**Reclus, a New Database for Investigating the Tectonics of the Earth: An Example From the East African Margin and Hinterland**

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**Abstract** The open availability of global scientific databases is key to advancing research of the Earth system and facilitating cross-disciplinary studies. There are numerous data sets available for investigating tectonics, but none that provide an internally consistent representation of the structural framework, crustal architecture, and geodynamics. We present Reclus, a suite of global, integrated databases that fill this gap, thereby providing the community with the key components for investigating the Earth system. Reclus includes databases of the following: (a) structural elements, which define the three-dimensional geometry of the rock volume, including folds and faults; (b) “crustal” facies describing the geometry and composition/ rheology of the lithosphere; (c) igneous features; and (d) geodynamics, representing the dominant thermo-mechanical processes acting on the lithosphere. These databases and workflows are applied to East Africa to investigate the geometry and heterogeneity of the margin and its hinterland. This margin is often summarized in the literature as a “transform margin,” represented by a single structural feature, the “Davie Fracture Zone,” but it is much more complicated. We show how the pre-existing structure, the superimposition of successive tectonic cycles, and crustal heterogeneity dictate the complexity observed.

**Plain Language Summary** Scientific databases are important for developing and testing ideas. For studying plate tectonics, there are a large number of databases available. But, absent from this list are detailed, global databases that link interpretations of faults and folds with the distribution of different crustal compositions and thicknesses. These databases are important because these features dictate how the crust responds to tectonic forces, which may result in changes in where sediments are deposited, new folding and faulting, and uplift or subsidence. We have built a suite of databases, collectively called Reclus, that fills this gap. These are spatial databases interpreted primarily from remote sensing and seismic data. They are supported by a comprehensive audit trail that explains what the interpretations are based on and how confident a researcher can be in using them. These databases are designed to provide a baseline resource for the scientific community with which we can test hypotheses, look at large-scale patterns, and identify where new data and research is needed.

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**1. Introduction**

Observational data are fundamental to scientific advancement. Recently many governments and research bodies have made their data, and the data obtained through their funding, open to the public. This has proved invaluable for furthering our understanding of the Earth system. Primary data, including Landsat imagery (NASA Landsat Program, 2000), radar (SRTM: Shuttle Radar Topography Mission), and the results of the DSDP and ODP drilling programs, provided by the US Government are amongst the most important contributions to Earth sciences available. Other countries, notably Australia, Canada, New Zealand, and Norway, make industry acquired potential field, seismic, and well data available after a specified duration of time. For tectonics, there are a range of digital data sets now available, including the following: plate models (Meredith et al., 2021; Müller et al., 2019; Seton et al., 2012; Torsvik et al., 2019); plate polygons (Bird, 2003); sedimentary basins (CGG Robertson, 2020; USGS World Energy Assessment Team, 2000); hotspots (Whittaker et al., 2013); isochrons (Müller et al., 1997; Royer et al., 1992); ocean age (Müller et al., 2008; Pérez-Díaz & Eagles, 2017; Seton et al., 2020); ocean fabric (Gahagan et al., 1988; Matthews et al., 2011; Royer et al., 1989; Tozer et al., 2019); large igneous provinces (Coffin & Eldholm, 1994;
Absent from this list are detailed global databases of structural elements, crustal composition and geometry, and geodynamics. But these are fundamental in constraining plate models, defining basin form (basin dynamics), and understanding the development and distribution of accommodation and heat flow (a key input in both maturity modeling in petroleum exploration and geothermal exploration). The interplay between geodynamics and crustal architecture dictates landscape evolution, and therefore paleogeography and source-to-sink stratigraphic analysis. It is upon the resulting landscape that the geological record is built. Many major transport pathways (rivers and submarine canyons) are structurally defined, for example, the Benue River through the Benue Trough, the Zambezi River via the Middle and Lower Zambezi basins, the Amazon River along the Amazonas shear zone, and Lurio Rivers in East Africa.

The notion of a database and maps depicting crustal architecture predates plate tectonic theory, for example, Boué's global map of "geological structure" (published in Johnston [1856]) or Reclus' (1876) global maps of volcanoes and mountain belts. Reference to the "architecture of the crust" was first made by Hunt (1873), who saw it as key to interpreting the geological record by underpinning what he called "paleogeographic maps"—reconstructions of the surface of the Earth through time. This was a view supported by subsequent paleogeographers (Schuchert, 1910, 1928; Ziegler et al., 1985).

With the advent of plate tectonics in the late 1960s, the need for up-to-date global maps resulted in Exxon's "Tectonic map of the world" (Exxon Production Research Company, 1985), showing the distribution of major structural elements, basins, isopachs, and basement. Subsequently, published data sets included the compilations of the CGMW (2010) and Bally et al. (2012). Yet, the representation of the crustal architecture and structural elements on these maps is still quite generalized. More detailed maps are available, for example, the DOTSEA and DOTMED databases (Chamot-Rooke et al., 2005; Pubellier et al., 2005), but these are geographically limited and lack a comprehensive attribution and audit trail.

This study aims to construct and make openly available a baseline suite of databases that can be used by the community to further our understanding of the Earth system. We have called this suite Reclus, after the French geographer "Jacques Élisée Reclus", whose 19 volume work, La Nouvelle Géographie Universelle, la Terre et Les Hommes, examined the physical and human geography of every continent, including some of the first maps illustrating the global distribution of volcanoes and mountains. Reclus has been designed to enable cross-disciplinary integration and use in analyses including the following: geodynamic modeling; plate reconstructions; structural analysis; paleogeography; paleobiogeography; paleoecology; source-to-sink analysis; paleoclimatology and Earth system modeling. To achieve this, Reclus is fully integrated across its components, reflecting the close interplay of each element in the Earth system.

Reclus differs from existing databases in the following ways: (a) it includes a consistent representation of global crustal types, especially along passive margins where this is required for a broad application in restoration modeling, heat flow modeling, and plate tectonic restoration; (b) a more detailed and consistent structural elements database; (c) a geodynamics component that explicitly records the time since the last thermo-mechanical event to affect any part of the crust; (d) it forms part of a more comprehensive, integrated workflow developed to build paleogeographic maps and paleolandsapes as the backdrop for understanding the Earth system (Markwick, 2019).

The problem of representing and classifying the structural framework and crustal architecture is exacerbated in geographic areas such as East Africa, where multiple tectonic cycles have resulted in a complex, superimposed history that dictates how the margin and hinterland develop (Macgregor, 2015; Reeves, 2017; Reeves et al., 2016). This complexity makes it an ideal test of the utility of the Reclus baseline databases and workflows. This includes their application in resource exploration, geohazard, and environmental studies. East Africa is an area of on-going exploration for oil and gas (Brownfield, 2016), minerals, metals, and
geothermal energy (Delvaux et al., 2010; Kraml et al., 2014; Martinelli et al., 1995; Mnjokava, 2012). The Durban Basin offshore SE Africa is the site of investigations for carbon storage (Hicks & Green, 2017). Figure 1 shows the study area used in this paper. From this area, we develop three examples to illustrate how these databases provide a systematic baseline with which to understand the regional context of detailed studies and how our interpretations compare and contrast with existing interpretations: (a) The Davie Deformational Zone (DDZ); (b) the interplay of pre-existing fabrics; (c) the Biera High and Mozambique Lowlands.

2. Materials and Methods

The Reclus databases have been designed, compiled, and managed using ESRI’s ArcGIS software (ESRI, 2017). They are underpinned by a comprehensive data management system and systematic attribution; details are included in Supporting Information S1. The availability of such a comprehensive audit and attribution are key if the data are to be used and improved upon, especially when used as input to AI (Artificial Intelligence) systems, which includes machine learning.
2.1. Workflow

The workflow used to generate the databases is based upon that described in Markwick (2019) and is summarized in Figure 2. We present a summary of each database, including the input data, below and provide full methodology and details within Supporting Information S1.

2.2. Definitions

Table 1 provides definitions for key terms commonly used in the literature, which have specific meanings for the databases presented here.

2.3. Input Data

The primary data sets used in this study include published satellite gravity (Sandwell & Smith, 2009; Sandwell et al., 2014), magnetics (Lesur et al., 2016; Maus et al., 2007, 2009), radar (Farr et al., 2007), Landsat (NASA Landsat Program, 2000) and published well and seismic data (Figure 1). More detailed field-based gravity data, including Full Tensor Gravity Gradiometry (FTG) surveys, and aeromagnetic data (e.g., Ruotoistenmäki, 2008), have been used where these are published. The bathymetric data set employed is that of Gebco (IOC et al., 2003), as this was the last version to be based on soundings without including bathymetric interpretations from gravity inversion. Secondary data (published interpretations from other researchers) are used to provide information on the geological significance of features, including age, kinematics, petrology, and depositional environments.
2.4. Scale and Resolution, Confidence and Precision

For digital spatial databases, the term “scale” is problematic because the same information can be represented at any “scale,” whatever its original compilation scale and intended purpose.

Markwick and Lupia (2002) described the importance of scale and resolution in geological problem solving and recommended the use of the term “resolution” rather than “scale” in describing spatial data. They adopted the concept of the “minimal resolvable feature” resolution (Tobler, 1988) as a useful way of indicating spatial limitations. Each input data set used in our interpretations has its intrinsic grain (the grain is the minimum resolution of an observation or data; the smallest spatial or temporal interval of observation) and coverage density, which can vary with depth and geographical location depending on the capture methods (viz., the grain of magnetic data coarsens with the depth to the magnetic layer). This dictates the minimum resolvable size of interpreted features.

An important role of database attribution is to provide users information on the provenance (explanation, input data, and references) and confidence in each interpretation. Confidence fields in the databases are qualitative and indicate the repeatability of an interpretation, whether placement (mapping uncertainty) or age (how likely the age assignment is to be changed). We follow the schemes of Markwick (2019) and Markwick and Lupia (2002), which are based on those of Ziegler et al. (1985) and reflect the source(s) of information, data density, and data grain (e.g., cell size). Confidence is not a synonym for uncertainty, which is the quantitative estimation of error present in the data (viz., age uncertainty being the error assigned to an absolute age derived from an analytic technique; a detailed description of confidence attribution is provided in Supporting Information S1).

| Table 1 | Definitions of the Key Terms Used Throughout This Paper |
|---|---|
| Term | Definition | Notes |
| Crustal architecture | The geometry (spatial extent and thickness), character (composition and rheology), and structural framework of the Earth’s crust | Crustal architecture is the product of past geodynamic processes, but in turn, dictates how the crust responds to subsequent geodynamics resulting from changes in the tectonic regime. The term was originally coined by Thomas Sterry Hunt in 1873 (“The structure and arrangement of the materials of the earth's crust, its architecture, as it were” p. 416). In application, the term “crustal architecture” includes consideration of the whole lithosphere |
| Structural framework | The three-dimensional geometry of the rock record as the product of deformation and therefore the record of the strain applied to the rock volume | This deformation is the response of the existing crustal architecture to geodynamic forcing. The structural framework is an integral part of the crustal architecture, but in most usage referred to separately |
| Geodynamics | The dynamic processes that shape the Earth. These comprise the dominantly horizontal stresses resulting from and leading to the motion of tectonic plates, and the dominantly vertical stresses resulting from mantle processes and, locally, igneous activity | The direct consequence of geodynamics is deformation (including uplift and subsidence), the product of which is the revised crustal architecture with the specific deformational activity recorded by the structural framework. How the Earth responds to geodynamic forcing’s will vary depending on the stresses involved and the pre-existing crustal architecture |
| Tectonics | The description of the processes that “build” the Earth’s crust and define its evolution through time | The term “tectonics” encompasses both crustal architecture and geodynamics and is explicitly linked with the concept of plate tectonics, especially the largely horizontal plate motions that drive and result from horizontal stresses. Therefore, tectonics, like crustal architecture, considers more than just the crust, and requires an understanding of lithospheric and mantle processes |

3. Structural Elements Database

The Structural Elements database comprises the following key structural components: faults (features with “evidence” of displacement), lineaments (features that may be structural but with no unequivocal offset or other evidence of motion), bedding (S0), folds, and foliation. All have been captured as lines (polylines in ArcGIS) rather than polygons and therefore represent the position of the fault without implying displacement or rock volume loss/repetition.
Although automated methods have been used to identify lineaments using remote sensing data sets (Cascone et al., 2016; Royer et al., 1989), in this study, the majority of features have been captured manually. This reflects problems we have found with automated methods when interpretations are based on multiple, diverse data sets; for example, using breaks in magnetic anomaly data to pick out fracture zones, which may coincide with continuous bathymetric scarps or troughs, and continuous gravity lows (see Supporting Information S1).

The resolution, precision, and accuracy of mapped structural features vary according to the input data sets used in each interpretation resulting in systematic differences between features mapped offshore and onshore (e.g., Angoche or Majunga Basins in comparison to the East African rift system, Figure 3). This combination of resolutions is less problematic than may be expected because it also reflects application as well as data provenance. Structural features in deep-water settings, such as fracture zones, are most frequently used to constrain plate kinematic models, where the detailed mapping within a fracture zone is unnecessary. On continental margins and onshore the availability of often commercially acquired data, including seismic or high-resolution aeromagnetic data and FTG surveys, results in significant variations in mapping resolution. End-users must be aware of the resolution of the database they are using.

In the deep oceans (e.g., West Somali Basin, Figure 3), where the crust is considered to be relatively homogeneous and thin (~7 km), deviations in the gravity field largely reflect bathymetric changes. These can be due to juxtaposed differences in crustal thickness due to faulting (e.g., fracture zones) and igneous extrusions (seamounts and plateaus) or thermal and mechanical processes (e.g., spreading ridges and subduction

Figure 3. The Structural Elements Database for the southern area of the East Africa margin from Tanzania to the South African border with Mozambique. This exhibits a complex history and variety of tectonic settings to test out the mapping methodologies and workflows. The symbology follows standard conventions for showing kinematics based on that published by the USGS. A full explanation is given in Markwick (2019). Features mentioned in the text are labeled in the figure. References for the base map are given in Figure 1 caption.
zones). These gravity anomalies are further exacerbated by compensation effects when using the free-air correction (viz., subduction zones represented by deep gravity lows with the subduction zone feature drawn along the axis of the lows, corresponding, usually to the deepest part of the corresponding bathymetric trench; spreading ridges represented by narrow gravity lows bounded by highs orientated perpendicular to fracture zones).

Continental margins are typically structurally more complex with a higher density of structuralization than in the deep ocean (e.g., Majunga and Angoche Basins, Figure 3). The workflow used here to capture features is similar, with the main inputs being gravity data and bathymetry. Also, on many margins, the availability of controlled source reflection seismic data, often acquired by industry, provides significantly higher resolution.

The onshore structural mapping is based on more detailed remote sensing data, including radar (SRTM3: 90 m resolution), Landsat (30 m resolution), and published aeromagnetic data. Also, there is a much higher density of publications, sections, field-based studies, and geological mapping (e.g., Lake Malawi portion of the East African Rift system). Folds are the clearest expression of deformation that can be identified onshore usually using the geometry of topographic ridges. Faults, as lineation's picked out by continuous scarps or narrow valleys that cut the surface fabric, with the highest confidence where these features truncate and offset folds. These are captured using both Landsat and SRTM3 grids.

Landsat is clearest in semi-arid to arid areas where bedrock is exposed, and there is limited vegetation to obscure patterns. In vegetated areas, we have used different bandwidths to pick out subtle changes that may indicate structure. The radar data (SRTM3) can penetrate vegetation but does require topographic relief to be able to identify structures. Derivatives are used to expose geological features, including calculations of slope comparable to the total horizontal derivate used in potential field analysis and high pass filters (see Supporting Information S1 for details). We have also used different azimuths and sun angles to generate hill-shades to highlight possible topographic features that may indicate structure. Detailed, published aeromagnetic data are used where available. Georeferenced geology maps provide further confirmation of interpretations and are used throughout this study to add information on kinematics and timing, where this is not clear from primary data.

The Structural Elements database is used to define sedimentary basins, the nature and geometry of crustal blocks, provide an indication of the dominant stress-field at the time the features were active (geodynamics), and as a guide to landscape response (viz., the position of scarps through time and river pathways in paleogeography and source-to-sink analysis). Major faults on now separate continental plates can be used to tie pre-rift plate geometries.

4. Igneous Features Database

The Igneous Features database includes information on the geometry, age, petrology, and tectonic environment of intrusive and extrusive igneous features (Figure 4). It comprises two feature classes in ArcGIS, one each for polygons and lines. Most igneous features are mapped as polygons, but igneous dikes are stored mainly as lines—exceptions include large-scale vertical intrusions such as the Great Dyke of Zimbabwe, which can be up to 11 km wide (Schoenberg et al., 2003).

In the oceans, gravity, bathymetric and magnetic data are used to identify probable igneous features constrained by published papers, dredge samples, and wells. Examples of this include the magma addition to the West Somali Basin oceanic floor and localized volcanism within the Davie Deformational Zone (Figure 4).

Onshore features are largely constrained using Landsat imagery. Features can be differentiated from surrounding bedrock by color and textural differences (see Supporting Information S1), especially in areas where vegetation is limited or absent and where the volcanics are relatively young (e.g., Rukwa Volcanics, East African Rift, Figure 4). In areas of dense vegetation, the morphology of volcanics may be more apparent using radar data and drainage networks. Geological maps and publications are used to assign crystallization ages, petrological, and tectonic setting information.
The Igneous Features database was originally designed to provide input for constraining plate kinematic reconstructions, geodynamic and basin modeling (heat-flow). However, the mapping resolution we have adopted provides a level of detail that can also be applied to provenance studies, source-to-sink analysis, mineral exploration, and paleogeography. Igneous features can have a major effect on landscape evolution and sediment supply through differential weathering and erosion, vegetation cover, and drainage evolution. Major volcanic extrusions, for example, can instantaneously affect drainage evolution by blocking or deflecting rivers.

5. Crustal Facies Database

The Crustal Facies database records the geometry, thickness, and composition of the Earth's crust. The crust represents the chemically distinct upper layers of the Earth. Rheologically, the crust forms part of the lithosphere, which must be considered in geodynamic modeling. Where the crust is absent, e.g., in areas of hyper-extension, we incorporate the presence of exhumed mantle. Existing methods for categorizing crustal types are commonly associated with the tectonic processes involved, such as compressional margin, hyper-extended (Péron-Pinvidic & Manatschal, 2010), or volcanic passive margins. This is problematic from a global database perspective as it combines observations with process while also mixing crustal type with geodynamics.

Here we take a different approach and differentiate by composition (“continental,” “oceanic,” or “mantle”) and thickness with reference to “standard” continental crust of 30–35 km and oceanic crust of 5–7 km
The composition reflects the history of that crust (previous tectonic cycles) but is independent of the geodynamic processes acting on the crust once formed. Consequently, interpretations of crustal facies will change through geological time. The default in our databases is the present-day status. Separate databases are built for each timeslice reconstructed as part of the paleogeography workflow (Markwick, 2019).

The different compositions, and corresponding crustal thicknesses (Figure 5), are mapped from an analysis of gravity and magnetic data, geological maps, seismic and 2D profiles. In the oceans, thick crust, ocean arcs, and isolated continental blocks usually have a bathymetric and gravity expression. This expression is readily identified and can be checked against seismic, well, and dredge samples where available. The thick crust on the continents will usually be topographically high if it is in isostatic equilibrium, with a corresponding gravity (Bouguer) signature. Geological data (outcrop samples, well cores, geological maps, and published papers) provide information on the composition, including the igneous features database.

In the offshore, we have followed the work of Williams et al. (2010). They found that amplitude changes in the Bouguer total horizontal derivative (Ba THD) provide information on the transition from “true” ocean crust to continental crust along many margins. This is here referred to as the limit of “standard” (“normal”) ocean crust.

The domain between the limit of “standard” oceanic crust and unstretched continental crust is more problematic. Commonly this is defined as “transitional crust,” but given the potential variability in margin composition, this forms a significantly ambiguous term that is problematic when applied in the database. Instead of using “transitional crust,” the database uses the following classification, which can be derived directly from available global databases: (a) thin (or very thin) continental crust with no magmatic addition, (b) continental crust with magmatic addition, which incorporates inner seaward dipping reflectors, (c) mantle, (d) mantle with magmatic addition, and (e) thick oceanic crust, which incorporates outer seaward dipping reflections (Norcliffe et al., 2018; Paton, Pindell, et al., 2017).

The resulting map (Figure 5) provides input for defining plate polygons in plate kinematic modeling, reconstructing potential heat flow as a critical input to maturity modeling and geothermal exploration, understanding basin formation and evolution, and paleogeographic reconstruction and paleolandscape dynamics.

6. Geodynamics Database

The Geodynamics database records the age and nature of the last thermo-mechanical event with respect to the paleogeographic timeslice being reconstructed. The default database records this information for the present-day. This method was first discussed in Markwick and Valdes (2004) as tectonophysiology, which described areas above the contemporary base-level and, therefore, areas of net erosion (sediment source areas in source-to-sink analysis). The age of the last thermo-mechanical event was added to represent better the decay of landscapes (Campanile et al., 2007; Pazzaglia, 2003; Tucker & Slingerland, 1994; Van der Beek & Braun, 1998; Whipple & Meade, 2004) following the ideas presented in the 1997 USGS thermo-tectonic age map of the world that was used to model heat flow following Pollack et al. (1993) and crustal thickness and structure (Mooney et al., 1998).

In this new database, the geodynamic state is assigned to the whole Earth, not just those areas above the contemporary base-level. This is classified into those processes characterized by (a) a dominantly vertical stress field and (b) those represented by dominantly horizontal stresses. Vertically dominated geodynamics can then be divided into medium, and long-wavelength (spatial distance in the xy plane) processes mainly driven by mantle processes (dynamic topography) and shorter wavelength effects due to localized volcanics, mantle hotspots, flexural and isostatic rebound. Horizontal stresses are divided into compressional and extensional settings. The symbology of each thermo-mechanical state is shown as solid color when active at the time of the mapped interval and then by increasing widths of diagonal lines colored with the symbol for anorogenic land as the time since activity increases (Figure 6).

Anorogenic land is the landscape expression of the long-term “equilibrium” state. This is the “Monadnock phase” in the geomorphological evolutionary scheme of Strahler (1964), represented by a concave-up hypsometric curve. Geologically, this represents crust in isostatic equilibrium with no tectonic forces acting on it. In reality, the point at which any landscape reaches “equilibrium” will vary according to the type of
Figure 5. (a) The Crustal Facies Database for East Africa. Features mentioned in the text are labeled in the figure. References for the base map are given in Figure 1 caption. (b) The classification that is used to map crustal facies, which is based on composition, geometry, and thickness. The crustal facies are derived from analysis of potential field, well, and seismic data, supported by published interpretations. The tectonic setting quoted reflects the relationship between crustal composition and tectonics.
Figure 6.
thermo-mechanical event, bedrock, vegetation cover, and climate evolution. There is also the added complication of dynamic topography (Barnett-Moore et al., 2017; Burgess & Gurnis, 1995; Lithgow-Bertelloni & Silver, 1998; Liu & Nummedal, 2004; Stephenson, 2019) due to mantle processes that may not have been recognized. In this database, we have classified crustal areas that have not been affected by geodynamics for more than 300 million years as “anorogenic.” In most settings, either “equilibrium” would have been established long before this, or a subsequent geodynamic “event” would have occurred and overprinted the original geodynamic effects.

The geodynamics database is used in combination with the crustal facies database to investigate the potential response of the landscape, which is then used as input into reconstructions of relative paleo-elevation (Markwick, 2019; Markwick & Valdes, 2004; Ziegler et al., 1985) and the geometry of uplifts (viz., mantle driven vertical uplift is typified by broad, long-wavelength uplifts, whilst compressional systems can be more localized). Given the long-wavelength over which geodynamic processes occur, the full extent of their influence can be difficult to ascertain in comparison to more easily identified short-wavelength controls such as geomorphology or local rheological variations. By integrating across these scales, the influence of the implied stress field from the geodynamic mapping on the more local structure and magmatic mapping can be considered. An example of this is the interplay of the African Superswell and the Karoo-aged extensional features in East Africa (Figure 6 caption for further details). The derivation of a consistent stress field across these scales is an essential input for plate/kinematic modeling.

7. The East African Crustal Architecture

We consider that the greatest value of the Reclus databases is the ability to place detailed observations into a broader, regional context using a coherent framework. This enables users to move between scales and diverse data sets and so quickly see how observations fit or do not fit within the bigger picture. We can then test hypotheses, pose new ones, identify data gaps, and focus attention, including new data collection, on areas of major uncertainty or equivocation. The ability to investigate natural phenomena at different scales and resolutions and to be able to move easily between these scales is a fundamental strength of this methodology.

In this section, we show how the Reclus databases can be used in practical studies. Here we focus on three examples from East Africa: (a) the large- and fine-scale crustal geometry of the East Africa margin and what this represents tectonically; (b) the interplay of pre-existing fabrics and how these may or may not partition and dictate subsequent basin and hinterland development; (c) the nature of the controversial Beira High and Mozambique Lowlands, which until recently have suffered from a lack of data, but whose structure and crustal architecture have major implications for the Gondwana plate fit, local heat flow, basin evolution, and sediment accommodation.

Figure 6. (a) The classification used to map geodynamics. This divides areas by the nature of tectonic forcing (the last thermo-mechanical “event” acting on an area) and the time that has elapsed since cessation of that activity. In this paper, we show only the present-day geodynamics database. But the same approach can be applied to any time in the geological past. For each paleogeographic map the mapped geodynamics represents the elapsed time between the last thermo-mechanical event and the reconstruction age of the paleogeography. (b) The Geodynamics Database for the southern East African margin. Interpretations are based on an investigation of the age and type of deformation, metamorphism, stratigraphic relationships, drainage and landscape analysis, and uplift (denudation). The full extent of dynamic topography (incorporated within our “mantle” designation, “M”) is not always clear from the geological data. For example, Karoo rift basins, such as the Luangwa and Middle Zambezi basins, can be easily identified as “relict” extensional Karoo-aged features using local geology and geomorphology. But the last thermo-mechanical forcing acting on this area is mantle-driven uplift—the late Cenozoic “African Superswell” (Braun et al., 2014; Moucha & Forte, 2011; Nyblade & Robinson, 1994). The Karoo-basins have been passively uplifted on this broader mantle-related uplift. The Geodynamics Database is designed to store both the last thermo-mechanical definition, in this case the African Superswell, but also all important short-wavelength features and their geodynamic origin that have been passively affected. This reflects the original aim of the geodynamics database to provide input to landscape modeling for paleogeographic reconstruction as part of Earth system modeling. In this figure, we have symbolized the interpretations using the database attribute that includes these short-wavelength relict features. Features mentioned in the text are labeled in the figure. References for the basemap are given in Figure 1 caption.
7.1. The Davie Deformational Zone (DDZ)

The East African margin marks the break-up between East and West Gondwana. Understanding the architecture and evolution of this boundary provides insights into regional tectonics and the underlying controlling processes. But this requires integration of observations at a variety of scales, which is why the Reclus databases provide an appropriate framework for such a study.

Tectonic reconstructions of the East Africa margin are traditionally dominated by a single feature, the “Davie Fracture Zone” (DFZ). This transform boundary was recognized by Scrutton (1978) as a kinematic requirement to accommodate the Jurassic and Early Cretaceous opening of the West Somali Basin between Madagascar and Somalia. Whilst subsequent authors have described a much more complex margin (Figure 7) reflecting multiple tectonic cycles (Jacques et al., 2006; MacGregor et al., 2017; Mahanjane, 2014), the absence of a regionally coherent crustal architecture map precludes a fully integrated understanding of the margin.

An immediate observation from the presented extract of the Reclus databases (Figure 7) is the diffuse and variable nature of the deformation along this margin; we, therefore, refer to this zone of deformation collectively as the “Davie Deformational Zone” (DDZ), restricting the use of the term “Davie Fracture Zone” to Scrutton’s (1978) original transform fault when it was active during the Mesozoic. The DDZ, as mapped in the Reclus databases, extends for over 2,000 km from the Davie-Walu Ridge (marker 1 in Figure 7a) in the north to southern Madagascar in the south (Figure 7b). In Scrutton’s definition, the DFZ sensu stricto connected the active spreading ridges of the West Somali Basin and Mozambique Ocean, with spreading in the...
West Somali Basin ceasing around chron M10n (~133 Ma, Tuck-Martin et al., 2018) or chron M0 (~125 Ma, Phethean et al., 2016).

As a consistent method of mapping has been applied, Reclus readily illustrates the fundamental difference in the mapped crustal architecture between the northern (Figure 7a) and southern DDZ (Figure 7b). In the north, the DDZ encompasses a broad zone of heterogeneous crust up to 300 km across. There is no sharp ocean-continent boundary as might be expected in a typical transform margin. Klimke and Franke (2016) found no evidence for the DFZ in their seismic study offshore northern Mozambique and Tanzania. This 300 km zone is frequently characterized as “transitional crust” (Vormann & Jokat, 2021), neither clearly continental nor oceanic. In the Reclus databases we have tried to provide more granularity by hypothesizing what that “transitional crust” represents (Section 5). These interpretations are based on published seismic data, 2D profiles, and potential field analyses following the methods outlined by Williams et al. (2010).

An important strength of the methodology is that the uncertainty of the interpretations is captured in the databases and can be updated with new data. An example of this is the area mapped as “mixed magmatic-thinned continental” crust (marker 2, Figure 7a), which is characterized by a gravity signature that is more akin, but not exactly, to ocean crust. This signature comprises low amplitude anomalies using the total horizontal derivative of the Bouguer gravity anomaly (generated from Sandwell et al., 2014). Based on similar signatures on other margins, this could be interpreted as slightly thickened ocean crust or very thin continental crust with magmatic additions (similar to the Afar Triangle). Given the uncertainties, this is assigned a low mapping confidence in the database (Figure 7a insert). Subsequent to the Reclus mapping, Sinha et al. (2019) using potential field data and deep seismic provided by ION interpreted this area as an incipient ridge (ION lines ION-TZ1-3000 and ION-TZ3-1200). This is consistent with our interpretation and therefore the databases can be updated to reflect a higher degree of confidence in the interpretation.

The results of Sinha et al. (2019) further demonstrate the application of Reclus in providing a context to compare alternative interpretations. Sinha et al. (2019) postulate in their dynamic model that the interpreted incipient ridge formed prior to the DFZ as an early formed ocean segment bounded to the west by the Seagap fault as a transform fault. The significance of the Seagap fault (Figure 7a) is contentious. Some authors show this as a continuous feature parallel with the DFZ from the Mozambique-Tanzania border north to the Davie-Walu Ridge (Tuck-Martin et al., 2018, their Figure 1), but other authors describe a more discontinuous feature (the interpretation of Joana Mencos as redrawn in Figure 1 of Sadiki et al., 2021), that curves NW as it passes Mafia Island (Fuhrmann et al., 2020, their Figure 1a). Our interpretation from Reclus is for a more discontinuous feature overprinted by Cenozoic extensional kinematics (Figure 7a). Although we show this zone of mixed magmatic crust with an inferred ridge continuing the trend of that in the West Somali Basin, based on the juxtaposition of mapped features, we accept that the hypothesis of Sinha et al. (2019) is a viable alternative and that this zone may be part of an earlier incipient ocean, related to the Phase 1 rifting of Tuck-Martin et al. (2018, discussed below). This would then be a southward continuation of the Somali margin (Mortimer et al., 2020) with the Davie-Walu Ridge as a transform fault, with a now obscured SE extension of the Precambrian Nyangere Shear Zone (Figure 7a) creating a possible transfer zone to the south. This requires further investigation. Although not shown here, the database enables the activation timing of specific structures to be identified, thus enabling structural overprinting to be considered.

Today, the northern extent of the DDZ is bounded by the Davie-Walu Ridge (marker 1, Figure 7a), a Late Cretaceous-Paleogene inversion structure, which is orientated parallel to the flowlines that trace the initial SE-NW opening direction of the West Somali Basin (Phethean et al., 2016). This extensional phase is dated between ~183 Ma to ~170 or 165 Ma (Tuck-Martin et al., 2018). The stress field this implies is consistent with the NE-SW orientated Permo-Triassic “Karoo” basins (Catuneanu et al., 2005; Delvaux, 2001) that intersect the DDZ in this area. These include the Selous, Rovuma, and Rufuji basins (Figure 7a, see marker 3). The juxtaposition and interplay of thin Karoo continental crust with the NW-SE extension in the Jurassic may explain the complexity of the crust in this area. The development of the DFZ sensu stricto with the switch to the N-S opening of the West Somali Basin at ~170 or 165 Ma (Tuck-Martin et al., 2018) may have comprised a complex strike-slip fault system, similar to that seen on other transform margins, for example the San Andreas system (Scharer & Streig, 2019), southern African Agulhas (Smithard, 2019) or the northern Caribbean (Davison et al., 2020). We see no evidence of this in the current data. But any fault
and the DFZ itself would have become obfuscated by subsequent tectonic cycles when spreading ceased (Figure 6).

The mapping in Reclus reveals a change in crustal character between the Mandawa and Rovuma Basins at the border of Tanzania and Mozambique (Figure 7a). This coincides with our interpreted eastward extension of the Mwembeshi Shear Zone (MSZ) (marker 4, Figure 7a). This marks an offset in thin continental crust onshore coincident with uplift and erosion in the present-day and the termination of the anomalous crust we have interpreted as mixed very thin continental magmatic crust. The zone of deformation in this area is still c. 300 km across, but the boundary with “standard” demonstrable ocean crust is much sharper in the gravity data. This is also marks the northern limit of active late Cenozoic rifting and the development of the Keribas and Lacerda grabens (marker 5, Figure 7a). The cause of the offset of crustal facies by the MSZ is unclear. Brown et al. (2014) suggest that the MSZ is currently active and may have been in the Mesozoic. However, we see no evidence of strike-slip and postulate that the MSZ acted as a “passive” transfer zone during the Late Jurassic to present-day. In Botswana Jurassic dyke swarms cut across the MSZ in Botswana without offset (Igneous Features databases, Figure 8).

The databases reveal the importance of understanding the distribution of passive transfer zones in controlling both the location of changes in crustal architecture (derived from the structure and crustal facies databases) and the superimposition of associated volcanics (derived from the igneous features database). To the south of the MSZ is the Lurio Belt (LB), which may also act as a passive transfer zone. The intersection of the LB with the DDZ marks another change in crustal facies. To the south, we see a narrow zone of

![Figure 8](image-url). The relationship of Jurassic igneous dikes in northern Botswana with the Mwembeshi Shear Zone and incipient Okavango Rift Basin. The absence of significant offset in the dikes precludes major strike-slip motion on this part of the Mwembeshi Shear Zone since ~178.9 Ma. The dikes in the Igneous Features database are interpreted from the aeromagnetic data presented in Lehmann et al. (2015). Age assignment is that given in Elburg and Goldberg (2000). Basemap references are given in Figure 1.
thin continental crust along the outer margin (marker 6, Figure 7b) and the development of the N-S Davie Ridge (marker 7, Figure 7b), although this is itself complex, as indicated by seismic (Bassias, 2016; Mahanjane, 2014). To the west of the Davie Ridge, along its full length, is a narrow zone of thin continental crust defined today by a very distinct, linear gravity low (Sandwell et al., 2014). This is superimposed by the Lac erda Graben in the north and broken by intermittent bathymetric volcanic highs in the south (the Anadroy Seamount and Sakalaves Platform, Figure 7b, marker 8). These volcanics include alkaline volcanics that are compositionally similar to the Late Cretaceous volcanics on Madagascar (Bassias & Bertagne, 2015). The continental-oceanic boundary of the DDZ in this southern area is much sharper than that seen in the north. It is also marked by structural provinces, which Intawong et al. (2019) have interpreted as a possible incipient subduction of Middle Jurassic Angoche Basin ocean crust beneath the Davie Ridge. Whether this is subduction sensu stricto is questionable—there is no evidence of arc development. But the orientation of fracture zones in the oceanic Angoche Basin and their truncation along this feature (Figure 7b, marker 9) would suggest some loss of surface area due to overthrusting of Madagascar along this boundary. This transient phase of compression occurred approximately at the same time as middle Cretaceous volcanism on and around Madagascar (c.95–80 Ma; Cucciniello et al., 2013; Storey et al., 1997). This volcanism has been interpreted as marking the trace of the Marion hotspot (Storey et al., 1997). This gravity low tapers out to the south along the western edge of the southern Morondava Basin, where evidence for compression ends, marking the limit of the demonstrable DDZ (marker 10, Figure 7b). In the Geodynamics database, we have tentatively shown the ridge with a compressional origin (Figure 6). But, we recognize that much of this has been overprinted with extensional tectonics during the Cenozoic. This highlights the importance of mapping geodynamics through time and how the same methodologies can be applied to paleogeography.

Superimposed on this history are Cenozoic rifting (East African Rift System, EARS) and mantle dynamics (Dynamic topography) (Figure 6). Today, seismicity along the DDZ is mostly limited to the Cenozoic rifts offshore Kenya and the line of the DDZ from the MSZ south to the southern Morondava Basin (USGS, 2019). Earthquakes in this region have extensional, not strike-slip focal solutions (Grimison & Chen, 1988) and are related to active rifting across the region. This is clearly shown in the databases by differentiating structures based on whether there is evidence of recent activity (red symbology) or not (black symbology) (Figure 3).

### 7.2. The Interplay of Pre-Existing Fabrics

The role of inheritance on tectonics has been documented since the 19th century (Şengör et al., 2018). Phillips et al. (2016) found that large-scale shear zones on the Norwegian margin act as a “template” for fault initiation, although the role of crustal heterogeneity on lithospheric break-up can be more uncertain (Gouiza & Paton, 2019; Paton, Mortimer, et al., 2017). The Reclus databases allow us to consider this question. This may explain our observations in East Africa. For example, the juxtaposition of crustal-scale Precambrian boundaries (e.g., Mwembeshi SZ and Lurio Belt) with changes in the geometry of the DDZ (Figures 3, 5, and 7).

The distribution of Karoo basins is similarly dictated by the distribution of Precambrian and Pan-African mobile (orogenic belts) (Figure 5). Karoo basins on the Kaapvaal craton are dominantly foreland basins or sags. The longevity of these Karoo basins and their accommodation varies depending on orientation and location. For example, the N-S Rukwa, and northern Malawi basins have relatively long depositional histories, from the Permo-Triassic into at least the Cretaceous (Catuneanu et al., 2005; Roberts et al., 2004). But the NW-SE orientated Luangwa Basin stratigraphy has a major hiatus after the Triassic (Catuneanu et al., 2005) but a geomorphic and depositional activity today. These basins influence the distribution of present-day rivers, but also the locus of Cenozoic rifting and volcanism, for example, the Rungwe volcanics (Figure 9).

But the Cenozoic picture is far from simple. The Cenozoic northern Malawi Basin reactsivate the older Karoo Rukwa Basin, influenced by the pre-existing Pan-African fabric (Mortimer et al., 2007, 2016). But to the south, the N-S Cenozoic Malawi rift cuts across the NW-SE orientated Karoo Metangula and Ruhuhu basins, although these do alter the rift Malawi geometry (Figure 5). The Malawi Rift is orthogonal to the strike of the Mwembeshi Shear zone with only minor effects. This complicated relationship between pre-existing fabrics and rifting is seen even more clearly in Tanzania in which rifting propagates into cratonic crust - the Northern Tanzania Divergence (Ebinger et al., 1997; Foster et al., 1997; Smith & Mosley, 1993; Yang & Chen, 2010) (Figure 10). A similar evolution has been described by Paton, Mortimer, et al. (2017) in the
South Atlantic, with initial rifting following the pre-existing crustal fabric (Cape Fold Belt) but then, with a change in the dominant stress-field, a second phase of rifting cut across all fabrics. By interrogating the Reclus baseline databases, we can see the interplay of structure, crustal facies, geodynamics, and igneous activity—for example, the location of the Rungwe volcanics at the intersection of Karoo and Cenozoic rifts, or the interaction of well-constrained onshore crustal fabrics with offshore basin evolution along the Diaz Marginal Ridge, South Africa.

### 7.3. The Beira High and Mozambique Lowlands

We have considered the application of Reclus databases in regions of tectonic complexity that have well-constrained data; we now consider its application where there is a sparse data coverage and significant uncertainty in the crustal configuration. The nature of the crust underlying the Beira High and Mozambique lowlands has been a source of uncertainty for decades because of the sparsity of published data. This is an active petroleum exploration area given the gas discoveries at Pande and Temane on the Mozambique coast (Figure 11) and oil and gas in the Rovuma Basin. In the last decade, seismic (Mahanjane, 2012) and 2D potential fields modeling (Mueller, 2017) have been published that clarify the continental origin of the Beira High and its relationship to the hinterland. This is seen in our databases Figure 11, which expand interpretations into the Mozambique lowlands, which is still poorly resolved (Figure 11b shows a map of our mapping confidence for the crustal facies interpretations. As with the DDZ example (Section 7.1), the
methodology enables the assignment of mapping confidence that provides the opportunity to assess the viability of alternative hypotheses). The Beira High is interpreted as a rifted continental block, bounded landward by a failed rift with SDRs (Senkans et al., 2019), represented in our crustal facies scheme by mixed magmatic—continental crust. The margin narrows to the east in the Angoche Basin. We postulate that this variation may reflect the interplay with Karoo basins. Gravity lows in the northern Mozambique lowlands are consistent with this failed rift continuing westward. However, in our current interpretation, there is a spur of thin, non-magmatic continental crust that seems incongruous and requires further modeling and/or seismic coverage. This demonstrates a key benefit of including within the Reclus databases assessments of mapping and interpretation confidence, and recording explanations of each feature. This allows users to identify equivocal interpretations and data gaps that require further investigation, enabling researchers to focus their resources and time.

The crustal interpretation over much of the rest of the Mozambique lowlands is more problematic. Well data show that volcanics floor much of the region, likely related to the Lebombo Karoo volcanics (c.182–180 Ma; Duncan et al., 1997; Riley et al., 2004). But whether these volcanics erupted onto early formed ocean crust or thin continental crust is less clear, hence the low mapping confidence (Figure 11b). Our interpretation of the existing potential fields, seismic and well data shows a band of continental crust along the margin, with thin mixed magmatic—continental crust behind, similar to what is mapped for the Biera High area. Circular features in the high-resolution aeromagnetic have been interpreted as calderas (Ruotoistenmäki, 2008) but also have a similar concentric form to intrusions, as shown here.
Figure 11. A detail showing (a) the relationship of the nature and geometry of our proposed crustal facies for the Biera High and Mozambique lowlands. The distribution of gas (red polygons) and oil (green polygon) fields published by the Instituto Nacional de Petroleo (INP, 2014) are coincident with the extent of magmatic mixed crust and may indicate changes in heat flow consistent with the crustal interpretation (P, Pande; T, Temane; I, Inhassoro; N, Njika). See Figure 5b for explanation of crustal facies symbology. References for the basemap DEM are given in Figure 1. (b) The mapping confidence assigned to the crustal interpretations. A full explanation of the mapping confidence scheme is provided in Supporting Information S1.
Rifting parallel to the Lebombo margin is reported in various commercial studies and is shown in Davison and Steel (2017). The satellite gravity data and magnetics support this. In this example, the databases capture the uncertainty of the possible interpretations and provide a context and focus for additional research.

8. Final Remarks

Reclus is an open resource designed to provide researchers with a comprehensive, audited, baseline suite of databases upon which to further their own research and our understanding of the tectonics of the Earth system. In this paper, four components have been described: structural elements; igneous features; crustal facies; geodynamics. These features are interpreted from primary data (Landsat, radar, seismic, well data, gravity, and magnetics) supported by secondary data sources (geological maps, literature, published academic studies, reports). Elements within each database have been interpreted using a systematic, integrated workflow. Applications of the databases range from tectonics and basin dynamics to mineral and hydrocarbon exploration, hydrogeology, and paleogeography. We envisage that the Reclus databases will continue developing and improving as more research is added to them.

The examples shown in this paper illustrate how a systematic approach to capturing tectonic information can provide insights on the juxtaposition and geometry of crustal and structural features in a complex geological area such as East Africa and pose new hypotheses to explain them. The superimposition and interplay between successive tectonic cycles is much clearer when viewed regionally and systematically.

Only by considering detailed phenomena within the context of the big picture can we fully understand how the system works.

Data Availability Statement

On publication, the ArcGIS databases described in this paper will be made available through the Pangaea data repository https://doi.org/10.1594/PANGAEA.937401. Supporting Information S1 provided here includes background documentation for each database.

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