skogseid et al. (2000), Coward et al. (2003), Erratt et al. (2010), and Schiffer et al. (2020). Inset shows main rift corridors during the Late Jurassic (150 Ma). D—Denmark; Fin—Finland; Ger—Germany; Ir—Ireland; NL—Netherlands; No—Norway; Pol—Poland; Por—Portugal; Swe—Sweden; UK—United Kingdom. Modified after Peacock (2004).

inset). We shall focus on the first corridor, which between Greenland and Norway includes the Hammerfest Basin, East Greenland Basin, and Halten Terrace (Fig. 1). To the south, the North Sea is home to the Viking Graben in the north, the Central Graben, and the Inner- and Outer Moray Firth (Figs. 1 and 2).

Note, however, that the SSW-ENE–oriented Inner Moray Firth does not follow a suture, and that at present, the crust has retained most of its original thickness there (Ziegler, 1990; Figs. 1 and 2A). By contrast, the crust is significantly thinned below the NW-SE oriented Central Graben and Outer Moray Firth (henceforth referred to as the Central Graben–Outer Moray Firth) and below the N-S–striking Viking Graben (with Moho depths reduced to <20 km, rather than the original >30 km; Ziegler, 1990; Fig. 2A). This significant and localized thinning of the crust, together with a distinct unconformity, is a clear indication that these basins attained the necking stage before rifting halted in the North Sea (Erratt et al., 2010; Fig. 1). Farther north, the various basins between Greenland and Norway also reached the necking stage around Late Jurassic times before undergoing hyperextension and subsequent breakup (Chenin et al., 2015).

A peculiar phenomenon is recorded during the necking stage in the North Sea, where a tectonic reorganization occurred along the Central Graben–Outer Moray Firth (Erratt et al., 1999). Whereas Callovian–Early Kimmeridgian depocenters and boundary faults form a left-stepping en échelon arrangement along the general NW-SE Central Graben–Outer Moray Firth trend, subsequent Early Kimmeridgian–Tithonian depocenters and border faults are oriented (sub-)parallel to this NW-SE trend (Figs. 2B and 2C). Meanwhile, the depocenter and boundary fault orientations remained fairly constant in the Inner Moray Firth and Viking Graben.

Recognizing this peculiar realignment of basin depocenter and fault orientations in the Late Jurassic North Sea, Erratt et al. (1999) proposed a scenario involving a shift from an initial general E-W plate divergence to a SW-NE divergence as a possible explanation (Figs. 2B and 2C). Such a shift in plate divergence direction is, however, in contradiction with the plate kinematics in the overall North Atlantic domain, which suggest continued general E-W plate divergence (Doré et al., 1999; Schiffer et al., 2020). Therefore, alternative scenarios should be considered.

INSIGHTS FROM 3-D ANALOGUE TECTONIC MODELS

A recent 3-D analogue tectonic modeling study by Zwaan et al. (2022) reproduced very similar overprinting relationships to those seen in the Late Jurassic North Sea (Fig. 3). The authors applied brittle-viscous analogue models, where the brittle upper crust and ductile lower crust were represented by a brittle sand layer overlying a layer of viscous material (Figs. 3A and 3C). Both layers were placed on top of a base plate, the edge of which represented a linear inheritance in the strong lithospheric mantle (e.g., a suture) that was reactivated as a mantle shear zone by pulling this base plate (Figs. 3A–3D). In the simulated upper crust, inheritance with a different orientation than that in the mantle below was implemented in the shape of linear weaknesses (Figs. 3A–3C). When these models were deformed by pulling the base plate at a low velocity of 10 mm/h, these crustal weaknesses were all reactivated so that basins formed throughout the model (Fig. 3E). A subsequent ten-fold velocity increase caused the overprinting of these initial basins by a series of new rift basins that were aligned along the mantle weakness below (Fig. 3E).

The cause for this overprinting of early distributed rift basins by a strongly localized rift

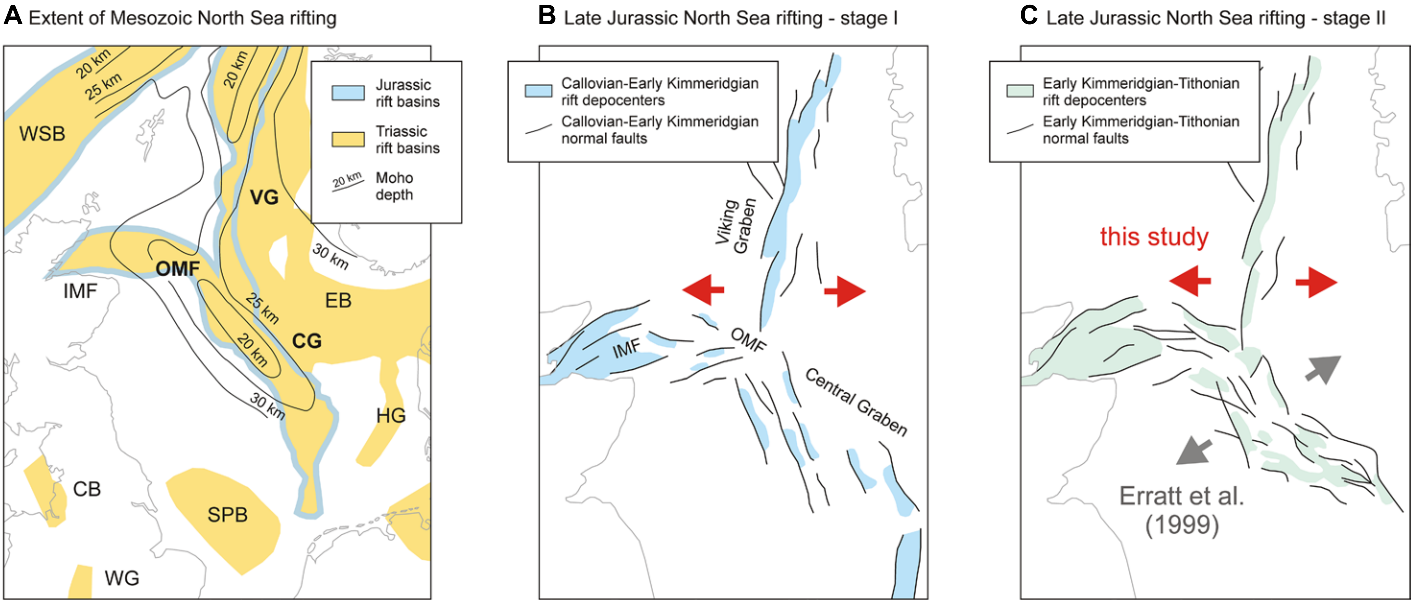

Figure 2. Details of the Mesozoic North Sea rift system. (A) Map of the extent of Triassic (stretching-stage) and Jurassic (necking-stage) rift basins, as well as Moho depth. Modified after Ziegler (1990) and Goldsmith et al. (2003). (B–C) Shift of the North Sea rift basin depocenter configuration during Late Jurassic rifting. Erratt et al. (1999) proposed a scenario involving a transition from E-W divergence to SW-NE divergence (gray arrows) to explain this shift in depocenter configurations. We propose an alternative scenario with continuous E-W divergence (red arrows) and increased coupling between mantle and upper crust. Modified after Erratt et al. (1999). CB—Cheshire Basin; CG—Central Graben; EB—Egersund Basin; HG—Horn Graben; IMF—Inner Moray Firth; Outer Moray Firth; SPB—Sole Pit Basin; VG—Viking Graben; WG—Worchester Graben; WSB—West-Shetland Basin.

basin in these models is the degree of coupling between the simulated mantle and upper crust, as a function of the strain rate–dependent rheology of the simulated ductile crust in between (e.g., Brun, 1999; Zwaan et al., 2019). Under low strain rate conditions, the viscous layer representing the ductile crust is relatively weak, whereas the viscous layer will be relatively strong under high strain rate conditions. Consequently, slow deformation rates will lead to decoupling between mantle and brittle crust so that basin formation can be dominated by upper crustal inheritance. Conversely, high strain rates cause coupling so that basin formation focuses along the mantle inheritance. Thus, when slow rifting is followed by fast rifting in these models, the overprinting relation is reminiscent of the one in the Late Jurassic North Sea.

Importantly, coupling is not only a function of divergence velocity, but also of lower crustal thickness: the thinner the ductile crust, the higher the coupling (e.g., Brun, 1999; Zwaan et al., 2019). As such, a similar increase in coupling over time is expected to occur when the ductile crust becomes sufficiently thinned, i.e., during necking (Zwaan et al., 2021, 2022).

DISCUSSION

Coupling and the Delayed Impact of Mantle Inheritance

We observe that Late Jurassic necking-stage rift basins in the magma-poor Mesozoic Northeast Atlantic Rift generally follow the sutures bordering Baltica (Fig. 1). Using the model results from Zwaan et al. (2022), we can now propose a scenario to explain the processes behind this rift basin arrangement (Fig. 4). During the initial stretching stage, the ductile crust allows decoupling between the upper crust and mantle, allowing for widespread rift basin development dominated by deformation processes (and, as such, inheritance) in the upper crust. However, as soon as the ductile crust is thinned out at the transition to the necking stage, coupling increases to the degree that a reactivated mantle inheritance (e.g., a suture) can directly transfer deformation into the upper crustal layer. As a result, more strongly localized deformation occurs above the mantle inheritance, overprinting previously formed basins.

An Updated Scenario for North Sea Rifting

We can now also propose a variation of the Erratt et al. (1999) scenario for North Sea rifting that is both in line with regional plate kinematics and with the delayed impact of mantle inheritance in magma-poor rift systems. Stretching-stage North Sea rifting was widespread because crustal inheritance was widespread, including a wide range of orientations that could be expressed due to the low coupling during this initial stage. However, as necking initiated under an E-W divergence regime in the Late Jurassic, deformation roughly concentrated along the reactivated Caledonian sutures below the Central Graben–Outer Moray Firth and the Viking Graben (Figs. 1 and 2B). The earlier en échelon depocenter arrangement observed in the Central Graben–Outer Moray Firth is typical of the oblique rifting due to the general E-W divergence and the NW-SE suture zone trend (Fig. 2B; Erratt et al., 1999). However, the shift in the Latest Jurassic depocenter orientation does not warrant the shift in divergence direction proposed by Erratt et al. (1999), as increased coupling between mantle and upper crust could simply have realigned the next generation of necking basins along the mantle suture–controlled rift trend. Continued E-W divergence in combination with increasing coupling thus provides a simple explanation for the evolution of the North Sea Central Graben–Outer Moray Firth (Figs. 2B and 2C). Importantly, in this continuous E-W divergence scenario the ~N-S–oriented Viking Graben always remained well oriented for orthogonal rifting and as such did not develop any clear shift in basin arrangement (Figs. 2B and 2C). Moreover, although the SW-NE oriented Inner Moray Firth did not experience necking as indicated by the absence of significant crustal thinning there, its Late Jurassic evolution was characterized by transtension, which fits well with continuous E-W divergence superimposed on the N-E striking Caledonian lineaments (Ziegler, 1990; Figs. 1 and 2).

CONCLUSION

By revisiting the Mesozoic early-stage rift history of the North Atlantic domain and by comparing it to insights from tectonic modeling studies, we describe how mantle inheritance can be an important or even dominant factor during early-stage strain localization in magma-poor rift systems. We argue that mantle-controlled deformation may simply overprint any previous

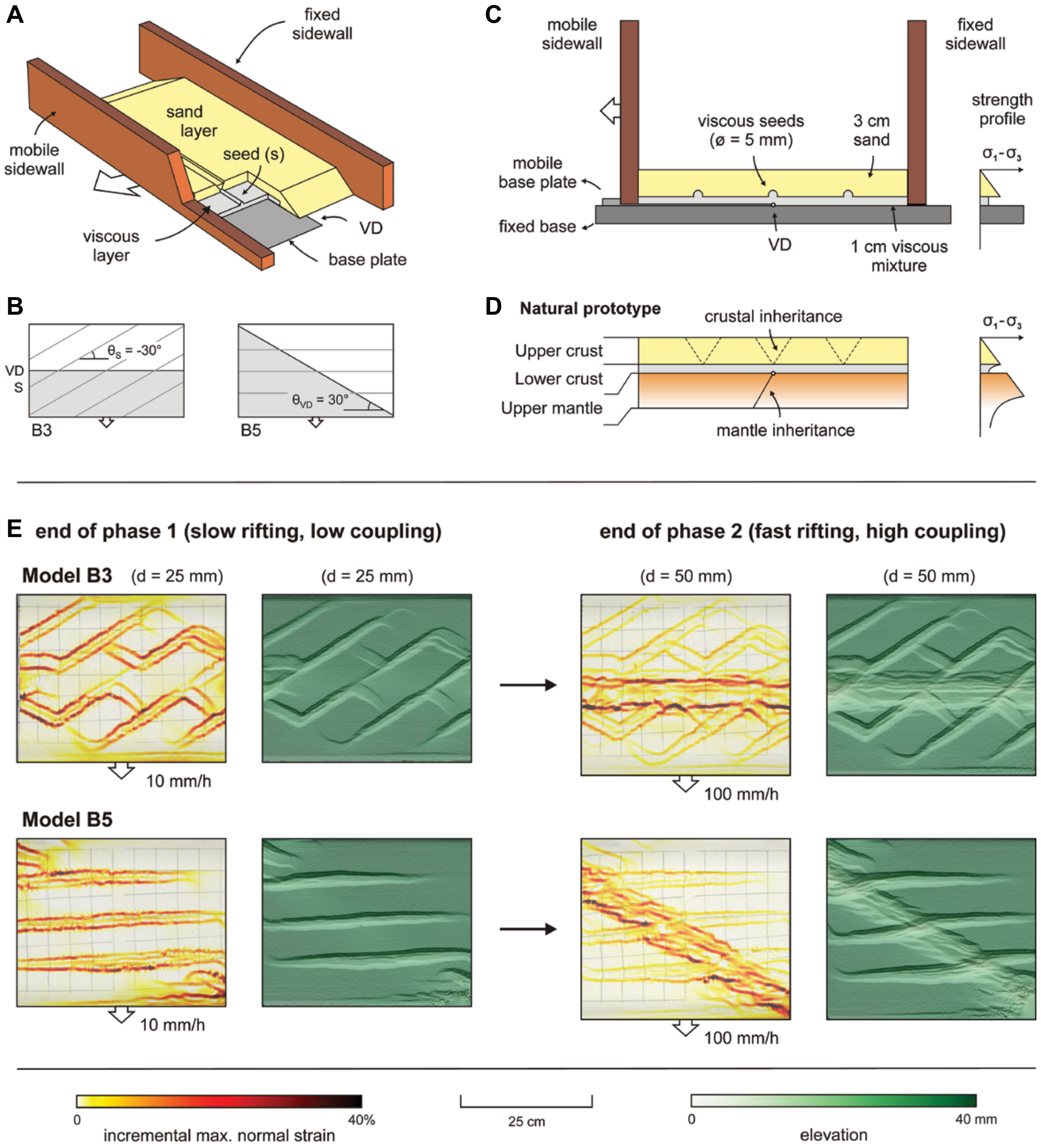

Figure 3. Overview of set-up and results from key analogue models from Zwaan et al. (2022) showing the impact of coupling between mantle and upper crust on rift basin evolution. (A) 3-D sketch of model set-up. (B) Top view sketch showing the orientations of the velocity discontinuity (VD), representing mantle inheritance, and seeds (S), representing crustal inheritance, in models B3 and B5. (θ_s = obliquity of seeds, θ_{VD} = obliquity of VD). (C) Cross-section sketch of model layering and seed location, of which the natural prototype is shown in (D). (E) Maximum normal strain (indicating active normal faulting) and topography analysis of models B3 and B5. The models underwent a shift from low to high coupling (as a result of increasing divergence velocity), leading to the initial development of crustal structures, controlled by the crustal inheritances, that are subsequently overprinted by a phase of mantle-controlled deformation. d—VD displacement.

rift basin trends as soon as sufficient coupling between mantle and upper crust is achieved through thinning of the ductile crust during necking. This results in a delayed expression of mantle inheritance–controlled strain localization at the transition from stretching to necking in magma-poor rift systems. This new concept required us to rethink the link between the kinematic evolution/strain distribution on the one hand and changes in the regional stress field versus controls by inheritance on the other hand. In the case of the North Sea scenario, introducing a delayed expression of mantle inheritance–controlled strain localization allows for consistency with a constant E-W divergence, as suggested by most plate kinematic models. Moreover, applying the concept of delayed mantle inheritance–controlled strain localization may change the strain/stress analysis for many early stages of rift systems around the world (e.g., the eastern Gulf of Aden, the Australian North West Shelf, and the Labrador Sea; Autin et al., 2013; Belgarde et al., 2015; Heron et al., 2019; Deng et al., 2022).

ACKNOWLEDGMENTS

We thank J.K. Welford, T. Doré, J. Maynard, and an anonymous reviewer, as well as editor R. Strachan, for their helpful feedback. This research was funded by the Swiss National Science Foundation (grant 200021-178731, http://p3.snf.ch/Project-178731). F. Zwaan received additional support from the GFZ Discovery Fund. CNRS UMR 7063 ITES covered the open access publication costs through the M6 research consortium.

REFERENCES CITED

Autin, J., Bellahsen, N., Leroy, S., Husson, L., Beslier, M.-O., and d'Acremont, E., 2013, The role of structural inheritance in oblique rifting: Insights from analogue models and application to the Gulf of Aden: Tectonophysics, v. 607, p. 51–64, https://doi.org/10.1016/j.tecto.2013.05.041.

Belgarde, C., Manatschal, G., Kuznir, N., Scarselli, S., and Ruder, M., 2015, Rift processes in the Westralian Superbasin, North West Shelf, Australia: Insights from 2D deep reflection seismic interpretation and potential fields modelling: APPEA Journal (Australian Energy Producers Journal), v. 55, 400–400, https://doi.org/10.1071/AJ14035.

Brun, J.-P., 1999, Narrow rifts versus wide rifts: Inferences for the mechanics of rifting from laboratory experiments: Philosophical Transactions of the Royal Society A, v. 357, p. 695–712, https://doi.org/10.1098/rsta.1999.0349.

Buck, R., 2006, The role of magma in the development of the Afro-Arabian Rift System, *in* Yirgu, G., et al., eds., The Afar Volcanic Province within the East African Rift System: Geological Society, London, Special Publication 259, p. 43–54, https://doi.org/10.1144/GSL.SP.2006.259.01.05.

Chenin, P., and Beaumont, C., 2013, Influence of offset weak zones on the development of rift basins: Activation and abandonment during continental

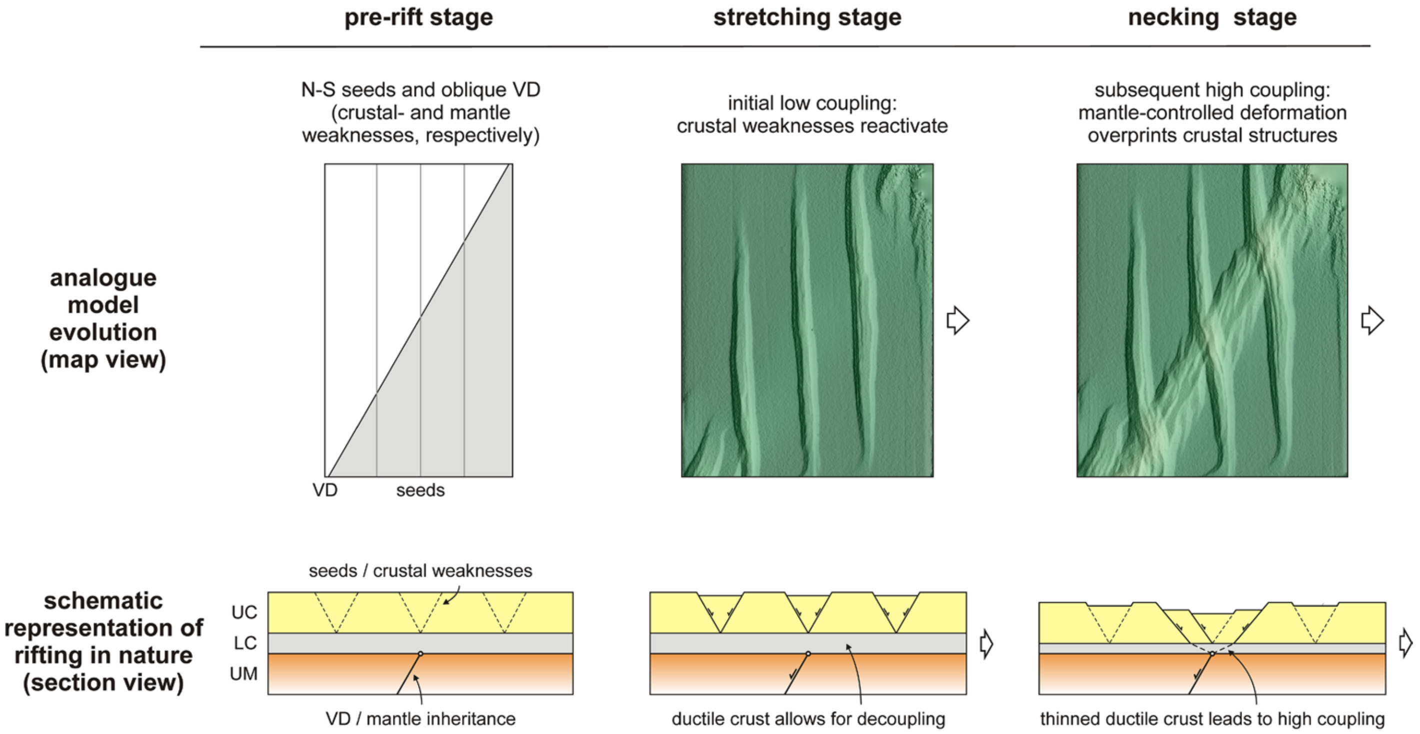

Figure 4. The concept of how increased coupling due to thinning of the ductile crust can lead to the overprinting of previous crustal structures by mantle-controlled deformation. Note that favorably oriented crustal structures can still show reactivation. UC—upper crust; LC—lower crust; UM—upper lithospheric mantle; VD—velocity discontinuity. Modified after Zwaan et al. (2022). See Figure 3 for details on model set-up.

extension and breakup: Journal of Geophysical Research: Solid Earth, v. 118, p. 1698–1720, https://doi.org/10.1002/jgrb.50138.

Chenin, P., Manatschal, G., Lavier, L.L., and Erratt, D., 2015, Assessing the impact of orogenic inheritance on the architecture, timing and magmatic budget of the North Atlantic rift system: A mapping approach: Journal of the Geological Society, v. 172, p. 711–720, https://doi.org/10.1144/jgs2014-139.

Chenin, P., Jammes, S., Lavier, L.L., Manatschal, G., Picazo, S., Müntener, O., Karner, G.D., Figueredo, P.H., and Johnson, C., 2019, Impact of mafic underplating and mantle depletion on subsequent rifting: A numerical modeling study: Tectonics, v. 38, p. 2185–2207, https://doi.org/10.1029/2018TC005318.

Coward, M.P., Dewey, J.F., Hempton, M., and Holroyd, J., 2003, Tectonic evolution, *in* Evans, D., et al., eds., The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea: London, The Geological Society, p. 17–33.

Deng, H., McClay, K., and Belgarde, C., 2022, Low-angle normal faults on the NW Shelf of Australia: Implications for Late Paleozoic rifting: Tectonics, v. 41, https://doi.org/10.1029/2021TC007088.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, Ø., Eliassen, P.E., and Fichler, C., 1999, Principal tectonic events in the evolution of the northwest European Atlantic margin: Geological Society, London, Petroleum Geology Conference Series, v. 5, p. 41–61, https://doi.org/10.1144/0050041.

Erratt, D., Thomas, G.M., and Wall, G.R.T., 1999, The evolution of the Central North Sea Rift, *in* Fleet, A.J., and Boldly, S.A.R., eds., Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference: Geological Society, London, Petroleum Geology Conference Series, v. 5, p. 63–82, https://doi.org/10.1144/0050063.

Erratt, D., Thomas, G.M., Hartley, N.R., Musum, R., Nicholson, P.H., and Spitsto, Y., 2010, North Sea hydrocarbon systems: Some aspects of our evolving insights into a classic hydrocarbon province, *in* Vining, B.A., and Pickering, S.C., eds., Petroleum Geology: From Mature Basins to New Frontiers—Proceedings of the 7th Petroleum Geology Conference: Geological Society, London, Petroleum Geology Conference Series, v. 7, p. 37–56, https://doi.org/10.1144/0070037.

Goldsmith, P.J., Hudson, G., and Van Veen, P., 2003, Triassic, *in* Evans, D., et al., eds., The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea: London, The Geological Society, p. 105–127.

Heron, P.J., Peace, A.L., McCaffrey, K.J.W., Welford, J.K., Wilson, R., van Hunen, J., and Pysklywec, R.N., 2019, Segmentation of rifts through structural inheritance: Creation of the Davis Strait: Tectonics, v. 38, p. 2411–2430, https://doi.org/10.1029/2019TC005578.

Lavier, L.L., and Manatschal, G., 2006, A mechanism to thin the continental lithosphere at magma-poor margins: Nature, v. 440, p. 324–328, https://doi.org/10.1038/nature04608.

Manatschal, G., Lavier, L., and Chenin, P., 2015, The role of inheritance in structuring hyperextended rift systems: Some considerations based on observations and numerical modeling: Gondwana Research, v. 27, p. 140–164, https://doi.org/10.1016/j.gr.2014.08.006.

Peacock, D.C.P., 2004, The post-Variscan development of the British Isles within a regional transfer zone influenced by orogenesis: Journal of Structural Geology, v. 26, p. 2225–2231, https://doi.org/10.1016/j.jsg.2004.05.005.

Phillips, T.B., Jackson, C.A.-L., Bell, R.E., Duffy, O.B., and Fossen, H., 2016, Reactivation of intrabasement structures during rifting: A case study from offshore southern Norway: Journal of Structural Geology, v. 91, p. 54–73, https://doi.org/10.1016/j.jsg.2016.08.008.

Planke, S., Symonds, P.A., Alvestad, E., and Skogseid, J., 2000, Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins: Journal of Geophysical Research: Solid Earth, v. 105, p. 19,335–19,351, https://doi.org/10.1029/1999JB900005.

Schiffer, C., et al., 2020, Structural inheritance in the North Atlantic: Earth-Science Reviews, v. 206, https://doi.org/10.1016/j.earscirev.2019.102975.

Skogseid, J., Planke, S., Faleide, J.I., Pedersen, T., Eldholm, O., and Neverdal, F., 2000, NE Atlantic continental rifting and volcanic margin formation, *in* Nøttvedt, A., ed., Dynamics of the Norwegian Margin: Geological Society, London, Special Publication 167, p. 295–326, https://doi.org/10.1144/GSL.SP.2000.167.01.12.

Ziegler, P.A., 1990, Tectonic and Palaeogeographic evolution of the North Sea Rift System, *in* Blundell, D.J., and Gibbs, A., eds., Tectonic Evolution of North Sea Rifts: Oxford, Clarendon Press, p. 1–36.

Zwaan, F., Buiter, S.J.H., and Schreurs, G., 2019, A systematic comparison of experimental set-ups for modelling extensional tectonics: Solid Earth, v. 10, p. 1063–1097, https://doi.org/10.5194/se-10-1063-2019.

Zwaan, F., Chenin, P., Erratt, D., Manatschal, G., and Schreurs, G., 2021, Complex rift patterns, a result of interacting crustal and mantle weaknesses, or multiphase rifting?: Insights from analogue models: Solid Earth, v. 12, p. 1473–1495, https://doi.org/10.5194/se-12-1473-2021.

Zwaan, F., Chenin, P., Erratt, D., Manatschal, G., and Schreurs, G., 2022, Competition between 3D structural inheritance and kinematics during rifting: Insights from analogue models: Basin Research, v. 34, p. 824–854, https://doi.org/10.1111/bre.12642.

Printed in the USA