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All scales must be considered to understand rifts

Cynthia Ebinger, Jolante van Wijk, Lydia Olaka, Catherine Mériaux & Karen Fontijn

Feedbacks between chemical, physical, and biological processes at rift zones evolve through various time (seconds to 10^7 yrs) and spatial (microns to 10^6 m) scales. Consideration of these scales is needed to tap rift energy, water, and mineral resources safely and equitably while preserving biodiversity in these changing settings.

During tectonic extension, the lithosphere responds to forces arising from the superposed processes of mantle dynamics, tectonics, magmatism, metamorphism, and climate (Fig. 1). In any rift system at any point in its evolution, the geological responses and biological ecosystems are shaped by some or all of these connected processes, which operate over time scales that span nine orders of magnitude in time (seconds to tens of millions of years) and twelve orders of magnitude in space (microns to thousands of kilometres). For example, the time scales are 10^6–10^4 years for rift flank uplift, 10^5–10^2 years for changes in climate, 10^3–10^0 years for earthquake and volcanic eruption cycles, and seconds to hours for fault slip and/or co-seismic deformation[1]. The response of the rock layers comprising tectonic plates depends on factors such as the rate of applied stresses and their hydration state, which can change suddenly with the movement of magma, or with fluids injected by human activities. Time scales of biological processes are also important; the evolving topographic relief and geochemical diversity of the lithology control biodiversity by modulating climate, hydrology and chemical cycling, including nutrient distribution. Hence, time and dimensions matter.

A new dimension to the time scales of rifting processes was revealed by an intense period of faulting and magmatism that began in the Afar Depression, northeast Africa, in 2005, ref. 2. Faulting created 5 m-high fault scarps across a ~10 km-wide damage zone, while the ~60 km-long rift segment was intruded by dikes sourced from a magma chamber beneath the segment centre. These events were followed by at least 13 more dike intrusions and 2 fissure eruptions over the next 5 years.

Changes in rheology and mineralogy are studied experimentally and results are incorporated into numerical models of rifting through constitutive equations. Geodynamic models solve equations on numerical grids that are limited in resolving rheological processes or material changes on scales less than 100 m, meaning the various scales of crustal fabrics, sedimentary processes, and other local heterogeneities are not well represented. Earth materials possess time-dependency in behaviour that is the basis for physical models, for example, ductile rocks can deform in a brittle manner when stressed rapidly or during interaction with fluids. However, numerical simulations typically only consider strains that accumulate over time steps of ~1,000 years or more. Short-duration events, such as the Afar Rifting crisis mentioned above, cause new hydrothermal activity, volcanic eruptions, landslides, and activate trans-crustal magmatic plumbing systems. Such intense events are yet to be considered in numerical models and their coupling with longer-term processes remains poorly understood.

The current limitations of numerical modelling capabilities pose a challenge to emerging societal needs associated with hazard preparedness, resource management, biodiversity and climate response, necessitating novel numerical and analogue solutions. We argue that to understand the complexity of rifting and, by association, rift hazards and resources, researchers must embrace and consider all spatiotemporal scales with new approaches to modelling, data collection and cross-disciplinary research. We propose strategies for the rift community to observe and characterize interactions of processes occurring over such varying scales.

Increasing observational resolution

Observatory-type monitoring of rifts that enable a compare and contrast approach (for example, active cratonic and post-orogenic rifts with and without magmatism) using a range of instruments will provide constraints on 4D processes, including surface processes, in physical models of rifting on short (daily to weekly) timescales. Owing to the time-dependent behaviour of these processes, it is critical to constrain the physical properties of materials in 4D and to test discrete-event and time-averaged models. Continuous monitoring of seismic, geodetic, and potential field data, gas emissions and measurements of surface deformation using Lidar and InSAR, as is done at a few volcano observatories, will quantify the frequency and scale of intrusive magmatic events, subsurface fluid flow, the aseismic component of transient deformation[3], seasonal hydrological effects on fault systems[4], and other processes. Coincident measurements of seismic velocity and resistivity provide critical information on fluids within sedimentary layers, the crust and mantle, as well as the nature of the fluids themselves. Resolving temporal variations in these datasets informs geo-engineering projects such as fluid injection for CO_2 sequestration and geothermal energy. Observations across multiple seismic or magma-intrusion cycles, or cycles of decadal climate variability, provide insights into cumulative effects.

4D data from continuous monitoring of active rifts could then be combined with constraints from past rifts, such as from rift basin sediments and rifted margin structures. Rift zone sedimentary strata are high-fidelity recorders of past tectonic and climatic processes. For example, sedimentary layers in tropical rift lakes offer datable materials and paleoclimatic tools to deconvolve signals[5,6]. Geochronology and geochemical finger-printing of pyroclastic deposits and lava flows enable the detection of past eruptions' location and frequency[6]. Stratigraphic time gaps are key indicators of rapid change, and clues into intense events, past and future. Where dated sequences are mapped

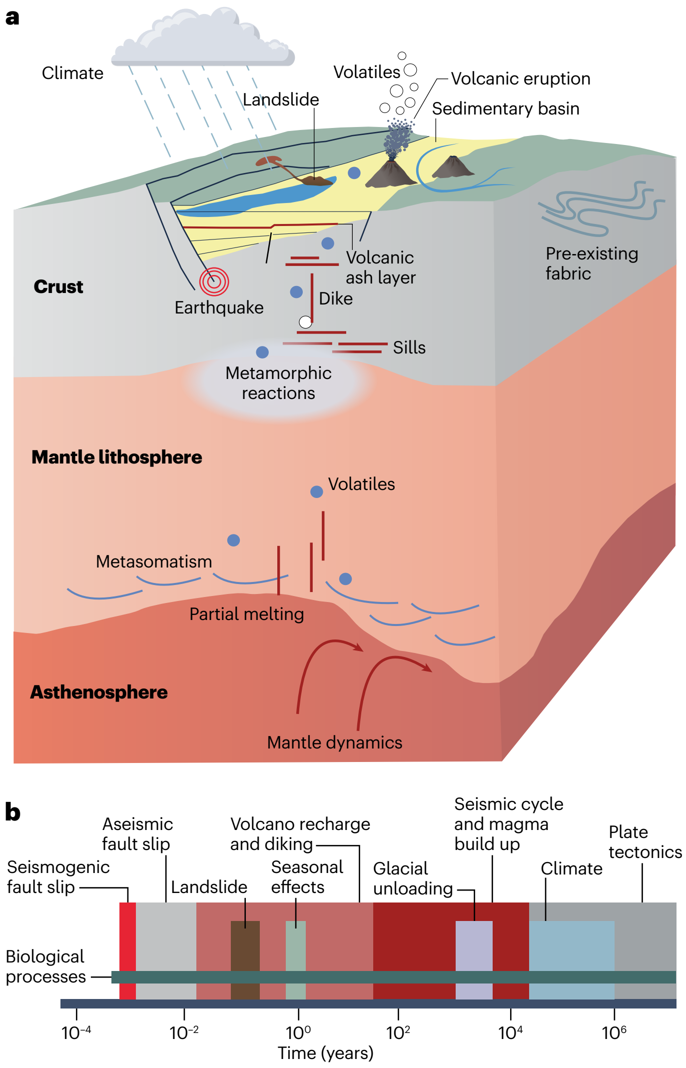

Fig. 1 | Structure and timescales of rifting. a, Continental rift structure is dependent on lithospheric heterogeneities, spatially varying mantle dynamics, radiogenic heat production and heating by magmatic and aqueous fluids. Volatiles (blue and white circles) like water and CO_2 escape from rising magmas or from metasomatic reactions, contributing to heterogeneities in composition, temperature, and rheology. The base of the lithosphere is susceptible to entrainment by mantle flow[10]. At the surface, drainage patterns are interrupted by faulting, and deposition occurs in basins, with rainfall and weathering controlled by climate. **b**, Rift processes occur on varying timescales from seconds to 10^7 yrs.

in space and time using seismic images and bore hole data, the rift basin history should be directly compared to numerical model time steps, and model parameters adjusted, or assumptions re-evaluated.

Next-generation numerical models

Constraints on the timing of past events and their conditions are the tests of the time-averaged multi-physics models. Existing computational capabilities can be applied (or modified) for studying rifts at all scales. These include simulation platforms that bridge spatio–temporal scales by integrating finite element analysis, discrete element analysis and computational fluid dynamics[7]; physics-based machine learning techniques that enhance predictive modelling capabilities[8]; development of reduced-order models to decrease computational requirements, and other techniques. These developments will require long-term community investment in code development in tandem with the observational and experimental advances discussed above.

Outlook

Timely achievement of these scientific goals is critical to enabling an equitable transition to renewable energy, for resource management, and for hazard mitigation. Continental rift zones, back-arc basins, and rifted continental margins have produced, and continue to provide, a substantial portion of the world's energy supply and other natural resources. Active rift zones offer additional geothermal resources, and the topographic relief contrast is favourable for wind energy.

To enable increased understanding of rift processes at all scales, we advocate for community-building opportunities to engage industry, academics, and government laboratories in 5 + year-long projects that enable meaningful exchanges between multi-disciplinary and multinational teams. Academic partnerships with government laboratories and industry enable access to super-computing facilities for the new generation of models, whereas the release of seismic reflection and well data from oil and gas exploration zones opens doors for high-resolution 4D studies. Although Africa hosts the Earth's archetypal rift zone, African scientists have been significantly underrepresented in international geoscience literature[9]. We recommend that international collaborative partnerships are designed to increase and financially support the development of in-country scientific leadership, research infrastructure, mentoring, and training opportunities in Africa and other underrepresented countries to facilitate increased observational and model resolution.

Cynthia Ebinger[1] ✉, **Jolante van Wijk**[2], **Lydia Olaka**[3], **Catherine Mériaux**[4] **& Karen Fontijn**[5]

[1]Earth and Environmental Sciences, Tulane University, New Orleans, LA, USA. [2]Energy and Natural Resources Security, Los Alamos National Laboratory, Los Alamos, NM, USA. [3]Department of Geoscience and the Environment, Technical University of Kenya, Nairobi, Kenya. [4]East African Institute for Fundamental Research, Kigali, Rwanda. [5]Université libre de Bruxelles, Brussels, Belgium.

✉e-mail: cebinger@tulane.edu

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Author contributions

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Competing interests

The authors declare no competing interests.