The Knowing Earth

Standard Legend for Paleogeography 2023

Dr. Paul Markwick

Public Edition

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Standard Legend for Paleogeography
2023
Public Edition

AUTHOR

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All photographs by Paul Markwick

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COVER PHOTOGRAPH

Maastrichtian (Late Cretaceous) paleogeography centered on the eastern US seaboard. The base map shows the distribution of continents, land, and sea at the end of the Cretaceous and represents our latest generation of paleogeographic maps (Generation 3). Data points show the distribution of fossil vertebrates (grey squares), including dinosaur localities (orange squares), crocodilians (red circles), crocodylomorphs (red and pink half circles), and turtles (blue triangles). Red dots mark the location of rotated DSDP, ODP, and IODP drill sites. Other points represent outcrop and well data used to build the map. The art of map-making is to ensure that the data is clear to the user. That depends on the map legend used, the data displayed, and how.

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Understanding the **Present**
Revealing the **Future**

Pan African granites of the Cape Granite Suite, Boulder Beach, Simonstown, South Africa.

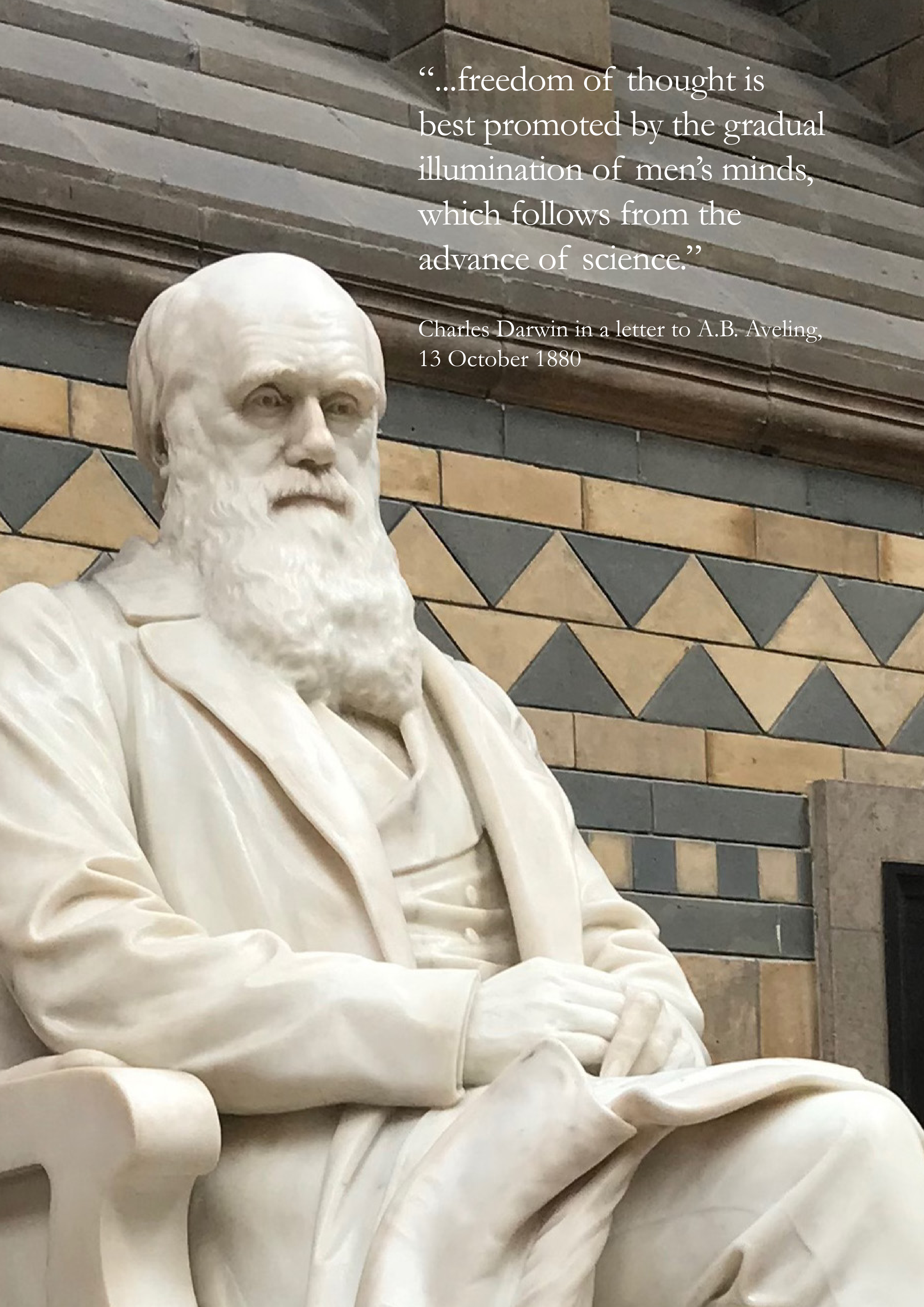
Welcome to

KNOWING.EARTH

Our passion at Knowing Earth is in helping people better understand the Earth system so we can make more informed decisions about the search for natural resources and how to manage the environment.

This is not easy. The Earth is complex, and no single process acts independently. Our advantage is in being able to fit the components together, by understanding the vocabulary of diverse scientific fields, knowing where to look for information, the right questions to ask of it, and the right people to seek for help when needed.

For further information please contact us.



"...freedom of thought is best promoted by the gradual illumination of men's minds, which follows from the advance of science."

Charles Darwin in a letter to A.B. Aveling, 13 October 1880

Executive Summary

The Knowing Earth Standard Legend for Palaeogeography comprises a set of mapping symbols designed to be used with the palaeogeographic mapping workflow described in Markwick (2019).

This workflow brings together data, knowledge, and understanding from diverse scientific fields. From crustal architecture to depositional environments and palaeo-rivers to elevation and climatology. Only by seeing how all these elements interact as part of the Earth system can we fully understand any individual component of that system and draw insights that enable us to solve problems and make informed decisions.

To make this tractable, the representation of results must be clear and simple. This is a major impetus for the design of our mapping legend and underpins the decisions that have been made on how the information is treated and classified, the colors and patterns used throughout the legend, and the underlying data management design.

A second driver is to make this legend available to the community to help promote a standard approach to paleogeography to facilitate communication and application across Industry and Academia.

This book provides a description of the 2023 edition of the mapping legend. This is an update to our 2018 release, which was published as supplemental material in Markwick (2019). An expanded version of this book is available to our sponsors. Digital versions of the legend for use with ESRI's ArcGIS software (ESRI 2017) are available from the Knowing Earth website.

Dr. Paul Markwick
February, 2023

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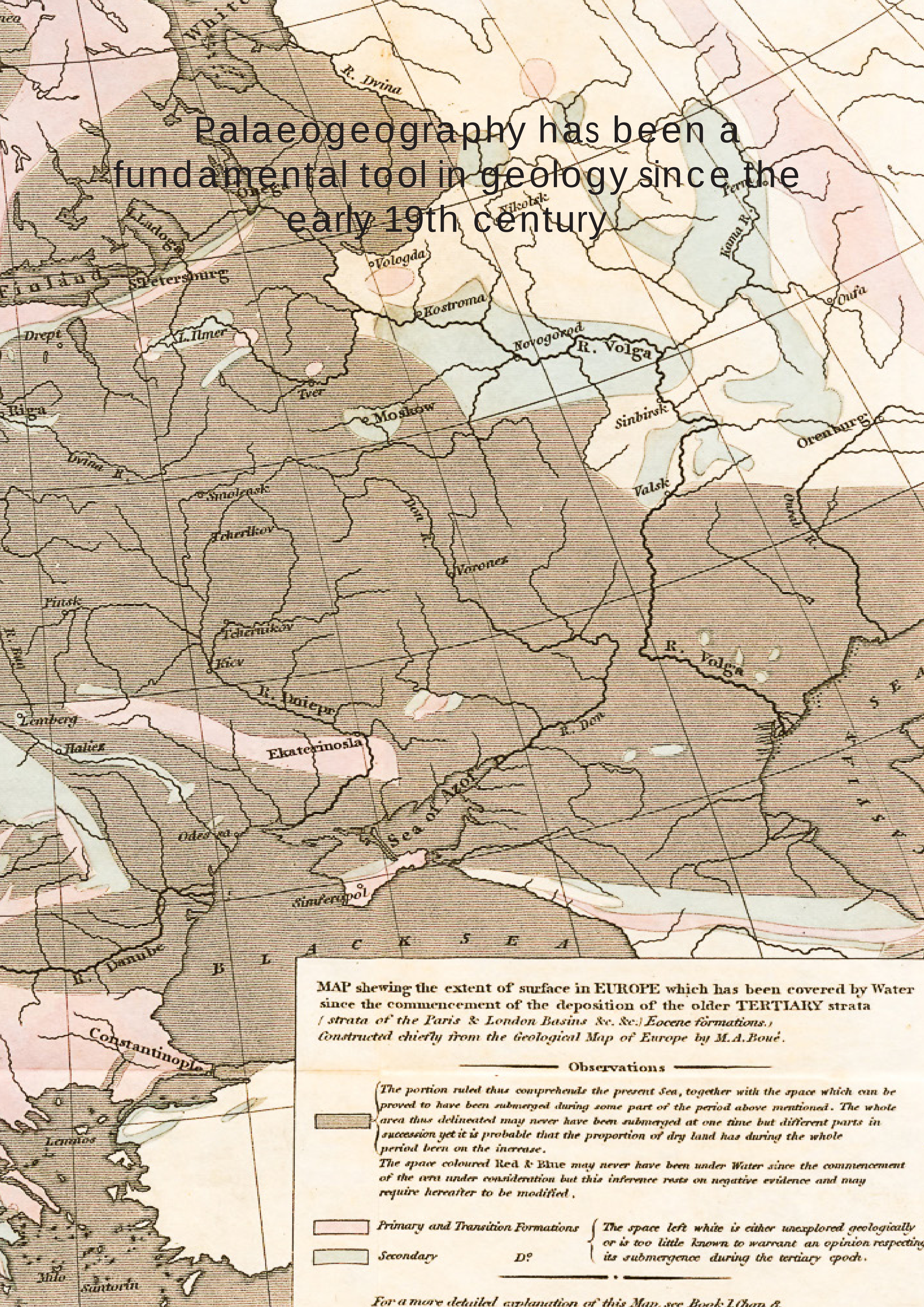
Palaeogeography has been a fundamental tool in geology since the early 19th century



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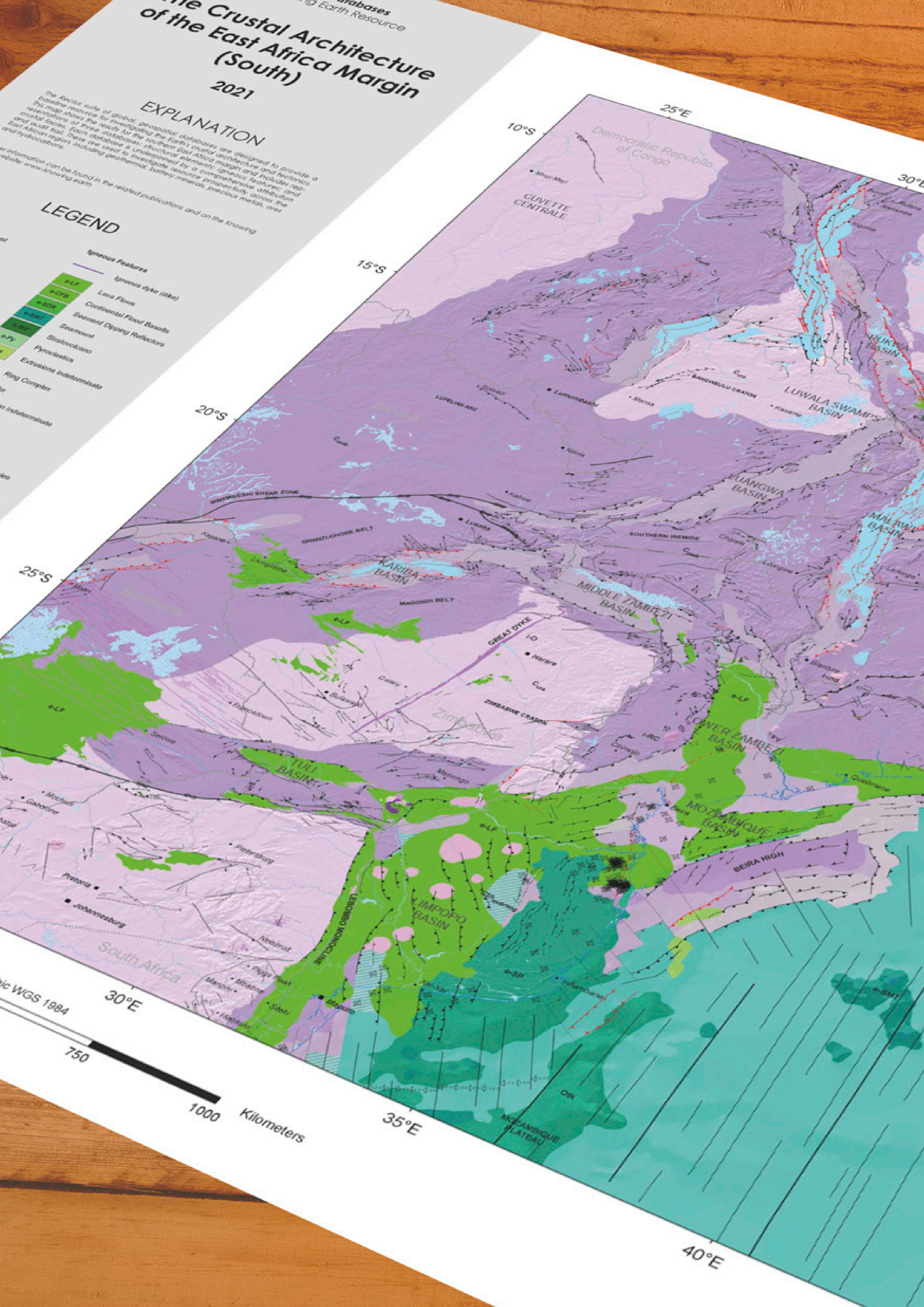


The Crustal Architecture
of the East Africa Margin
(South)
2021
EXPLANATION
LEGEND
Igneous Features
Igneous dyke (dike)
Lava Flows
Continental Flood Basalts
Seaward Dipping Reflectors
Seamount
Stratovolcano
Pyroclastics
Extrusions indeterminate
Ring Complex
e-LF
e-CFB
e-SDR
e-SMT
e-SV
e-Py
25°E
30°E
35°E
40°E
10°S
15°S
20°S
25°S
Democratic Republic of Congo
CUVETTE CENTRALE
BANGWEULU CRATON
LUWALA SWAMPS BASIN
RUKWA BASIN
LUANGWA BASIN
MALAWI BASIN
SOUTHERN IRUMIDE
LUFILIAN ARC
MWEMBESHI SHEAR ZONE
GHANZI-CHOBE BELT
Lusaka
KARIBA BASIN
MAGONDI BELT
MIDDLE ZAMBEZI BASIN
GREAT DYKE
Harare
ZIMBABWE CRATON
Zimbabwe
Botswana
Bulawayo
TULI BASIN
LOWER ZAMBEZI BASIN
MOZAMBIQUE BASIN
BEIRA HIGH
LIMPOPO BASIN
LEBOMBO MONOCLINE
Pretoria
Johannesburg
South Africa
Gaborone
MOZAMBIQUE PLATEAU
Maputo
ic WGS 1984
750
1000
Kilometers

1. Introduction

Good map-making is about conveying spatial information as clearly and intuitively as possible. The choice of map symbology – colors, ornamentation, line work, and text – is a crucial part of this communication. For some mapped data, there are (relatively) standard symbologies. For example, the symbols for structural elements, lithological patterns, and chronostratigraphic age assignments are broadly similar, although not without exception. But for paleogeographic mapping, depositional environments, and tectonics, there is no standard symbology. However, there are some recurring usages of particular colors, such as yellow for delta top depositional environments or shades of blues for marine settings. Part of the problem is that paleogeography encompasses many different components, with different research groups and companies focusing on their specific area of expertise. This diversity creates a challenge in defining **what paleogeography is.**

[Paleogeographies] can be a very powerful tool for managing and analysing diverse, large datasets, with which to better understand the juxtaposition and interplay of Earth processes and the products of those processes

1.1. Paleogeography Defined

The original definition of paleogeography proposed by Thomas Sterry Hunt was as a field within geology to describe the “geographical history” of the geological record. To Hunt, this included depositional environments, such as deserts and seas (Hunt 1873). Bailey Willis (1910) expanded this definition to explicitly include the state of the contemporary atmosphere (paleoclimatology) and oceans (palaeoceanography).

This breadth of usage is not surprising and is, in many ways, a reflection of the broad definition of geography itself, as

“the study of the physical features of the earth and its atmosphere, and of human activity as it affects and is affected by these, including the distribution of populations and resources and political and economic activities. The nature and relative arrangement of places and physical features.”

(OxfordLanguages, Oxford University Press, 2022, https://languages.oup.com/)

In our definition (Markwick, 2019; 2020), a paleogeographic map is the representation of the past surface state of the Earth (Hunt, 1873) at a specific moment in time (Kay, 1945).

This definition encompasses a spatial and temporal component.

Why does this focus on the surface state of the Earth? Because it is upon this surface that the rock record is built. A particle ‘sees’ topography, rivers, and oceans. It does not see mantle convection nor hyper-extension, at least not directly, only through the landscape.

In practice, facies maps, GDE (Gross Depositional Environments) maps, plate reconstructions, as well as reconstructions of past landscapes (paleotopography and paleobathymetry) are all referred to as “paleogeographic maps.”

All of these different components must be clearly and systematically differentiated. This is the challenge we have tried to address with the Knowing Earth Paleogeographic Map Legend.

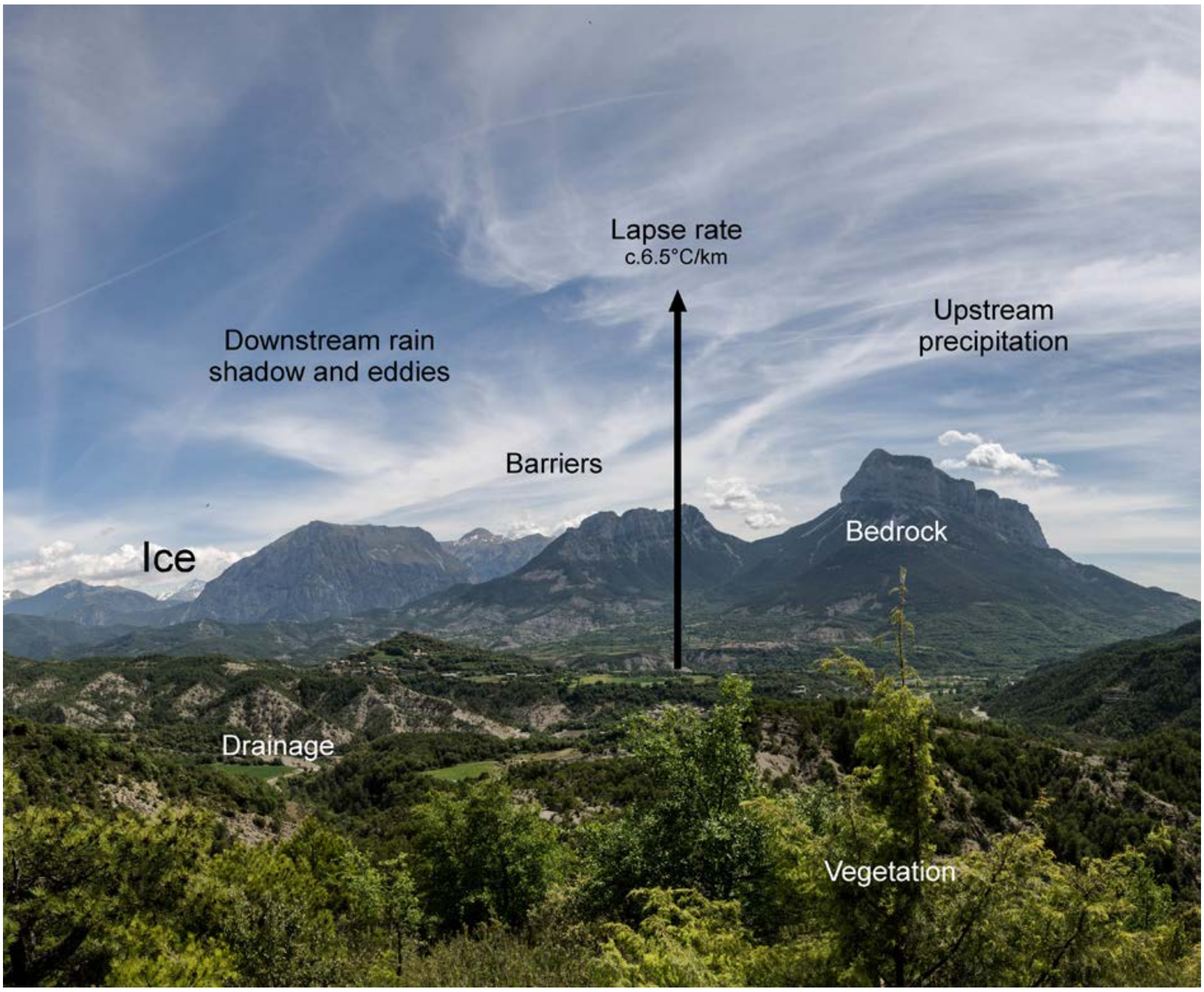


Figure 1. Because it is on this landscape that the rock record is built, a particle sees topography, rivers, and oceans. It does not see mantle convection or hyper-extension, at least not directly, only through the landscape.

1.2. The Knowing Earth Mapping Legend

The Knowing Earth mapping legend presented in this report was originally developed in 2018 and published as the supplementary data (SI) to Markwick (Markwick, 2019). This map legend included symbology for crustal facies, geodynamics, structural elements, lithologies, and depositional environments.

The choice of colors and symbologies reflects two main challenges:

1. Representing the diversity of data clearly, especially when different datasets are superimposed.
2. Building on existing standard or well-used symbology where possible.

Much of this legend follows standard geological symbology, especially for fault kinematics, lithologies, and, to a lesser extent, depositional environments (Federal Geographic Data Committee, 2006; Hulshof, 2012; Reynolds et al., 1995); see also references in Markwick (2019). The Shell legend (Hulshof, 2012) is now available for ArcGIS Pro, and ESRI provides a geological legend that is based on the USGS 1995 Open-File Report 95-525 (Reynolds et al., 1995).

Other workflow components do not have standard published legends, such as geodynamics or crustal facies (Markwick et al., 2021; Markwick et al., 2023). In those circumstances, we have tried, where possible, to pick symbols that are both aesthetically 'clean' and consistent so that the resulting paleogeography is evident, especially where multiple elements are superimposed. For example, to distinguish between depositional environments and thermo-mechanical states (geodynamics).

This 2023 version includes updates for crustal facies and lithologies and more explicitly addresses the needs of tectonics. Based on user feedback, we are also making this accompanying explanatory report available to the community. This report provides details on each symbol so they can be replicated in other software beyond ArcGIS.

The aim of releasing this legend to the community is to promote the development of a standard approach to paleogeography to facilitate communication and application across Industry and Academia.

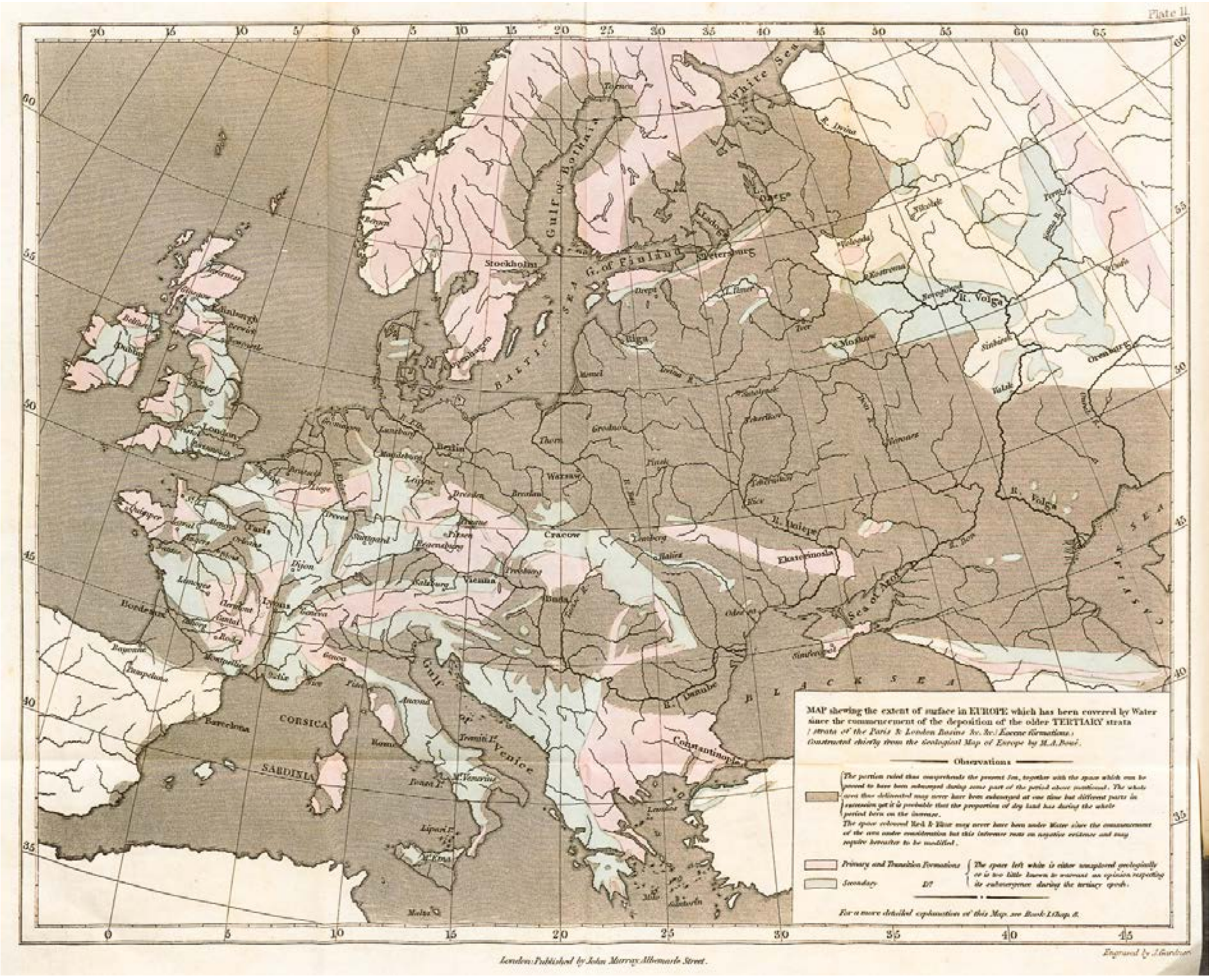


Figure 2. An early representation of the distribution of land and sea during the Paleogene of NW Europe (Lyell, 1837)

FURTHER INFORMATION

In addition to this book version, the legend is available from the following websites:

Supplementary material for Markwick (2018): **http://journals.cambridge.org/geo**
Digital explanatory notes and ArcGIS style files: **www.knowing.earth**
Digital explanatory notes and ArcGIS style files: **www.palaeogeography.net**


So much to take in...

...the need to bring it all together

The challenge is to take account of all the components of the Earth system. As can be seen here in the central Pyrenees, this comprises a large array of diverse components. There is simply so much to take in. Palaeogeography provides a context for mapping and investigating that diversity. The view north from the Castle of Samitier looking across the Ainsa Basin. Ainsa lies at the northern end of the Mediano Reservoir. The mountains in the background comprise the Axial Zone.

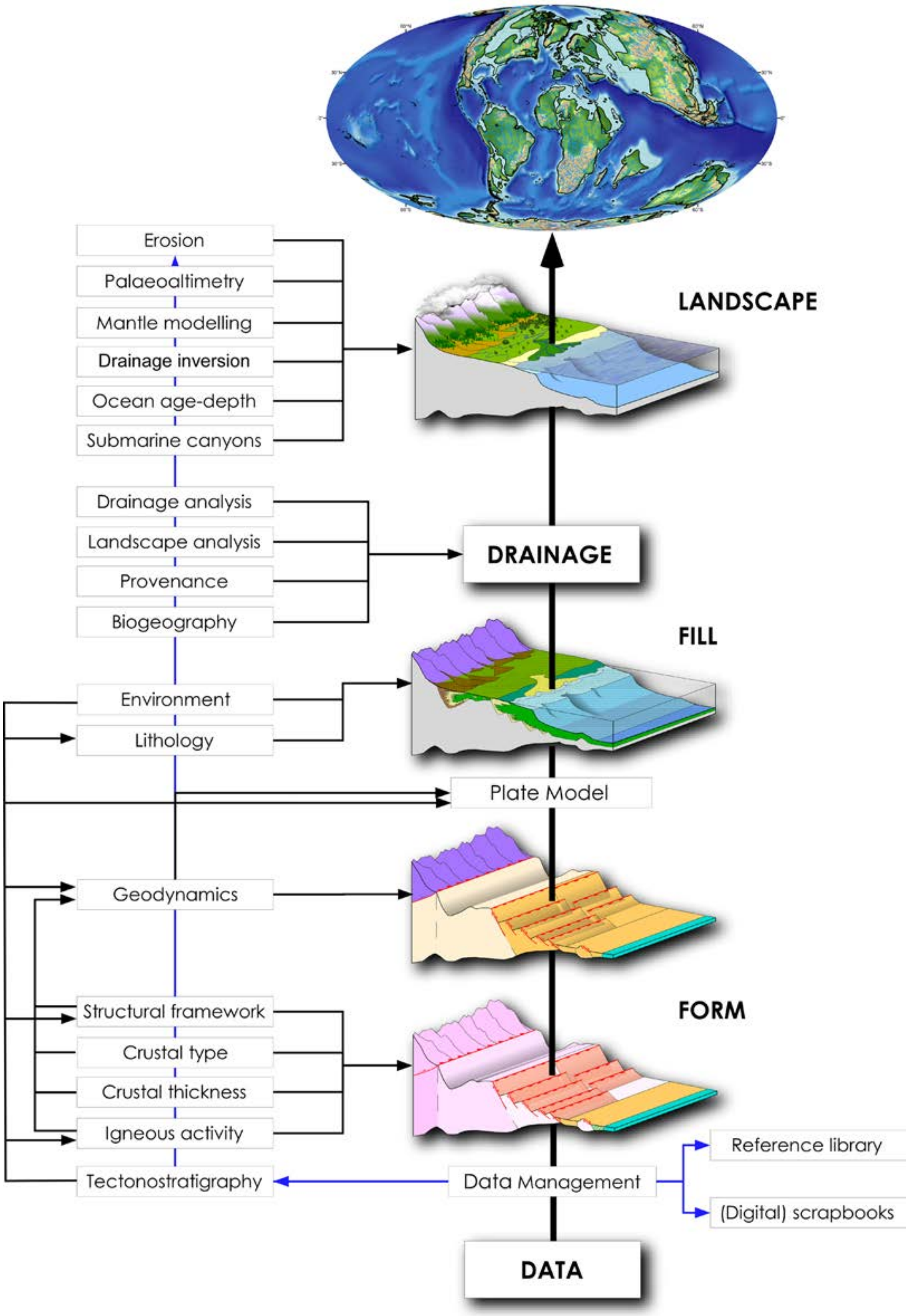


Figure 3. The palaeogeographic mapping workflow described in Markwick (2018). This follows the structure of the Earth by building up from the crustal architecture through the basin fill to drainage and landscape following ideas originally presented in the late 19th and early 20th centuries (Hunt, 1873; Schuchert, 1910; Schuchert, 1928; Ziegler et al., 1985). This builds from the underlying crustal architecture to reconstruct the basin and hinterland geometries, which then define the accommodation space and source-to-sink stories. It is also a key input into plate modeling. With the structural foundation in place, this is filled with depositional environments and dominant lithologies. The palaeo-drainage is then added with all the other components used to build the palaeo-landscape that acts as the boundary conditions for Earth system modeling. In reality, this is an iterative process. For clarity in this figure, only the top two levels of the workflow are shown. The block diagrams show how each stage of the workflow builds to form a hypothetical workflow.

2. The Paleogeography Workflow

The paleogeography workflow represented in this map legend (Figure 3) is designed to make tractable any investigation of the diversity and complexity of the Earth system, as seen in any landscape and the processes acting on it (Figure 4).

Paleogeographic maps can be much more than just an image. They can be a very powerful tool for managing and analyzing diverse, large datasets to understand better the juxtaposition and interplay of Earth processes and the products of those processes. Paleogeographic-based analytics can include a range of applications, including the following: paleobiogeographic, paleoecological, and paleobiodiversity analyses; palaeoclimatic reconstruction and Earth system model testing (paleogeography provides the boundary conditions for these models); water, mineral, and hydrocarbon exploration including the interrogation and analysis of the distribution and relationship of play elements (viz., source, reservoir and seal rocks, trap distribution, maturity). By visualizing these complex systems in map form, we can better understand which elements are important and which are not. This enables us to focus on the questions we need to ask, saving time, resources, and monies (Markwick 2019).

To fulfill the potential of paleogeography as a tool, we need to systematically capture all the components responsible for any geography (landscape). The first palaeogeographers recognized this in the late 19th and early 20th centuries. As a result, they formulated a palaeogeographic mapping workflow that reflected how the Earth is built, starting with the reconstruction of the underlying crustal architecture (structural framework and crustal type) (Hunt 1873; Schuchert 1910, 1928; Kay 1945; Ziegler et al. 1985). This workflow has been modified and improved over the subsequent century (Ziegler et al. 1985; Markwick and Valdes 2004; Markwick 2019), but the fundamental concepts and components remain the same.

There are three advantages of this approach:

1. When building a map, we can audit each component;

2. We can take the system apart, investigate each part separately (with experts in each), then put the system back together to see the whole and how it functions;

3. We can more easily distinguish between (1) the landscape, (2) the processes acting on the landscape, (3) the processes that created the landscape, and (4) the rock record that is the product of all of the above.

Each of these advantages is faciliated by the map symbology we use.

The first step is to define the crustal architecture (Hunt 1873). This architecture includes the structural framework (the geometry and kinematic evolution of faults, folds, and other products of deformation: section 4) and crustal character (the composition, thickness, and geometry: section 6). This is then acted on by geodynamics, which comprises the thermo-mechanical effects of the mantle and tectonic processes (section 7). The interaction of geodynamics and crustal architecture dictates the geometry and timing of accommodation space (basin form), hinterland uplift (hinterland form), and in many places, the loci of transport pathways, such as palaeo-rivers and palaeo-canyons, along which sediment is moved from sediment source areas to depositional sites (sinks). For example, the aulacogens that define the position of major rivers, such as the Niger and Zambezi Rivers, or the Precambrian fabrics that dictate the trend of rivers, such as the Ntem River in West Africa, or Lurio and Rovuma rivers in East Africa.

Depositional environments (section 10) are, by definition, areas below the contemporary base level (Markwick and Valdes 2004) in which deposition can occur and has the potential to be preserved. The environments present at any moment in time are a function of the basin form, surface processes (ultimately sediment supply), and base-level as expressed in most models by sea-level, both relative and global (eustatic). In turn, these also reflect other inputs such as hinterland geometry, bedrock, climate, and drainage, as discussed in most texts on basin analysis (Allen and Allen 2013) and sequence stratigraphy (Emery and Myers 1996).

Lithologies (section 10) deposited in these environments at the time of the map can be added as the basin fill and are shown on most palaeogeographies, although sensu stricto these represent the rock record and the products of the processes being investigated.

The transport pathways (sections 12) are then used with reconstructions of elevation and base-level to build palaeo-topographies and palaeo-bathymetries as palaeoDEMs (Markwick and Valdes 2004). These palaeoDEMs with the palaeodrainage are an explicit boundary condition for Earth system modeling.

The resulting palaeogeographies can provide the spatial context for investigating the relationships between all the processes that determine the formation of the landscape and other geographic information. For exploration, this other geographic information can include the distribution of play elements (source, seal, reservoir, trap), as well as assets such as blocks, fields, seismic surveys and wells.

Throughout this guide, we will use a block diagram representation of a hypothetical landscape (Figure 4) to show how these different elements look conceptually. This will be supplemented with a suite of worked examples from the areas including the central Pyrenees, Red Sea, West Africa, East Africa, and South Atlantic to illustrate what the various stages of the workflow look like in practice. This workflow can be applied at any scale and for any time in the past to reconstruct a palaeogeographic map.

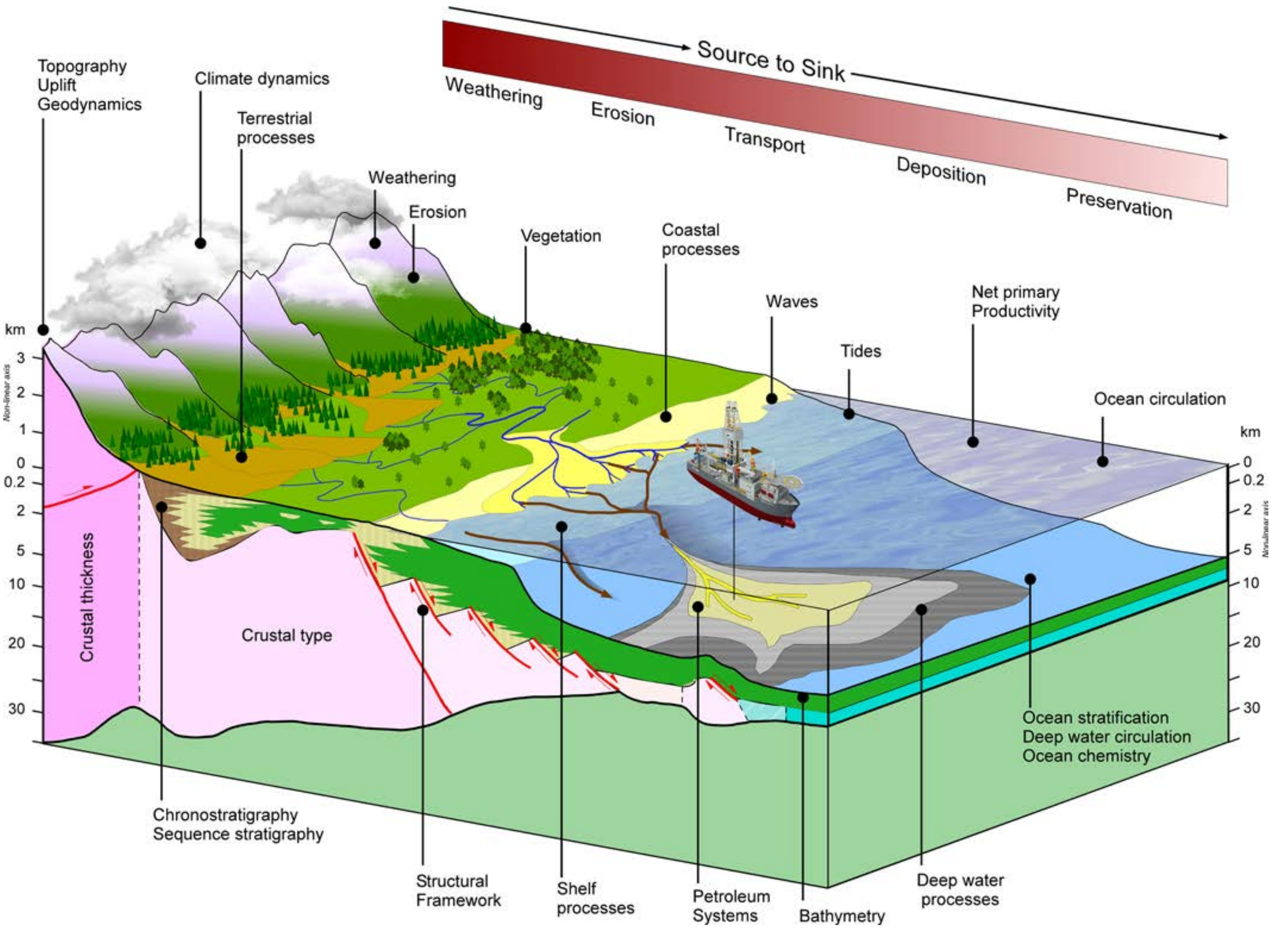


Figure 4. A block diagram showing the relationship of a hypothetical landscape to the underlying basin and hinterland form, source-to-sink pathways, and basin fill. This brings together all the components of basin dynamics, basin analysis, and source-to-sink analysis (Markwick, 2018).

3. Data Management

The Earth system is complex. If we look at any landscape and the processes responsible for forming it and which are acting on it, such as in the central Pyrenees shown above, we are faced with something of a dilemma: **There is simply so much to take in.**

Paleogeographic maps can summarise a wealth of geological information in a simple, visual way by distilling the record into representations of depositional environments and structures. This then allows additional information to be added and juxtapositions and relationships investigated.

Spatial databases follow the same rules of data management as all relational databases. Data integrity is critical if the databases can be used with confidence. The worked examples shown in this volume have been built in ESRIs ArcGIS software (ESRI 2017), and each is underpinned by a comprehensive attribution (as database tables) and metadata (Figure 9). The legend has been designed to best illustrate this diversity of databases.

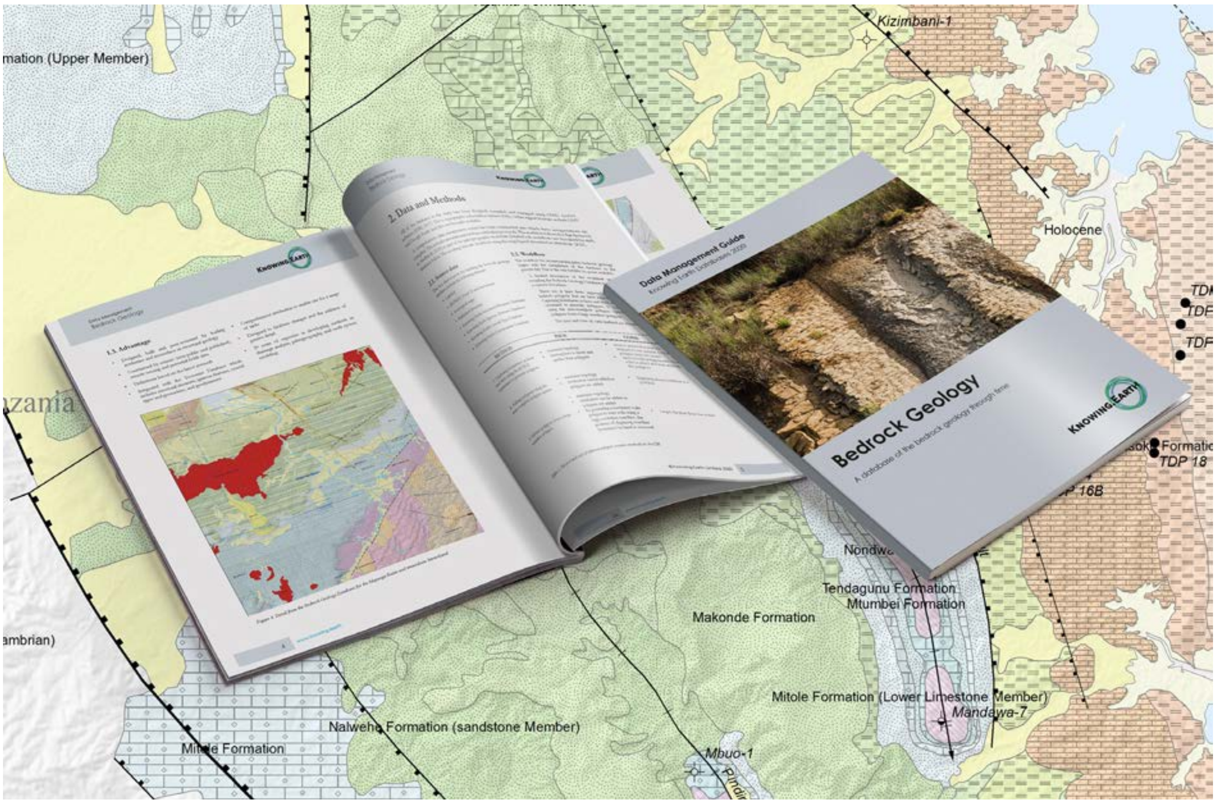


Figure 5. An example of the documentation for each database that comprises the paleogeography workflow. This example shows the database documentation for the Bedrock Geology database. This is directly related to the Igneous Features database.

3.1. Formats and Attribution

Currently, the legend is available in hardcopy form (printed and pdf) and as style files (section 3.2.1) for use in ArcGIS 10.x. ArcGIS layer files have also been constructed for specific tasks (section 3.2.2). More will be added to this resource based on user feedback.

3.1.1 ArcGIS style files

Two versions of the legend .style file are available:

1. a version that includes a description of the feature in addition to the symbol code, which gives the user the flexibility to choose their own symbols from the symbol set;
2. a version with only the symbol codes that facilitate direct loading of the symbol set where the user has used the symbol ID codes in this legend via the 'Match to symbols in a style' option under 'Symbology/Categories' in the 'Layer Properties' in their copy of ArcGIS.

Both style files are compatible with ArcGIS versions 10.5 and later.

For ArcGIS users, features are linked to the symbol set stored in the .style file using a symbol code. This code is comprised of a text field of 6 characters. Each code begins with a letter(s) that indicates the type of feature (e.g. structural, sedimentary, geomorphological), a numerical code that is unique for what the feature represents (e.g. normal fault, fluvial environment, canyon) and then a qualifier to show the state of that feature (viz., 'inferred', 'active', 'inactive') if this is appropriate.

Although the name of this field can vary because in ArcGIS the user will be asked what field contains the symbol code when linking to a .style file, it is recommended that users keep this consistent in their own databases - "Symbol_ID" is a good standard field name and easily understood.

In this guide, the symbol code is shown above or next to each map legend line and fill symbol.

Further information about ESRI style files can be found at http://desktop.arcgis.com/en/arcmap/latest/map/working-with-arcmap/using-symbols-and-styles.htm).

3.1.2. ArcGIS layer files and representations

In addition to the .style files, ArcGIS layer files have been built for a selection of other features for which there are currently no symbol codes. These are more specific in their application but may be useful to users. Again, these will be made available via the Knowing Earth website and my research website.

I have not used ESRI "representations" in these examples, although this is a powerful way of assigning symbologies to feature types within a database (see http://desktop.arcgis.com/en/arcmap/latest/map/working-with-layers/what-are-representations-.htm). The reason for not using them here is because "representations" are an explicit part of a geodatabase feature class which means that the user does not have the flexibility to change these or find particular symbols that they want to use.

3.1.3. Geodatabases, database design, and attribution

The current Knowing Earth GIS databases are generated and managed as feature classes within geodatabases in ArcGIS (ESRI 2017). Each database comprises an extensive attribution table that provides an audit trail for all mapped features. An example of a typical attribute table is shown in Figure 10. This is the main structural element table, which is linked to an Activation Table that records the history of each feature. This one-to-many relationship is relatively standard in geological databases, such as well locations linked to top tables. Further information on the full attribution used is available to academic researchers and Knowing Earth clients on request. The database design and confidence management follow the methodologies outlined in Markwick and Lupia (2002), Markwick (1996).

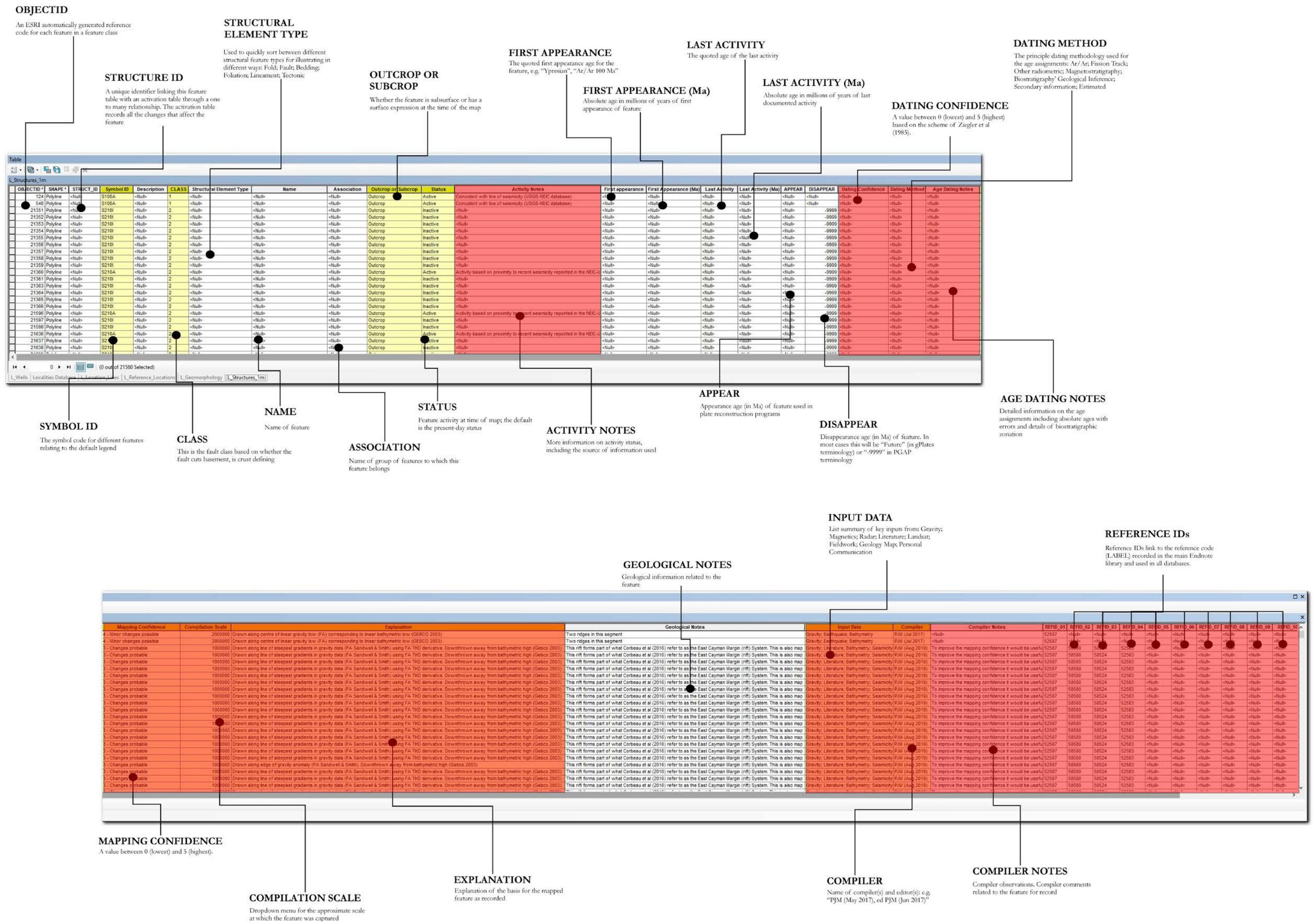


Figure 6. An example of an attribute table, in this case, the main structural elements table from our Structural Elements database. This shows the range of information that needs to be stored to record not only geological information but also to audit each feature (red shading). Fields in yellow must be populated. The auditing includes the following: the source of information; confidence in its geometry (mapping), precision, age-dating confidence.

3.2. Constraining and Recording Data Confidence and Uncertainty

Auditing also needs to include an assessment of data uncertainty – viz. precision, accuracy, and error. In our databases, we provide a semi-quantitative statement of "confidence" (Figure 7) for mapping and (geological) interpretation. This follows the methodologies outlined in Ziegler et al., (1985), Markwick and Lupia (2001), Markwick (1996). Confidence, as used here, is a semi-quantitive record of the 'probability' of a particular result or need for action (see the Summary column in Figure 7). We do not provide a numerical value for this probability because (1) to keep data entry as simple as possible, so it is completed, and (2) our confidence scheme is used for different data with different inputs and, therefore, different inherent uncertainties and errors.

Therefore these semi-quantitive confidence assignments are distinct from quoted analytical errors and are designed to give the user an easy-to-use indication of how confident the compiler was in positioning the spatial data (point, line, or polygon), their interpretation of the feature and even the age assignment, where appropriate. This, therefore, includes an implicit assessment of uncertainty. More explicit records of uncertainty and error can be included in the comments fields. By keeping this simple and in the hands of the compiler, the idea is that this information is more likely to be entered, which is important.

Strictly speaking, uncertainty comprises precision and accuracy, and we are investigating adding explicit fields for these. One old example in our databases is "Geographic Precision," which records the (approximate) precision with which a locality (point location) is known (Markwick 1996). Although these schema pre-date the ready availability of satellite-based location systems, such as the US GPS (Global Positioning System), constraining data auditing is still critical, and these simple schemes still have some value. More advanced techniques, such as the use of control groups to constrain significant absence of data, can then be applied with confidence.

RGB	Code	Summary	Age Dating Confidence	Mapping & Geological Confidence
0 / 176 / 80	5	No changes expected	Multiple lines of information converging on precise dates (very high temporal resolution)	Geometry, position, and geological description constrained by multiple lines of primary evidence supported by geological information in reputable publications. All lines of evidence are consistent. Polygon features constrained by the high density of data
168 / 208 / 141	4	Minor changes possible	Good biostratigraphic control and/or radiometric ages (high temporal resolution)	Geometry, position, and geological description constrained by multiple lines of primary evidence and a good spread of data, supported by geological information in reputable publications. But, interpretations are equivocal. Minor changes in geometry possible with more data.
226 / 239 / 217	3	Changes possible	Some biostratigraphic control (low temporal resolution); correlation from an area with more precise, high confidence, information	The feature identified and interpreted from limited primary sources, supported by other published data, but the spread of detail of data is limited, and interpretations are equivocal. Changes probable with more lines of evidence, especially consideration of higher resolution primary data and model testing. e.g. features based on only potential field data to constrain boundaries, which are not as highly resolvable as those through seismic, Landsat, or field observations.
255 / 229 / 153	2	Changes expected	Geological inference: stratigraphic relationships (e.g onlapping, cross-cutting relationships) with dated rocks;	Interpretation from a secondary source(s) which references supporting primary data (but not seen). Geological interpretation is equivocal or limited to one source. Geological interpretation may be generalized or absent, e.g. no information on kinematics for structural features. The feature requires testing against primary data.
255 / 167 / 127	1	Revision & testing required	Secondary information: age from publication but without explanation of methods used	Feature captured from a single secondary source with no supporting information as to why and no evidence in primary data. e.g. Information is taken directly from an image in a paper, but which has not been checked against other data and is without supporting information.
255 / 0 / 0	0	Revision & testing essential	Source unknown	Source unknown. The feature is unchecked with no constraining secondary or primary information. e.g. a feature based on an image found on the internet, or anecdotal.

Figure 7. An explanation of the confidence codes used in the palaeogeographic mapping workflow. The Age Dating Confidence is modified from that in Ziegler et al. (1985). The Mapping and Geological Confidences are now separated in the updated attribute tables to distinguish between the location/geometry of a feature and its geological interpretation. The RGB colors are those then used to display the confidence assignment.

3.3. Auditing Data: Point and Line Locations and Reference Footprints

Ensuring that all data in a database has an audit trail is a key requirement of any database. Therefore, in addition to the reference and quality control information stored in each feature class described in this book, we have also built three other databases to qualify data. This comprises a location points database, a location line database, which stores the location of all sections and seismic positions, and a reference footprint database that stores the geographic area represented by each paper in the reference database (Figure 8).

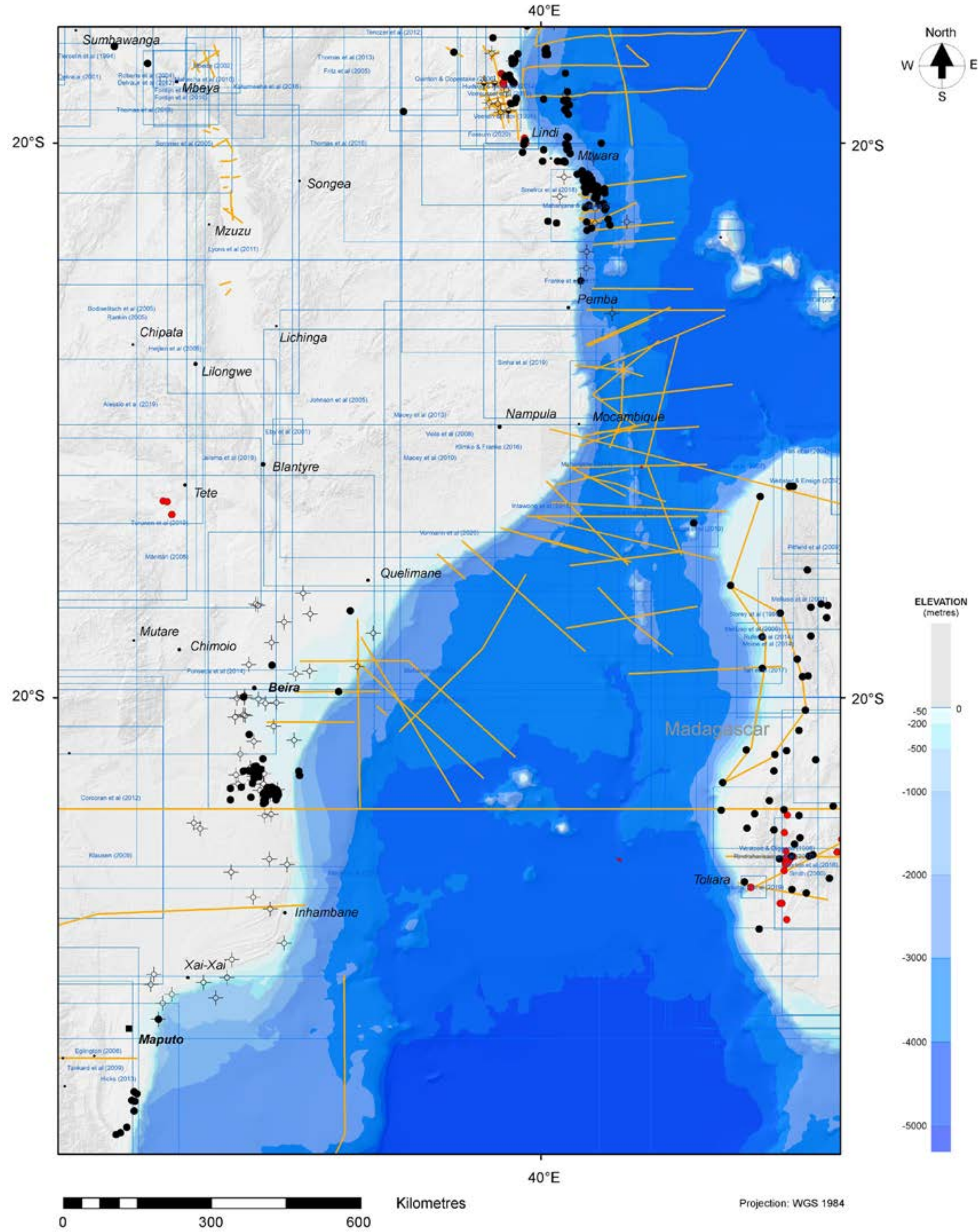
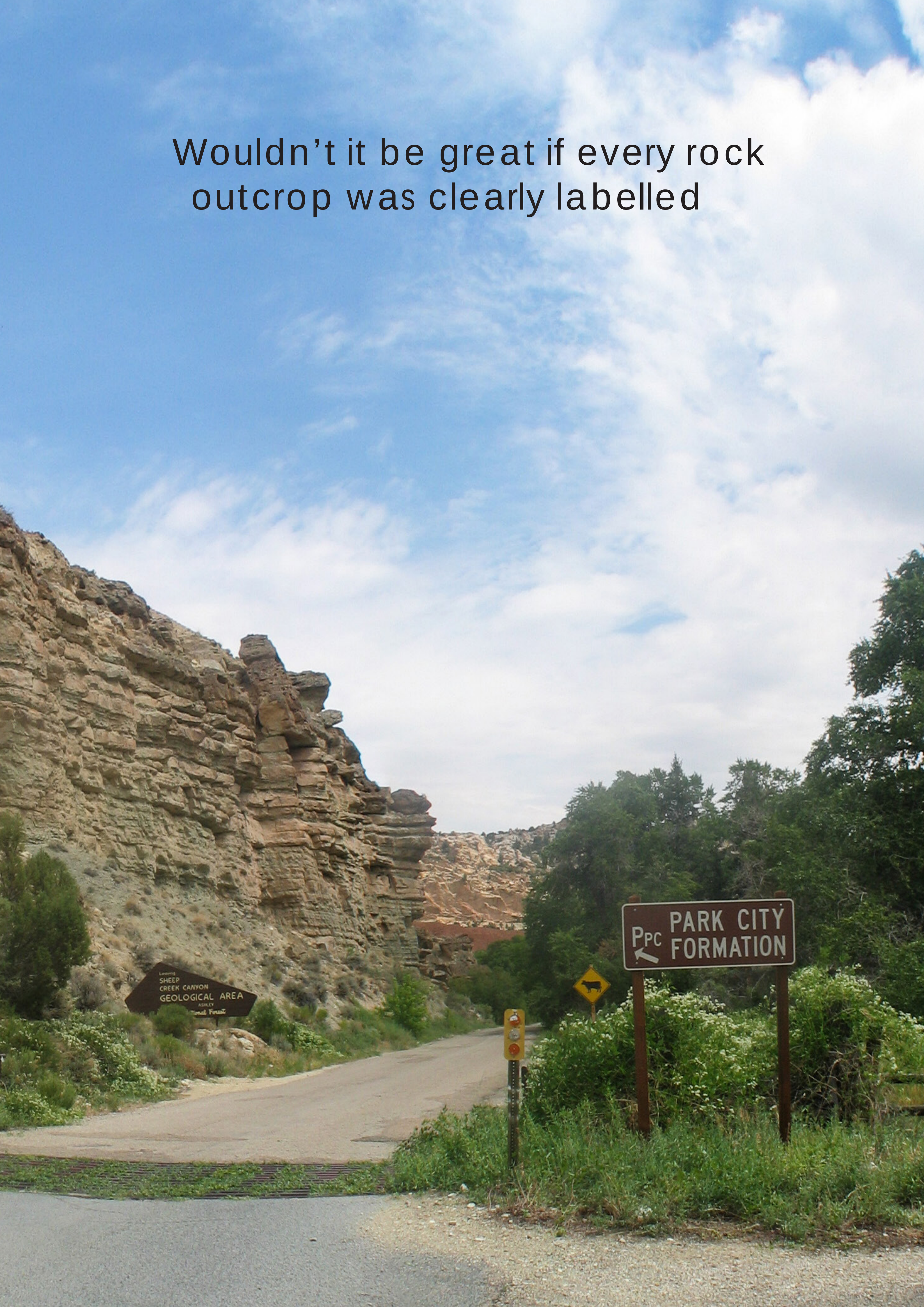


Figure 8. An example from the databases showing the reference datasets used to constrain the interpretation databases, including wells, published seismic and section lines (Orange lines), the footprints of published papers (blue rectangles). This example is from our East Africa study.

Wouldn’t it be great if every rock outcrop was clearly labelled



An example of a class 2 structure, in this case a thrust fault that brings Devonian over Triassic in the Axial Zone of the central Pyrenees. Gerri de Sal.

4. Structural and Tectonic Elements

The structural framework underpins all other parts of the palaeogeographic workflow and is fundamental to the veracity of subsequent interpretations and analyses. If the structural framework is wrong, the paleogeography will be wrong. Consequently, the structural and tectonic elements databases have the most extensive attribution and audit trail, especially " confidence assignments." This is also reflected in the systematic map representation provided in this legend.

The map representation of structural and tectonic elements is relatively standard around the world. Here the legend largely follows the symbology used by the USGS (United States Geological Survey) (Reynolds et al. 1995; Federal Geographic Data Committee 2006), with modifications where there are no corresponding symbols or to avoid confusion. Colours and symbol weights are used to differentiate the crustal significance of features, activity, and mapping confidence (Figure 9). These are specific to the scheme presented here. Each feature symbol comprises either a line (dashed or solid) with or without an associated marker symbol, which represents the type of feature and kinematics. These are built within ArcGIS, and screen images of how are shown in Figures 10-16.

The compilation of structural and tectonic elements is highly dependent on map resolution. Resolution is a function of the application, what is the mapped feature being used for, and what is possible with the source data used. In the Knowing Earth databases, a field has been added to each database table to record the compilation scale, which is the map scale at which the feature was identified and recorded. In addition, we have created separate databases where the resolution difference is so large as to cause problems. In these cases, database names are suffixed with the representative feature resolution.

All structural element symbol codes are prefixed with the letter "S".

4.1. Class

In this legend, structural and tectonic features are classified according to their influence on the crust and stratigraphy using different line weighting for each (Table 1). This is through what is referred to here as 'classes' of features and has been done in order to facilitate clarity on the maps when high densities of features are presented (Figure 9):

- **Class 1 – 'crustal scale'** - features cut through the crust and (may) offset the base of the crust, e.g., major shear zones and sutures.
- **Class 2 – 'basement scale'** - features cut into the basement (upper levels of crust). Includes thick-skinned tectonics, e.g., thrusts in the anticlinal stack of the Pyrenean Axial Zone or rift bounding faults, major basin bounding faults.
- **Class 3 – 'local basement scale'** - features cut into lithified stratigraphy above regional basement (usually the Precambrian). This includes thin-skinned tectonic features, e.g., thrusts defining allochthonous thrust sheets in the central Pyrenees.
- **Class 4 – 'sedimentary scale'** - features that cut the sedimentary pile only, e.g., toe thrusts in pro-deltas such as the Niger Delta.

There is a separate code for lineaments, which are not divided by class. Lineaments are defined as linear features identified in the Earth, but where both the kinematics and nature are unknown.

The class allocation is tied to map resolution. For example, a transform fault and associated fracture zone would be mapped as a class 1 feature in this definition when represented by a single line. But, at a high spatial resolution, this single feature is revealed as a zone of deformation, in which no one individual mapped feature at the surface can be seen to cut through the whole crust. In this case, individual faults might be allocated as class 2 or even class 3, depending on whether they cut the underlying oceanic crust (basement) or overlying stratigraphy. Again, we stress that the use of 'classes' of structural and tectonic features in this scheme is designed to give the user flexibility in assigning symbology (visualization) and geological significance. Any ambiguity or different usage can be clarified in the feature comments field within each database table.

4.2. Activity

Tectonic and structural elements are attributed as 'active' or 'inactive' depending on whether there is evidence of displacement or deformation at the time of the map on which they are displayed. The default representation is the present-day activity status constrained by seismicity or published evidence of motion. This is then linked to an activation history table, which records the kinematic evolution through time. The convention adopted here is to show active faults (at the time of the map) in red and inactive faults in black, which is relatively standard throughout geology.

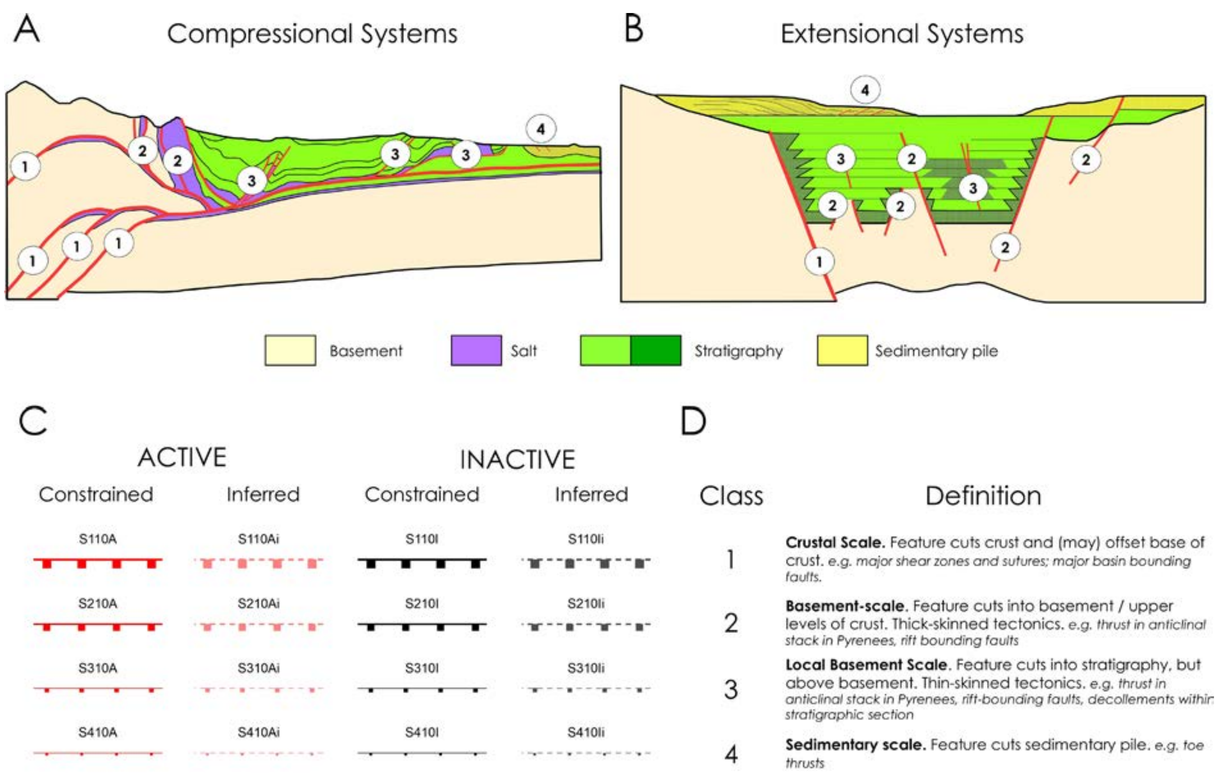


Figure 9. Structures are classified according to their effect on the crust (class). This is designed to provide graphical depth and facilitate queries of the underlying database. (a) Examples of each class of structural feature in a typical compressional system. (b) Examples of each class in an extensional system. (c) An example of the attribution of structural features (normal faults in this case but applies to all kinematic types) to reflect activity at the time of the map and mapping confidence ('Defined': evidence from at least one primary source. 'Inferred': required by the kinematics of the area, but not clearly seen in the data. Line weighting is used to differentiate the fault class, which is a visual representation of the scale effect of each feature on the crust.

4.3. Defined or Inferred?

The underlying database includes a field for whether the field is 'Defined' or 'Inferred' (Figure 9). This is shown symbolically using color shading and a dashed line for 'inferred' versions of features:

- 'Defined' – features that can be interpreted from a 'signal' in the primary data. This can include Landsat imagery, where the structural nature is clear-cut (folded bedding, fault with offsets or scarp), seismic sections, satellite gravity data, high-resolution station-based gravity and aeromagnetic data (where the interpretation is unequivocal); features supported by observational data and/or evidence of motion (GPS, seismicity).
- 'Inferred' – features that are required to exist to satisfy a model, but for which there is no clear evidence from any input dataset; features for which there is some evidence, but where the input data is either of poor resolution or relationship is unclear (e.g. low-resolution gravity data onshore).

Dashed line symbols are frequently used on maps to denote confidence. Although this is implicit within this scheme, there is a separate attribute within the Knowing Earth databases that assigns confidence in the mapping position and interpretation and the age assignment, which can be queried and symbolized independently.

Class	RGB (Active)	RGB (Inactive)	Weight	Notes
1	Constrained 255/0/0 Inferred 255/127/127	Constrained 0/0/0 Inferred 78/78/78	2.0	Inferred features use dashed lines
2			1.4	
3			0.8	
4			0.4	

Table 1. Line weighting and color for each class and activity state of structural elements. The line weighting used to differentiate between 'classes' of structural and tectonic elements. This is designed to help the user assess crustal significance to features, but also to make the resulting maps clearer in areas of high feature density.

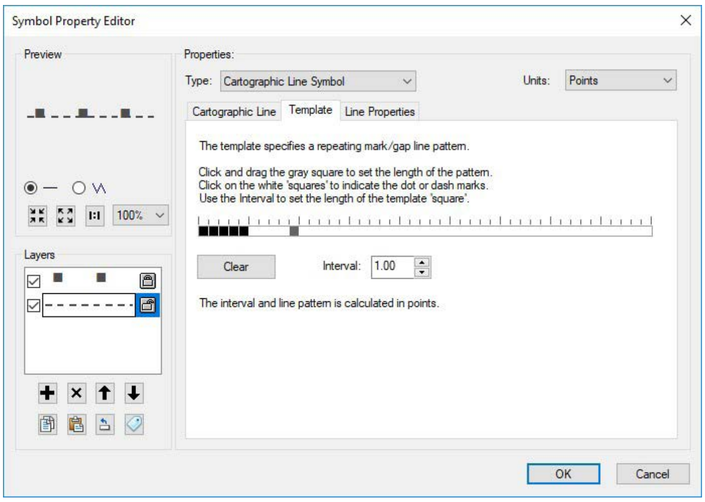


Figure 10. A screen capture of the symbol properties dialogue box in ArcGIS showing the template used to construct the dashed lines used for inferred line features. This example shows the marker and line characteristics for inferred inactive normal faults. For each class, the line weighting changes (Table 1), as does the size of the marker symbol. The spacing here is that used for the majority of the structural elements.

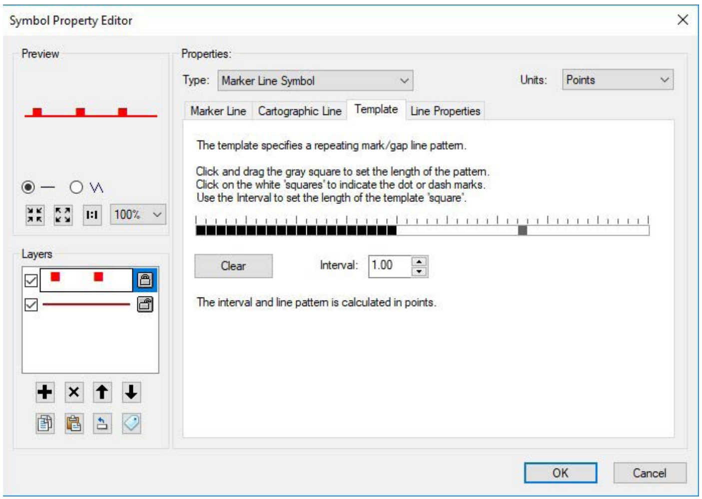


Figure 11. A screen capture of the symbol properties dialogue box in ArcGIS showing the template used to construct the marker symbol interval, in this case, to represent normal faults. By experiment, the chosen spacing has been found to work for most mapping. Users can change this to reflect their own preferences and needs by simply accessing the symbol dialogue and changing any of the inputs, including the template (shown here), for marker spacing.

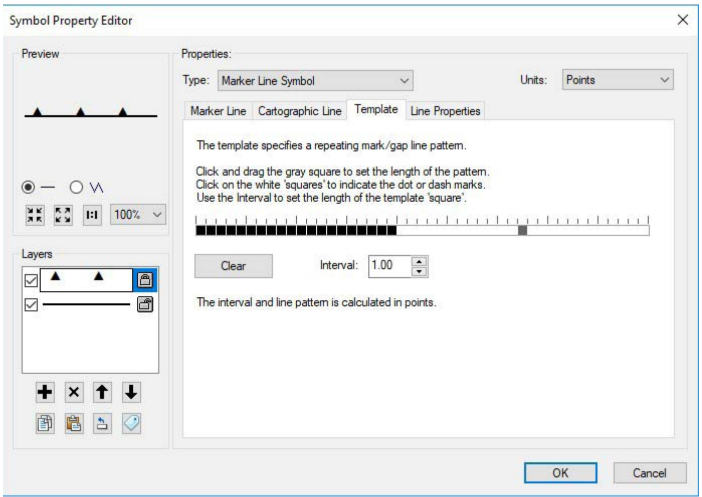


Figure 12. A screen capture of the symbol properties dialogue box in ArcGIS showing the template used to construct the marker symbol interval, in this case, to represent thrust faults. The spacing used is the same as that for normal fault markers (Figures, 9, 18). Following the mapping convention, the upper plate is in the direction of the triangle apex, away from the line. If you find that when applied to your features, the markers are on the wrong side of the fault, then in edit mode in ArcGIS, you can FLIP the line, which will place the markers on the correct side.

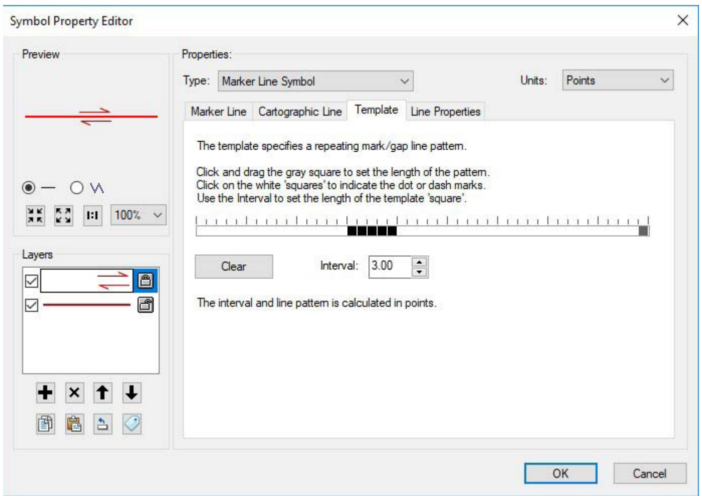


Figure 13. A screen capture of the symbol properties dialogue box in ArcGIS showing the template used to construct the marker symbol interval representing the sense of lateral displacement arrows relating to strike-slip faults. This is more problematic to build since the distance from the line, the arrow's size, and the interval need to be considered. In this legend, the spacing is quite large so that the arrows do not over-complicate the resulting map.

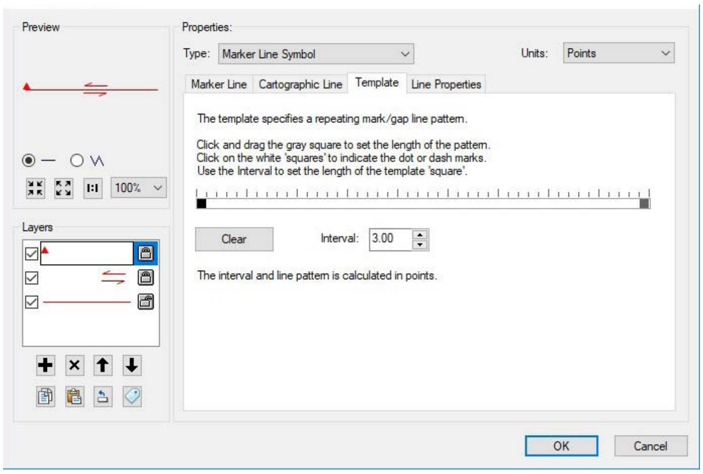


Figure 14. A screen capture of the symbol properties dialogue box in ArcGIS showing the template used to construct the marker symbol interval used for transpressional faults (the intervals used for the marker symbols of transtensional symbols is the same). These are more complex to construct because they require two markers associated with the feature, and these two markers cannot interfere with one another. In this image, the spacing for the upper plate interval is shown. This interval is quite large in the 2018 edition of this legend, but from further investigation, this interval may be shortened in the next release.

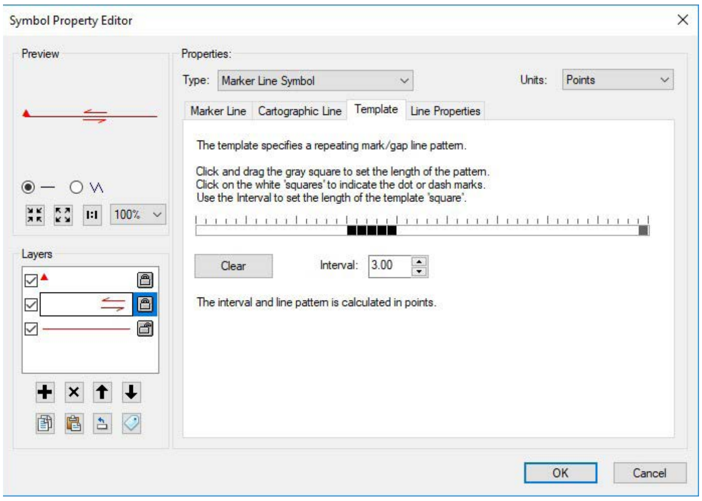


Figure 15. A screen capture of the symbol properties dialogue box in ArcGIS showing the template used to construct the second marker symbol interval, in this case, to represent transpressional faults and the sense of shear arrows.

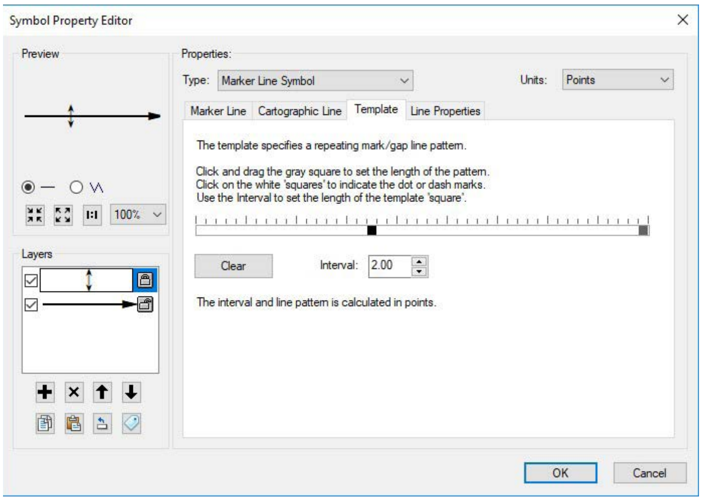


Figure 16. A screen capture of the symbol properties dialogue box in ArcGIS showing the template used to construct the marker symbol interval for folds. As with other line symbols in this dataset, the marker interval has been kept quite broad to avoid interference between symbols and features.

4.4. Tectonic Elements

Tectonic elements (Figure 17) comprise crustal-scale features that define either plate boundaries and intra-plate, crustal-scale folds, commonly referred to in the literature as 'arches.' All features that represent plate boundaries will cut the crust through to the Moho and are, therefore, class 1 (see Section 4.1) features by definition.

SYMBOL: ACTIVE, Defined	SYMBOL: ACTIVE, Inferred	SYMBOL: INACTIVE, Defined	SYMBOL: INACTIVE, Inferred	CLASS	DESCRIPTION
S100A	S100Ai	S100I	S100Ii	1	Spreading Ridge
S102A	S102Ai			1	Transform Fault
		S104I	S104Ii	1	Fracture Zone (Major)
		S106I	S106Ii	1	Fracture Zone (Minor)
S108A	S108Ai	S108I	S108Ii	1	Subduction Zone
S109A	S109Ai	S109I	S109Ii	1	Basement Arch
S209A	S209Ai	S209I	S209Ii	2	Basement Arch

Figure 17. Tectonic symbols with associated symbol codes used in the structural elements databases. The format for all structural symbol codes is as follows: "S" + "Class" + "##" + active or inactive + defined or inferred. The class is the numerical value shown in figure 9, which indicates the impact on the sedimentary, stratigraphic and/or crustal section. The two-digit number value differentiates the type of structural feature, usually based on its kinematics (see description). Active features are assigned an "A," and inactive features are given an "I." There is no suffix for defined features; an "i" is added for an inferred feature, which includes any features that have a mapping or geological confidence assignment of "1" or "0".

4.5. Normal and Reverse Faults

The symbology for normal, reverse, thrust, and undifferentiated faults are shown in Figure 18. All four fault types can be of any scale, from major basin bounding faults that may cut the crust down to the Moho and therefore be considered as Class 1 to smaller faults in the overburden or even features within surficial deposits. Whilst the larger features can be identified using seismic data, satellite imagery (Landsat), and even potential fields data, the finer-scale features are mostly only resolvable through careful field mapping. Whilst surface and sub-surface geometries may be readily mappable, the depth significance of most features is often difficult to assess without good seismic data.

The symbology of both normal and reverse faults comprises two components in ArcGIS:

1. a solid (defined) or dash (inferred) line, that defines the geometry of the feature (this will be at the present-day surface unless otherwise specified) – the line weight will vary by class (see Table 1);

2. a marker line symbol that denotes the type of fault (square for normal faults, triangle for thrusts and reverse faults) and dip-slip direction (square on the down-thrown side for normal faults; triangles point towards the upper plate for thrust and reverse faults). The template used for the marker repeat interval is shown in Figure 11.

SYMBOL				CLASS	DESCRIPTION
ACTIVE		INACTIVE			
Defined	*Inferred*	*Defined*	*Inferred*		
S110A	S110Ai	S110I	S110Ii	1	Normal fault
S210A	S210Ai	S210I	S210Ii	2	Normal fault
S310A	S310Ai	S310I	S310Ii	3	Normal fault
S410A	S410Ai	S410I	S410Ii	4	Normal fault
S120A	S120Ai	S120I	S120Ii	1	Reverse fault
S220A	S220Ai	S220I	S220Ii	2	Reverse fault
S320A	S320Ai	S320I	S320Ii	3	Reverse fault
S420A	S420Ai	S420I	S420Ii	4	Reverse fault
S125A	S125Ai	S125I	S125Ii	1	Thrust fault
S225A	S225Ai	S225I	S225Ii	2	Thrust fault
S325A	S325Ai	S325I	S325Ii	3	Thrust fault
S425A	S425Ai	S425I	S425Ii	4	Thrust fault
S199A	S199Ai	S199I	S199Ii	1	Fault undifferentiated
S299A	S299Ai	S299I	S299Ii	2	Fault undifferentiated
S399A	S399Ai	S399I	S399Ii	3	Fault undifferentiated
S499A	S499Ai	S499I	S499Ii	4	Fault undifferentiated

Figure 18. Normal and reverse faults with their associated symbol codes used in the structural elements databases. The color differentiation between active, inactive, defined, and inferred features is the same as in Figure 9. The format for all structural symbol codes is as follows: "S" + "Class" + "##" + active or inactive + defined or inferred. The class is the numerical value shown in Figure 9, which indicates the impact on the sedimentary, stratigraphic and/or crustal section. The two-digit number value differentiates the type of structural feature, usually based on its kinematics (see description). Active features are assigned an "A", inactive features are assigned an "I." There is no suffix for defined features; an "i" is added for an inferred feature, which includes any features that have a mapping or geological confidence assignment of "1" or "0".

4.6. Strike-slip Faults

Strike-slip faults (Figure 19) like most of the other structural elements in this legend, follow the traditional symbolization used by the USGS (Federal Geographic Data Committee 2006) with the addition of variants for defined, inferred, active and inactive (see Figure 9). Arrows indicate sense-of-shear where this is documented. An undifferentiated strike-slip fault symbol has been included here where the sense-of-shear is equivocal or there is disagreement in the literature. This is the same symbol used for undifferentiated faults (Figure 18). As part of the mapping workflow, bedding and foliation are mapped in order to provide indications of sense-of-shear (section 4.12).

SYMBOL				CLASS	DESCRIPTION
ACTIVE		INACTIVE			
Defined	*Inferred*	*Defined*	*Inferred*		
S130A	S130Ai	S130I	S130Ii	1	Strike-slip fault, undiff.
S230A	S230Ai	S230I	S230Ii	2	Strike-slip fault, undiff.
S330A	S330Ai	S330I	S330Ii	3	Strike-slip fault, undiff.
S430A	S430Ai	S430I	S430Ii	4	Strike-slip fault, undiff.
S140A	S140Ai	S140I	S140Ii	1	Dextral strike-slip fault
S240A	S240Ai	S240I	S240Ii	2	Dextral strike-slip fault
S340A	S340Ai	S340I	S340Ii	3	Dextral strike-slip fault
S440A	S440Ai	S440I	S440Ii	4	Dextral strike-slip fault
S145A	S145Ai	S145I	S145Ii	1	Sinistral strike-slip fault
S245A	S245Ai	S245I	S245Ii	2	Sinistral strike-slip fault
S345A	S345Ai	S345I	S345Ii	3	Sinistral strike-slip fault
S445A	S445Ai	S445I	S445Ii	4	Sinistral strike-slip fault

Figure 19. Strike-slip faults symbols with their associated symbol codes used in the structural elements databases. The undifferentiated strike-slip line graphic is the same as for an undifferentiated fault, but the symbol code is different. The format for all structural symbol codes is as follows: "S" + "Class" + "##" + active or inactive + defined or inferred. The class is the numerical value shown in figure 9, which indicates the impact on the sedimentary, stratigraphic and/or crustal section. The two-digit number value differentiates the type of structural feature, usually based on its kinematics (see description). Active features are assigned an "A", inactive features are assigned an "I." There is no suffix for defined features; an "i" is added for inferred feature, which includes any features that have a mapping or geological confidence assignment of "1" or "0".

4.7. Transpressional and Transtensional Faults

The symbology for transpressional and transtensional faults is shown in Figure 20. These are used where evidence of translation and dip-slip are clearly defined. In many cases, this may reflect multiple phases of activity.

SYMBOL ACTIVE Defined	SYMBOL ACTIVE Inferred	SYMBOL INACTIVE Defined	SYMBOL INACTIVE Inferred	CLASS	DESCRIPTION
S150A	S150Ai	S150I	S150Ii	1	Dextral transtensional fault
S250A	S250Ai	S250I	S250Ii	2	Dextral transtensional fault
S350A	S350Ai	S350I	S350Ii	3	Dextral transtensional fault
S450A	S450Ai	S450I	S450Ii	4	Dextral transtensional fault
S155A	S155Ai	S155I	S155Ii	1	Sinistral transtensional fault
S255A	S255Ai	S255I	S255Ii	2	Sinistral transtensional fault
S355A	S355Ai	S355I	S355Ii	3	Sinistral transtensional fault
S455A	S455Ai	S455I	S455Ii	4	Sinistral transtensional fault
S160A	S160Ai	S160I	S160Ii	1	Dextral transpressional fault
S260A	S260Ai	S260I	S260Ii	2	Dextral transpressional fault
S360A	S360Ai	S360I	S360Ii	3	Dextral transpressional fault
S460A	S460Ai	S460I	S460Ii	4	Dextral transpressional fault
	S165Ai	S165I	S165Ii	1	Sinistral transpressional fault
S265A	S265Ai	S265I	S265Ii	2	Sinistral transpressional fault
S365A	S365Ai	S365I	S365Ii	3	Sinistral transpressional fault
S465A	S465Ai	S465I	S465Ii	4	Sinistral transpressional fault

Figure 20. Transtensional and transpressional faults symbols with their associated symbol codes used in the structural elements databases. The format for all structural symbol codes is as follows: "S" + "Class" + "##" + active or inactive + defined or inferred. The class is the numerical value shown in figure 9, which indicates the impact on the sedimentary, stratigraphic and/or crustal section. The two-digit number value differentiates the type of structural feature, usually based on its kinematics (see description). Active features are assigned an "A", and inactive features are assigned an "I." There is no suffix for defined features; an "i" is added for an inferred feature, which includes any features that have a mapping or geological confidence assignment of "1" or "0". The number of dip-slip symbol markers has been kept to a minimum in this representation, given the potential for cartographic interference with the strike-slip arrows. This will be kept under review as the symbol set is used more.

4.8. Undifferentiated Folds

Undifferentiated folds (Figure 21) have been symbolized to account for folds identified (especially) from Landsat imagery where bedding is clear, but dip and age relationships are not. This allows for fold trends to be quickly captured which may be checked later against detailed geological maps if these are available. This is not a traditional standard symbol.

SYMBOL ACTIVE Defined	SYMBOL ACTIVE Inferred	SYMBOL INACTIVE Defined	SYMBOL INACTIVE Inferred	CLASS	DESCRIPTION
S177A	S177Ai	S177I	S177Ii	1	Fold undiff.
S277A	S277Ai	S277I	S277Ii	2	Fold undiff.
S377A	S377Ai	S377I	S377Ii	3	Fold undiff.
S477A	S477Ai	S477I	S477Ii	4	Fold undiff.
S175A	S175Ai	S175I	S175Ii	1	Plunging fold undiff.
S275A	S275Ai	S275I	S275Ii	2	Plunging fold undiff.
S375A	S375Ai	S375I	S375Ii	3	Plunging fold undiff.
S475A	S475Ai	S475I	S475Ii	4	Plunging fold undiff.
S179A	S179Ai	S179I	S179Ii	1	Double plunging fold undiff.
S279A	S279Ai	S279I	S279Ii	2	Double plunging fold undiff.
S379A	S379Ai	S379I	S379Ii	3	Double plunging fold undiff.
S479A	S479Ai	S479I	S479Ii	4	Double plunging fold undiff.

Figure 21. Undifferentiated fold symbols with associated symbol codes used in the structural elements databases. This is especially useful for interpretations based on remote sensing data, such as Landsat, where the age relationships of the beds are not known, and the bedding dip direction is unclear. The format for all structural symbol codes is as follows: "S" + "Class" + "##" + active or inactive + defined or inferred. The class is the numerical value shown in figure 9, which indicates the impact on the sedimentary, stratigraphic and/or crustal section. The two-digit number value differentiates the type of structural feature, usually based on its kinematics (see description). Active features are assigned an "A", inactive features are assigned an "I." There is no suffix for defined features; an "i" is added for an inferred feature, which includes any features that have a mapping or geological confidence assignment of "1" or "0".

4.9. Anticlines and Antiforms

Anticline and antiform symbology follow the traditional use of arrows to indicate dip direction on either side of an axis (Figure 22). The arrow marker symbol used is that provided with ArcGIS (ESRI 2017) as the "ESRI Geology USGS 95-525" character marker symbol set. These are the symbols presented in the USGS Open-File Report 95-525 (Reynolds et al. 1995).

SYMBOL				CLASS	DESCRIPTION
ACTIVE		INACTIVE			
Defined	*Inferred*	*Defined*	*Inferred*		
S170A	S170Ai	S170I	S170Ii	1	Antiform / Anticline
S270A	S270Ai	S270I	S270Ii	2	Antiform / Anticline
S370A	S370Ai	S370I	S370Ii	3	Antiform / Anticline
S470A	S470Ai	S470I	S470Ii	4	Antiform / Anticline
S172A	S172Ai	S172I	S172Ii	1	Plunging Antiform / Anticline
S272A	S272Ai	S272I	S272Ii	2	Plunging Antiform / Anticline
S372A	S372Ai	S372I	S372Ii	3	Plunging Antiform / Anticline
S472A	S472Ai	S472I	S472Ii	4	Plunging Antiform / Anticline
S174A	S174Ai	S174I	S174Ii	1	Pericline
S274A	S274Ai	S274I	S274Ii	2	Pericline
S374A	S374Ai	S374I	S374Ii	3	Pericline
S474A	S474Ai	S474I	S474Ii	4	Pericline

Figure 22. Fold symbols with their associated symbol codes for anticlines and antiforms used in the structural elements databases. The format for all structural symbol codes is as follows: "S" + "Class" + "##" + active or inactive + defined or inferred. The class is the numerical value shown in figure 9, which indicates the impact on the sedimentary, stratigraphic and/or crustal section. The two-digit number value differentiates the type of structural feature, usually based on its kinematics (see description). Active features are assigned an "A", inactive features are assigned an "I." There is no suffix for defined features; an "i" is added for an inferred feature, which includes any features that have a mapping or geological confidence assignment of "1" or "0".

4.10. Synclines and Synforms

Syncline and synform symbology, like that for anticlines and antiforms, follows the traditional use of arrows to indicate the dip direction on either side of an axis (Figure 23). The arrow marker symbol is provided with ArcGIS (ESRI 2017) as the "ESRI Geology USGS 95-525" character marker symbol set. These are the symbols presented in the USGS Open-File Report 95-525 (Reynolds et al. 1995). There appears to be some confusion in the literature about the correct geometry of arrows indicating the plunge direction for closed, double-plunging ("basin") fold features, with some mappers showing plunge direction away from a basin feature. In the scheme presented here, we show the arrows dipping into the feature, which in our view is the only correct geometry since this follows the bedding dip direction.

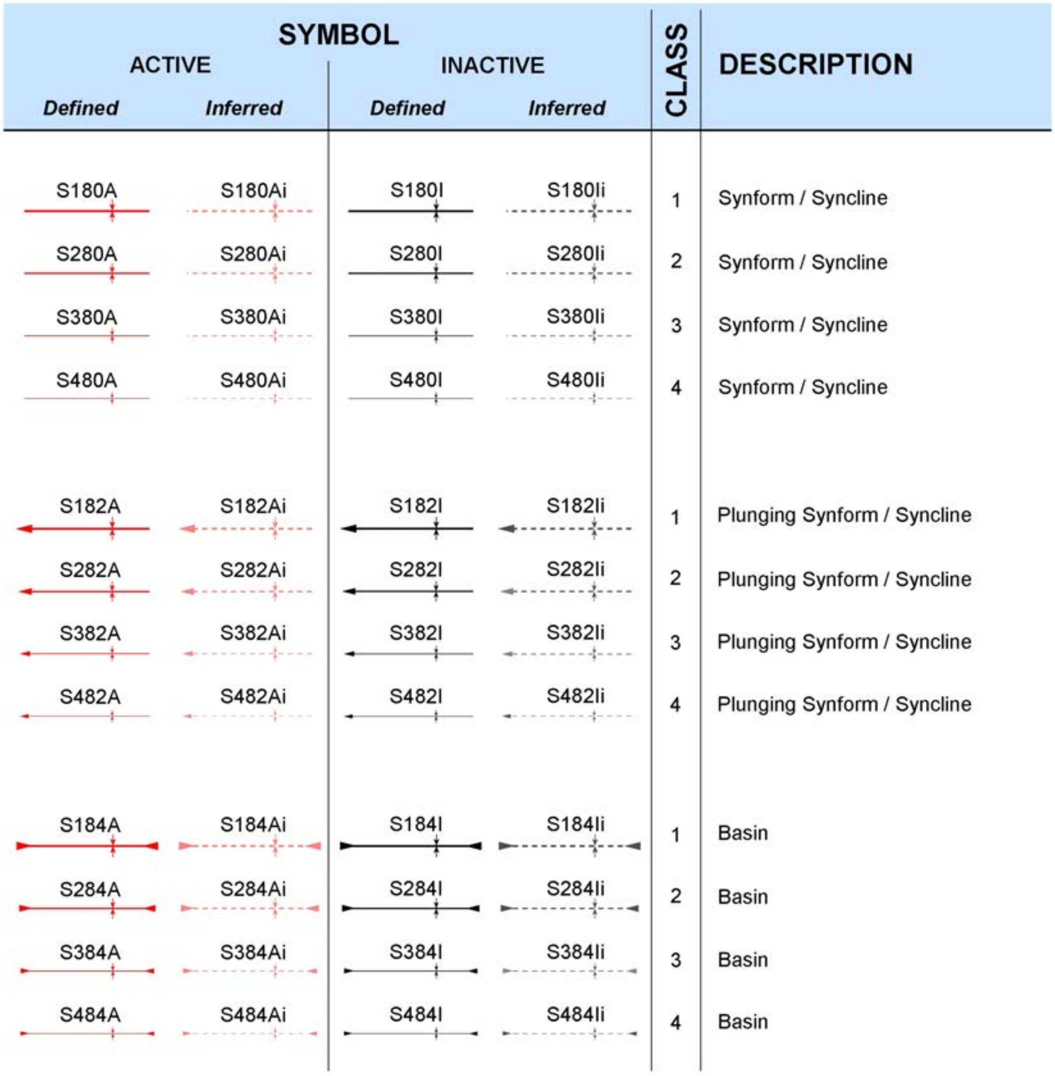


Figure 23. Fold symbols with their associated symbol codes for synclines and synforms used in the structural elements databases. The format for all structural symbol codes is as follows: "S" + "Class" + "##" + active or inactive + defined or inferred. The class is the numerical value shown in figure 9, which indicates the impact on the sedimentary, stratigraphic and/or crustal section. The two-digit number value differentiates the type of structural feature, usually based on its kinematics (see description). Active features are assigned an "A", and inactive features are assigned an "I." There is no suffix for defined features; an "i" is added for an inferred feature, which includes any features that have a mapping or geological confidence assignment of "1" or "0".

An example of a class 2 structure. In this case, this is a thrust fault within Devonian metamorphosed carbonates and shales, near the village of Gistain in the Axial Zone of the central Pyrenees. This feature has had a complex kinematic history and is interpreted to have begun life as a normal fault during the Devonian. The mix of brittle and ductile deformation around the fault indicates that the subsequent compressional phases were far from simple. All this information can be captured in a well-designed database

4.11. Inverted and Over-turned Folds

Inverted and over-turned folds (Figure 24, 25) reflect a complex deformational history. Care must be taken to ensure that the sense of fold inversion or over-turning is correctly recorded when lines are captured digitally (in ArcGIS this will depend on the direction in which the line is digitized, which can be easily managed using the "Flip" command). The marker symbols are those used by the USGS (Reynolds et al. 1995; Federal Geographic Data Committee 2006) and which are provided with ArcGIS (ESRI 2017) as the "ESRI Geology USGS 95-525" character marker symbol set.

Figure 24. Over-turned Triassic beds in the Axial Zone, near Pont de Suert, central Pyrenees. Note the erosional truncation at the top of the picture and coarsening direction. This is where the use of the activation table becomes most important.

SYMBOL: ACTIVE — Defined	ACTIVE — Inferred	INACTIVE — Defined	INACTIVE — Inferred	CLASS	DESCRIPTION
S176A	S176Ai	S176I	S176Ii	1	Inverted anticline
S276A	S276Ai	S276I	S276Ii	2	Inverted anticline
S376A	S376Ai	S376I	S376Ii	3	Inverted anticline
S476A	S476Ai	S476I	S476Ii	4	Inverted anticline
S186A	S186Ai	S186I	S186Ii	1	Inverted syncline
S286A	S286Ai	S286I	S286Ii	2	Inverted syncline
S386A	S386Ai	S386I	S386Ii	3	Inverted syncline
S486A	S486Ai	S486I	S486Ii	4	Inverted syncline
S178A	S178Ai	S178I	S178Ii	1	Overturned anticline
S278A	S278Ai	S278I	S278Ii	2	Overturned anticline
S378A	S378Ai	S378I	S378Ii	3	Overturned anticline
S478A	S478Ai	S478I	S478Ii	4	Overturned anticline
S188A	S188Ai	S188I	S188Ii	1	Overturned syncline
S288A	S288Ai	S288I	S288Ii	2	Overturned syncline
S388A	S388Ai	S388I	S388Ii	3	Overturned syncline
S488A	S488Ai	S488I	S488Ii	4	Overturned syncline

Figure 25. Fold symbols with their associated symbol codes for overturned and inverted folds used in the structural elements databases. The format for all structural symbol codes is as follows: "S" + "Class" + "##" + active or inactive + defined or inferred. The cass is the numerical value shown in figure 9, which indicates the impact on the sedimentary, stratigraphic and/or crustal section. The two-digit number value differentiates the type of structural feature, usually based on its kinematics (see description). Active features are assigned an "A", and inactive features are assigned an "I." There is no suffix for defined features; an "i" is added for an inferred feature, which includes any features that have a mapping or geological confidence assignment of "1" or "0".

4.12. Lineaments, Bedding, and Foliations

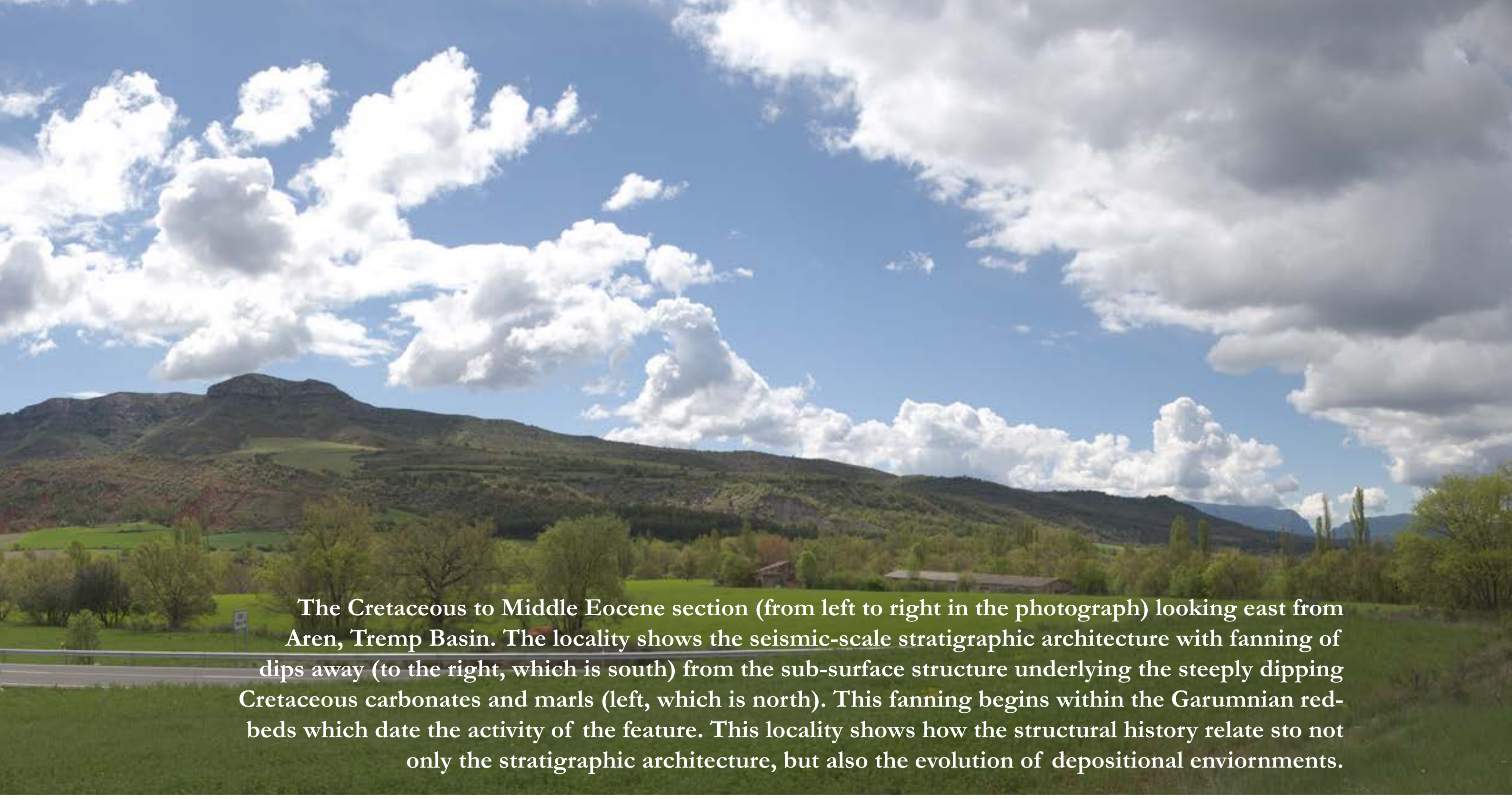
Lineaments are linear features expressed in either the surface or sub-surface that lack any information about kinematics or geological cause. Lineaments may be updated to faults or lithological boundaries with additional information. Alternatively, an investigation may reveal that these features are data artifacts. The key here is being able to assess the significance and update the database records accordingly.

Bedding and foliation are extremely useful for identifying folds or the large-scale sense of shear around translational features.

In the 2023 version of the legend we have added symbols for (angular) unconformities and active and inactive major joints. These are under review.

SYMBOL		DESCRIPTION	RGB	LINE WEIGHT
Defined	*Inferred*			
S9000	n/a	Lineament undifferentiated	130 / 130 / 130	0.4 pt
S9100	n/a	Bedding / Lithological Boundary	168 / 112 / 0	0.3 pt
S9200	n/a	Foliation	169 / 0 / 230	0.4 pt
S9300	n/a	(Angular) Unconformity	85 / 255 / 0	1.0 pt
S9500A	n/a	Joint (large-scale), Active	255 / 0 / 0	0.3 pt
S9500	n/a	Joint (large-scale)	0 / 0 / 0	0.3 pt

Figure 24. Line symbols with their associated symbol codes for lineaments, bedding, and foliations used in the structural elements databases. The format for these structural symbol codes is as follows: "S" + "####" + active or inactive + defined or inferred. The four-digit number value differentiates the type of structural feature, usually based on its kinematics (see description). Active features are assigned an "A", and inactive features are assigned an "I." There is no suffix for defined features; an "i" is added for an inferred feature, which includes any features that have a mapping or geological confidence assignment of "1" or "0".



The Cretaceous to Middle Eocene section (from left to right in the photograph) looking east from Aren, Tremp Basin. The locality shows the seismic-scale stratigraphic architecture with fanning of dips away (to the right, which is south) from the sub-surface structure underlying the steeply dipping Cretaceous carbonates and marls (left, which is north). This fanning begins within the Garumnian red-beds which date the activity of the feature. This locality shows how the structural history relate sto not only the stratigraphic architecture, but also the evolution of depositional enviornments.

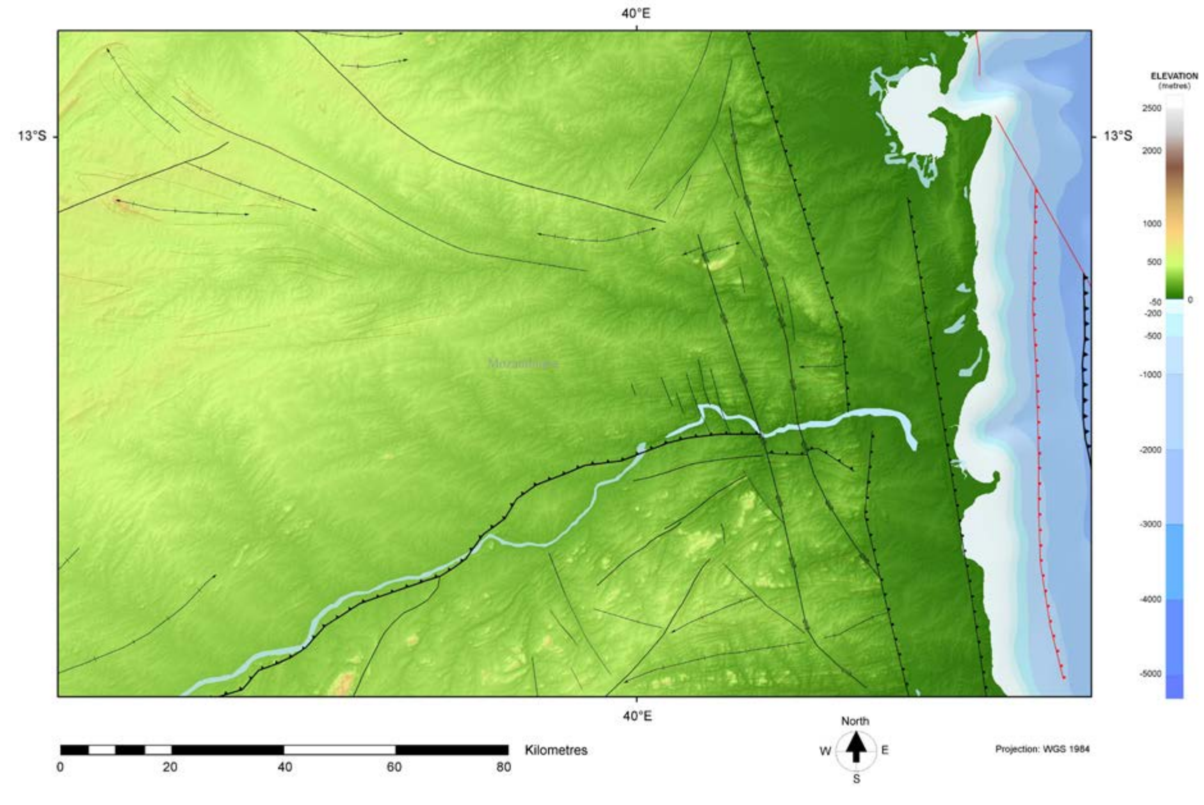
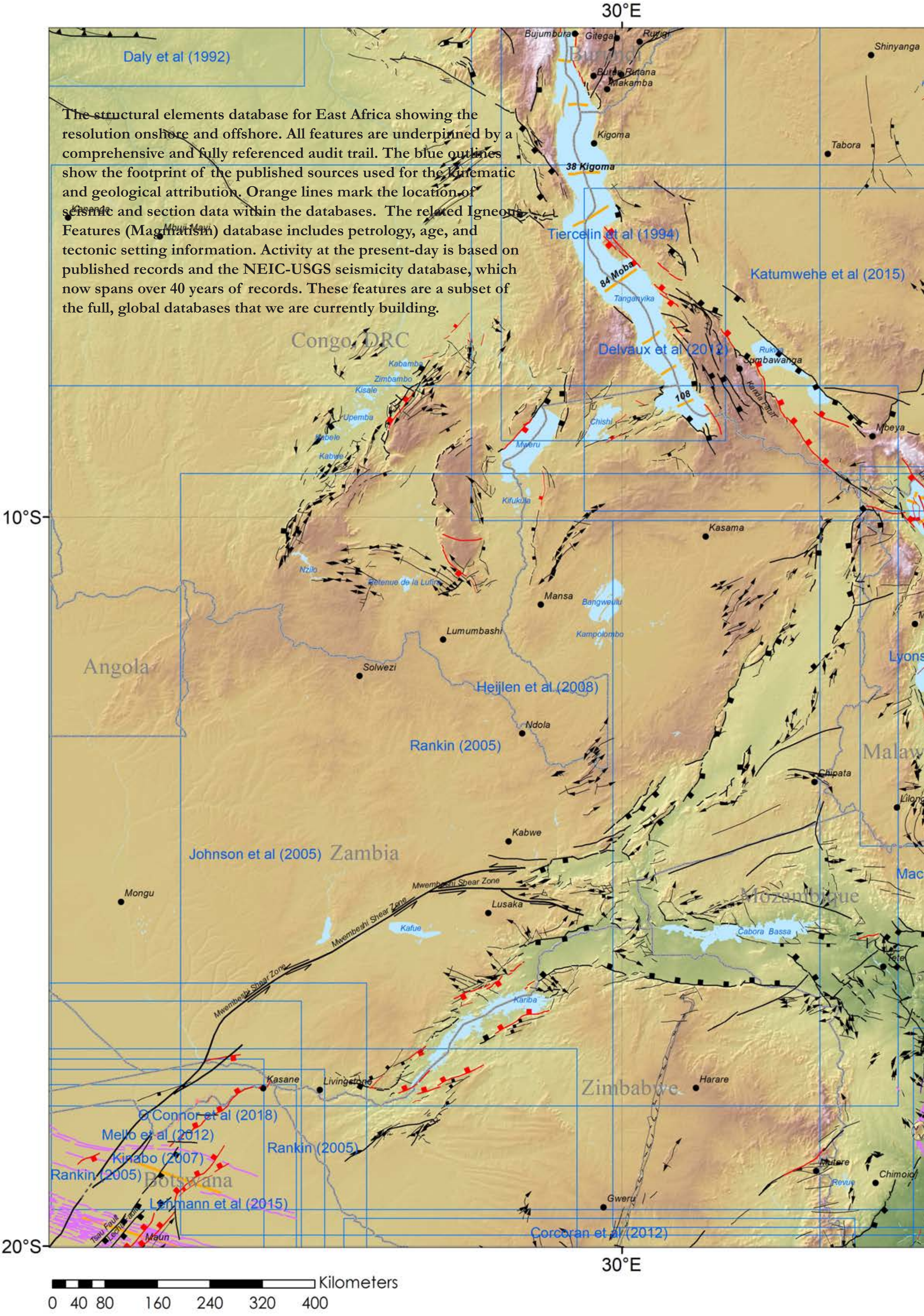
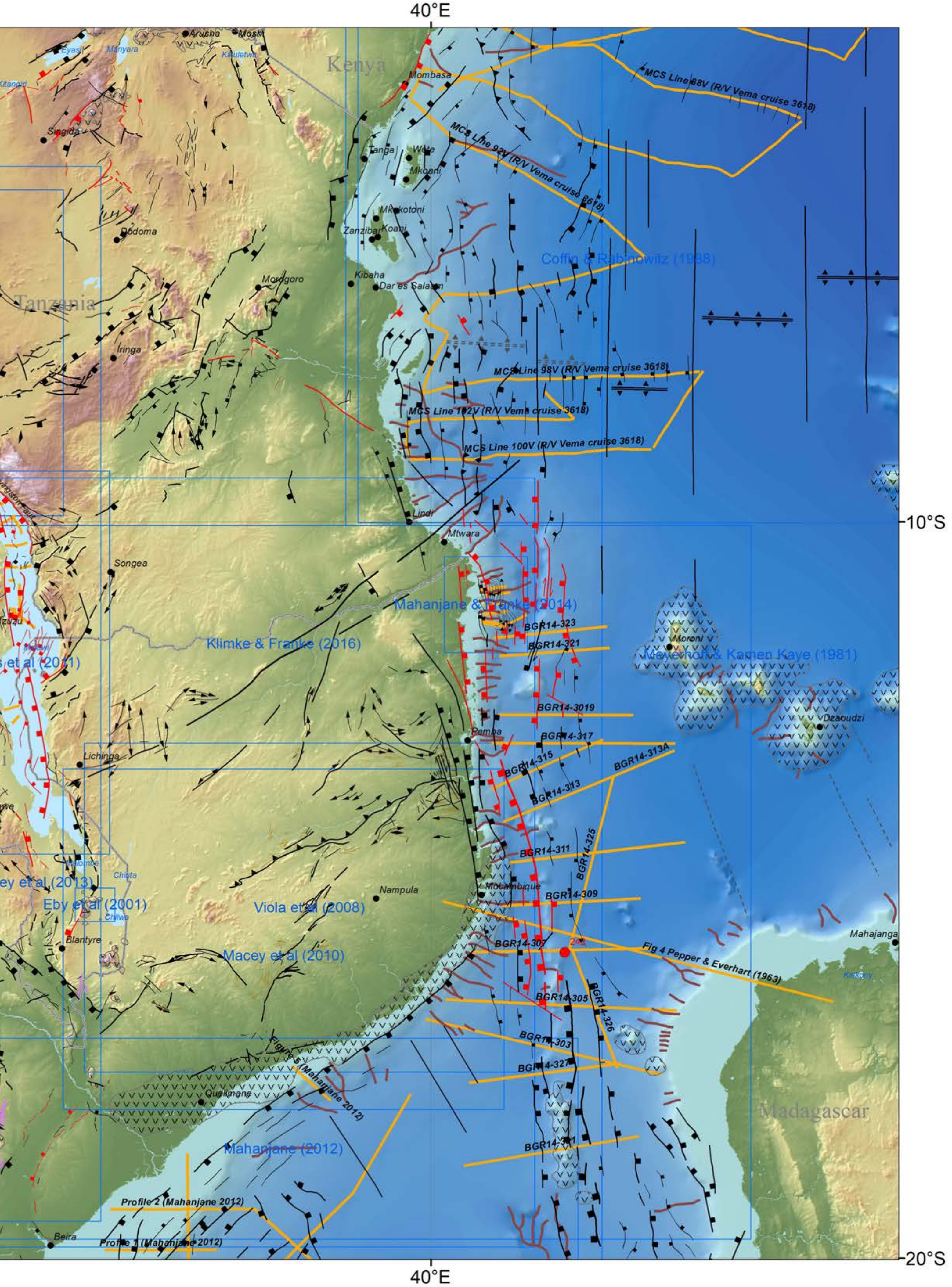


Figure 25. Mapped folds, faults, and bedding along the East African margin in north-eastern Mozambique. The river across the center of the image is the Lurio River. This figure shows several important features: 1. the use of bedding (thin brown lines) to help clarify the geometry of fold axes and shear zones; 2. the truncation of bedding along subsequent faults, in this case, normal faults along the margin; 3. The relation of the present-day drainage systems to pre-existing structures (the Lurio River and underlying Lurio collisional belt). The map also illustrates the differences in resolution between the use of Landsat imagery (for the folds and fold axes) and offshore gravity data (extensional faults). One question we are looking at here is the line weighting of bedding, which tends to get 'lost' in some of the mapping. This is partly intentional, because the main emphasis of our mapping is the kinematics of structures to underpin the crustal architecture.



The structural elements database for East Africa showing the resolution onshore and offshore. All features are underpinned by a comprehensive and fully referenced audit trail. The blue outlines show the footprint of the published sources used for the kinematic and geological attribution. Orange lines mark the location of seismic and section data within the databases. The related Igneous Features (Magmatism) database includes petrology, age, and tectonic setting information. Activity at the present-day is based on published records and the NEIC-USGS seismicity database, which now spans over 40 years of records. These features are a subset of the full, global databases that we are currently building.



40°E
-10°S
-20°S
Kenya
Tanzania
Madagascar
Mombasa
Tanga
Wete
Mkoani
Mkokotoni
Zanzibar
Koani
Kibaha
Dar es Salaam
Lindi
Mtwara
Pemba
Moçambique
Nampula
Quelimane
Beira
Blantyre
Lichinga
Songea
Iringa
Morogoro
Dodoma
Singida
Arusha
Moshi
Moroni
Dzaoudzi
Mahajanga
Eyasi
Manyara
Kitangiri
Kikuletwa
Chiuta
Chilwa
MCS Line 88V (R/V Vema cruise 3618)
MCS Line 92V (R/V Vema cruise 3618)
MCS Line 98V (R/V Vema cruise 3618)
MCS Line 102V (R/V Vema cruise 3618)
MCS Line 100V (R/V Vema cruise 3618)
Coffin & Rabinowitz (1988)
Mahanjane & Franke (2014)
Klimke & Franke (2016)
Meyerhoff & Kamen Kaye (1981)
Viola et al (2008)
Macey et al (2010)
Eby et al (2001)
Mahanjane (2012)
BGR14-323
BGR14-321
BGR14-3019
BGR14-317
BGR14-315
BGR14-313A
BGR14-313
BGR14-325
BGR14-311
BGR14-309
BGR14-307
BGR14-305
BGR14-326
BGR14-303
BGR14-327
BGR14-301
242
Fig 4 Pepper & Everhart (1963)
Figure 5 (Mahanjane 2012)
Profile 2 (Mahanjane 2012)
Profile 1 (Mahanjane 2012)

Small dike (UK, dyke) on the foreshore at Sea Point, Cape Town. These mafic dikes form part of the Early Cretaceous False Bay Dolerite Dike Swarm. Such igneous dikes are below the resolution of the current mapping, but these are associated with larger features that can be represented as lines.

5. Igneous Features

The igneous features (magmatism) database records the distribution of intrusive and extrusive rocks and their tectonic setting.

Igneous activity is a direct expression of contemporary geodynamics and tectonic setting. As such, it can provide clues to the tectonic evolution of an area, which can be used to constrain plate reconstructions and models of basin and landscape dynamics. The igneous activity also has a direct, and often instantaneous impact on drainage evolution (e.g. Miocene-Pliocene volcanism in southern Vietnam and Patagonia) and affects the character and composition of downstream sediments on the composition of the igneous material and climate acting on it (weathering and erosion).

The distribution and composition of igneous features can play direct and indirect roles in mineral and hydrocarbon exploration.

Mineral accumulations in igneous bodies can occur through primary differentiation in magma chambers by fractional crystallization and crystal segregation due to settling or floating of early formed minerals (viz., Bushveld complex rich in platinum group metals, iron, tin, chromium, titanium, and vanadium), or more often associated with hydrothermal mineralization within and around intrusions (e.g., Cu-porphyry deposits). Recent work (Ovalle et al. 2018) has described the relationship between explosive volcanic eruptions and mineralization, in this case, Fe-mineralization in the Andes. The direct link between mineral resources and volcanic ash has a long history. In England, Fullers' Earth deposits, comprising smectite clays formed by the breakdown of volcanic ash layers (specifical feldspars), have a wide range of applications from paper making to cosmetics to drilling fluids.

In hydrocarbon exploration, the emplacement of igneous bodies can affect local and, potentially, regional heat flow and, consequently, maturity and expulsion histories (Allen 2016; Eide et al. 2016).

Placer deposits are a consequence of the location of igneous bodies and associated mineralization and subsequent weathering, erosion, and downstream transport. For fluvial transport, this requires a knowledge of drainage networks and landscape evolution, as well as vegetation and climate.

A similar workflow to that for placer deposits has been applied to reservoir retrodiction using source-to-sink analysis. This can be quite complex. For example, in the Phu Khan Basin, the hinterland comprises Indosinian granites into which have been emplaced Miocene – Recent basalt lavas. Depending on the exact drainage geometry, a river outfall can produce good-quality reservoirs (from the granites), or clay-rich clastics from weathering and erosion of the basalts. In lithofacies modeling, contemporary volcanism can affect downstream net primary productivity (Langmann et al. 2010) and climate (Hopcroft et al. 2018)

In both mineral and hydrocarbon exploration, there is now a need to better understand each system as the search for new resources expands, especially how the tectonics and mineralogy are related and how this may dictate the distribution and quality of accumulations. This is quite a major step-change for mineral exploration, which has traditionally been geographically very focused. Hydrocarbon exploration has considered hinterland processes (source-to-sink), but existing databases of key components, including igneous features, are either focused on specific settings or geographies or are of too coarse resolution.

In our database, the aim is to capture key information at a resolution commensurate with the needs of hydrocarbon and mineral exploration, as well as to further our understanding of the spatial juxtaposition and evolution of igneous activity in response to tectonic forcing. Explorationists need a regional context to understand and assess the geology and exploration risk of their assets. Part of that workflow is to model basin evolution (subsidence, fill, uplift, erosion) and maturity (heat flow). The igneous activity can affect this depending on the nature (timing, geometry, and petrology) of the activity.

5.1. Mapping

The igneous features database is built using remote sensing data, geological maps, and published literature. Offshore interpretations are dominantly based on gravity and bathymetry data; we have found that, surprisingly, magnetic data can be equivocal. Onshore Landsat and geological maps are the primary sources of information.

5.1.1. Oceans

In the oceans, igneous features are dominated by extrusions that form prominent bathymetric expressions. Gravity and magnetics have been used on the margins to identify potential intrusions and extrusions. Magnetic data has, oddly, been found to be often misleading (e.g., eastern seaboard, Equatorial margin).

5.1.2. Onshore

Onshore, igneous features can generally be mapped at a much higher resolution than with offshore data sources. However, the complications onshore are weathering and vegetation. Whether this obscures or enhances delineation and identification depends on the differentiation in rheology and composition between igneous features and the country rock.

Basic volcanics tend to result in highly fertile areas with distinct vegetation cover, usually reddish or dark green in color.

Sharp boundaries typify intrusions and, depending on the prevailing climate, will show a distinct weathering pattern characterized by exfoliation and jointing. Most joints will not propagate into the country rock, which is key, although where joints have become faults, these can continue beyond the contact depending on age and subsequent history. Vegetation can also distinctly differ between intrusion and country rock depending on country-rock permeability.

Volcanoes and volcanic fields with cones and craters are very distinct both in radar (SRTM3) data and especially Landsat (Figure 28). The size of the feature that can be resolved will depend on the input data. (SRTM3 has a 90m resolution, Landsat typically 30m).

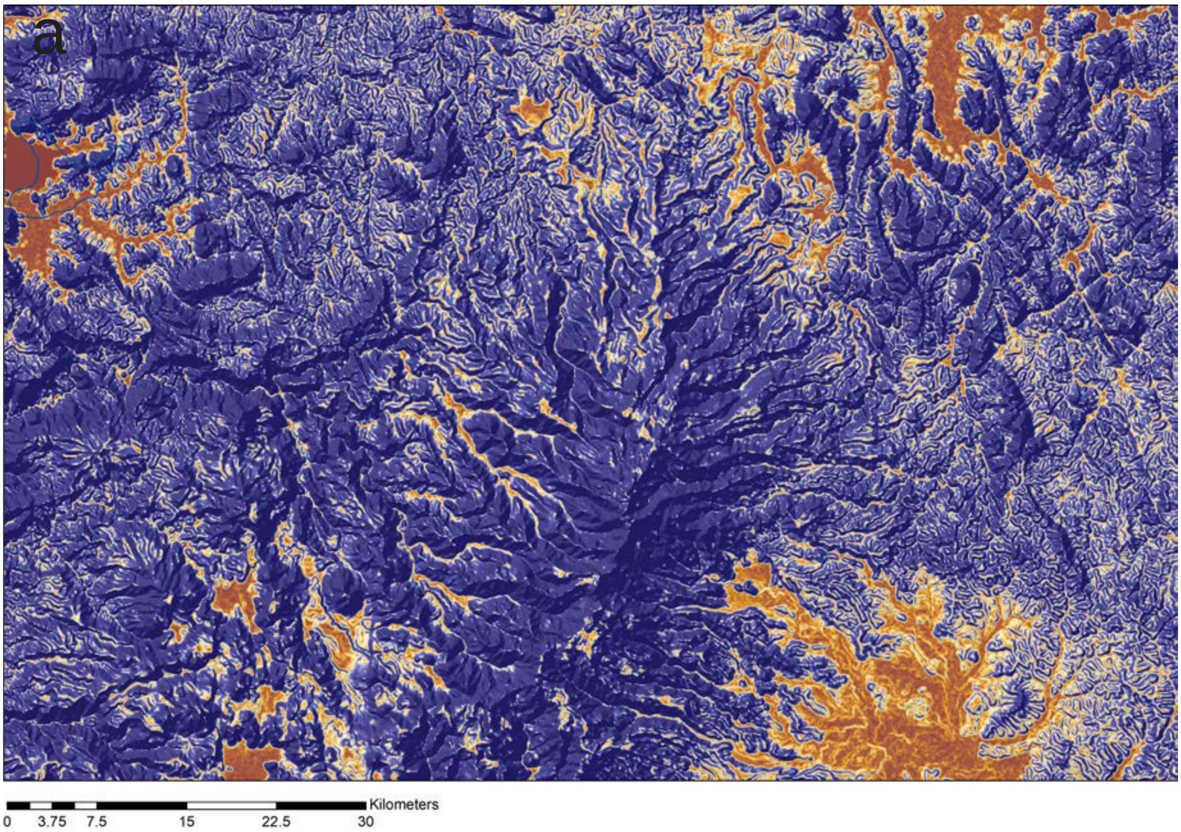
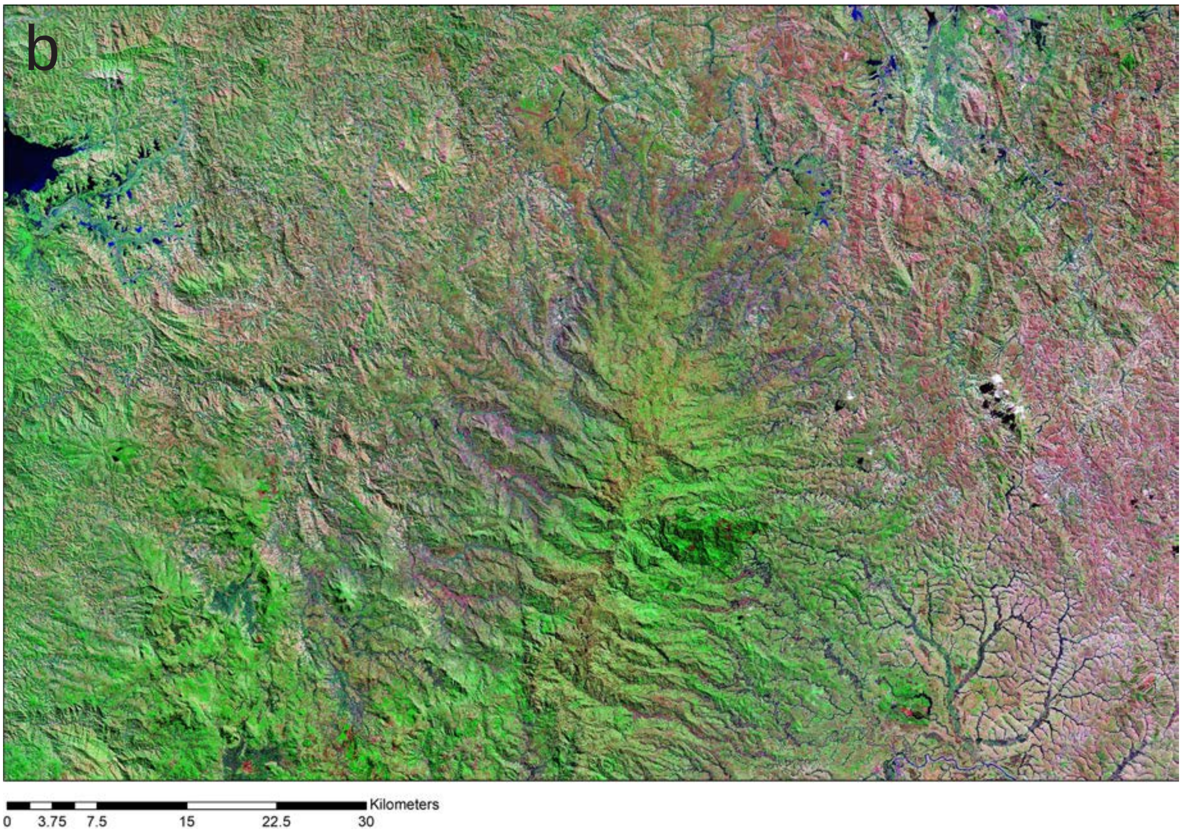


Figure 28. An example of a typical lava flow surface morphology, in this case, from central Madagascar. (a) topographic slope derivative which enhances the relief morphology, (b) Landsat imagery (c) database interpretation (e-Stv, Strato-volcano; e-Cra, crater; e-CC, cinder cone; sV, sub-volcanic feature such as a volcanic neck; e-LF, lava flows). Further information is provided in the database documentation for igneous features.



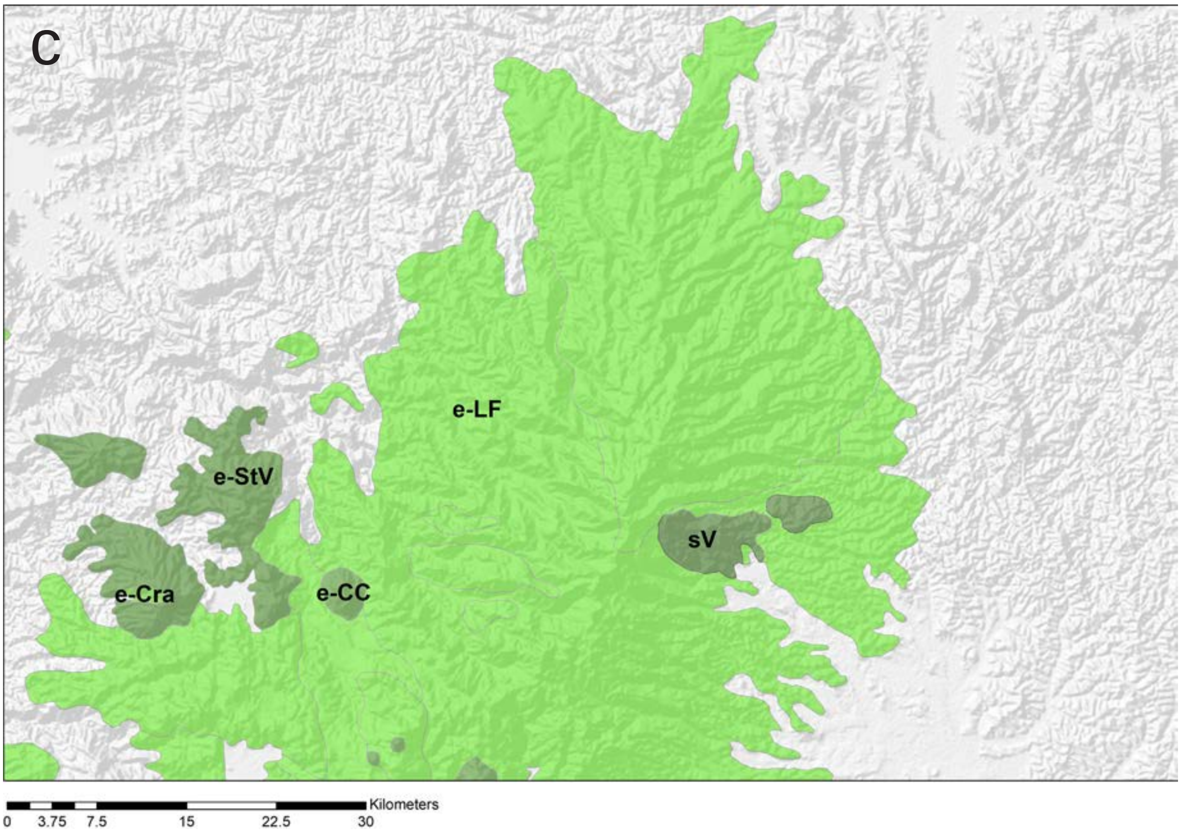


Figure 28 (contd.). An example of a typical lava flow surface morphology, in this case, from central Madagascar. (a) topographic slope derivative which enhances the relief morphology, (b) Landsat imagery (c) database interpretation (e-Stv, Strato-volcano; e-Cra, crater; e-CC, cinder cone; sV, sub-volcanic feature such as a volcanic neck; e-LF, lava flows). Further information is provided in the database documentation for igneous features.

5.2. Classification & Symbology

5.2.1. General Features

The simplest symbol set differentiates igneous features as either intrusive or extrusive (Figure 29). Where there is a mixture of intrusives and extrusives, or the nature cannot be differentiated, then users should use the "Igneous feature, undiff." assignment.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
IG300		Igneous feature, undifferentiated	255 / 190 / 190	Lithological picture (bitmap; black) superimposed on color fill
IG310		Extrusive feature, undifferentiated	255 / 0 / 0	Lithological picture (bitmap; black) superimposed on color fill
IG320		Intrusive feature, undifferentiated	255 / 227 / 229	Lithological picture (bitmap; black) superimposed on color fill

Figure 29. The fill, symbol ID code, and petrology symbology used to differentiate between intrusive and extrusive igneous features. This is the default symbology for igneous features. The format for all igneous symbol codes is as follows: "IG" + "###". The three-digit number value differentiates the type of igneous feature (see description). There is no differentiation in the symbology between active and inactive features. However, this is recorded in the database attribute table. Note: the pattern used for the undifferentiated igneous features is under review. We welcome suggestions.

5.2.2. Igneous Geomorphological Classification

For resource exploration, landscape dynamics, and tectonic reconstruction, the geomorphological character of igneous extrusions and intrusions can provide important information. For example, in hydrocarbon exploration, maturation differs depending on whether the igneous activity is dominated by sills, large intrusive bodies, or localized intrusions and extrusions (viz., Kimberlites). To accommodate, we have created a symbolization scheme using the geomorphological and geometric form of igneous features (Figures 30-33). This version is a mixture of surface expression and traditional nomenclature and is currently undergoing testing. Nevertheless, we have included it in this version of the mapping legend to solicit user suggestions and feedback.

SYMBOL	DESCRIPTION	RGB	NOTES
e-ind	Extrusion undifferentiated	163 / 255 / 115	For features that are extrusive but with no other descriptive information. For 'large' expanses of extrusions, you may want to use Large Igneous Province, Silicic Large Igneous Province, Continental Flood Basalt, or Oceanic Flood Basalt. But this is to cover all of the possible vagaries in the literature. **Map abbreviation field entry, "e-ind"**
e-CFB	Continental Flood Basalt	76 / 230 / 0	Used for any large volume of basaltic lavas and related intrusions erupted on continental crust. This is a generic designation in the absence of more precise information. If you can differentiate lavas and other features this should be done. **Map abbreviation field entry, "e-CFB"**
e-OFB	Oceanic Flood Basalt	0 / 186 / 132	A broad area of basaltic extrusion formed in ocean basins. This is a generic term and is frequently used synonymously with LIPS (Large Igneous Provinces). It has been included here as a catch-all for citations in the literature and in the absence of a better descriptive assignment. **Map abbreviation field entry, "e-OFB"**
e-SP	Submarine Plateau	0 / 186 / 132	A broad bathymetric platform formed by extrusion of material, although often with related intrusions. As a geomorphological term, a submarine plateau could be applied to an area of non-volcanic features, but in this database, it has a specific definition. A plateau is likely made up of multiple volcanic episodes, which may or may not be apparent from the plateau form, especially when seen in the gravity record. **Map abbreviation field entry, "e-SP"**
e-SR	Submarine Ridge	0 / 186 / 132	Like submarine plateaux, ridges, as a geomorphological term, could apply to volcanic and non-volcanic features. In this database, it is restricted to linear bathymetric highs formed by extrusion. In common use, a ridge might refer to parts of what was formerly a broader plateau feature, such as the Broken Ridge in the Southern Ocean. Both Submarine Plateaus and Submarine Ridges have the same color fill. **Map abbreviation field entry, "e-SR"**
e-SMT	Seamount	0 / 150 / 132	Volcanic extrusions on the seafloor that are represented as isolated features, usually near circular in plan (in bathymetric, seismic and gravity data). Guyots are flat-topped seamounts reflecting erosion. In this database, the term seamount is applied to any isolated, near-circular feature in the oceans representing a single extrusive source, whether this is totally in isolation on the abyssal plain or within a broader extrusive province such as represented by a plateau or ridge, which are geomorphological terms but which provide evidence of more extensive extrusions. **Map abbreviation field entry, "e-SMT"**
e-SDR	Seaward Dipping Reflectors	76 / 230 / 0	Originally named for the high amplitude reflectors seen in passive margin seismic, SDRs in this database refer to the volcanic part of the succession. Many of these may have formed sub-aerially in environments such as the present-day Afar region of Ethiopia, with subsequent subsidence resulting after the break-up to give the term its characteristic 'seaward dipping' geometry. However, recent work has shown that not all SDRs need be seaward dipping later in their history. **Map abbreviation field entry, "e-SDR"**

Figure 30. The fill symbology, RGB colors, and map abbreviations used for general extrusive igneous forms. The outline for all igneous polygons is 0.4pt grey (110/110/110) or black (0/0/0) unless this is removed altogether to enhance map clarity.

SYMBOL	DESCRIPTION	RGB	NOTES
e-LF	Lava flows	76 / 230 / 0	Used for all lava flows regardless of composition **Map abbreviation field entry, "e-LF"**
e-VF	Volcanic Field	56 / 168 / 0	An area of volcanic cones, lavas, and ash layers. These are often distinct in Landsat imagery. Volcanic fields may lie within larger extrusive areas. **Map abbreviation field entry, "e-VF"**
e-LD	Lava Dome	56 / 168 / 0	Usually a small, roughly circular in plan, and conical in form resulting from the slow extrusion of viscous lava. These are most common in silicic volcanics, given the viscosity of the lavas. **Map abbreviation field entry, "e-LD"**
e-Cld	Caldera	70 / 190 / 0	A roughly circular collapse feature resulting from the evacuation of magma. These features are usually clear on Landsat imagery. A crater is different in that it represents the vent of a volcano. The two will often be superimposed, and a caldera may follow the formation of craters over time. An individual crater will usually be much smaller in size than a caldera. **Map abbreviation field entry, "e-Cld"**
e-Cra	Crater, undifferentiated	70 / 190 / 0	A roughly circular feature resulting from eruptions. These features are usually clear on Landsat imagery. **Map abbreviation field entry, "e-Cra"**
e-CC	Cinder Cone	45 / 130 / 0	A cinder cone (scoria cone) is a steep conical feature comprising pyroclastic material. **Map abbreviation field entry, "e-CC"**
e-FV	Fissure Vent	56 / 168 / 0	A fissure vent is a linear volcanic fissure along which extrusives erupt. Depending on the map scale, this could be represented in GIS as a polygon or a line feature. **Map abbreviation field entry, "e-FV"**
e-ShV	Shield Volcano	38 / 115 / 0	A volcano, usually circular in plan, with gentle slope profiles. This type of volcano forms from low-viscosity lavas. **Map abbreviation field entry, "e-ShV"**
e-StV	Strato Volcano	38 / 115 / 0	A volcano with a steep conic profile formed of high-viscosity lava flows and pyroclastics. Like shield volcanoes, their plan is frequently circular around each vent. **Map abbreviation field entry, "e-StV"**
e-PyF	Pyroclastic Flow	150 / 204 / 112	Pyroclastic flows are those in which there is evidence of flow, resulting in rocks, including ignimbrites. **Map abbreviation field entry, "e-PyF"**
e-Py	Pyroclastics, undifferentiated	150 / 204 / 149	It can be used for any features described as comprising pyroclastics, but where they are not only demonstrably ash or formed from a flow(s). **Map abbreviation field entry, "e-Py"**
e-Ash	Volcanic Ash	161 / 184 / 176	This is used for any ash layer(s). If the feature is mixed material, then use Pyroclastics, undiff. **Map abbreviation field entry, "e-Ash"**
sV	Sub-volcanic	35 / 100 / 0	Sub-volcanic features include necks and domes that are never fully erupted but are directly associated with extrusion. E.g. Devils Tower, Wyoming. **Map abbreviation field entry, "sV"**

Figure 31. The fill symbology, RGB colors, and map abbreviations used for extrusive and sub-volcanic igneous forms. The outline for all igneous polygons is 0.4pt grey (110/110/110) or black (0/0/0) unless this is removed altogether to enhance map clarity.

SYMBOL	DESCRIPTION	RGB	NOTES
i-ind	Intrusions undifferentiated	255 / 190 / 232	Used for any intrusions whether more detailed information on their form is not available. **Map abbreviation field entry, "i-ind"**
i-D	Dyke / Dike	223 / 115 / 255	A linear, vertical planar intrusion. In most cases, the width of these features in our databases means they are best represented as lines. But there are exceptions, such as the Great Dyke of Zimbabwe. **Map abbreviation field entry, "i-D"**
i-DS	Dyke Swarm	223 / 115 / 255	Used for a mass of related dykes. However, in use, this designation is probably not going to be used since dyke swarms will be represented by individual line features in the databases. **Map abbreviation field entry, "i-DS"**
i-S	Sill	169 / 0 / 230	A horizontal, or near-horizontal planar intrusion. **Map abbreviation field entry, "i-S"**
i-BS	Stock	255 / 225 / 232	A large volume of intrusive (plutonic) igneous rock defined as smaller than 100 km^2 in the area. **Map abbreviation field entry, "i-BS"**
i-B	Batholith	255 / 220 / 232	A large volume of intrusive (plutonic) igneous rock defined as larger than 100 km^2 in the area. A batholith might be made up of multiple plutons. **Map abbreviation field entry, "i-B"**
i-Lop	Lopolith	255 / 190 / 232	A large, saucer-shaped intrusion of igneous rock convex down and is usually concordant with the strata into which it intrudes—often layered. **Map abbreviation field entry, "i-Lop"**
i-Lac	Laccolith	255 / 190 / 232	A large, dome-shaped intrusion (inverted saucer) of igneous rock convex up and is usually concordant with the strata into which it intrudes. **Map abbreviation field entry, "i-Lac"**
i-RC	Ring Complex	240 / 150 / 240	A complex of intrusive bodies, including ring-dykes, nested intrusions, and cone-sheets, formed at relatively shallow depths. Recent work has suggested that carbonatite ring complexes may be related to caldera collapse (Andersson et al., 2013). **Map abbreviation field entry, "i-RC"**

Figure 32. The fill symbology, RGB colors, and map abbreviations used for intrusive igneous features. The outline for all igneous polygons is 0.4pt grey (110/110/110) or black (0/0/0) unless this is removed altogether to enhance map clarity.

SYMBOL	DESCRIPTION	RGB	NOTES
Ig	Igneous undifferentiated	255 / 0 / 0	A generic designation for an igneous body with no additional information. **Map abbreviation field entry, "Ig"**
LIP	Large Igneous Province	230 / 0 / 0	A generic designation for a large area of igneous activity with no additional information. By linking multiple features into one province, there is an explicit assumption that the features are causally linked. **Map abbreviation field entry, "LIP"**
sLIP	Silicic Large Igneous Province	255 / 85 / 0	A generic designation for a large area of igneous activity that is dominantly silicic. In most cases, the individual constituent igneous features will have a description assigned. By linking multiple features into one province, there is an explicit assumption that the features are causally linked. **Map abbreviation field entry, "sLIP"**
IgC	Igneous Complex	168 / 0 / 0	An igneous complex usually refers to a series of related, but often diverse igneous features of limited areal extent (at least when compared with an Igneous Province. To that end, an Igneous Province might comprise many Igneous Complexes. An igneous complex might, in turn, comprises volcanoes, intrusions, etc. The inclusion of this term here is a catch-all for what compilers may find in the literature. **Map abbreviation field entry, "IgC"**

Figure 33. The fill symbology and abbreviations used for undifferentiated igneous features. The outline for all igneous polygons is 0.4pt grey (110/110/110) or black (0/0/0) unless this is removed altogether to enhance map clarity.

5.2.3. Igneous line features

SYMBOL	DESCRIPTION	RGB	LINE WEIGHT
IG20A	Igneous dike/dyke, active	169 / 0 / 230	2.0 pt
IG20Ai	Igneous dike/dyke, active inferred	169 / 0 / 230	2.0 pt
IG20I	Igneous dike/dyke, inactive	223 / 115 / 255	2.0 pt
IG20Ii	Igneous dike/dyke, inactive inferred	223 / 115 / 255	2.0 pt

Figure 34. Igneous line symbols representing dykes/dikes. Depending on the map scale, dykes/dikes can also be represented as polygons (see Figure 32).

PHOTO: Interpreted pyroclastics, ignimbrites, and volcaniclastics of the Erill Castell Formation (Stephanian, Carboniferous) in the central Pyrenees to the east of the town of Pont de Suert.

5.3. Igneous Petrology Fill Patterns

The fill patterns used for igneous petrologies are less ubiquitously adopted than sedimentary lithological symbols. We have tried to use the symbol set of the USGS where possible, but we have had to diverge in many places given the need to find symbols for a range of petrologies that are not covered in most symbology sets.

All petrology symbol codes are prefixed with the letter "L" consistent with the lithological symbol codes. As for the lithological symbols, the petrological symbols are colored based on the mapping confidence, which reflects whether the interpretation is based on data from outcrops, subcrop, or is inferred. A default symbology can also be used where the confidence color symbology might be misleading or obscure the story being told.

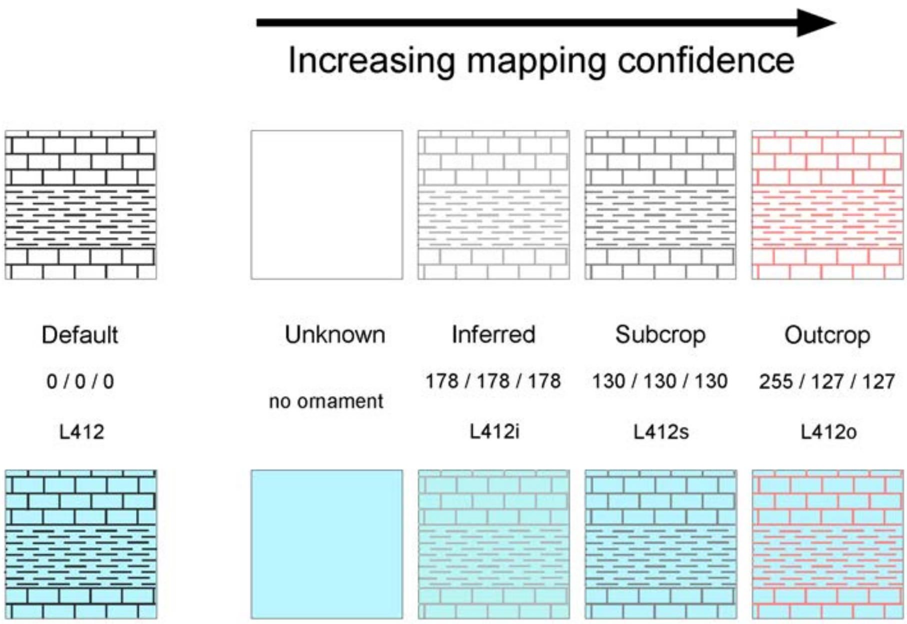


Figure 35. The petrological and lithological fill patterns are colored according to the source of information: outcrop, suffix "o; subcrop, suffix "s"; inferred, suffix "i." This provides a visual indication of interpretation confidence following the methodologies used in the paleogeographic maps of Vinogradov et al (1968). In the lower examples the lithological symbology is superimposed on the depositional environmental coding, in this case, deep shelf (see section 10). This is discussed further in section 10.5.

5.3.1. Undifferentiated Igneous petrologies and volcaniclastics

This includes the symbols used for intrusives and extrusive igneous rocks with no detailed petrological information. It also includes pyroclastic rocks.

CODE	SYMBOL	DESCRIPTION	NOTES
L800		Igneous undifferentiated	Picture bitmap by PJM (under review). Used for any igneous feature where the feature's nature is unknown.
L810		Volcanic extrusives undifferentiated	Based on the picture bitmap USGS 731. Used by the USGS for vitrophyre. Used for any extrusive feature where there is no information about petrology.
L830		Igneous Intrusive, undifferentiated	Based on the picture bitmap USGS 712. Used by USGS for crystal tuff. Used for any intrusive feature where there is no information about petrology.

Figure 36. The default fill pattern, symbol ID code, and explanation for the composition of mapped igneous rocks. The format for all igneous petrology symbol codes is as follows: "L" + "###" + "Confidence." The "L" stands for "Lithology" which ensures consistency with the lithological symbol codes. The three-digit number value differentiates the type of igneous petrology (see description). "Confidence" in this context refers to the confidence with which the petrology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 35.

5.3.2. Volcaniclastics and pyroclastics

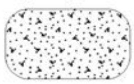
CODE	SYMBOL	DESCRIPTION	NOTES
L825		Pyroclastics undifferentiated	Based on picture bitmap USGS 723. This is one of the USGS igneous rock options. Sedimentary clastic rocks composed solely or primarily of volcanic materials formed during eruptions.
L820		Volcanic ash, tuff	Based on picture bitmap USGS 729 (porphyritic rock). Fine-grained volcanic material formed from settling of fine volcanic particles through the air column from volcanic eruptive clouds.
L827		Volcanic breccia, agglomerate, hyaloclastite	Picture bitmap modified from breccia symbol. The coarsest form of pyroclastics, typical of explosive eruptions usually within a crater.
L829		Volcaniclastics	Picture bitmap modified from L827. Further work is needed to improve this. Pyroclastics where the material has then been transported and reworked through mechanical action.

Figure 37. The default fill pattern, symbol ID code, and explanation for the composition of mapped volcaniclastic and pyroclastic rocks. The format for all igneous petrology symbol codes is as follows: "L" + "###" + "Confidence." The "L" stands for "Lithology" which ensures consistency with the lithological symbol codes. The three-digit number value differentiates the type of igneous petrology (see description). "Confidence" in this context refers to the confidence with which the petrology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 35.

5.3.3. Acid igneous compositions

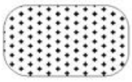
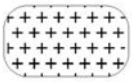
CODE	SYMBOL	DESCRIPTION	NOTES
L840		Rhyolite	Based on the picture bitmap USGS 721. Acid extrusives. Although labelled as "rhyolites", other acid extrusives can be included here with details writing in the petrology field: obsidian, pitchstone, 'felsite'. Pumice should be included under pyroclastics.
L845		Granite	Based on the picture bitmap by PJM. Acid intrusives. Any felsic intrusive rock with the broad composition of 'granite', so 20-50% quartz, >35% feldspar (usually 5-30% K-feldspar, 5-40% plagioclase) and 20-30% hornblendes and micas, and minor pyroxenes. Monzonites and adamellites can be grouped here (details added to petrology field in the attribute table)

Figure 38. The default fill pattern, symbol ID code, and explanation for the composition of mapped 'acidic' igneous rocks. The format for all igneous petrology symbol codes is as follows: "L" + "###" + "Confidence." The "L" stands for "Lithology" which ensures consistency with the lithological symbol codes. The three-digit number value differentiates the type of igneous petrology (see description). "Confidence" in this context refers to the confidence with which the petrology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 35.

5.3.4. Intermediate igneous compositions

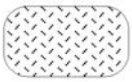
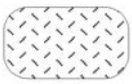
CODE	SYMBOL	DESCRIPTION	NOTES
L850		Andesite	Based on the picture bitmap USGS 728 (USGS Igneous rock 8th option). Intermediate extrusives compositionally between basalts and rhyolites.
L855		Diorite	Based on the picture bitmap USGS 711 (USGS tuffaceous rock symbol). Intermediate intrusives.

Figure 39. The default fill pattern, symbol ID code, and explanation for the composition of mapped 'intermediate' igneous rocks. The format for all igneous petrology symbol codes is as follows: "L" + "###" + "Confidence." The "L" stands for "Lithology" which ensures consistency with the lithological symbol codes. The three-digit number value differentiates the type of igneous petrology (see description). "Confidence" in this context refers to the confidence with which the petrology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 35.

5.3.5. Basic igneous compositions

CODE	SYMBOL	DESCRIPTION	NOTES
L860		Basalt	Picture bitmap by PJM Fine-grained mafic extrusives.
L863		Dolerite	Picture bitmap by PJM Medium-grained mafic intrusives
L865		Gabbro	Picture bitmap by PJM Coarse-grained mafic intrusives.

Figure 40. The default fill pattern, symbol ID code, and explanation for the composition of mapped 'basic' igneous rocks. The format for all igneous petrology symbol codes is as follows: "L" + "###" + "Confidence." The "L" stands for "Lithology" which ensures consistency with the lithological symbol codes. The three-digit number value differentiates the type of igneous petrology (see description). "Confidence" in this context refers to the confidence with which the petrology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 35.

5.3.6. Ultramafic igneous compositions

CODE	SYMBOL	DESCRIPTION	NOTES
L870		Peridotite, Dunite	Based on the picture bitmap USGS 724. Ultramafic intrusives.

Figure 41. The default fill pattern, symbol ID code, and explanation for the composition of mapped 'ultrabasic' igneous rocks. The format for all igneous petrology symbol codes is as follows: "L" + "###" + "Confidence." The "L" stands for "Lithology" which ensures consistency with the lithological symbol codes. The three-digit number value differentiates the type of igneous petrology (see description). "Confidence" in this context refers to the confidence with which the petrology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 35.

5.3.7. Alkali igneous compositions

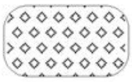
CODE	SYMBOL	DESCRIPTION	NOTES
L880		Syenite, phonolite	Based on the picture bitmap ESRI pattern. Alkali intrusives.
L885		Trachyte	Based on the picture bitmap ESRI pattern. Alkali extrusives.

Figure 42. The default fill pattern, symbol ID code, and explanation for the composition of mapped alkali igneous rocks. The format for all igneous petrology symbol codes is as follows: "L" + "###" + "Confidence." The "L" stands for "Lithology" which ensures consistency with the lithological symbol codes. The three-digit number value differentiates the type of igneous petrology (see description). "Confidence" in this context refers to the confidence with which the petrology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 35.

5.3.8. Carbonatites and related compositions

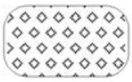
CODE	SYMBOL	DESCRIPTION	NOTES
L890		Carbonatite	Based on the picture bitmap USGS 728. Carbonatite, indeterminate.

Figure 43. The default fill pattern, symbol ID code, and explanation for the composition of mapped carbonatite and related igneous rocks. The format for all igneous petrology symbol codes is as follows: "L" + "###" + "Confidence." The "L" stands for "Lithology" which ensures consistency with the lithological symbol codes. The three-digit number value differentiates the type of igneous petrology (see description). "Confidence" in this context refers to the confidence with which the petrology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 35.

Lavas, Lava Beds National Monument, northern California

Porphyritic granite of the Town Mountain Granite (Proterozoic), part of the Llano uplift, central Texas. Phenocrysts are of microcline feldspar. The Town Mountain Granite comprises a series of small plutons (up to 20 km in diameter).

6. Crustal Facies

The Crustal Facies Database records information on the geometry, thickness, and composition of the Earth's crust. This provides input for defining plate polygons in plate kinematic modeling, reconstructing potential heat flow as a key input to maturity modeling, understanding basin formation and evolution, and paleogeographic reconstruction and paleolandscape dynamics.

The crust represents the chemically distinct upper layers of the Earth. Rheologically the crust forms part of the lithosphere together with the upper mantle, which needs to be considered in geodynamic modeling.

In the classification used here, we have differentiated the crust by composition and thickness (Figure 45; a legend for sections is also provided, Figure 46) to create a suite of facies, borrowing the term from sedimentology. The crustal composition reflects the history of that crust but is independent of the geodynamic processes acting on the crust once formed, which is stored in a separate geodynamics database.

Crustal facies can be combined into assemblages to facilitate a comparison between margins. We are currently building a portfolio of examples, which we will present later in 2023.

All crustal facies symbol codes are prefixed with the letter "C".

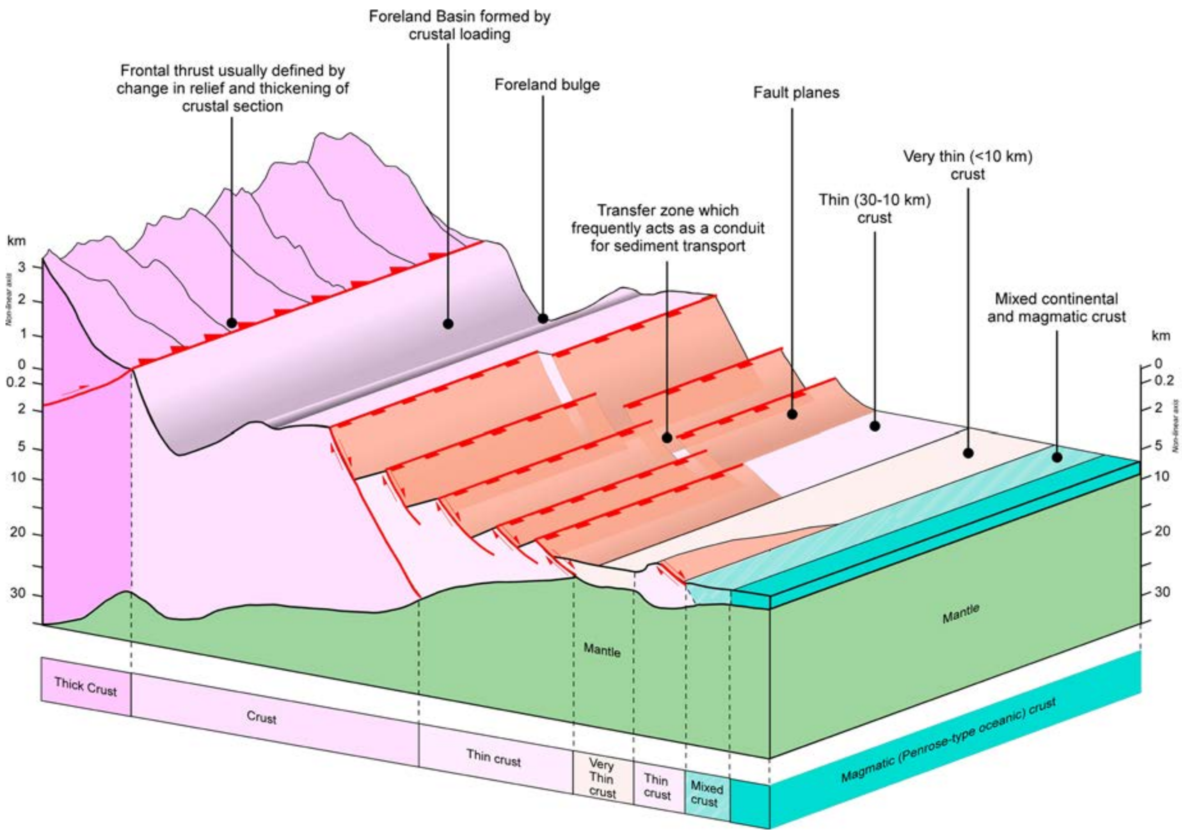


Figure 44. A block diagram showing the crustal types that underlie the hypothetical landscape shown in Figure 4 (Markwick, 2018). The fault planes are shown in red to illustrate the structural geometry in relation to the crustal architecture. The figure is not to scale.

Basaltic pillow lavas within the late Neoproterozoic – Cambrian Mona Complex on the beach at Ynys Llanddwyn, Newborough Warren, Anglesey, UK. Maruyama et al., (2010) interpreted these as forming within a Pacific-type accretionary complex.

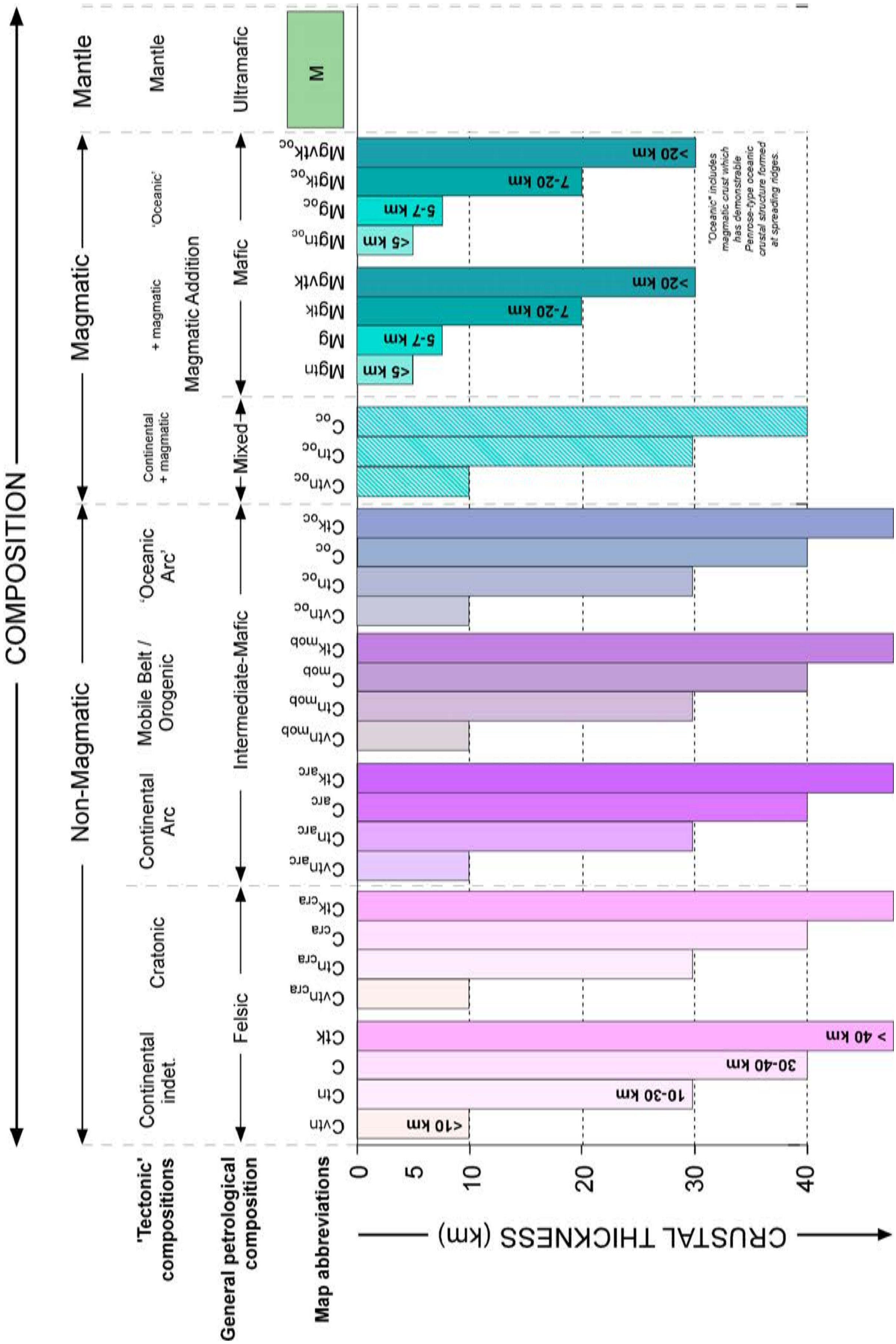


Figure 45. The classification of crustal facies modified from Markwick et al., (2021; 2023).

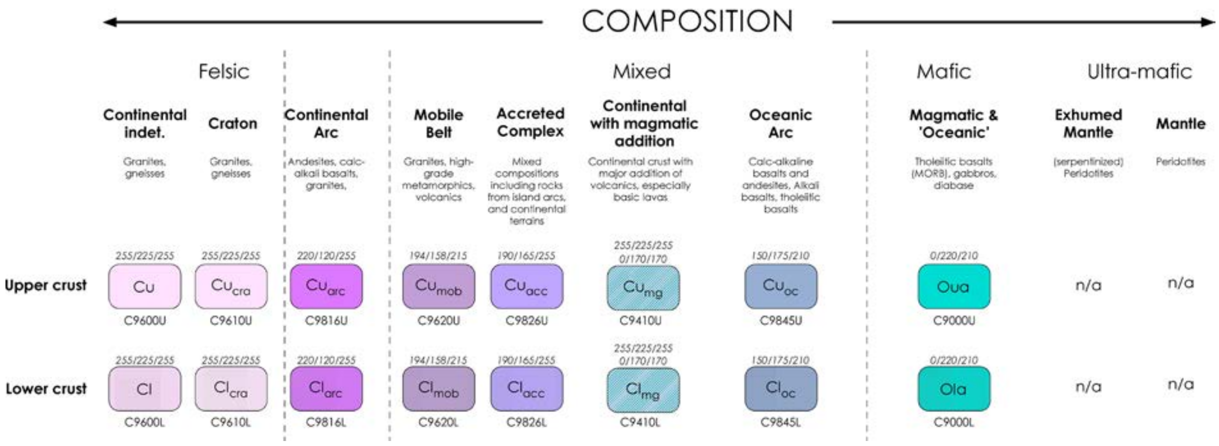


Figure 46. The classification of crustal facies (types) used in this study with a symbology for use in developing 2D sections.

Ultimately all crust has been formed by differential fractionation of mantle material. The most highly differentiated are the felsic-dominated compositions typical of cratonic continental crust, much of which was formed during the Archaean. There is some compositional variation within cratons (greenstone belts), but the bulk composition is felsic. Intermediate to mafic composition crust includes those formed originally in, or typical of, continental arcs, accreted complexes, and ocean arcs. Mobile belts are orogenic belts incorporating a range of compositions and are important because numerous studies, including our own work, has shown that their location can have a major influence on subsequent rifting and landscape dynamics, for example, in the Equatorial Atlantic. These five categories are grouped into what we are loosely referring to as 'non-magmatic' crust. This does not mean that some of the crustal volumes were not formed by magmatic processes, but that such material formed by melting of existing crust, for example, granitization or plutons from melting of subducting slabs. In contrast, 'magmatic' crust in our scheme refers to a crust with direct additions from differential fractionation of (primary) mantle material. The exceptions here are the inclusion in all crustal types of localized, mantle-sourced volcanics and intrusives related to hot-spots or other mantle anomalies (viz., kimberlites, Large Igneous Provinces). The 'mixed' crust category includes crust with a mixture of magmatic and non-magmatic material usually associated with what has traditionally been referred to as transitional crust in which magma from mantle sources has intruded stretched or other crust.

The thickness designations have been defined to reflect what is possible to interpret globally from available remote sensing data, seismic and publications, and to ensure some level of commonality with existing classifications. It also reflects preliminary applications to different margins. For 'non-magmatic' crustal types, we have defined the following thickness categories: 'typical' crust, 30-40 km; thick crust, >40 km; thin crust, 10-30 km, and very thin crust, <10 km. Note the use of adjectives to describe the crustal categories, not adverbs ("thin" not "thinned") in order to avoid the explicit allocation of process. However, we are cognizant of how the classification will be used, hence the inclusion of a "very thin crust" defined as <10 km, which will match the definition of "hyper-extended"

Figure 47. A classification using 'traditional' crustal facies assemblage groupings.

crust in the schemes of Manatschal and co-workers (Péron-Pinvidic and Manatschal 2009; Manatschal et al. 2010). For 'magmatic' crust we have differentiated between the following: 'typical' crust, 5-7 km; thin crust, < 5 km; thick crust, 7-20 km; very thick crust, >20 km. The "exhumed mantle" has a crustal thickness of 0 km by definition

These different facies can then be brought together into facies assemblages. Each margin will likely represent a different facies assemblage reflecting its own unique history. This then provides a powerful yet simple way to describe margin heterogeneity.

However, it may also be useful to generalize these assemblages, relating them to traditional classifications, for example, by different tectonic settings: collisional, continental (anorogenic), extensional, transitional, and oceanic (Figure 47).

6.1. Non-magmatic ('Continental') Crustal Types

In our definition, 'non-magmatic' crust refers to crust not formed directly from primary mantle material (cf. ocean crust) at the time mapped – the last thermo-mechanical phase. All crust is ultimately formed by differential melting of mantle compositions, but the rheological behavior of crustal types is a function of composition and the time since it formed.

Continental areas also include those parts of the continental crust thickened due to the addition of volume by plutons and magma (viz, continental arcs such as parts of the Andes, and the Western Cordillera of North America), and by compression and underplating (viz., Tibetan Plateau).

6.1.1. Continental crust undifferentiated

This is the default classification for areas of continental crust, but where, for whatever reason, no assignment has been provided for whether this represents craton or mobile belts. It is expected that as the database is populated, the use of these allocations will become fewer.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9600D	Ci	Continental crust undiff. *Thickness undefined*	255 / 225 / 255	This represents a default categorization of 'continental' crust where the thickness is not known. **Map abbreviation field entry, "Ci"**
C9800	Ctk	Thick Continental crust undiff. *Thickness >40 km*	255 / 175 / 255	Continental crust that is thicker than 'typical' crust. **Map abbreviation field entry, "Ctk"**
C9600	C	Continental crust undiff. *Thickness 30-40 km*	255 / 225 / 255	This represents 'typical' continental crust that has not been substantially thickened nor thinned. **Map abbreviation field entry, "C"**
C9400	Ctn	Thin Continental crust undiff. *Thickness10-30 km*	255 / 237 / 255	Continental crust that is thinner than typical continental crust. **Map abbreviation field entry, "Ctn"**
C9425	Cvtn	Very Thin Continental crust undiff. *Thickness <10 km*	255 / 240 / 240	Continental crust that is <10 km thick which is defined as "hyper-extended crust" by other authors. **Map abbreviation field entry, "Cvtn"**

Figure 48. The fill color, RGB code, symbol ID code, and explanation for the composition of mapped continental undifferentiated crustal facies. The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description). A "D" suffix is added where there is no thickness constraint.

6.1.2. Cratonic continental crust

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9610D	Ci_{cra}	Cratonic crust *Thickness undefined*	255 / 225 / 255	This represents a default categorization of cratonic 'continental' crust where the thickness is not known. **Map abbreviation field entry, "Ci_{cra}"**
C9605	Ctk_{cra}	Thick cratonic crust *Thickness >40 km*	255 / 175 / 255	Cratonic crust that is thicker than 'typical' crust. **Map abbreviation field entry, "Ctk_{cra}"**
C9610	C_{cra}	Cratonic crust *Thickness 30-40 km*	255 / 225 / 255	This represents 'typical' cratonic continental crust that has not been substantially thickened nor thinned. **Map abbreviation field entry, "C_{cra}"**
C9615	Ctn_{cra}	Thin cratonic crust *Thickness 10-30 km*	255 / 237 / 255	Cratonic continental crust that is thinner than typical continental crust. **Map abbreviation field entry, "Ctn_{cra}"**
C9616	$Cvtn_{cra}$	Very thin cratonic crust *Thickness <10 km*	255 / 240 / 240	Cratonic continental crust <10 km thick which is defined as hyper-extended crust by some authors. **Map abbreviation field entry, "Cvtn_{cra}"**

Figure 49. The fill color, RGB code, symbol ID code, and explanation for the composition of mapped continental cratonic crustal facies. The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description). A "D" suffix is added where there is no thickness constraint.

6.1.3. Continental arc crust

Continental arc compositions are typified by andesites and granites formed primarily in Ocean-Continent (O-C) collisions in which ocean crust subducts beneath the continental crust. Simple mixing models suggest that in most arcs, the dominant source of magma is from the melting of the subducting slab and lower crust (c.65%), with 35-40% from mantle sources (Asmerom et al. 1991). Melting of the subducted material results in the compositions of igneous rocks observed. Deformation associated with the O-C collision can result in arcs, including elements that may be better classified as orogenic belts (with major deformation) and mantle-derived (magmatic) material due to the thickening of the crust.

The geometry and nature of compressional systems vary depending on the angle (shallow or steep) and azimuth (angle of incidence of subducting plate with the continent) of subduction (Stevenson and Turner 1977).

6.1.4. Orogenic / Mobile belt crust

Mobile belts are zones that surround cratons and are characterized by high-grade metamorphism, granitization, and structural complexity, often including evidence of transcurrent and/or transpressional kinematics (e.g., Lurio Belt). The term "mobile belt" is frequently used for Precambrian or early Paleozoic orogenic systems, although orogenesis has not always been established fully (Dott Jr 1964). Greenstone belts are not the same as mobile belts and are meta-volcanic and meta-sedimentary assemblages within cratonic areas.

In this classification, we classify mobile belts together with orogenic belts and suggest a common origin.

The term "mobile belt" was originally coined by Bucher (Bucher 1924) to encompass continuous zones of deformation that resulted from large-scale stresses. "Mobile" refers to the movement of material. Although the mechanism to explain the geography and nature of

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9816D	Ci_{arc}	Continental volcanic arc *Thickness undefined*	220 / 120 / 255	This represents a default categorization of 'continental' arc crust where the thickness is not known. **Map abbreviation field entry, "Ci_{arc}"**
C9810	Ctk_{arc}	Thick continental volcanic arc *Thickness >40 km*	204 / 102 / 255	Thick continental volcanic arc composition crust. **Map abbreviation field entry, "Ctk_{arc}"**
C9816	C_{arc}	Continental volcanic arc *Thickness 30-40 km*	220 / 120 / 255	This represents 'typical' continental crust that has not been substantially thickened nor thinned. **Map abbreviation field entry, "C_{arc}"**
C9815	Ctn_{arc}	Thin continental volcanic arc *Thickness 10-30 km*	230 / 170 / 255	Continental arc crust that is thinner than typical continental crust. **Map abbreviation field entry, "Ctn_{arc}"**
C9818	$Cvtn_{arc}$	Very thin continental volcanic arc *Thickness <10 km*	230 / 200 / 255	Continental arc crust that is <10 km thick which is defined as hyper-extended crust by some authors. **Map abbreviation field entry, "Cvtn_{arc}"**

Figure 50. The fill color, RGB code, symbol ID code, and explanation for the composition of mapped continental arc crustal facies. The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description). A "D" suffix is added where there is no thickness constraint.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9620D	Ci_{mob}	Orogenic/mobile belt crust *Thickness undefined*	194 / 158 / 215	This represents a default categorization of 'mobile belt' crust where the thickness is not known. **Map abbreviation field entry, "Ci_{mob}"**
C9618	Ctk_{mob}	Thick orogenic/mobile belt crust *Thickness >40 km*	194 / 130 / 227	Mobile belt thicker than 40 km. **Map abbreviation field entry, "Ctk_{mob}"**
C9620	C_{mob}	Orogenic/mobile belt crust *Thickness 30-40 km*	194 / 158 / 215	This represents 'typical' continental crust thickness. **Map abbreviation field entry, "C_{mob}"**
C9625	Ctn_{mob}	Thin orogenic/mobile belt crust *Thickness 10-30 km*	210 / 187 / 220	Mobile belt continental crust that is thinner than typical continental crust. **Map abbreviation field entry, "Ctn_{mob}"**
C9630	$Cvtn_{mob}$	Very thin orogenic/mobile belt crust *Thickness <10 km*	220 / 210 / 220	Mobile belt continental crust that is <10 km thick which is defined as hyper-extended crust by some authors. **Map abbreviation field entry, "Cvtn_{mob}"**

Figure 51. The fill color, RGB code, symbol ID code, and explanation for the composition of mapped continental orogenic (mobile belt) crustal facies. The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description). A "D" suffix is added where there is no thickness constraint.

these mobile zones was not clear, the pattern had been mapped back in the 1800s (Boue 1834; Reclus 1876).

An orogenic belt is therefore considered to be the zone of deformation rather than the total geographic area influenced by the collision. Thus, in this scheme, the Himalayas would be mapped as the orogenic belt, but the Tibetan plateau behind the front range would be considered thick continental crust. Within the Tibetan plateau are old orogenic belts that have been caught up within the uplift due to under-thrusting by the Greater India plate.

In terms of thickness, this is the state at the present-day.

6.1.5. Accreted complex crust

Accreted complexes comprise the amalgamation of island arcs and continental arcs, especially in oceanic settings (O-O, O-C). Consequently, they have more oceanic affinities than other collisional systems.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9826D	Ci_{acc}	Accretionary complex undiff. *Thickness undefined*	190 / 165 / 255	This represents a default categorization of 'accreted complex' crust where the thickness is not known. **Map abbreviation field entry, "Ci_{acc}"**
C9820	Ctk_{acc}	Thick Accretionary complex *Thickness >40 km*	185 / 150 / 255	Accretionary complex crust that is thicker than 'typical' continental crust **Map abbreviation field entry, "Ctk_{acc}"**
C9826	C_{acc}	Accretionary complex *Thickness 30-40 km*	190 / 165 / 255	This represents 'typical' continental crust thickness. **Map abbreviation field entry, "C_{acc}"**
C9827	Ctn_{acc}	Thin Accretionary complex *Thickness 10-30 km*	210 / 175 / 255	Accretionary complex crust that is thinner than typical continental crust. **Map abbreviation field entry, "Ctn_{acc}"**
C9828	$Cvtn_{acc}$	Very Thin Accretionary complex *Thickness <10 km*	230 / 190 / 255	Accretionary complex crust that is <10 km thick which is defined as hyper-extended crust by some authors. **Map abbreviation field entry, "Cvtn_{acc}"**

Figure 52. The fill color, RGB code, symbol ID code, and explanation for the composition of mapped accreted complex crustal facies. The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description). A "D" suffix is added where there is no thickness constraint.

6.1.6. Oceanic arc crust

Oceanic or intra-oceanic arcs are formed by the subduction of oceanic crust beneath the ocean crust of the interacting plate. Consequently, derived magmas are compositionally different from continental arc compositions because of differences in the parent material.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9840D	Ci_{oc}	Oceanic volcanic arc undiff. *Thickness undefined*	150 / 175 / 210	This represents a default categorization of 'oceanic volcanic arc crust where the thickness is not known. **Map abbreviation field entry, "Ci_{oc}"**
C9842	Ctk_{oc}	Thick oceanic volcanic arc *Thickness >40 km*	145 / 160 / 210	Island arc compositional crust with thickness > 40 km. **Map abbreviation field entry, "Ctk_{oc}"**
C9840	C_{oc}	Oceanic volcanic arc *Thickness 30-40 km*	150 / 175 / 210	This represents island arc crust that 'typical' continental crust thicknesses. **Map abbreviation field entry, "C_{oc}"**
C9845	Ctn_{oc}	Thin oceanic volcanic arc *Thickness 10-30 km*	180 / 185 / 215	Oceanic volcanic arc crust that is thinner than typical continental crust. **Map abbreviation field entry, "Ctn_{oc}"**
C9848	$Cvtn_{oc}$	Very thin oceanic volcanic arc *Thickness <10 km*	200 / 200 / 220	Oceanic arc crust that is <10 km thick which is defined as hyper-extended crust by some authors. **Map abbreviation field entry, "Cvtn_{oc}"**

Figure 53. The fill color, RGB code, symbol ID code, and explanation for the composition of mapped oceanic arc crustal facies. The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description). A "D" suffix is added where there is no thickness constraint.

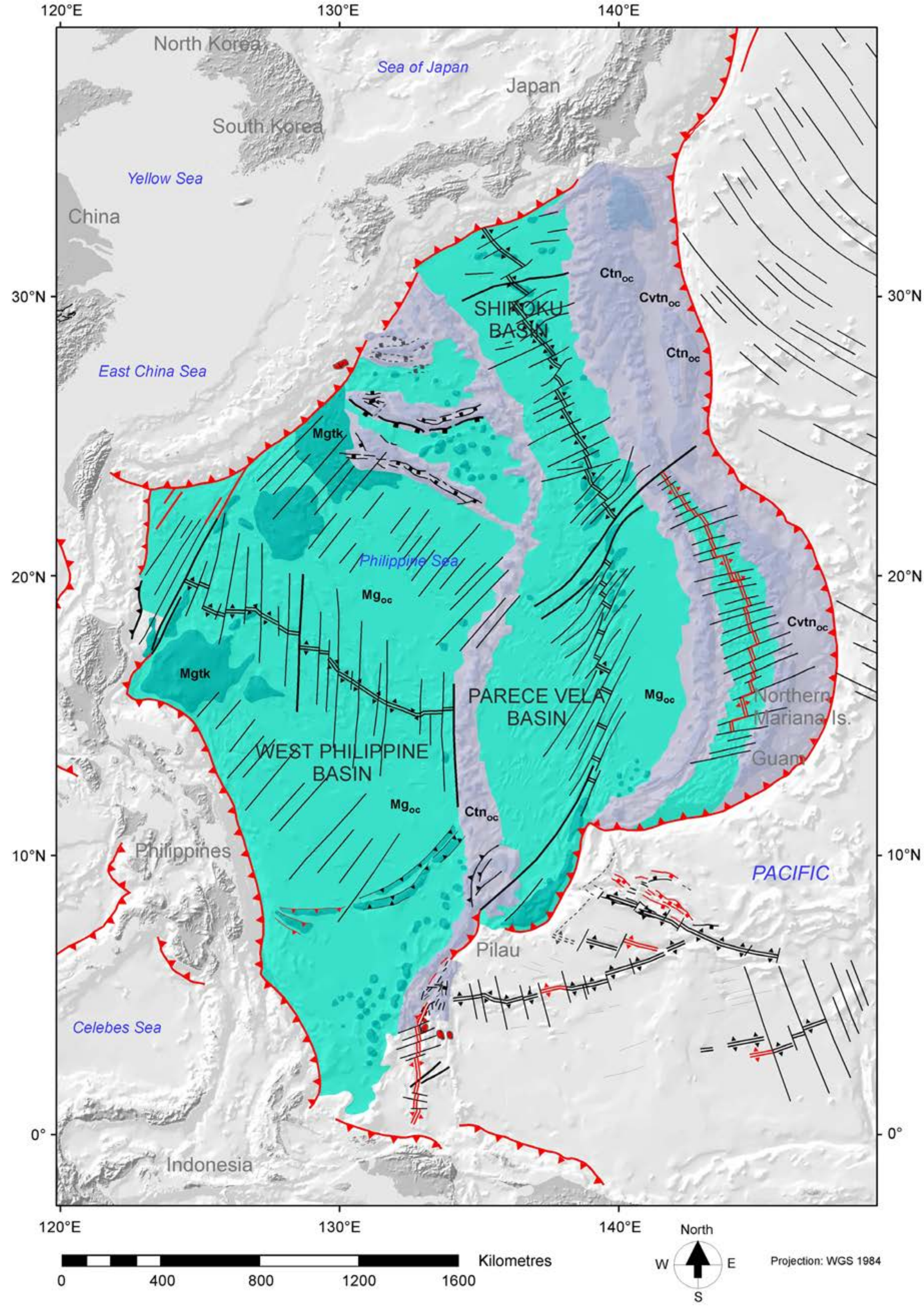


Figure 54. An example of the ocean (magmatic) and oceanic volcanic arc crustal facies applied to the Philippine Sea. This shows how the methodology can be applied to any tectonic setting and geography. This is from an active project on resource exploration of the marginal basins of the western Pacific.

6.2. 'Mixed' Crustal Types Resulting from Magmatic Addition

Mixed crustal compositions include those areas of continental crust that are highly intruded by mantle material (magmatic addition). The bulk composition consists of a large proportion of mafic and andesitic/felsic components.

6.2.1. Mixed continental crust with magmatic addition

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9232D	Ci_{mg}	Continental crust undiff. with magmatic addition *Thickness undefined*	0 / 190 / 180 255 / 225 / 255	This represents a default categorization of 'mixed' crust where the thickness is not known. **Map abbreviation field entry, "Ci_{mg}"**
C9230	C_{mg}	Continental crust with magmatic addition *Thickness 30-40 km*	0 / 190 / 180 255 / 225 / 255	This represents a combined thickness consistent with 'typical' continental crust. Diagonal pattern with two colors. **Map abbreviation field entry, "C_{mg}"**
C9232	Ctn_{mg}	Thin continental crust with magmatic addition *Thickness 10-30 km*	0 / 190 / 180 255 / 237 / 255	This represents a combined thickness consistent with thin continental crust. Diagonal pattern with two colors. **Map abbreviation field entry, "Ctn_{mg}"**
C9234	$Cvtn_{mg}$	Very thin continental crust with magmatic addition *Thickness <10 km*	50 / 235 / 210 255 / 240 / 240	This represents a combined thickness consistent with very thin continental crust. Diagonal pattern with two colors. **Map abbreviation field entry, "Cvtn_{mg}"**

Figure 55. The fill color, RGB code, symbol ID code, and explanation for the composition of mapped mixed continental with magmatic addition crustal facies. The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description). A "D" suffix is added where there is no thickness constraint.

6.2.2. Mixed mobile belt/orogenic crust with magmatic addition

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9252D	Ci_{mob+mg}	Mixed magmatic-orogenic crust *Thickness undefined*	0 / 170 / 170 194 / 158 / 215	This represents a default categorization of 'mixed' orogenic and magmatic crust where the thickness is not known. **Map abbreviation field entry, "Ci_{mob+mg}"**
C9250	C_{mob+mg}	Mixed magmatic-orogenic crust *Thickness 30-40 km*	0 / 170 / 170 194 / 158 / 215	This represents a combined thickness consistent with orogenic continental crust. Diagonal pattern with two colors. **Map abbreviation field entry, "C_{mob+mg}"**
C9252	Ctn_{mob+mg}	Thin mixed magmatic-orogenic crust *Thickness 10-30 km*	0 / 190 / 180 210 / 187 / 220	This represents a combined thickness consistent with thin orogenic crust. Diagonal pattern with two colors. **Map abbreviation field entry, "Ctn_{mob+mg}"**
C9254	$Cvtn_{mob+mg}$	Very thin mixed magmatic-orogenic crust *Thickness <10 km*	50 / 235 / 210 220 / 210 / 220	This represents a combined thickness consistent with very thin orogenic crust. Diagonal pattern with two colors. **Map abbreviation field entry, "Cvtn_{mob+mg}"**

Figure 56. The fill color, RGB code, symbol ID code, and explanation for the composition of mapped mixed orogenic (mobile belt) continental crust with magmatic addition crustal facies. The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description). A "D" suffix is added where there is no thickness constraint.

6.3. Magmatic Crustal Types

Magmatic crust includes crustal areas that are entirely juvenile – formed from differentiation and expulsion from the mantle.

6.3.1. Magmatic crust

In our original classification, we differentiated graphically between "magmatic crust" and "oceanic magmatic" crust (Penrose-type). Although our research suggests that this differentiation is significant, in our current symbol set, both magmatic and oceanic magmatic have the same color fill. However, a different symbol ID is assigned to each. The reasons for maintaining a difference in the database reflect a difference in the results of the gravity analyses we found. Interestingly, in many areas, such as the Gulf of Mexico, the 'anomalous' ocean crust (magmatic crust in this classification) corresponds to what other authors call "proto-oceanic." This is under investigation.

Thickened magmatic crust, in this classification, refers to areas (especially oceanic areas) where the magmatic material has been added by subsequent volcanism or intrusion. This new material is almost exclusively comprised of basic volcanics and associated intrusions, and includes submarine plateaus, such as the Agulhas and Ontong Java plateaus, seamounts, and other positive features on the deep ocean floor formed from igneous activity. The addition by magmatism is classified as "magmatic" rather than "magmatic oceanic" because the composition and especially crustal structure are different from 'typical' "Penrose-type" ocean crust.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9035D	Mgi	Magmatic crust indet. *Thickness undefined*	50 / 235 / 210	This represents a default categorization of magmatic crust where the thickness is not known and the composition and structure is not demonstrably "Penrose-type" ocean crust. **Map abbreviation field entry, "Mgi"**
C9030	Mgvtk	Very thick magmatic crust *Thickness >20 km*	25 / 150 / 165	Represents very thick magmatic crust (>20 km). Typical of major 'oceanic' plateaus which have been extruded through "Penrose-type" ocean crust. **Map abbreviation field entry, "Mgvtk"**
C9020	Mgtk	Thick magmatic crust *Thickness 7-20 km*	0 / 190 / 180	Represents magmatic crust that is c.7-20 km thick where the composition and structure is not demonstrably "Penrose-type" ocean crust. Typical of seamounts and some plateaus. **Map abbreviation field entry, "Mgtk"**
C9035	Mg	Magmatic crust *Thickness 5-7 km*	50 / 235 / 210	Represents magmatic crust that is c.5-7 km thick consistent with typical "Penrose-type" ocean crustal thicknesses. but where the composition and structure is not demonstrably "Penrose-type" ocean crust. This includes 'anomalous' ocean crust identified using gravity analysis (see text). **Map abbreviation field entry, "Mg"**
C9040	Mgtn	Thin magmatic crust *Thickness <5 km*	130 / 235 / 225	Represents thin (<5 km) magmatic crust where the composition and structure is not demonstrably "Penrose-type" ocean crust. **Map abbreviation field entry, "Mgtn"**

Figure 57. The fill color, RGB code, symbol ID code, and explanation for the composition of mapped magmatic crustal facies. The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description). A "D" suffix is added where there is no thickness constraint.

6.3.2. Magmatic 'ocean' (Penrose-type) crust

Ocean crust forms at spreading ridges through decompression melting of upwelled mantle, which results in a dominantly basaltic composition (MORB) with an average density of about 2.9 g/cm3 (White and Klein 2014). This is fundamentally different from the typical granitic composition of continental crust. Ocean crust is destroyed at subduction zones

In section, oceanic crust comprises a series of layers identified from ophiolitic sections onshore and, for the upper layers, deep-sea drilling. In typical "Penrose-type" the crust ranges in thickness from 5-7km (average c.6.5km), with a relatively homogeneous compositional structure deduced from deep sea drilling, seismic studies, and preserved onshore examples as ophiolites. The uppermost igneous layer underling the sedimentary pile consists of c.800-1000m of basaltic lava flows (including pillow lavas) erupted at, or around the ridge. This layer is underlain by 300-1200m of sheeted doleritic (diabase) dykes and basaltic lavas, beneath which is the bulk of the ocean crust comprising 3.5-5.5 km of gabbroic intrusives. In ophiolite sections, these three layers sit above a layer, or layers, of peridotite that may represent the top of the mantle rather than the crust. This is an average section, and studies have shown variations in the ocean crust. Variations due to differential melting and spreading rates can occur and may result in a gravity and bathymetric expression (the ridge-parallel lineaments captured in the structural elements database). The formation of new ocean crust at spreading ridges is a central tenet of

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9000D	Mgi_{oc}	Magmatic, Penrose-type ocean crust indet. *Thickness undefined*	50 / 235 / 210	This represents a default categorization of magmatic crust with typical ocean (Penrose-type) composition and structure, but where the thickness is not known. **Map abbreviation field entry, "Mgi_{oc}"**
C9008	$Mgvtk_{oc}$	Very thick magmatic, Penrose-type ocean crust *Thickness >20 km*	25 / 150 / 165	Represents very thick magmatic crust, but which comprises typical ocean (Penrose-type) composition and structure. Usually this will be through tectonic thickening rather than extrusion, which is categorized as magmatic. **Map abbreviation field entry, "Mgvtk_{oc}"**
C9010	$Mgtk_{oc}$	Thick magmatic, Penrose-type ocean crust *Thickness 7-20 km*	0 / 190 / 180	Represents thicker than normal ocean magmatic crust (Penrose-type composition and structure). Usually this will be through tectonic thickening rather than extrusion, which is categorized as magmatic. **Map abbreviation field entry, "Mgtk_{oc}"**
C9000	Mg_{oc}	Magmatic, Penrose-type ocean crust *Thickness 5-7 km*	50 / 235 / 210	Represents 'typical' or 'normal' Penrose-type ocean crust (composition and structure). **Map abbreviation field entry, "Ctn_{oc}"**
C9015	$Mgtn_{oc}$	Thin magmatic, Penrose-type ocean crust *Thickness <5 km*	130 / 235 / 225	Represents thin magmatic crust, but which comprises typical ocean (Penrose-type) composition and structure. Usually this will be through tectonic thinning of ocean crust. **Map abbreviation field entry, "Cvtn_{oc}"**

Figure 58. The fill color, RGB code, symbol ID code, and explanation for the composition of mapped magmatic crustal facies formed at spreading ridges and typified by typical Penrose-type compositions and layering. The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description). A "D" suffix is added where there is no thickness constraint.

tectonics, dating back to the original hypothesis of Harry Hess (1962).

Thickened ocean crust, in this classification, refers to areas of ocean crust where the material has been added largely by tectonics. The addition by magmatism would be classified as "magmatic" because the composition and especially crustal structure would be different from typical "Penrose-type" ocean crust.

See the review of White and Klein (2014) for further information.

6.4. Mantle

Exhumed mantle can occur in zones of hyper-extension in which the underlying mantle is exposed at the surface as the footwall to shallow detachment faults. In our classification, we have differentiated between serpentinized exhumed mantle and mantle because of the major density and volume differences between the two. Serpentinization results in a density change from 3.3 gcm-3 to c.2.7 gcm-3 and a volume increase of 20-40%, concomitant with a significant release of heat (+260C) that can have important effects on hydrothermal systems, especially at spreading ridges.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9270	M	Mantle *Thickness unspecified*	158 / 212 / 158	The map representation of areas of exhumed mantle where there is no documented evidence of serpentinization. By definition these are areas where the crustal thickness is zero. **Map abbreviation field entry, "M"**
C9260	M_{sp}	Serpentinized mantle *Thickness unspecified*	158 / 212 / 158	The map representation of areas of exhumed, serpentinized mantle. By definition these are areas where the crustal thickness is zero. **Map abbreviation field entry, "M_{sp}"**

Figure 59. The fill color, RGB code, symbol ID code, and explanation for the composition of mapped mantle – this represents areas of exhumed mantle. The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description).

6.5. Legend for 'Traditional' Crustal Facies Assemblages

In this section, we provide a crustal classification that matches many of the more commonly published margin tectonic maps. These mix processes and composition. They comprise broad zones, including areas of uncertainty on passive margins frequently labeled as "transitional" crust, which lie between regions of demonstrably ocean crust and demonstrable continental crust (Figure 60). The inclusion of this in our databases provides continuity with the existing literature and a means of comparing the different classification methods.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
CF9800	Col	Collisional	220 / 120 / 255	This represents a default categorization of 'mobile belt' crust where the thickness is not known. **Map abbreviation field entry, "Col"**
CF9600	C	Anorogenic	255 / 220 / 255	Associations of continental crustal types representing areas that have not been affected by changes due to thermo-mechanical activity in the last phase of activity affecting contiguous areas. **Map abbreviation field entry, "C"**
CF9400	E	Extensional	255 / 237 / 255	Crustal type associations (composition and thickness) caught up within areas in which the latest phase of activity is dominated by extensional processes, but in which compositions are dominantly continental. **Map abbreviation field entry, "E"**
CF9420	En	Extensional non-volcanic	255 / 237 / 255	Extension dominated margin crustal facies associations with no major volcanic addition. **Map abbreviation field entry, "En"**
CF9440	Ev	Extensional Volcanic	255 / 237 / 255	Extension dominated margin crustal associations with major volcanic addition. **Map abbreviation field entry, "Ev"**
CF9300	SS	Strike-slip	253 / 169 / 201	Crust modified or formed in response to strike-slip activity. **Map abbreviation field entry, "SS"**
CF9200	T	Transitional	255 / 206 / 109	Crustal associations typifying areas in what has been traditionally referred to as the "transitional" zone in extensional settings. **Map abbreviation field entry, "T"**
CF9000	O	Oceanic	0 / 220 / 210	Associations of ocean crust. **Map abbreviation field entry, "O**

Figure 60. The fill color, RGB code, symbol ID code, and explanation for a crustal classification based on traditional divisions, including areas on a passive margin that are neither clearly 'oceanic' nor 'continental' and which have frequently been labeled as "transitional." The format, in this case, has been modified from crustal facies as follows: "CF" + "####." The four-digit number value differentiates the crustal type (see description).

6.6. Crustal Processes

The inclusion of crustal processes is designed to ensure continuity with well-known, published passive margin classification schemes, based principally on the work of Manatschal and his group (Manatschal et al. 2010; Péron-Pinvidic et al. 2015). This divides margins into four zones that relate to specific processes of extension (Péron-Pinvidic et al. 2015):

- **the proximal zone,** formed of fault-bounded basins with normal faults soling at mid-crustal levels. The dominant deformational process is stretching, which can be influenced by inheritance.
- **the necking zone,** represented by a localized area in which the continental crust thins to less than 10 km. The dominant deformational process is thinning.
- **the distal zone,** formed of hyper-extended crust (< 10 km thick). Formed by stretching; Manatshal calls the process "hyperextension"
- **the outer zone**, equated to the OCT (Ocean-Continental transitional zone) in Manatschal et al. (2010), and affected by the processes of exhumation and 'oceanization.'

ID	SYMBOL	DESCRIPTION	RGB	NOTES
C9910	P	Proximal (stretching)	255 / 230 / 255	Map abbreviation field entry, "P"
C9920	N	Necking (thinning)	255 / 220 / 70	Map abbreviation field entry, "N"
C9930	D	Distal (hyper-extension)	250 / 254 / 72	Map abbreviation field entry, "D"
C9940	O	Outer (exhumation-oceanization)	171 / 255 / 185	Map abbreviation field entry, "O"

Figure 61. The RGB colours, map abbreviations, and explanations associated symbol codes for differentiating crustal processes using the definitions presented in Péron-Pinvidic and Manatschal (Manatschal, 2012; Péron-Pinvidic and Manatschal, 2010). The format for all crustal facies symbol codes is as follows: "C" + "####." The four-digit number value differentiates the crustal facies (see description).

Hercynian deformation of early Paleozoic sediments in the Catalan Frontal Range, Barcelona. This is a related part of the Pyrenean story that must be considered as we look at the broader regional context

7. Geodynamics

The Geodynamics databases are digital, global databases showing the geometry and nature of the last thermo-mechanical event to affect the Earth's lithosphere. These include the present-day geodynamic state, which provides analogs and a basis for investigating the interaction of geodynamics with crustal architecture and landscape dynamics. The geodynamic state changes through time. Therefore, geodynamics databases must be constructed for each mapped timeslice (paleogeography). These databases are designed to provide the information needed for modeling basin evolution, plate kinematics, paleogeographic reconstruction, and paleolandscape dynamics.

The landscape on which the geological record is built at any point in the past is a consequence of the balance between those forces that uplift the surface and those responsible for decreasing it. One of the major forcings on both sides of that equation is tectonics, combining physical, mechanical processes and those due to thermal changes.

These thermo-mechanical processes act on the existing lithosphere and, depending on the nature of

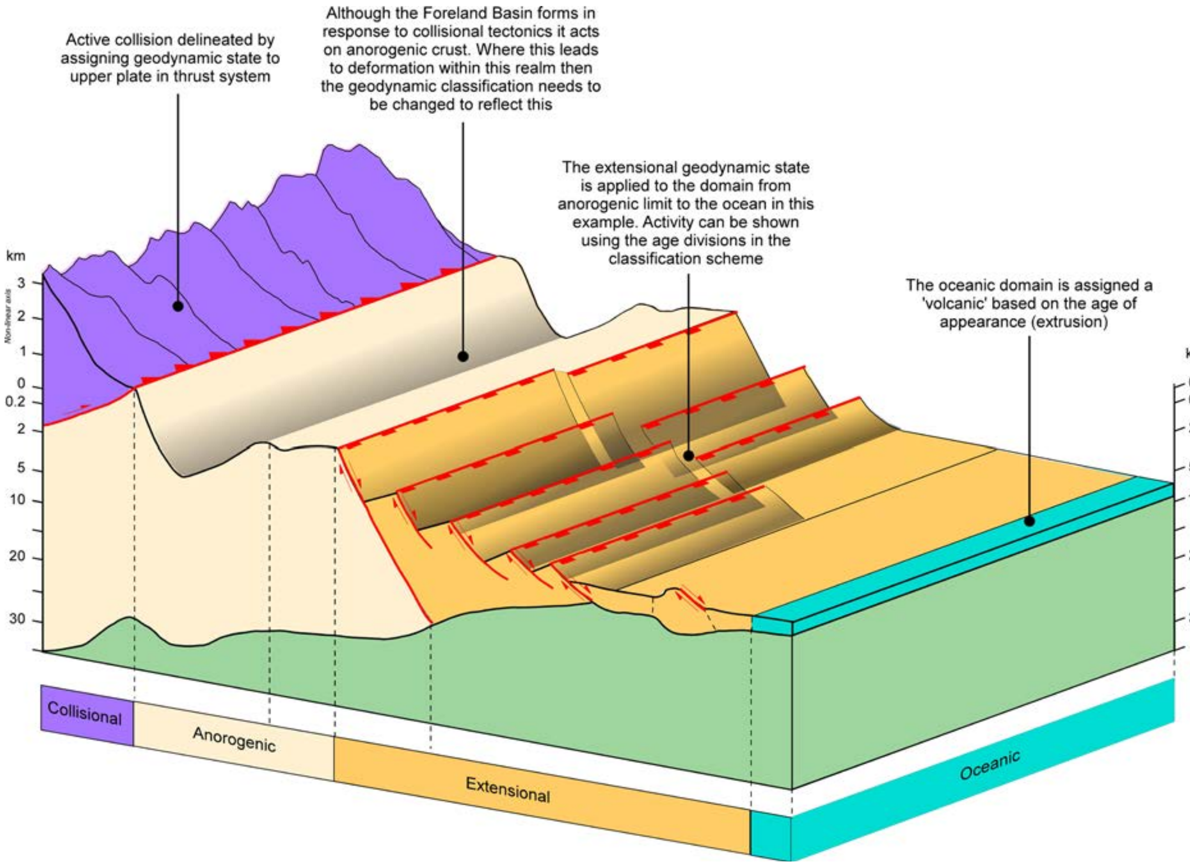


Figure 62. A block diagram showing the expression of geodynamics on the landscape represented in Figure 4. This is the thermo-mechanical action that is either active (in progress) at the time of mapped time slice/interval, or where it is not contemporary activity, then it is the representation of the last thermo-mechanical activity to affect that part of the crust.

the contemporary 'crustal' architecture, dictate how the landscape responds. This process is represented by mapping the age and the nature of the last thermo-mechanical event with respect to the palaeogeographic timeslice being reconstructed. This method was first discussed in Markwick and Valdes as tectonophysiography (Markwick and Valdes 2004) with regards to defining areas above 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 better represent the decay of landscapes (Tucker and Slingerland 1994; Van der Beek and Braun 1998; Pazzaglia 2003; Whipple and Meade 2004; Campanile et al. 2007) 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). The resulting highs and lows (tectonophysiography), together with sea-level and sediment flux, determine local and regional base-level, and therefore ultimately, accommodation space and the geometry of sedimentary basins.

Understanding this interaction is critical in reconstructing paleogeography and any analyses that derive from this, for example, climate modeling, source-to-sink analysis, depositional, and lithofacies modeling. They are also key in understanding basin evolution and dynamics, which in turn dictate heaty flow and maturation in petroleum systems analysis.

The problem is that this interaction and its consequences are complex.

To mitigate this complexity, we have separated the thermo-mechanical information from the crustal architecture and depositional systems. The difference between crustal facies and geodynamics in section is shown in Figure 63.

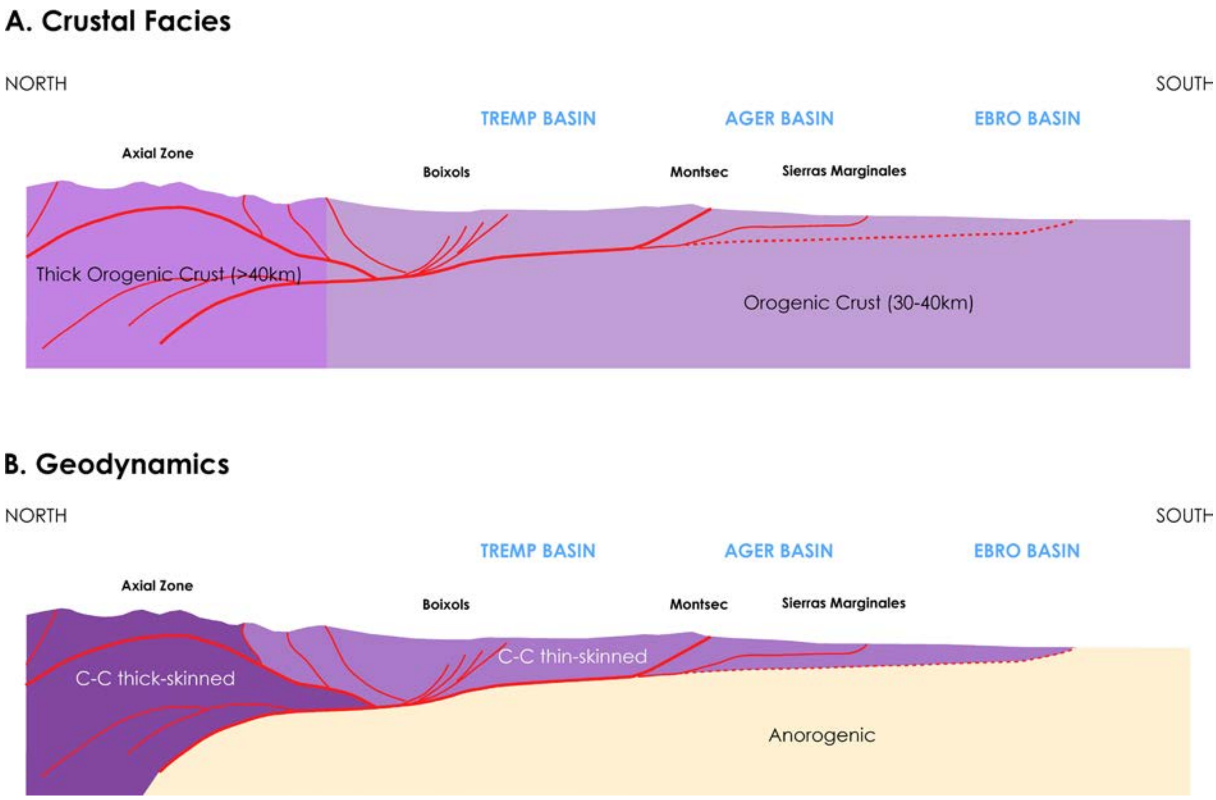


Figure 63. The difference between the crustal facies definition, which describes the entire crustal section at a point (A), and the geodynamics acting on that crust (B). This example is for the south-central Pyrenees.

In the Geodynamics Database, the last thermo-mechanical activity is classified according to the age relative to the mapped timeslice, and the dominant stress field acting on the crust.

Where the thermo-mechanical forcing is active at the time of the mapped timeslice, then the fill is solid fill. Colors have been chosen to be consistent with existing publications where possible. Diagonal lines colored with

Millions of years (Myr) prior to age represented by map

0.01 5 10 25 50 75 100 150 200 300 Myr

No thermo-mechanical activity <300 Myr before map

			Active	Inactive ('relict')										Anorogenic
Horizontal stress field dominant	Compression, undiff.	C	T2000	T2001	T2002	T2003	T2004	T2005	T2006	T2007	T2008	T2009	A	T1000
	C-C, undiff	CC	T2100	T2101	T2102	T2103	T2104	T2105	T2106	T2107	T2108	T2109	A	T1000
	C-C, thick-skinned	CCtk	T2110	T2111	T2112	T2113	T2114	T2115	T2116	T2117	T2118	T2119	A	T1000
	C-C, thin-skinned	CCtn	T2120	T2121	T2122	T2123	T2124	T2125	T2126	T2127	T2128	T2129	A	T1000
	C-O, undiff.	CO	T2200	T2201	T2202	T2203	T2204	T2205	T2206	T2207	T2208	T2209	A	T1000
	C-O, thick-skinned	COtk	T2210	T2211	T2212	T2213	T2214	T2215	T2216	T2217	T2218	T2219	A	T1000
	C-O, thin-skinned	COtn	T2220	T2221	T2222	T2223	T2224	T2225	T2226	T2227	T2228	T2229	A	T1000
	O-O, undiff.	OO	T2300	T2301	T2302	T2303	T2304	T2305	T2306	T2307	T2308	T2309	A	T1000

0.01 5 10 25 50 75 100 150 200 300 Myr

Vertical stress field dominant	Extension, undiff.	E	T3000	T3001	T3002	T3003	T3004	T3005	T3006	T3007	T3008	T3009	A	T1000
	Sag	S	T5000	T5001	T5002	T5003	T5004	T5005	T5006	T5007	T5008	T5009	A	T1000
	Mantle	M	T6000	T6001	T6002	T6003	T6004	T6005	T6006	T6007	T6008	T6009	A	T1000
	Flexure	F	T6500	T6501	T6502	T6503	T6504	T6505	T6506	T6507	T6508	T6509	A	T1000
	Isostatic	I	T7000	T7001	T7002	T7003	T7004	T7005	T7006	T7007	T7008	T7009	A	T1000
	Volcanic	Volc	T8000	T8001	T8002	T8003	T8004	T8005	T8006	T8007	T8008	T8009	A	T1000

Figure 64. Fill colors and patterns with their associated symbol codes for differentiating the thermo-mechanical state of the crust, which is used to define the dynamics of the landscapes reconstructed as part of the palaeogeographic mapping. The patterns reflect the decreasing influence of the geodynamic forcing with time. In our classification by 300 myr after the cessation of activity, the crustal response in the landscape is effectively anorogenic. However, in reality, the crust's response to these geodynamic forcings varies hugely. These categories are explained in detail in the following sections.

the symbol for anorogenic land are added with increasing widths as the time since activity increases (Figure 64).

The geodynamic state is mapped for the time in the past represented by the map. Consequently, the thermo-mechanical history can be reconstructed.

All geodynamic symbol codes are prefixed with the letter "T", for thermo-mechanical.

7.1. Anorogenic Areas

Anorogenic land is considered to be the geodynamic state for which the last thermo-mechanical activity was so far in the past that the crust and its related landscape expression would have reached a 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 the crust in isostatic equilibrium with no tectonic forces acting on it.

In reality, the point at which any landscape reaches 'equilibrium,' allowing for all the caveats about what we mean by 'equilibrium,' will vary according to the type of thermo-mechanical event, bedrock, vegetation cover, and climate evolution. There is also the added complication of dynamic topography (Burgess and Gurnis 1995; Lithgow-Bertelloni and Silver 1998) due to mantle processes that have not been recognized (there is a mapping symbol for this where it can be identified from the geological record).

The use here of 300 million years as a cut-off for the onset of 'anorogenic' conditions is a convenient break, but 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.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
T1000	A	Anorogenic	255 / 240 / 210	Anorogenic applies to any areas that have not been subjected to geodynamic forcings for at least 300 Ma. **Map abbreviation field entry, "A"**

Figure 65. The RGB colors, map abbreviations, and explanations for anorogenic areas.

7.2. Mechanical and Thermo-mechanical

Mechanical processes are primarily limited to near the surface of the Earth. In reality, most tectonic activity has a thermal and mechanical component. The Dominant Process field TM_PROCESS) allows the user some flexibility to differentiate between the extent of thermal and mechanical drivers. For example, an incipient rift, such as those seen forming on the Mozambique lowlands today, does not have a deep crustal extent and is dominated by mechanical processes. As rifts develop, faults and effects propagate deeper into the crust and start to have a thermal effect, usually expressed by lithospheric thinning and the accompanying development of rift shoulders (thermo-mechanical)—similarly, passive margins transition from thermo-mechanical thermal processes through time.

7.2.1. Compressional

ID	SYMBOL	DESCRIPTION	RGB	NOTES
T2000	C	Compression, undiff.	215 / 195 / 230	Applies to areas where the dominant stress field is compressional, but there is no information as to what the interacting bodies are. **Map abbreviation field entry, “C”**
T2100	C-C	Continent-Continent, undiff.	160 / 110 / 190	Used where there is clear evidence that the compression is due to the interaction of two continental bodies/plates. **Map abbreviation field entry, “C-C”**
T2110	C-C$_{thick}$	Continent-Continent, thick-skinned	130 / 70 / 160	Used where the interaction affects the whole crustal column, e.g. Axial Zone, Pyrenees **Map abbreviation field entry, “C-C_{thick}””**
T2120	C-C$_{thin}$	Continent-Continent, thin-skinned	170 / 120 / 200	Used where the geodynamic processes affect layers within the crust due to decollement, e.g. frontal thrust sheets in the Pyrenees. **Map abbreviation field entry, “C-C_{thin}””**
T2200	C-O	Continent-Ocean, undiff.	190 / 160 / 250	Used where there is evidence that the compression is due to the interaction of a continental and ocean block / plate. **Map abbreviation field entry, “C-O”**
T2210	C-O$_{thick}$	Continent-Ocean, thick-skinned	175 / 135 / 250	Ocean-continental geodynamics that affects the whole crust, e.g. parts of the central Andes **Map abbreviation field entry, “C-O_{thick}””**
T2220	C-O$_{thin}$	Continent-Ocean, thin-skinned	205 / 180 / 250	Ocean-continental geodynamics that affects only the upper levels of the crust due to decollement on a surface(s), e.g. the Andean fold and thrust belt **Map abbreviation field entry, “C-O_{thin}””**
T2300	O-O	Ocean-Ocean, undiff.	195 / 180 / 250	Geodynamics due to the interaction of two ocean blocks / plates. **Map abbreviation field entry, “O-O**

Figure 66. The RGB colors, map abbreviations, and explanations for active compressional areas.

7.2.2. Extensional

ID	SYMBOL	DESCRIPTION	RGB	NOTES
T3000	Ext	Extension, undiff.	255 / 240 / 210	Extensional geodynamics is here represented by a single classification, although there is a great variety of expressions of extension. **Map abbreviation field entry, “Ext”**

Figure 67. The RGB colors, map abbreviations, and explanations for active extensional areas.

7.2.3. Extensional – Thermal relaxation

ID	SYMBOL	DESCRIPTION	RGB	NOTES
T5000	Sag	'Sag'	255 / 222 / 155	This refers to subsidence of a landscape due to relaxation of the forces supporting it. On a passive margin this is distinct from "Extensional" because the margin is not actively extending but responding to the consequences of extension. The allocation of this category to traditional "sag basins" is more problematic because many such basins (viz., Cuvette Centrale" may reflect mantle processes (dynamic topography), which are then categorized under "Mantle" in this classification **Map abbreviation field entry, "Sag"**

Figure 68. The RGB colors, map abbreviations, and explanations for active sag areas.

7.3. Mantle

ID	SYMBOL	DESCRIPTION	RGB	NOTES
T8000	M	'Sag'	245 / 75 / 0	The effects of mantle processes on the crust and lithosphere have generally been assumed to be long-wavelength, but work by Rowley et al (2013) has indicated that affects can operate on a variety of scales. To be sure that the effects are due to mantle processes requires additional information, either from modelling to provide hypotheses or indications of volcanism. **Map abbreviation field entry, "M"**

Figure 69. The RGB colors, map abbreviations, and explanations for mantle-related uplift areas ("dynamic topography").

7.4. Flexure

ID	SYMBOL	DESCRIPTION	RGB	NOTES
T6000	Fx	Flexure, undiff.	255 / 200 / 170	Flexure is usually due to loading effects (negative and positive). This usually requires calculation, but in some cases, such as along margins with major sediment influx it can be estimated. The impact inboard will depend on the Te (elastic thickness) of the crust involved. **Map abbreviation field entry, "Fx"**

Figure 70. The RGB colors, map abbreviations, and explanations for active flexural areas.

7.5. Isostatic

ID	SYMBOL	DESCRIPTION	RGB	NOTES
T6500	Iso	Isostatic, undiff.	255 / 220 / 205	Isostacy and flexure are closely related in most calculations. In the past isostacy has been calculated separately on a grid cell by cell basis. Like flexure, isostacy is best calculated, but can be assumed where the geological history indicates a load removed or added, e.g. ice sheets. **Map abbreviation field entry, "Iso"**

Figure 71. The RGB colors, map abbreviations, and explanations for active isostatic uplift areas.

7.6. Volcanic

ID	SYMBOL	DESCRIPTION	RGB	NOTES
T7000	Volc	Volcanic, undiff.	200 / 50 / 0	This applies to activity that is related directly to volcanism. In many cases the volcanism can be related to mantle or other tectonic processes. **Map abbreviation field entry, "Volc"**

Figure 72. The RGB colors, map abbreviations, and explanations for active volcanically driven uplift areas.

7.7. Vertical Undifferentiated

ID	SYMBOL	DESCRIPTION	RGB	NOTES
T5000	V	Vertical, undiff.	255 / 165 / 125	In some cases, the uplift, especially long-wavelength uplift is not clearly due to horizontal forcing, e.g. the uplift of southern Africa in the Cenozoic. This can be due to mantle processes (dynamic topography), isostatic and flexural rebound, and volcanism. Where the exact process is not known, which may be initially without detailed investigation, then the "Vertical, undiff.," allocation is a useful start. **Map abbreviation field entry, "V"**

Figure 73. The RGB colors, map abbreviations, and explanations for anorogenic areas.

7.8. Relict Thermo-mechanical State

To show the age of the last thermomechanical event relative to the palaeogeographic map timeslice, use the following legend. As the duration of time following the activity increases, more of the fill is represented in our symbol set by the anorogenic fill color (255/240/210).

ID (FORM)	EXAMPLE SYMBOL	DESCRIPTION	LINE WEIGHT	OFFSET
Txxx0	T2100	Active	n/a	n/a
Txxx1	T2101	Relict 0.01 – 5 myr	1	Angle: 45° Offset: 0 Separation: 10
Txxx2	T2102	Relict 5 – 10 myr	2	Angle: 45° Offset: 0 Separation: 10
Txxx3	T2103	Relict 10 – 25 myr	3	Angle: 45° Offset: 0 Separation: 10
Txxx4	T2104	Relict 25 – 50 myr	4	Angle: 45° Offset: 0 Separation: 10
Txxx5	T2105	Relict 50 – 75 myr	5	Angle: 45° Offset: 0 Separation: 10
Txxx6	T2106	Relict 75 – 100 myr	6	Angle: 45° Offset: 0 Separation: 10
Txxx7	T2107	Relict 100 – 150 myr	7	Angle: 45° Offset: 0 Separation: 10
Txxx8	T2108	Relict 150 – 200 myr	8	Angle: 45° Offset: 0 Separation: 10
Txxx9	T2109	Relict 200 – 300 myr	9	Angle: 45° Offset: 0 Separation: 10
T1000	T1000	Anorogenic	n/a	n/a

Figure 74. RGB codes for fill patterns and diagonal line weighting used to show the age of the relict states of each geodynamic forcing relative to the cessation of that forcing. For each setting the increase in age after the activity is shown by the increasing width of the anorogenic symbology (line weight value; the background color is that for the active geodynamic symbol color).

Folded Early Eocene distal turbidites at Broto, central Pyrenees.

Vertical Campanian turbidites of the Vallcarga Formation unconformably overlain by Late Eocene conglomerates. Tremp Basin, central Pyrenees, Spain.

8. Bedrock Geology

The Bedrock Geology databases describe the rock at the surface of the Earth at any specified time in the geological past. The default database is the global distribution of bedrock geology in the present-day. These databases are used in a range of applications, including as an input to building palaeogeographies, source-to-sink analysis, and mineral (placer) exploration.

Bedrock geology represents the outcrop of solid rock at the surface of the Earth as distinct from superficial, unconsolidated material such as soil (the weathering products of the bedrock). It is synonymous with the term "solid" geology in the older literature. Since much of the Quaternary record is unconsolidated material, this is usually not included in bedrock, but this is equivocal and depends on the questions being asked. For source-to-sink analysis, unconsolidated material and paleosols can be very important. In this database, we have included the Quaternary.

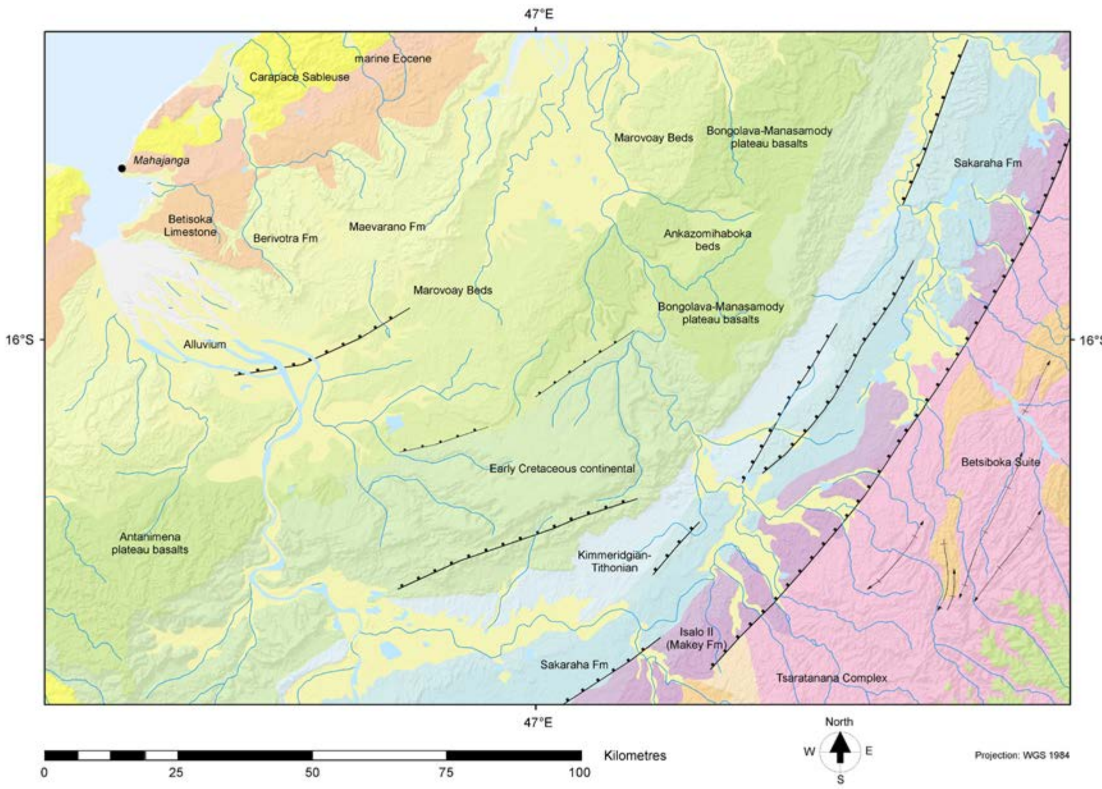


Figure 75. Bedrock with unit names for part of the Majunga Basin, Madagascar. The symbology represents the stratigraphic age colors from the ICS 2022 timescale for the bottom age of each mapped unit. The bedrock database in this example uses a 50% transparency to enable the topography to be seen – the topography is represented by a hillshade calculated from the SRTM3 DEM. The Bedrock database includes information on stratigraphic nomenclature for the mapped unit, depositional environments, and lithologies for the top and bottom of each unit, as well as the default audit information. This particular example is from our Madagascar digital atlas.

8.1.1 Quaternary

ERA	SYSTEM PERIOD	SERIES EPOCH		STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Cenozoic (Cz) 242 / 249 / 29	Quaternary (Q) 242 / 249 / 127	Holocene (Hol) 254 / 235 / 210		**Recent** 254 / 242 / 236	Rec	0.0117	0	0	0
		Pleistocene (Ple) 255 / 242 / 174	Late	**Upper Pleistocene** 255 / 242 / 211	Ple4	0.129	0.0117	-52	+29.8
			Middle	**Chibanian** 255 / 242 / 199	Chi	0.774	0.129		
			Early	**Calabrian** 255 / 242 / 186	Cal	1.800	0.774		
				Gelasian 255 / 237 / 179	Gel	2.58	1.800	-43.3	+28.3

Figure 76. Ages, RGB colors, and abbreviations for the Quaternary. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level).

8.1.2. Neogene

ERA	SYSTEM PERIOD	SERIES EPOCH		STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Cenozoic (Cz) 242 / 249 / 29	Neogene (Ng) 255 / 230 / 25	Pliocene (Plio) 255 / 255 / 153	Late 255 / 242 / 205	**Piacenzian** 255 / 255 / 191	Pia	3.600	2.58	-46.8	+63.5
			Early 255 / 242 / 195	**Zanclean** 255 / 255 / 179	Zan	5.333	3.600	-10	+88.7
		Miocene (Mio) 255 / 255 / 0	Late 255 / 236 / 140	**Messinian** 255 / 255 / 115	Mes	7.246	5.333	-16.6	+41.8
				Tortonian 255 / 255 / 102	Tor	11.63	7.246	-11.9	+31.4
			Middle 255 / 236 / 115	**Serravallian** 255 / 255 / 89	Srv	13.82	11.63	-47.8	+143.2
				Langhian 255 / 255 / 77	Lan	15.97	13.82	+73.5	+146.2
			Early 255 / 236 / 85	**Burdigalian** 255 / 255 / 65	Bur	20.44	15.97	+59.6	+139.2
				Aquitanian 255 / 255 / 51	Aqt	23.03	20.44	+92.4	+129.3

Figure 77. Ages, RGB colors, and abbreviations for the Neogene. The ages (BTM, age at base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level).

8.1. Mapping Legend

The principle symbology scheme used for bedrock is by age colored using the 2022 ICS RGB colors (https://stratigraphy.org/chart). The ICS colors are calculated from the CMYK colors composed by the CGMW/CCGM.

In our mapping, the default attribution uses the oldest age in millions of years as the basis for which age color to allocate. But this can be changed as needed. Lithological designations can follow the symbology schemes described in the Environments Database (see section 11).

In this legend, we have included the minimum and maximum global sea-level relative to the present-day calculated from Haq et al. (1987) following the rationale discussed in Rowley and Markwick (1992) and Markwick and Rowley (1998). This information is used as part of the paleogeographic mapping workflow (Markwick 2019) hence its inclusion here.

8.1.3. Paleogene

ERA	SYSTEM PERIOD	SERIES EPOCH		STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Cenozoic (Cz) 242 / 249 / 29	Paleogene (Pg) 253 / 154 / 82	Oligocene (Oli) 254 / 192 / 122	Late	Chattian 254 / 230 / 170	Cht	27.82	23.03	+34.4	+107.5
			Early	Rupelian 254 / 217 / 154	Rup	33.9	27.82	+68.4	+197.3
		Eocene (Eoc) 253 / 180 / 108	Late	Priabonian 253 / 205 / 161	Prb	37.8	33.9	+107.9	+154.6
			Middle	Bartonian 253 / 192 / 145	Bar	41.2	37.8	+108.3	+185.3
				Lutetian 253 / 180 / 130	Lut	47.8	41.2	+135.6	+209.8
			Early	Ypresian 252 / 167 / 115	Ypr	56.0	47.8	+89	+221.3
		Paleocene (Pal) 253 / 167 / 95	Late	Thanetian 253 / 191 / 111	Tha	59.2	56.0	+93.3	+192.9
			Middle	Selendian 254 / 191 / 101	Sel	61.6	59.2	+81.2	+192.6
			Early	Danian 253 / 180 / 98	Dan	66.0	61.6	+180	+194.2

Figure 78. Ages, RGB colors, and abbreviations for the Paleogene. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level).

8.1.4. Cretaceous

ERA	SYSTEM PERIOD	SERIES EPOCH	STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Mesozoic (Mz) 103 / 197 / 202	Cretaceous (K) 127 / 198 / 78	Upper Cretaceous (K2) 166 / 216 / 74	**Maastrichtian** 242 / 250 / 140	Maa	72.1	66.0	+122.3	+224.3
			Campanian 230 / 244 / 127	Cmp	83.6	72.1	+190	+242.3
			Santonian 217 / 239 / 116	San	86.3	83.6	+186.8	+219.3
			Coniacian 204 / 233 / 104	Con	89.8	86.3	+203.3	+227.9
			Turonian 191 / 227 / 93	Tur	93.9	89.8	+144.7	+251.7
			Cenomanian 179 / 222 / 83	Cen	100.5	93.9	+177.6	+242.9
		Lower Cretaceous (K1) 140 / 205 / 87	**Albian** 204 / 234 / 151	Alb	113.0	100.5	+117.3	+232.1
			Aptian 191 / 228 / 138	Apt	121.4	113.0	+92.5	+180.3
			Barremian 179 / 223 / 127	Brm	129.4	121.4	+129.6	+180.3
			Hauterivian 166 / 217 / 117	Hau	132.6	129.4	+3.9	+142
			Valanginian 153 / 211 / 106	Vlg	139.8	132.6	+36.8	+133.5
			Berriasian 140 / 205 / 96	Ber	145.0	139.8	+107	+136.2

Figure 79. Ages, RGB colors, and abbreviations for the Cretaceous. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level).

8.1.5. Jurassic

ERA	SYSTEM PERIOD	SERIES EPOCH	STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Mesozoic (Mz) 103 / 197 / 202	Jurassic (J) 52 / 178 / 201	Upper (J3) 'Malm' 179 / 227 / 238	**Tithonian** 217 / 241 / 247	Tth	149.2	145.0		
			Kimmeridgian 204 / 236 / 244	Kim	154.8	149.2		
			Oxfordian 191 / 231 / 241	Oxf	161.5	154.8		
		Middle (J2) 'Dogger' 128 / 207 / 216	**Callovian** 191 / 231 / 229	Clv	165.3	161.5		
			Bathonian 179 / 226 / 227	Bth	168.2	165.3		
			Bajocian 166 / 221 / 224	Baj	170.9	168.2		
			Aalenian 154 / 217 / 221	Aal	174.7	170.9		
		Lower (J1) Lias 66 / 174 / 208	**Toarcian** 153 / 206 / 227	Toa	184.2	174.7		
			Pliensbachian 128 / 197 / 221	Plb	192.9	184.2		
			Sinemurian 103 / 188 / 216	Sin	199.5	192.9		
			Hettangian 78 / 179 / 211	Het	201.4	199.5		

Figure 80. Ages, RGB colors, and abbreviations for the Jurassic. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level)

8.1.6. Triassic

ERA	SYSTEM PERIOD	SERIES EPOCH	STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Mesozoic (Mz) 103 / 197 / 202	Triassic (Tr) 129 / 43 / 146	Upper (Tr3) 189 / 140 / 195	**Rhaetian** 227 / 185 / 219	Rht	208.5	201.4		
			Norian 214 / 170 / 211	Nor	227	208.5		
			Carnian 201 / 155 / 203	Crn	237	227		
		Middle (Tr2) 177 / 104 / 177	**Ladinian** 201 / 131 / 191	Lad	242	237		
			Anisian 188 / 117 / 183	Ans	247.2	242		
		Lower (Tr1) 152 / 57 / 153	**Olenekian** 176 / 81 / 165	Ole	251.2	247.2		
			Induan 164 / 70 / 159	Ind	251.902	251.2		

Figure 81. Ages, RGB colors, and abbreviations for the Triassic. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level).

8.1.7. Permian

ERA	SYSTEM PERIOD	SERIES EPOCH	STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Paleozoic (Pz) 153 / 192 / 141	Permian (P) 240 / 64 / 40	Lopingian (P3) 251 / 167 / 148	**Changhsingian** 252 / 192 / 178	Chg	254.14	251.902		
			Wuchiapinguian 252 / 180 / 162	Wuc	259.51	254.14		
		Guadalupian (P2) 251 / 116 / 92	**Capitanian** 251 / 154 / 133	Cap	264.28	259.51		
			Wordian 251 / 141 / 118	Wor	266.9	264.28		
			Roadian 251 / 128 / 105	Roa	273.01	266.9		
		Cisuralian (P1) 239 / 88 / 69	**Kungurian** 227 / 135 / 118	Kun	283.5	273.01		
			Artinskian 227 / 123 / 104	Art	290.1	283.5		
			Sakmarian 227 / 111 / 92	Sak	293.52	290.1		
			Asselian 227 / 99 / 80	Ass	298.9	293.52		

Figure 82. Ages, RGB colors, and abbreviations for the Permian. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level).

8.1.8. Carboniferous

ERA	SYSTEM PERIOD	SERIES EPOCH		STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Paleozoic (Pz) 153 / 192 / 141	Carboniferous (C) 103 / 165 / 153	Pennsylvanian (Pen) 126 / 188 / 198	Upper (Pen3) 191 / 208 / 186	**Gzhelian** 204 / 212 / 199	Gzh	303.7	298.9		
				Kasimovian 191 / 208 / 197	Kas	307.0	303.7		
			Middle (Pen2) 166 / 199 / 183	**Moscovian** 179 / 203 / 185	Mos	315.2	307.0		
			Lower (Pen1) 140 / 190 / 180	**Bashkirian** 153 / 194 / 181	Bsh	323.2	315.2		
		Missippian (Mis) 103 / 143 / 102	Upper (Mis3) 179 / 190 / 108	**Serpukhovian** 191 / 194 / 107	Spk	330.9	323.2		
			Middle (Mis2) 153 / 180 / 108	**Visean** 166 / 185 / 108	Vis	346.7	330.9		
			Lower (Mis1) 128 / 171 / 108	**Tournaisian** 140 / 176 / 108	Tou	358.9	346.7		

Figure 83. Ages, RGB colors, and abbreviations for the Carboniferous. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level).

8.1.9. Devonian

ERA	SYSTEM PERIOD	SERIES EPOCH	STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Paleozoic (Pz) 153 / 192 / 141	Devonian (D) 203 / 140 / 55	Upper (D3) 241 / 225 / 157	**Famennian** 242 / 237 / 179	Fam	372.2	358.9		
			Frasnian 242 / 237 / 173	Frs	382.7	372.2		
		Middle (D2) 241 / 200 / 104	**Givetian** 241 / 225 / 133	Giv	387.7	382.7		
			Eifelian 241 / 213 / 118	Eif	393.3	387.7		
		Lower (D1) 229 / 172 / 77	**Emsian** 229 / 208 / 117	Ems	407.6	393.3		
			Pragian 229 / 196 / 104	Pra	410.8	407.6		
			Lochkovian 229 / 183 / 90	Loc	419.2	410.8		

Figure 84. Ages, RGB colors, and abbreviations for the Devonian. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level).

8.1.10. Silurian

ERA	SYSTEM PERIOD	SERIES EPOCH	STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Paleozoic (Pz) 153 / 192 / 141	Silurian (P) 179 / 225 / 182	Pridoli (Prd) 230 / 245 / 225		Prd	423.0	419.2		
		Ludlow (Lud) 191 / 230 / 207	Ludfordian 217 / 240 / 223	Ldf	425.6	423.0		
			Gorstian 204 / 236 / 221	Gor	427.4	425.6		
		Wenlock (Wen) 179 / 225 / 194	Homerian 204 / 235 / 209	Hom	430.5	427.4		
			Sheinwoodian 191 / 230 / 195	She	433.4	430.5		
		Llandovery (Lld) 153 / 215 / 179	Telychian 191 / 230 / 207	Tel	438.5	433.4		
			Aeronian 179 / 225 / 194	Aer	440.8	438.5		
			Rhuddanian 166 / 220 / 181	Rhu	443.8	440.8		

Figure 85. Ages, RGB colors, and abbreviations for the Silurian. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level).

8.1.11. Ordovician

ERA	SYSTEM PERIOD	SERIES EPOCH	STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Paleozoic (Pz) 153 / 192 / 141	Ordovician (O) 0 / 146 / 112	Upper (O3) 127 / 202 / 147	Hirnantian 166 / 219 / 171	Hir	445.2	443.8		
			Katian 153 / 214 / 159	Kat	453.0	445.2		
			Sandbian 140 / 208 / 148	San	458.4	453.0		
		Middle (O2) 77 / 180 / 126	Darriwilan 116 / 198 / 156	Dar	467.3	458.4		
			Dapingian 102 / 192 / 146	Dap	470.0	467.3		
		Lower (O1) 26 / 157 / 111	Floian 65 / 176 / 135	Flo	477.7	470.0		
			Tremadocian 51 / 169 / 126	Tre	485.4	477.7		

Figure 86. Ages, RGB colors, and abbreviations for the Ordovician. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level)

8.1.12. Cambrian

ERA	SYSTEM PERIOD	SERIES EPOCH	STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Paleozoic (Pz) 153 / 192 / 141	Cambrian (€) 127 / 160 / 86	Furongian (Fur) 179 / 224 / 149	**Stage 10** 230 / 245 / 201	Ca10	489.5	485.4		
			Jiangshanian 217 / 240 / 187	Jia	494	489.5		
			Paibian 204 / 235 / 174	Pai	497	494		
		Miaolingian (Mia) 166 / 207 / 134	**Guzhangian** 204 / 223 / 170	Guz	500.5	497		
			Drumian 191 / 217 / 157	Dru	504.5	500.5		
			Wuliuan 179 / 212 / 146	Wul	509	504.5		
		Series 2 (Ca2) 153 / 192 / 120	**Stage 4** 179 / 202 / 142	Ca4	514	509		
			Stage 3 166 / 197 / 131	Ca3	521	514		
		Terreneuvian (Trr) 140 / 176 / 108	**Stage 2** 166 / 186 / 128	Ca2	529	521		
			Fortunian 153 / 181 / 117	For	538.8	529		

Figure 87. Ages, RGB colors, and abbreviations for the Cambrian. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level)

8.1.13. Precambrian

ERA	SYSTEM PERIOD	SERIES EPOCH	STAGE	ABB	BTM AGE	TOP AGE	SL_{min}	SL_{max}
Precambrian (p€) 247 / 67 / 112	Proterozoic (Pro) 247 / 53 / 99	Neo-Proterozoic (Pro3) 254 / 179 / 66	**Ediacarian** 254 / 217 / 106	Edi	635	538.8		
			Cryogenian 254 / 204 / 92	Cry	720	635		
			Tonian 254 / 191 / 78	Ton	1000	720		
		Meso-Proterozoic (Pro2) 253 / 180 / 98	**Stenian** 254 / 217 / 154	Ste	1200	1000		
			Ectasian 253 / 204 / 138	Ect	1400	1200		
			Calymmian 253 / 192 / 122	Cly	1600	1400		
		Paleo-Proterozoic (Pro1) 247 / 67 / 112	**Statherian** 248 / 117 / 167	Stt	1800	1600		
			Orosirian 247 / 104 / 152	Oro	2050	1800		
			Rhyacian 247 / 91 / 137	Rhy	2300	2050		
			Siderian 247 / 79 / 124	Sid	2500	2300		
	Archean (Arc) 240 / 4 / 127	Neo-Archean (Arc4) 249 / 155 / 193			2800	2500		
		Meso-Archean (Arc3) 247 / 104 / 169			3200	2800		
		Paleo-Archean (Arc2) 244 / 68 / 159			3600	3200		
		Eo-Archean (Arc1) 218 / 3 / 127			4000	3600		
	Hadean (Had) 174 / 2 / 126				4567	4000		

Figure 88. Ages, RGB colors, and abbreviations for the Precambrian. The ages (BTM, age at the base of stage, TOP, age at the top of stage) and RGB colors are those for the 2022 ICS timescale (https://stratigraphy.org/chart). The SLmax and SLmin values are calculated using the maximum and minimum 3rd-order SL values from Haq et al. (1987), accepting caveats about this curve (Rowley and Markwick 1992; Markwick and Rowley 1998); values in meters (SL = Sea Level)

Whitby Mudstone Formation (Toarcian, Lower Jurassic) in the cliffs south of Whitby. A series of interbedded mudstones and siltstones with occasional fine-grained calcareous sandstone beds. Predominantly shallow marine with evidence of occasional influxes of terrestrial material.

9. Depositional Systems

The Depositional Environments databases are global, spatial databases showing the geometry, depositional environment, age, and dominant lithology of the Earth's surface for the present-day and each mapped timeslice in the geological past.

These are designed for mineral and hydrocarbon exploration and underpin the reconstruction of paleolandscapes used in source-to-sink analysis and as a boundary condition for Earth system modeling.

Depositional environments are one of the key steps in paleogeographic mapping. In our system, the depositional environments codes, attribution, and symbology are used in two suites of databases: 1. Bedrock Geology databases, with the environment of deposition recorded for the top and bottom of the mapped unit; 2. Paleogeography, with depositional environments for each of our standard timeslices, or for a specific times needed for bespoke studies or research.

In many exploration applications, these elements are important tools used to identify the character and juxtaposition of identified plays, especially source and reservoir facies. Although traditionally developed in hydrocarbon exploration, these techniques are also critically important in hydrogeology, waste burial, carbon storage, and mineral exploration.

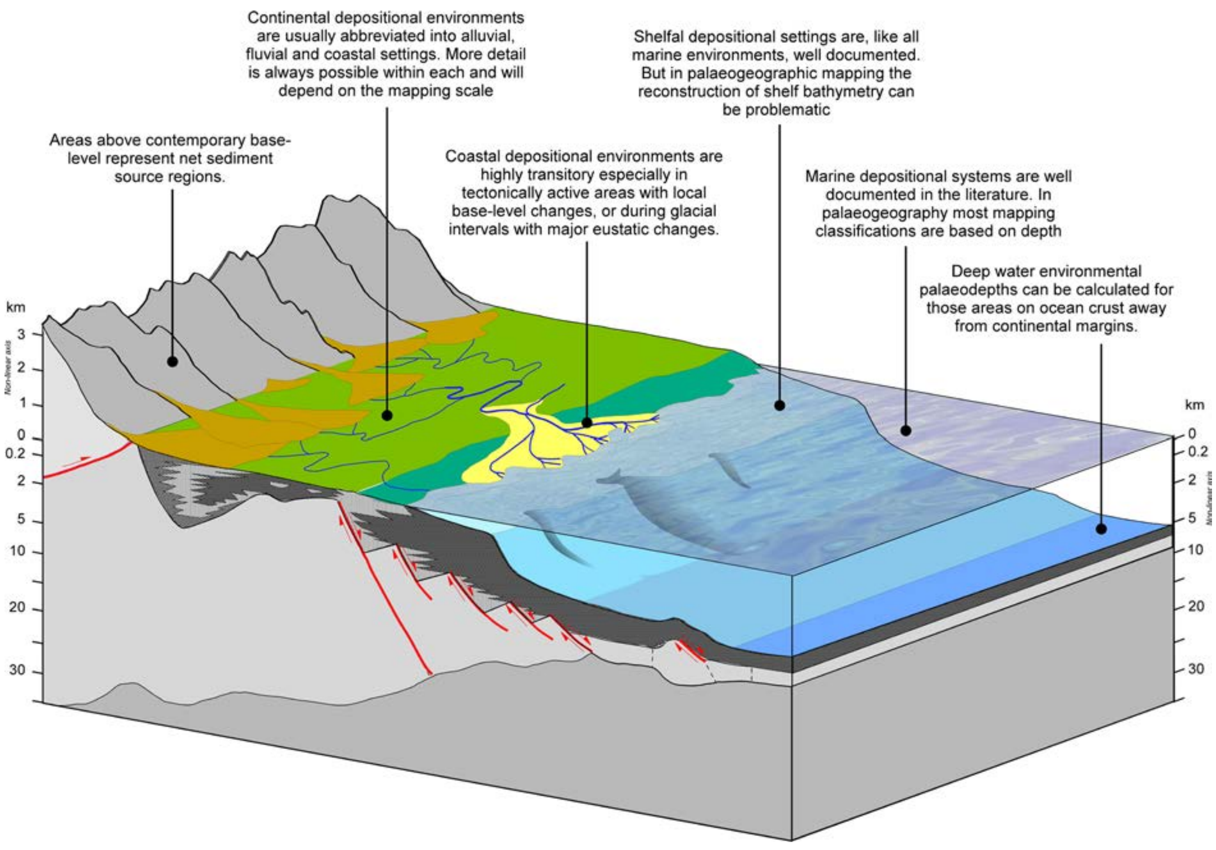


Figure 89. A block diagram showing the depositional environments comprising the landscape represented in Figure 4.

There is a distinction between the terms "(depositional) environment," "gross depositional environment," and "facies," although in operation, they are frequently used interchangeably. A (depositional) environment describes the combination of physical, chemical, and biological processes at a place and time on the surface of the Earth. On a paleogeographic map, these need not relate directly to the type of sediment being deposited, simply the state of the surface of the Earth. So, a fluvial (depositional) environment, as mapped in our examples, would show the distribution of rivers, lakes, ponds, marshlands, forests, etc., not the sediment, which is the product of those processes and the landscape. Gross Depositional Environments (GDEs) similarly describe the environments (processes) rather than the rocks, but usually for a time interval – this reflects the origin of GDE mapping in well and seismic analysis. In reality, GDEs and depositional environments are used interchangeably due to the geological record (see the discussion on time in section 1). A facies, describes the products of these depositional processes, combining the depositional environment with the lithologies and often fossil and other content. So, for example, we might describe a submarine canyon-fill facies, but the GDE and environment would be a submarine canyon.

This is why it is so important first to map out the underlying crustal architecture, accommodation, and landscape because this means that a resulting paleogeographic map can be used to show any of these three features, environments, GDEs, and facies.

The mapped depositional environment in our workflow represents the full reconstructed extent of each environment at the time of the palaeogeographic map. The preserved extent is distinguished from the inferred extent using database attribution and symbology.

This depositional extent represents areas below the contemporary base-level and potentially able to accumulate sediments (Markwick and Valdes 2004). But it will also include areas with no deposition due to by-passing. Base-level and depositional environments can vary rapidly in time and space, especially in tectonically active areas, and this must be considered.

Strictly speaking, depositional environment maps are distinct from a facies map, the latter representing the products of deposition (the rock record) - a paleogeography in this definition would show a submarine canyon system, slope, rise, and abyssal plain as environments, but not refer to a 'turbidite' depositional environment, which is a facies. With digital systems, these can be kept separate and overlain later during analysis. In reality, many published palaeogeographies 'mix' facies, gross depositional environments (GDEs), and depositional environments, and users should be aware of this.

Most symbology schemes for depositional environments are relatively standard, if not always self-explanatory, for example, the use of yellow polygon fill to denote delta tops has been used by numerous authors (Golonka et al. 1994; Markwick 2011). Most mappers use various shades of blue to represent marine conditions (Vinogradov et al. 1967; Vinogradov 1968; Vinogradov et al. 1968; Vinogradov 1969; Ziegler et al. 1985; Markwick and Valdes 2004), except for Ziegler (1990). Numerous published schemes are now available, including those of Shell (Hulshof 2012) and the USGS (Federal Geographic Data Committee 2006).

All depositional environment symbol codes are prefixed with the letter "E".

9.1. Terrestrial Depositional Systems

Our map legend divides terrestrial environments into fluvial, lacustrine, glacial, and desert environments. Subdivisions of these broad definitions have been generated to allow differentiation between meandering and braided fluvial systems, different lacustrine types (based on salinity), and alluvial environments as distinct from fluvial systems. These have been included, given the needs of source-to-sink analysis and climate modeling. This enables us to map depositional environmental data at different map resolutions.

At higher mapping resolutions, it may be appropriate, possible, to map individual components of fluvial systems. In this classification, we have included only the major features that might be of use in reconstructing the paleolandscape, or which have direct exploration significance either in placer or hydrocarbon exploration. The differentiation of channels may also be important in studies of aquifers.

9.1.1. Terrestrial / 'continental' undifferentiated

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E101	Cont	Continental, undifferentiated	225 / 250 / 175	In many publications, sediments are referred to as "continental" without further description of what continental environment is being represented. Because of this we have included a "continental undifferentiated" classification, although where possible this should be avoided. **Map abbreviation field entry, "Cont"**

Figure 90. The default fill pattern, symbol ID code, and explanation for the undifferentiated continental depositional systems. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description).

9.1.2. Fluvial Systems

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E100	F	Fluvial, undifferentiated	205 / 245 / 120	Terrestrial systems formed by rivers, but with no distinction as to the architecture. **Map abbreviation field entry, "F"**
E110	F_m	Fluvial, meandering	125 / 190 / 0	Fluvial systems comprising a single distinct channel with a sinuous plan view. Typical of systems on lower gradients dominated by suspended load and more cohesive banks. **Map abbreviation field entry, "F_m"**
E120	F_b	Fluvial, braided	204 / 204 / 0	Fluvial systems comprising a network of river channels separated by often temporary 'islands' called braid bars or eyots. Typified by systems with a high sediment load, steep profile, and fluctuating discharge. **Map abbreviation field entry, "F_b"**
E150	F-L	Fluvio-Lacustrine	50 / 200 / 80	Systems in the floodplain with a mixture of small lakes, ponds, swamps, and rivers Lower gradients with high freshwater discharge. Typical of the lower reaches of river systems or broad intracontinental basins. **Map abbreviation field entry, "F-L"**

Figure 91. The default fill pattern, symbol ID code, and explanation for fluvial depositional environments. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description).

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E115	F_{fp}	Floodplain	125 / 180 / 0	A generally flat area adjacent to a stream or river which extends from the riverbank (levee) to the valley boundary, usually marked by a major change in slope. Floodplains, as the name suggests, are subject to flooding during periods of high freshwater discharge or direct precipitation. Sediments in floodplains can range from coarse clastics, gravels, sands, silts to muds and clays depending on when they were deposited relative to flooding (settling histories). **Map abbreviation field entry, “F_{fp}”**
E116	F_{ch}	Channel	125 / 160 / 0	The path in which a stream or river is at least seasonally constrained. For most paleogeographic maps only the very largest channels would be resolvable. A channel is, by definition, an erosional feature. However, they will be material stored in the channel (viz., channel lag) so in most cases, a channel would either be shown as non-depositional (but below base-level), or as coarse clastics. **Map abbreviation field entry, “F_{ch}”**
E117	F_{bar}	Bar	220 / 210 / 55	A raised area of sediment deposited by flow in a river or marine depositional environment. This includes braid-bars in braided systems. A point-bar is different and represents the build-out of sediments in a meandering system. For most paleogeographic maps an individual bar is below the resolution of the map. Usually comprised coarse clastics, sand or gravel. **Map abbreviation field entry, “F_{bar}”**
E132	F_{bsw}	Backswamp	125 / 200 / 160	In fluvial systems, back swamps occupy parts of the floodplain where water accumulates and remains beyond the immediate effects of flooding. Typified by fine-grained clastics (clay and silt). Backswamps can result in peat accumulation. **Map abbreviation field entry, “F_{bs}”**

Figure 92. The default fill pattern, symbol ID code, and explanation for subenvironments within fluvial depositional environments. This list can be added to as more detailed maps are generated. The format for all depositional environment symbol codes is as follows: “E” + “###.” The three-digit number value differentiates the type of environment (see description).

9.1.3. Alluvial systems

The inclusion of "alluvial" systems is an outlier in the depositional systems described in this classification because it represents the deposit, not the environment per se. However, mapping these as an environment provides information on contemporary relative paleoelevation, which is important in paleogeographic reconstruction.

"Alluvial Plains" are, by definition, flat landforms formed by the deposition of sediment primarily by fluvial processes (Morang 1995; U.S. Department of Agriculture Natural Resources Conservation Service 2019). Consequently, the inclusion of "Alluvial Plains" is much less useful because it is already covered by fluvial environments.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E140	A_{fan}	Alluvial Fan	200 / 160 / 0	Triangular, fan-shaped depositional features of water-transported materials. Usually found at the base of topographic highs reflecting a change in gradient. Fans are a function of sediment supply and uplift. Map abbreviation field entry, "A_{fan}"
E145	A_{plain}	Alluvial Plain	240 / 220 / 0	A flat or gently sloping surface formed by the coalescence of alluvial fans and deposited from distributary rivers. Alluvial plains are synonymous with floodplains and other fluvial depositional environments especially the further away from the sourcing alluvial fans. It is included here because of it is commonly found in the literature in the absence of more detailed information. However, we recommend using fluvial environments where possible. Map abbreviation field entry, "A_{plain}"

Figure 93. The default fill pattern, symbol ID code, and explanation for alluvial fan and plain depositional environments. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description).

9.1.4. Lacustrine systems

Lakes are inland water bodies that are separate from the main ocean system. Deposition in lake systems is a function of lake size, depth, climate, and fluvial inputs.

In this classification, lakes are distinguished by their salinity, which can be identified using the fauna, flora, and biochemistry. Salinity is measured in units of PSU (Practical Salinity Unit), which is based on the properties of seawater conductivity. This is equivalent to parts per thousand ‰ or g/kg or g/L

Other classifications, such as those based on stratification and mixing (Katz 1995), can be calculated using climate model results with information added as new attributes. The underfill and overfill classification of Carroll and Bohacs (2001) describes the fill state at a moment in time rather than the mappable depositional environment.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E200	F_{fp}	Lacustrine undifferentiated	50 / 150 / 170	Any inland water body separate from the main ocean system. **Map abbreviation field entry, “L”**
E220	L_{f}	Lacustrine, freshwater	35 / 125 / 190	Inland water body with dissolved salt concentrations <0.5‰. **Map abbreviation field entry, “L_f”**
E208	L_{br}	Lacustrine, brackish	35 / 145 / 180	Inland water body with dissolved salt concentrations 0.5-30‰ (subsaline). e.g. Black Sea (13-23‰), Lake Van (23‰), **Map abbreviation field entry, “L_{br}”**
E210	L_{sal}	Lacustrine, saline	40 / 180 / 175	Inland water body with dissolved salt concentrations 30-50‰ (hyposaline-mesosaline). Mediterranean (38‰, up to 40‰), Salton Sea (44‰), Red Sea (36-41‰), Average Oceans (35‰). **Map abbreviation field entry, “L_{sal}”**
E212	L_{hsal}	Lacustrine, hypersaline	45 / 210 / 200	Hypersaline lakes are inland water bodies with dissolved salt concentrations >50 ‰ (hypersaline). E,g, Mono Lake (88‰), Great Salt Lake (50-270‰), Dead Sea (337‰), Lake Vanda (350‰), **Map abbreviation field entry, “L_{hsal}”**
E215	L_{playa}	Lacustrine, playa	130 / 230 / 205	Ephemeral inland water body generally typified by sand and salt flats rather than subaqueous deposition. Also known as salt pans (southern Africa), sabkhas (Middle East), takyrs (Central Asia), kavirs (Iran). **Map abbreviation field entry, “L_{playa}”**

Figure 94. The default fill pattern, symbol ID code, and explanation for lacustrine (lake) depositional environments. The format for all depositional environment symbol codes is as follows: “E” + “###.” The three-digit number value differentiates the type of environment (see description).

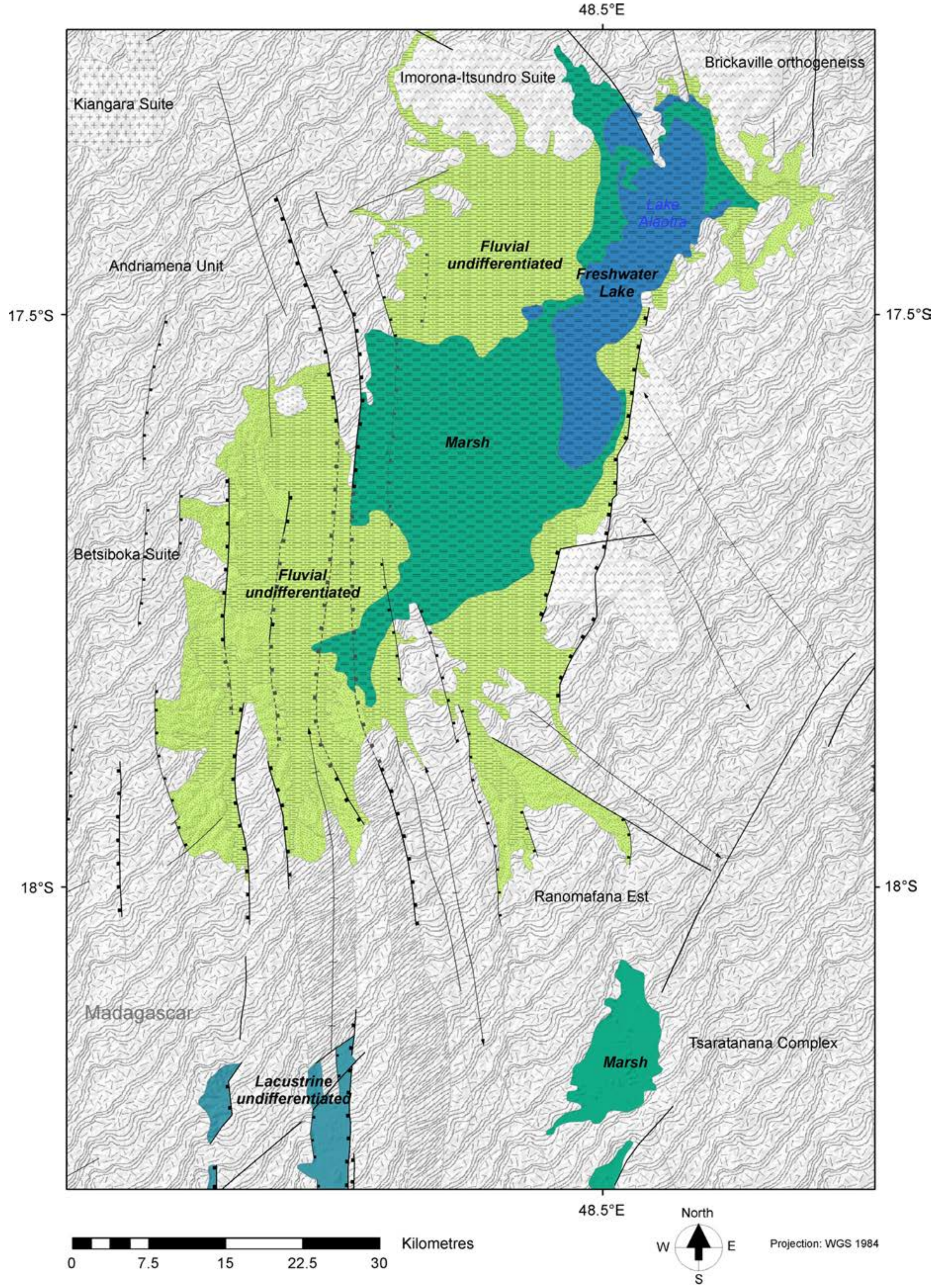


Figure 95. The present-day Lake Alaotra basin in north-central Madagascar showing the basic distribution of lake, fluvial, and marsh environments.

9.1.5. Wetland systems

Wetlands are depositional systems flooded by water, either permanently or seasonally. This includes both freshwater and brackish wetlands occurring in coastal and non-coastal settings. Floodplains, although a consequence of occasional flooding, are not included as wetlands in this classification because with the exception of localized back swamp areas and ponds (e.g., oxbow lakes), water will drain away from the plain.

Dominantly freshwater wetlands

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E130	W_{sw}	Swamp	75 / 180 / 125	A swamp is defined as a wetland dominated by trees. Examples include the Everglades in Florida and other cypress (*Taxodium*) swamps of the southeastern USA. **Map abbreviation field entry, "W_{sw}"**
E132	W_{bsw}	Backswamp	125 / 200 / 160	In fluvial systems, back swamps occupy parts of the floodplain where water accumulates and remains beyond the immediate effects of flooding. **Map abbreviation field entry, "W_{bsw}"**
E134	W_{bog}	Mire, Bog, Fen	65 / 160 / 110	A waterlogged area dominated by peat-forming plants especially mosses including sphagnum (Moore and Bellamy, 1974). **Map abbreviation field entry, "W_{bog}"**
E135	W_{fm}	Freshwater Marsh	125 / 200 / 180	A wetland dominated by herbaceous plants such as reeds and grasses rather than woody species (trees). Freshwater marshes are dependent on freshwater discharge. Typically found along rivers (freshwater marsh) but can form in coastal environments where freshwater discharge dominates over saltwater influx. **Map abbreviation field entry, "W_{fm}"**

Figure 96. The default fill pattern, symbol ID code, and explanation for freshwater wetland depositional environments. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description).

Brackish, coastal wetlands

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E136	W_{msw}	Mangrove Swamp	160 / 220 / 205	A wetland dominated by mangrove trees typical of brackish water in coastal settings. **Map abbreviation field entry, "W_{msw}"**
E137	W_{sm}	Salt Marsh	180 / 235 / 220	A wetland dominated by herbaceous plants including grasses rather than woody species (trees) or mosses and which forms in coastal environments (salt marsh). **Map abbreviation field entry, "W_{sm}"**

Figure 97. The default fill pattern, symbol ID code, and explanation for brackish wetland depositional environments. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description).

9.1.6. Desert

A desert is defined as an area with low precipitation usually quoted as <250 mm yr-1 (Glennie 1970; Sonnenfeld 1984). This can occur in cold and hot climates. Geologically most desert depositional environments are associated with hot deserts, typified by red-beds and sand seas.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E300	D	Desert, undifferentiated	250 / 200 / 130	Used for red-beds or descriptions of "desert" environments not covered by other environments (viz., sand seas, saline lakes, playa lakes). 'Fluvial' red-beds will be assigned to fluvial environments since this is the dominant environment. **Map abbreviation field entry, "D"**
E350	D_{ss}	Desert, sand sea	255 / 230 / 100	Sand seas are a distinct geological feature formed by wind (aeolian) processes, typified by dune bedded sandstones, usually red or orange in color. **Map abbreviation field entry, "D_{ss}"**

Figure 98. The default fill pattern, symbol ID code, and explanation for desert depositional environments. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description).

9.1.7. Glacial

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E400	G	Glacial, undifferentiated	160 / 170 / 215	Deposition related to glaciation, but exact relationship unclear. **Map abbreviation field entry, "G"**
E410	G_{sub}	Sub-glacial	195 / 200 / 230	Deposition under a glacier. Paleogeographically, this environment marks the extent of contemporary ice at the time of the mapping. **Map abbreviation field entry, "G_{sub}"**
E420	G_{peri}	Peri-glacial	220 / 225 / 240	Depositional environments adjacent to glaciers and directly influenced by the ice. **Map abbreviation field entry, "G_{peri}"**

Figure 99. The default fill pattern, symbol ID code, and explanation for glacial depositional environments. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description).

9.2. Coastal Depositional Systems

Coastal environments occur at the boundary between land and water bodies. This includes both lacustrine and marine coastal settings.

The classification of coastal depositional environments used here is based largely on that of Boyd et al. (1992). To this, I have added "Supratidal," "Intertidal," and "Shoreface." The reason for following Boyd et al. is that this covers the key environments of significance in terms of clastic reservoirs. Harris and Heap (2003) provide a very good summary of how this is applied to their database of Australian coastal depositional environments, which includes some helpful summary figures.

9.2.1. Delta Top

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E170	D	Delta top, undifferentiated	255 / 255 / 100	A delta top (also called a delta plain) is the subaerial exposure of a delta. Deltas form where rivers meet large water bodies resulting in a rapid change in flow and consequent deposition of material carried by the rivers. Delta tops comprise a variety of different environments, represented in the upper delta by floodplains, lakes and freshwater swamps and bogs. The lower delta plain is marine (or lake) influenced. In marine settings or very large lakes, these areas can be affected by tidal and wave processes, and a range of additional environments including salt marshes, lagoons, mangroves, and tidal flats. Same colors for all delta top types, but different abbreviations and descriptions. **Map abbreviation field entry, "D"**
E172	D_{tide}	Delta top, tide-dominated	255 / 255 / 100	A delta top dominated by tidal processes resulting in flow-parallel bars, tidal flats. Same colors for all delta top types, but different abbreviations and descriptions. **Map abbreviation field entry, "D_{tide}"**
E174	D_{wave}	Delta top, wave-dominated	255 / 255 / 100	A delta top dominated by wave processes, resulting in the development of bars perpendicular to river flow and parallel with the wavefront. Same colors for all delta top types, but different abbreviations and descriptions. **Map abbreviation field entry, "D_{wave}"**
E176	D_{fluv}	Delta top, fluvial-dominated	255 / 255 / 100	Fluvially-dominated delta systems are typified by the progradation of fluvial and fluvio-lacustrine environments. Same colors for all delta top types, but different abbreviations and descriptions. **Map abbreviation field entry, "D_{fluv}"**

Figure 100. The default fill pattern, symbol ID code, and explanation for delta top depositional environments. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description).

9.2.2. Estuaries

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E183	E	Estuary undifferentiated	0 / 200 / 165	An estuary is a partially enclosed, usually brackish, embayment formed by the flooding of a pre-existing valley during marine transgression. Boyd et al (1992) define an estuary as the "seaward portion of a drowned valley which receives sediment from both fluvial and marine sources, and which contains facies influenced by tide, wave and fluvial processes" **Map abbreviation field entry, "E"**
E181	E_{tide}	Estuary, wave-dominated	0 / 200 / 165	A partially enclosed, usually brackish, embayment formed by the flooding of a pre-existing valley during marine transgression dominated in this case by wave processes. See Boyd et al 1992. **Map abbreviation field entry, "E_{wave}"**
E182	E_{wave}	Estuary, tide-dominated	0 / 200 / 165	A partially enclosed, usually brackish, embayment formed by the flooding of a pre-existing valley during marine transgression dominated in this case by tidal processes. See Boyd et al 1992. **Map abbreviation field entry, "E_{tide}"**
E188	E_{fluv}	Estuary, fluvial-dominated	0 / 200 / 165	A flat, coastal wetland within the inter-tidal zone usually formed within sheltered areas such as bays, estuaries or lagoons. **Map abbreviation field entry, "E_{fluv}"**

Figure 101. The default fill pattern, symbol ID code, and explanation for estuarine depositional environments. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description).

9.2.3. Other coastal features

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E180	C	Coastal undifferentiated	0 / 170 / 130	An environment described as "coastal" but which is not differentiated any further. **Map abbreviation field entry, "C"**
E184	SP	Strand Plain	0 / 165 / 140	A belt of sand along a shoreline comprising well-defined shore-parallel or semi-parallel sand ridges. Boyd et al (1992) note that strand plains commonly preserve past shoreline positions and maybe underlain by more seaward facies. **Map abbreviation field entry, "SP"**
E185	Brr	Barrier	0 / 150 / 120	A barrier is an elongate, shore-parallel sandy body which can comprise several sandy units including beach, dunes, tidal deltas and estuary embayment's (Boyd et al., 1992). **Map abbreviation field entry, "Brr"**
E186	Lag	Lagoon	0 / 235 / 180	A shallow coastal water body separated from the ocean (or lake?) by a barrier. **Map abbreviation field entry, "Lag"**
E187	TF	Tidal Flat	100 / 255 / 215	A flat, coastal wetland within the inter-tidal zone usually formed within sheltered areas such as bays, estuaries or lagoons. **Map abbreviation field entry, "TF"**
E190	supT	Supratidal	230 / 245 / 200	Coastal area (also known as the splash zone) which lies above the level of spring high tide but can be inundated by extreme tides especially those augmented by storm surges. Includes coastal sabkhas and other environments inundated by the sea during extreme events such as storms. **Map abbreviation field entry, "supT"**
E500	intT	Intertidal	185 / 255 / 210	The foreshore, which is the area between high and low tides. **Map abbreviation field entry, "intT"**
E505	SF	Shoreface	235 / 255 / 255	The zone where offshore waves interact with the seabed. The upper shoreface is also known as the surf zone.This could also be treated as part of the marine depositional system.It is placed here because of the interaction with the shore. **Map abbreviation field entry, "SF"**
E195	CP	Coastal Plain	200 / 240 / 190	The coastal plain is a geomorphological description for the flat, low-lying area between the coast and first highland areas, often reflecting the extent of past transgressions. **Map abbreviation field entry, "CP"**

Figure 102. The default fill pattern, symbol ID code, and explanation for miscellaneous 'coastal' depositional environments. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description). Given the definition used here, coastal plains are relict features and therefore, non-depositional. If there is contemporary deposition on this surface, it will be by fluvial, glacial, or aeolian processes and classified accordingly. We suggest that for depositional mapping, if coastal plain is used, then it should be shown as non-depositional. This indicates to users that you consider it below the regional base-level, but with no sediments being deposited.

Figure 103. Bartonian deltaic and tidal flat deposits of the Belsué - Ararés Formation (deltaic) and Yeste-Arrés Formation (tidal flats) prograding over the marine Arguis Formation at the Pico Overview, Jaca Basin. The coarser units in this picture show bi-directional cross-bedding consistent with tidal activity.

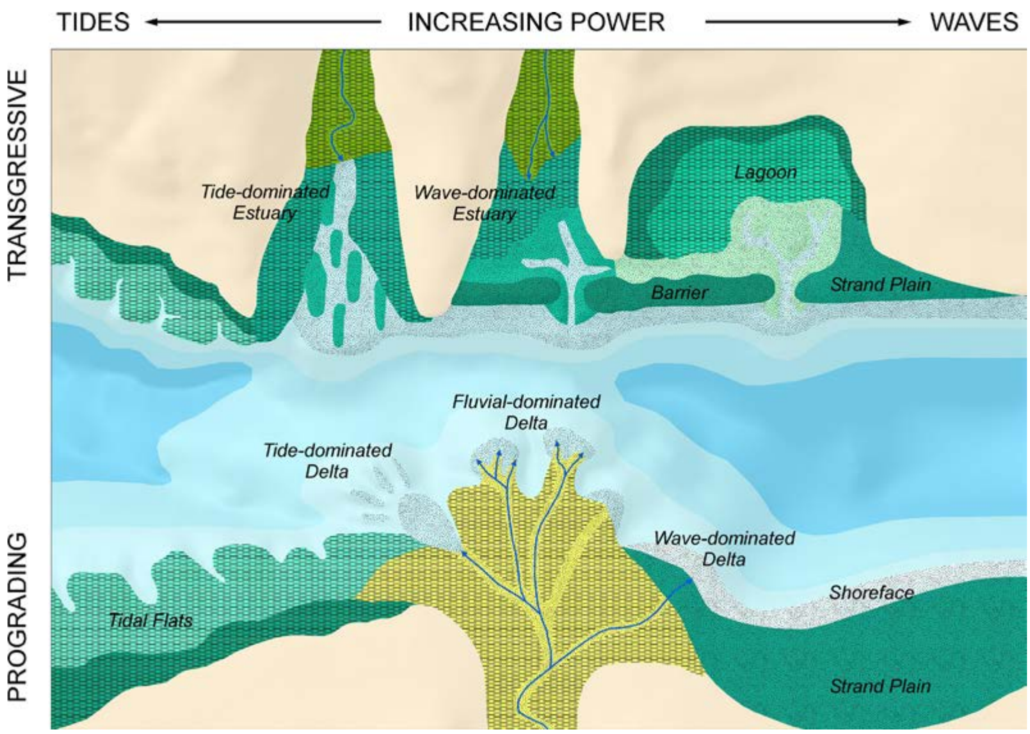


Figure 104. The symbol set defined in this paper applied to a modified version of the coastal and near-shore environments classification of Boyd et al. (1992).

Shallow marine Paleocene carbonates of the Navarri Formation at Navarri, central Pyrenees

9.3. Marine Depositional Systems

Marine environments are generally classified by depth following Ziegler et al. (Table 2 in Ziegler et al. 1985), who related environments to sedimentological and fossil evidence. Similar definitions were used by Vinogradov et al. (1967; 1968; 1968; 1969) and adopted to lesser or greater degrees by Scotese (1992; 2014b, a), Golonka (1994; 2011), Ziegler (1982, 1990), Markwick (2000; 2004; 2007; 2011; 2015), and most other palaeogeographers.

The classification used here follows that of Ziegler et al. (1985), differentiating shelf environments by depth (Figure 106).

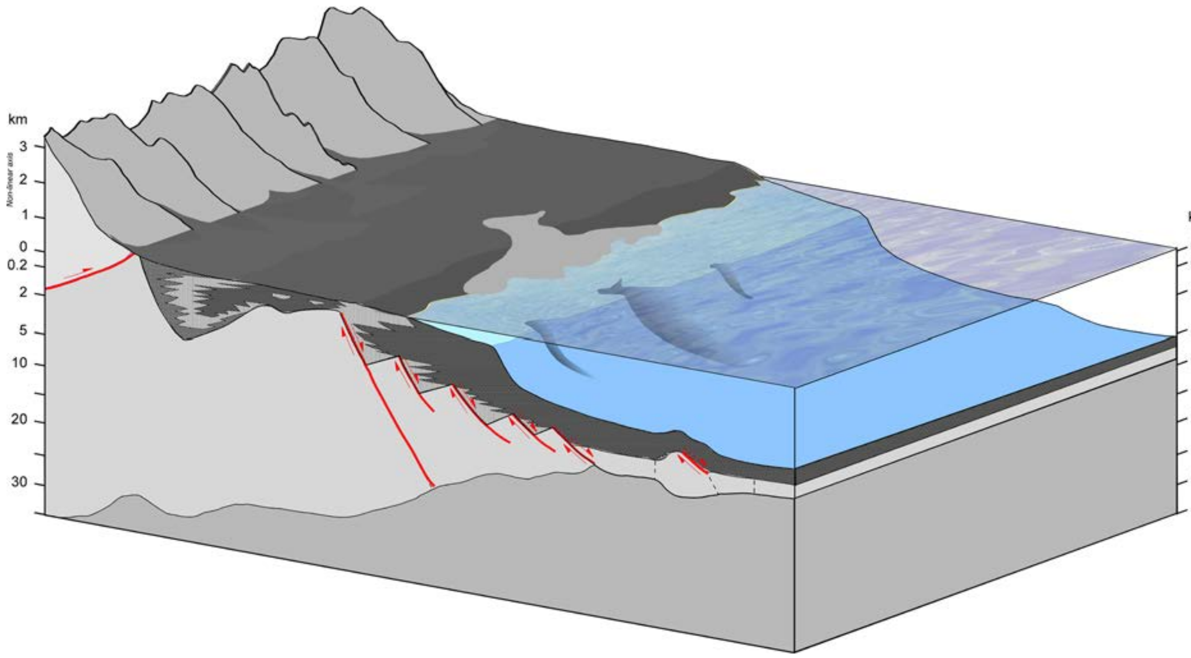


Figure 105. Block diagram with the distribution of marine depositional environments represented on the hypothetical landscape block diagram shown in Figure 4.

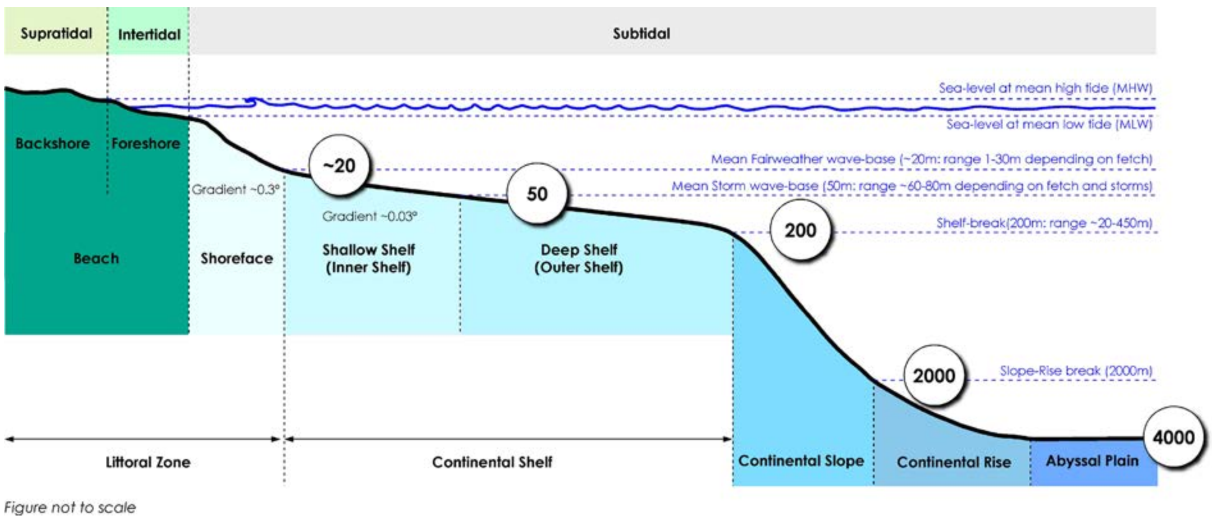


Figure 106. The distribution of marine and coastal environments related to water depth. The numbers in circles represent the typical depths used to define marine environments in paleogeographic mapping following Ziegler et al. (1985)

9.3.1. Shelf systems

Shelf environments are typically associated with marine settings on continental crust. Shelves extend from continental interiors (terrestrial to coastal environments) out to a point at which there is a significant change in slope, the shelf break. Although this is a description of the stratigraphic architecture and evolves through time, its position is underpinned by crustal architecture and the history of sedimentation.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E510	Sh_{sh}	Shallow shelf	205 / 250 / 255	From the shoreface down to average storm wave-base. For paleogeographic mapping, the shoreface is rarely preserved over large areas and so the shallow shelf category is, by default, taken to represent depths 0-50 m. Additional information may modify the depth assignment, such as the delineation of the shoreface or deeper shelf. **Map abbreviation field entry, "Sh_{sh}"**
E520	Sh_{dp}	Deep Shelf	185 / 245 / 255	From the storm-wave base down to the shelf break depth, which is today at c.200 m on average. For paleogeographic mapping, the shelf break is assumed to be at c.200m paleodepth, unless additional information modifies this. **Map abbreviation field entry, "Sh_{dp}"**
E530	Sh_{vdp}	Very Deep Shelf	165 / 240 / 255	Shelf depths below the average shelf break depth of 200m. This includes intrashelf basins and deep shelves at the distal ends of ramps during maximum transgression. This depth-related classification is used in paleogeographic mapping where there is additional information that indicates greater depths than are average for continental shelves today (>200m). Where there is no additional information then the assumption is that the shelf break is at c.200m and anything below that depth is the slope and therefore subject to slope processes. **Map abbreviation field entry, "Sh_{vdp}"**

Figure 107. The default fill pattern, symbol ID code, and explanation for continental shelf depositional environments. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description).

9.3.2. Deep marine depositional systems

ID	SYMBOL	DESCRIPTION	RGB	NOTES
E540	Sl	Slope	125 / 220 / 255	The continental slope is defined by Doyle & Pilkey (Doyle and Pilkey, 1979) the steeper part of the margin between the shelf break and the point at which the gradient becomes <1:40, which then defines the start of the Continental Rise. These boundaries can vary in depth. But for simplicity, and given uncertainties in the past we have used a cutoff value of -2000m. **Map abbreviation field entry, "Sl"**
E550	R	Rise	135 / 200 / 235	The Continental Rise is that part of the margin between the slope and Abyssal Plain typified by gradients of <1:40 Following Ziegler et al (A.M. Ziegler et al., 1985) we have assigned a depth to the limits of 2000 and 4000m. **Map abbreviation field entry, "R"**
E560	AP	Abyssal Plain	110 / 170 / 255	Representing the flatter areas of the ocean floor extending from the base of the continental rise to the 'rises' associated with mid-ocean ridges. These are the older parts of the ocean crust where the ocean crust has cooled sufficiently, and thermal subsidence is minimal. Although abyssal plains4000m - 5000m. **Map abbreviation field entry, "AP"**
E570	T	Trench	65 / 120 / 255	Trenches are narrow bathymetric lows parallel with and related to subduction marking the location at which one plate passes under another, By definition these mark plate boundaries. As crust is 'pulled' down by the subducting slab this results in a lowered bathymetry in which sediments can accumulate. Trench depths and geometries can vary depending on the angle of subduction, the age and composition of the plates involved and sediment supply. On the Peruvian margin areas of the trench are filled by sediment from the actively uplifting Andes. **Map abbreviation field entry, "T"**

Figure 108. The default fill pattern, symbol ID code, and explanation for deep marine depositional environments. The format for all depositional environment symbol codes is as follows: "E" + "###." The three-digit number value differentiates the type of environment (see description).

9.4. Base-level

ID	SYMBOL	DESCRIPTION	RGB	NOTES
n/a		Above base-level	204 / 204 / 255	These are areas of net erosion and no deposition.
n/a		Below base-level	204 / 255 / 153	These are areas of net (potential) deposition.

Figure 109. The default fill color, symbol ID code, and explanation for base-level. There is no symbol ID for this symbology.

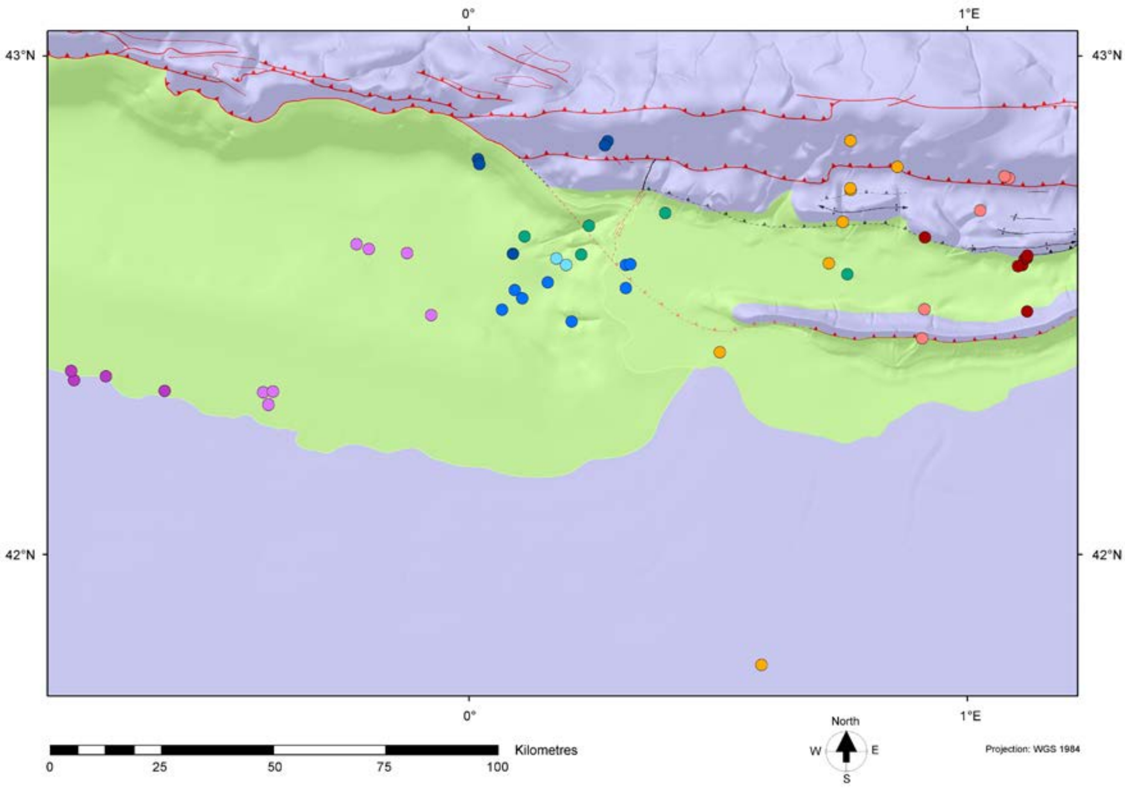


Figure 110. The distribution of contemporary base-level at the time of this Early Eocene, palinispastically reconstructed map of the central Pyrenees. This is shown with respect to a fixed Axial Zone (Markwick, 2018). The latitude and longitude are present-day. The colored circles mark restored field locations used in our Pyrenees paleogeography study.

Deformed Cretaceous carbonates at Plan De Larri in the Axial Zone of the central Pyrenees. An area of recent uplift above the contemporary base level.

Deep-water turbidite sands, silts and mudstones. Early Eocene, Arro, central Pyrenees, Spain.

9.5. Lithologies and Qualifiers

Lithologies, like depositional environments, can change rapidly spatially and temporally in response to changing accommodation space. In most paleogeographic reconstructions the 'dominant' lithology of the depositional environment is usually represented, which can miss key lithologies of interest. Lithological qualifiers can be used on the maps to show key lithological detail if needed, such as the presence of thin coal layers or evaporites used to constrain model results or the presence of thin, coarse sand units in turbidite systems that are critical for understanding reservoir potential. Alternatively, additional higher-resolution depositional and lithological maps need to be drawn.

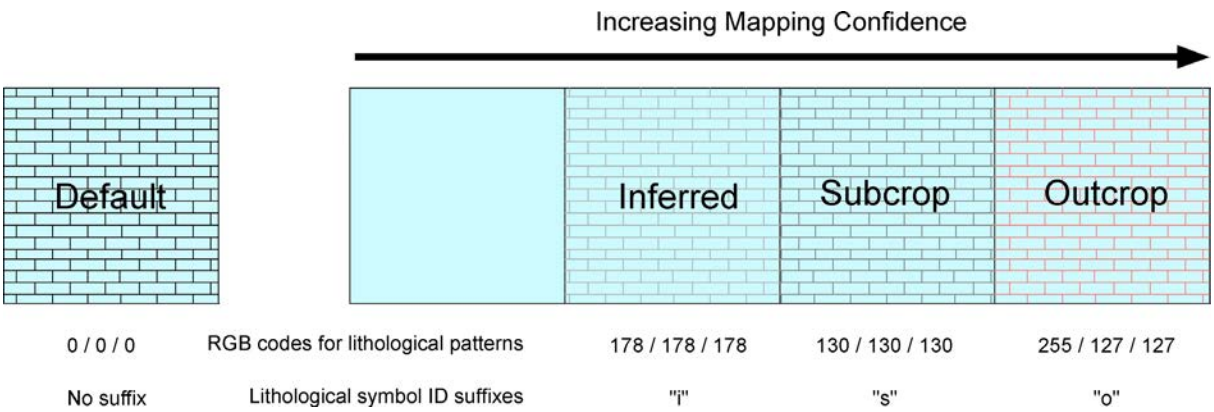


Figure 111. Mapping confidence. The use of fill patterns to show different levels of mapping confidence is based on the mapping methods of Vinogradov et al. (1968; 1969; 1967; 1968). Increasing mapping confidence is indicated by adding the lithological symbology with different line colors. The RGB color codes are for the lithological pattern. In this example, the background color represents the shallow shelf marine deposition environment. See Figure 113 for an example.

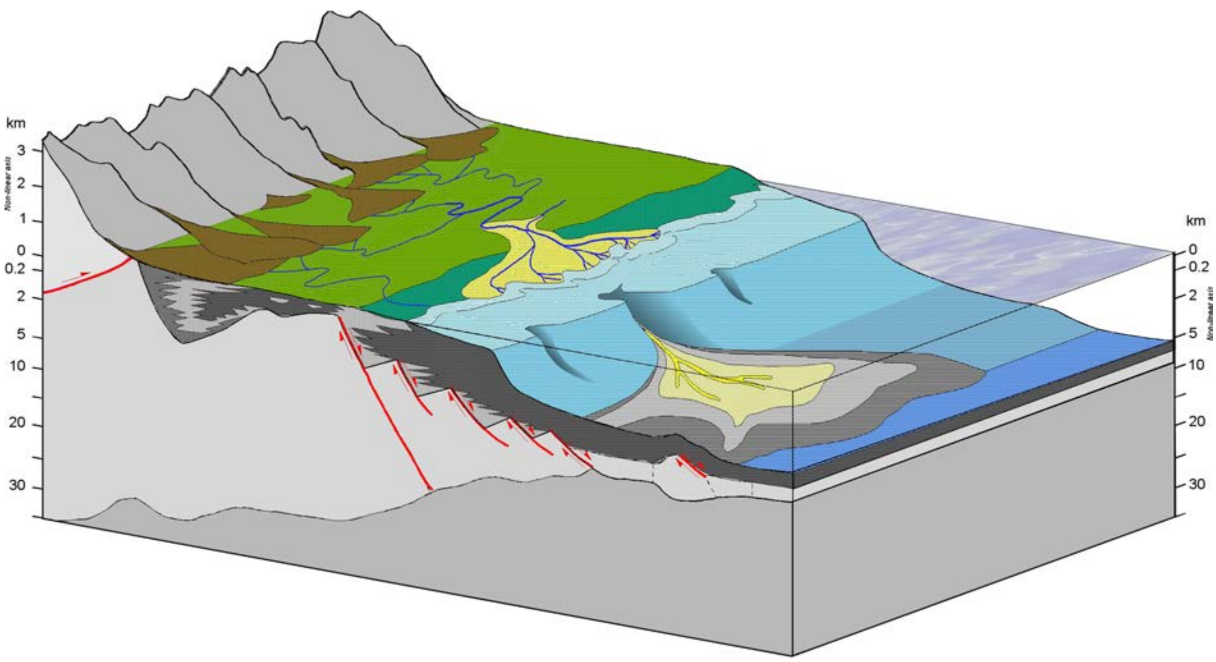


Figure 112. A block diagram showing the representation of the lithological information within the depositional settings in the schematic landscape shown in Figure 4.

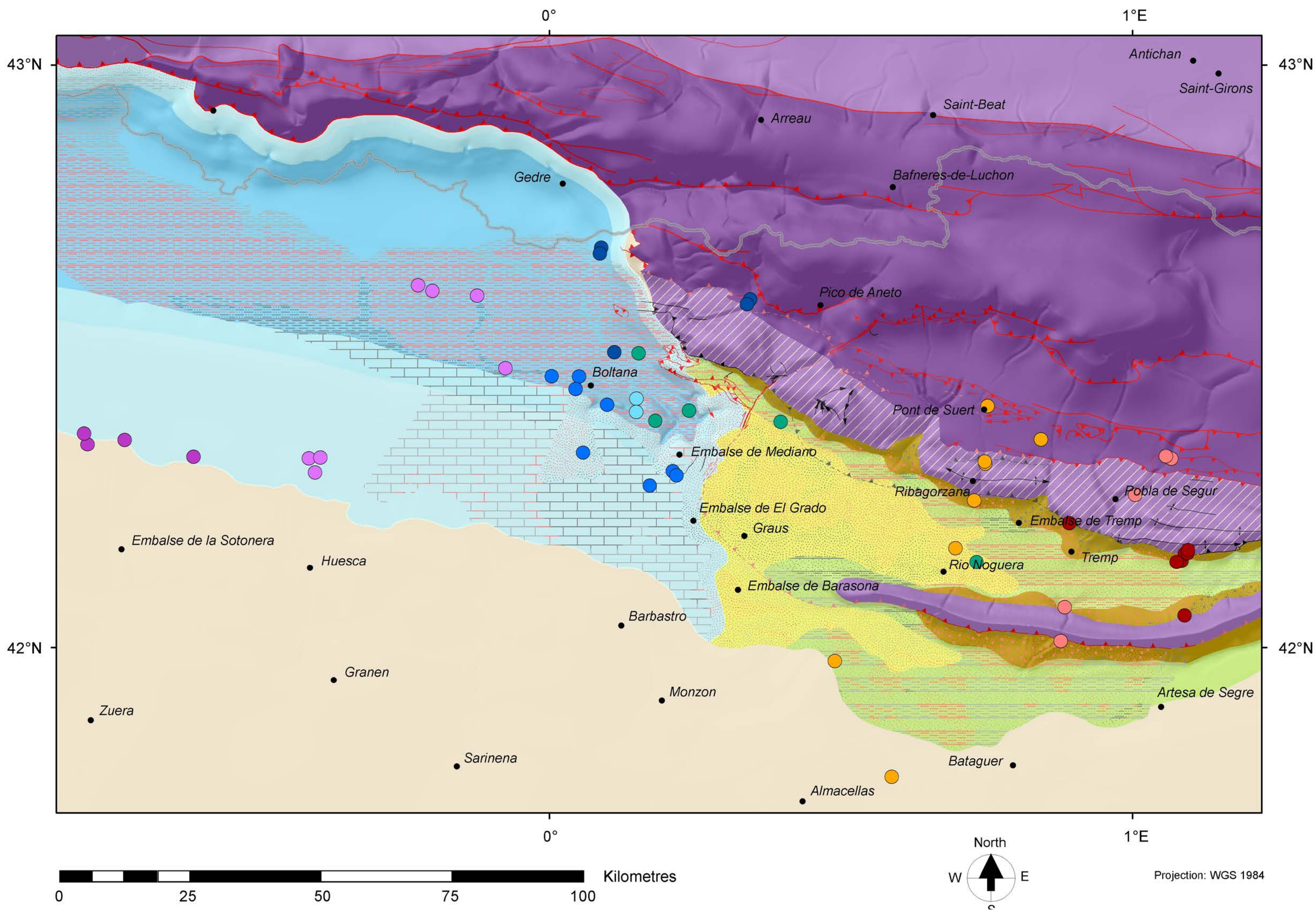


Figure 113. A map showing the use of lithological symbology to differentiate between areas based on outcrop data, subcrop, and inferred. The areas without any lithological symbology are those where the interpretation is most uncertain. This example uses the rigid plate palaeogeographic solution for the Early Eocene of the central Pyrenees. Outcrop extent is for the mapped Early Eocene as given on the BRGM and IGME 1:400 000 map of the central Pyrenees (BRGM and IGME, 2008). Colored circles are localities shown in Figure 110.

In this scheme, all lithological symbol codes are prefixed with an “L” and then a suffix is added to differentiate between lithologies based on “o” outcrop data, “s” subcrop data, or is “i” inferred. The default symbology has no suffix.

The graphical representation of lithologies is relatively standardized. The symbologies used here largely follow those of the USGS and reports of the deep-sea drilling projects (DSDP, ODP, and IODP). Following Vinogradov et al. (1967; 1968; 1968; 1969), the lithological symbology is also used to show data confidence and coverage (Figure 111).

9.5.1. Clastics

Coarse-grained

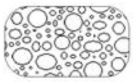
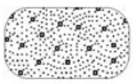
CODE	SYMBOL	DESCRIPTION	NOTES
L100		Conglomerate	Picture bitmap is drawn by PJM Rounded clasts > 2mm. Variable sorting Associated with beach or fluvial processes
L110		Breccia	Picture bitmap based on USGS 606 Angular clasts >2mm. Variable sorting Described as being an immature sediment having been subjected to limited or no reworking in fluvial, beach or marine settings.
L120		Gravel, Grit	Picture bitmap based on USGS 602 Clasts c.2- 4mm (synonymous with fine conglomerate). Grit is a colloquial term for a fine conglomerate or coarse sandstone. Gravel is usually a fine conglomerate though it is loosely applied. Grains are generally rounded, though this is not strictly enforced. Associated with high energy environments such as rivers or beaches.
L150		Diamictite	Picture bitmap is drawn by PJM Variable clast sizes, roundness, and sorting. Poor sorting indicates a lack of hydrodynamic sorting. Usually associated with glacial processes (tillites), but can form in mass transport deposits (MTDs).

Figure 114. The default fill pattern, symbol ID code, and explanation for the composition of mapped coarse-grained clastic rocks. The format for all lithology symbol codes is as follows: “L” + “###” + “Confidence.” The three-digit number value differentiates the type of lithology (see description). “Confidence” in this context refers to the confidence with which the lithology is assigned and whether this is based on data from outcrop (suffix “o”), subcrop (suffix “s”), or is inferred (suffix “I”); see Figure 111.

Medium to fine-grained

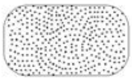
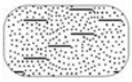
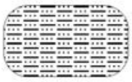
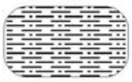
CODE	SYMBOL	DESCRIPTION	NOTES
L200		Sandstone	Picture bitmap based on USGS 607 Grain size 0.0625 – 2mm in size. Dominantly quartz grains. Arkoses >25% feldspar.
L240		Argillaceous sandstone	Picture bitmap based on USGS 612. Grains with a significant amount of clay or mud.
L250		Silt, siltstone	Picture bitmap based on USGS 616. Silt ranges in grain size from 0.0039 – 0.0625mm.
L280		Silty mudstone	Picture bitmap based on USGS 619. A mudstone with an admixture of silt-sized particles.

Figure 115. The default fill pattern, symbol ID code, and explanation for the composition of mapped medium to fine-grained clastic rocks. The format for all lithology symbol codes is as follows: "L" + "###" + "Confidence." The three-digit number value differentiates the type of lithology (see description). "Confidence" in this context refers to the confidence with which the lithology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 111.

Early Cretaceous clastics passing up section (right) into chalks and marls. Lulworth Cove, Dorset, England

Fine-grained

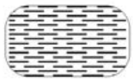
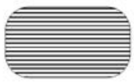
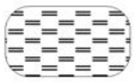
CODE	SYMBOL	DESCRIPTION	NOTES
L300		Mudstone	Picture bitmap based on USGS 607 Grain size 0.0625 – 2mm in size. Dominantly quartz grains. Arkoses >25% feldspar.
L310		Shale	Picture bitmap based on USGS 612. Grains with a significant amount of clay or mud.
L320		Clay, Claystone	Picture bitmap based on USGS 616. Silt ranges in grain size from 0.0039 – 0.0625mm.

Figure 116. The default fill pattern, symbol ID code, and explanation for the composition of mapped fine-grained clastic rocks. The format for all lithology symbol codes is as follows: "L" + "###" + "Confidence." The three-digit number value differentiates the type of lithology (see description). "Confidence" in this context refers to the confidence with which the lithology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 111.

9.5.2. Carbonates

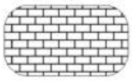
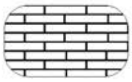
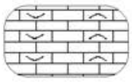
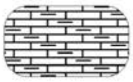
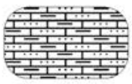
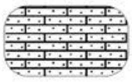
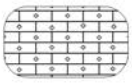
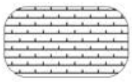
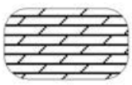
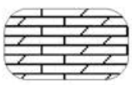
CODE	SYMBOL	DESCRIPTION	NOTES
L570		Carbonate, undifferentiated	A rock containing >50% carbonate minerals. *Picture bitmap created by pjm based on ESRI brick symbol.*
L500		Limestone	A sedimentary rock with >50% calcite (+aragonite) and dolomite, in which calcite is more abundant than dolomite (Rodgers 1954). *Picture bitmap based on USGS 627.*
L505		Marl	A mudstone that is rich in CaCO3. The Schlumberger Oilfield Glossary gives a composition of 35-65% clay and 65-35% CaCO3, though other definitions include mixtures with silt-sized grains of quartz and feldspar. *Picture bitmap created by pjm based on DSDP marl fill symbol.*
L503		Bioclastic (fossiliferous) limestone	A packstone in the Dunham classification. Which then includes coquinas (*ala* Rodgers 1954). *Modified from carbonate symbol with addition of 'shells'.*
L510		Argillaceous Limestone	Limestones including 10-40% clay minerals. *Picture bitmap based on USGS 638.*
L520		Silty Limestone	Limestones including a percentage of silt-sized clastic particles. *Picture bitmap based on USGS 637.*
L530		Arenaceous Limestone	Limestones including a percentage of sand-sized quartz, feldspar of other clastic particles. *Picture bitmap based on USGS 636.*
L565		Oolitic limestone	Limestones comprised of ooliths (carbonate spheres with a concentric internal structure) often cemented by a lime mud. *Redrawn by pjm from brick pattern to match USGS 635.*
L560		Chalk	A soft, white porous limestone formed primarily of coccoliths. *Picture bitmap created by pjm based on symbology used in the DSDP volumes.*
L550		Dolomite, Dolostone	A sedimentary rock with >50% calcite (+aragonite) and dolomite, in which dolomite is more abundant than calcite (Rodgers 1954). *Picture bitmap is based on USGS 642.*
L555		Dolomitic limestones	A limestone in which the mineral dolomite is <10%, but <50% of the carbonate constituents (Rodgers 1954). *Picture bitmap created by pjm based on USGS 641.*

Figure 117. The default fill pattern, symbol ID code, and explanation for the composition of mapped carbonate rocks. The format for all lithology symbol codes is as follows: "L" + "###" + "Confidence." The three-digit number value differentiates the type of lithology (see description). "Confidence" in this context refers to the confidence with which the lithology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 111.

9.5.3. Oozes

Oozes are typical of the abyssal plain environments.

Carbonate

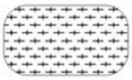
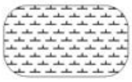
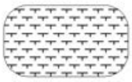
CODE	SYMBOL	DESCRIPTION	NOTES
L600		Calcareous ooze	An ooze with >30% CaCO3 with the remaining material comprised clay and fine silt (McCoy and Sancetta, 1985). *Picture bitmap by PJM based on DSDP.*
L610		Nannofossil ooze	A calcareous ooze comprising >30% nannofossil tests with the remaining material comprised clay and fine silt (McCoy and Sancetta, 1985). *Picture bitmap by PJM based on DSDP.*
L620		Foraminiferal ooze	A calcareous ooze comprising >30% foraminiferal tests with the remaining material comprised clay and fine silt (McCoy and Sancetta, 1985). *Picture bitmap by PJM based on DSDP.*

Figure 118. The default fill pattern, symbol ID code, and explanation for the composition of mapped carbonate ooze rocks. The format for all lithology symbol codes is as follows: "L" + "###" + "Confidence". The three-digit number value differentiates the type of lithology (see description). "Confidence" in this context refers to the confidence with which the lithology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 111.

Siliceous

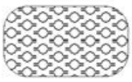
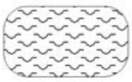
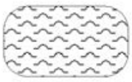
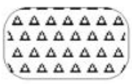
CODE	SYMBOL	DESCRIPTION	NOTES
L630		Siliceous ooze	An ooze with >30% SiO2 with the remaining material comprised clay and fine silt (McCoy and Sancetta, 1985). *Picture bitmap created by PJM based on DSDP symbology.*
L640		Diatom ooze	A siliceous ooze with >30% SiO2 dominated by diatom tests with the remaining material comprised clay and fine silt (McCoy and Sancetta, 1985). *Picture bitmap created by PJM based on DSDP symbology.*
L650		Radiolarian ooze	A siliceous ooze with >30% SiO2 dominated by radiolarian tests with the remaining material comprised clay and fine silt (McCoy and Sancetta, 1985). *Picture bitmap created by PJM based on DSDP symbology.*
L660		Porcellanite	A hard, siliceous rock with impurities including clay and carbonates, in which the silica is mostly opal-CT. Porcellanite is also distinguished by its texture with the appearance of unglazed porcelain, hence the name. Porcellanite is less dense and more porous than chert (Hein et al., 1981). *Picture bitmap created by PJM based on DSDP symbology.*

Figure 119. The default fill pattern, symbol ID code, and explanation for the composition of mapped siliceous ooze rocks. The format for all lithology symbol codes is as follows: "L" + "###" + "Confidence." The three-digit number value differentiates the type of lithology (see description). "Confidence" in this context refers to the confidence with which the lithology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 111.

Red clay

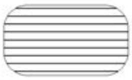
CODE	SYMBOL	DESCRIPTION	NOTES
L625		Red (Pelagic) Clay	Pelagic red clay is an ooze dominated by non-biogenic, clay particles and a biogenic concentration of <15% (McCoy and Sancetta, 1985). *Based on the symbol used in some DSDP reports for Pelagic clay*

Figure 120. The default fill pattern, symbol ID code, and explanation for the composition of mapped red (pelagic) clay rocks. The format for all lithology symbol codes is as follows: "L" + "###" + "Confidence." The three-digit number value differentiates the type of lithology (see description). "Confidence" in this context refers to the confidence with which the lithology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 111.

9.5.4. Chemical lithologies

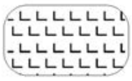
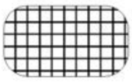
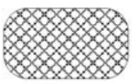
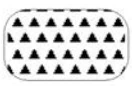
CODE	SYMBOL	DESCRIPTION	NOTES
L700		Evaporites, undifferentiated	Any water-soluble mineral formed by concentration and crystallization due to evaporation from an aqueous solution. *Picture bitmap created by PJM based on DSDP using ESRI cemetery symbol.*
L710		Halite	Halite (NaCl) Forms at concentrations of 10-12 x average seawater (Warren, 2016). *Picture bitmap created by PJM based on DSDP by building ESRI line symbol USGS 668.*
L720		Gypsum, Anhydrite	Gypsum (CaSO4.2H2O and anhydrite (CaSO4) Forms at concentrations of 4-5 x average seawater (Warren, 2016). *Picture bitmap created by PJM based on DSDP by building ESRI line symbol See also USGS 667.*
L730		Potash Salt	K-rich salts including sylvite (KCl), Carnallite (KMgCl3.6(H2O). These are much rarer in the record because of their solubility. Formed when average seawater has been concentrated 70-90 times (Warren, 2016). *Picture bitmap created by PJM based on DSDP by building ESRI line symbol USGS 661 (flint clay).*
L780		Chert	Chert refers to any silica-rich, hard, dense, vitreous sedimentary rock. In most cherts, the silica comprises quartz and chalcedony (Hein et al., 1981). *Picture bitmap created by PJM based on DSDP symbol.*

Figure 121. The default fill pattern, symbol ID code, and explanation for the composition of mapped chemical rocks. The format for all lithology symbol codes is as follows: "L" + "###" + "Confidence." The three-digit number value differentiates the type of lithology (see description). "Confidence" in this context refers to the confidence with which the lithology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 111.

9.5.5. Interbedded lithologies

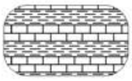
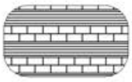
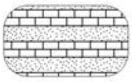
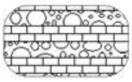
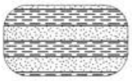
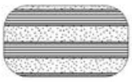
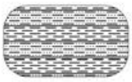
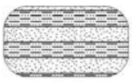
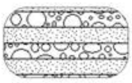
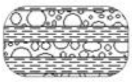
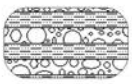
CODE	SYMBOL	DESCRIPTION	NOTES
L412		Interbedded Limestone and Mudstone	*Picture bitmap by PJM based on USGS symbols.*
L414		Interbedded limestone and shale	*Picture bitmap by PJM based on USGS symbols.*
L416		Interbedded limestone and sandstone	*Picture bitmap by PJM based on USGS symbols.*
L418		Interbedded limestone and conglomerate	*Picture bitmap by PJM based on USGS symbols.*
L422		Interbedded sandstone and mudstone	*Picture bitmap by PJM based on USGS symbols.*
L424		Interbedded sandstone and shale	*Picture bitmap by PJM based on USGS symbols.*
L425		Interbedded siltstone and mudstone	*Picture bitmap by PJM based on USGS symbols.*
L426		Interbedded sandstone and siltstone	*Picture bitmap by PJM based on USGS symbols.*
L428		Interbedded sandstone and conglomerate	*Picture bitmap by PJM based on USGS symbols.*
L448		Interbedded mudstone and conglomerate	*Picture bitmap by PJM based on USGS symbols.*
L458		Interbedded siltstone and conglomerate	*Picture bitmap by PJM based on USGS symbols.*

Figure 122. The default fill pattern, symbol ID code, and explanation for the composition of mapped interbedded units. The format for all lithology symbol codes is as follows: "L" + "###" + "Confidence". The three-digit number value differentiates the type of lithology (see description). "Confidence" in this context refers to the confidence with which the lithology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 111.

9.5.6. Non-deposition

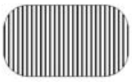
CODE	SYMBOL	DESCRIPTION	NOTES
L000		Non-deposition	For depositional environments with no deposition. By definition these are below contemporary base-level. *PJM, Vertical lines*

Figure 123. The default fill pattern, symbol ID code, and explanation for non-depositional settings. This is included as a lithology in our databases because it represents the potential for sediment deposition, but where that deposition has not occurred. The format for all lithology symbol codes is as follows: "L" + "###" + "Confidence." The three-digit number value differentiates the type of lithology (see description). "Confidence" in this context refers to the confidence with which the lithology is assigned and whether this is based on data from outcrop (suffix "o"), subcrop (suffix "s"), or is inferred (suffix "I"); see Figure 111.

9.6. Grain Size

These are based on the standard colors used in published chronostratigraphies and industry stratigraphic charts.

ID	SYMBOL	DESCRIPTION	RGB	NOTES
n/a	vcc	Very coarse clastics	255 / 170 / 85	e.g. breccias, conglomerates **Map abbreviation field entry, "vcc"**
n/a	cc	Coarse clastics	255 / 255 / 142	e.g. sands **Map abbreviation field entry, "cc"**
n/a	fc	Fine clastics	209 / 255 / 115	e.g. muds, shales, clays **Map abbreviation field entry, "fc"**
n/a	$-CO_3$	Carbonates	117 / 173 / 255	e.g. chalks, limestones, dolomites **Map abbreviation field entry, "$-CO_3$"**
n/a	evap	Evaporites	248 / 200 / 238	e.g. halite, gypsum **Map abbreviation field entry, "evap"**

Figure 124. The default fill colors, and explanation for grain size symbology. At the current time these are not allocated a symbol ID.

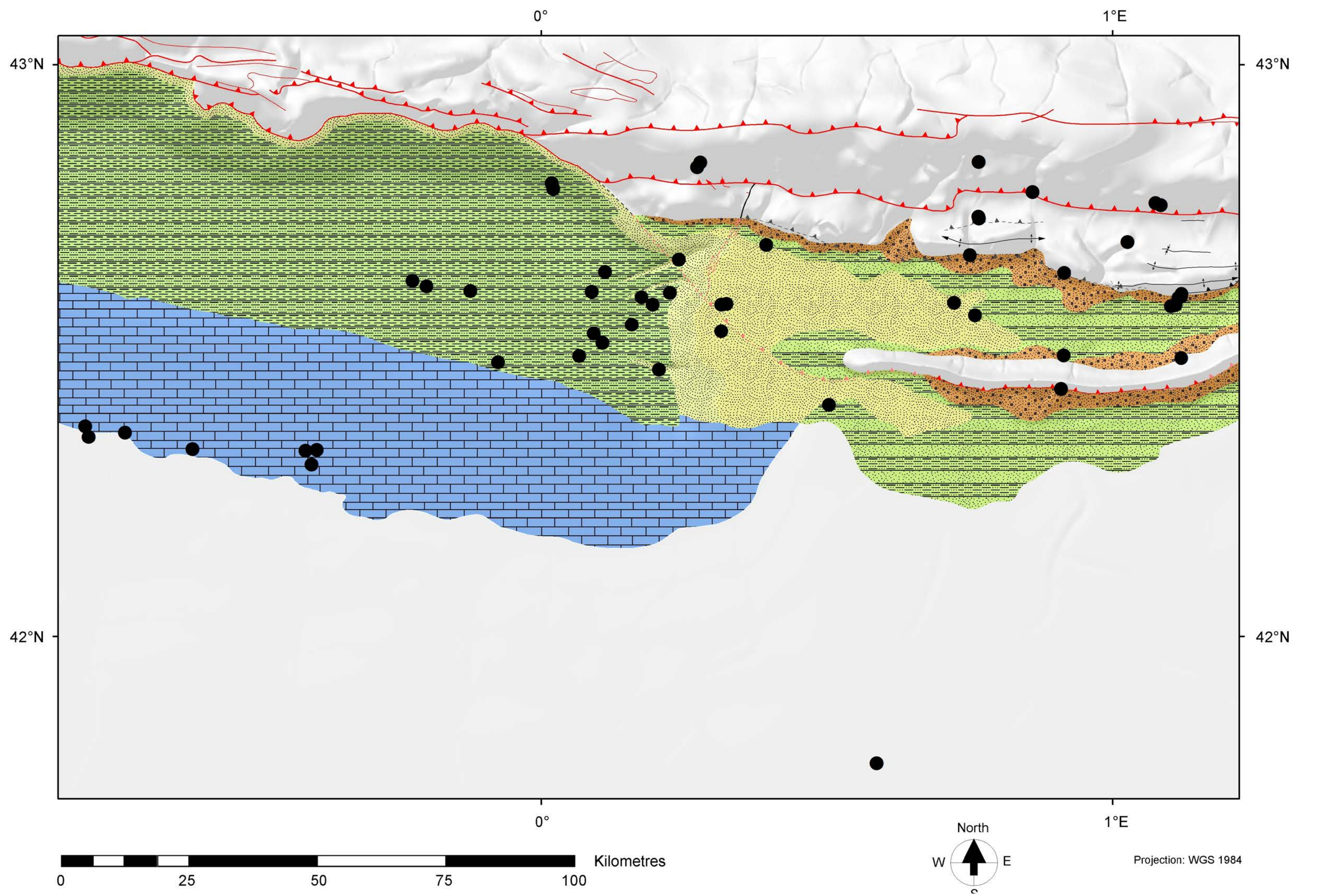


Figure 125. An Early Eocene palinspastically reconstructed map of the central Pyrenees symbolized according to the dominant lithology. This is a useful way of identifying large-scale changes in lithology, especially siliciclastic grain size trends and the distribution of carbonates compared with siliciclastics. The latitude and longitude are present-day. The black circles mark the restored field locations shown in Figure 111.

9.7. Lithological Qualifiers

Qualifiers are point data used to refine polygon definitions and/or provide additional information for analysis, for example, paleoclimate proxy data, provenance information, minerals, at a point in space and time. Ziegler et al. (1985) used numbers to summarize the proportion of clastics and carbonates (Table 2) and letters to represent lithologies (Table 3). We have included this scheme in our databases for continuity. We have also expanded this approach for a range of information tied to our Geological Localities database and Wells database.

In this 2023 edition, we provide only one set of examples from the lithological qualifiers databases for grain size (Figure 126).

ID	SYMBOL	DESCRIPTION	RGB	NOTES
n/a		Very coarse clastics	255 / 170 / 85	e.g. breccias, conglomerates.
n/a		Coarse clastics	255 / 255 / 142	e.g. sands.
n/a		Fine clastics	209 / 255 / 115	e.g. muds, shales, clays
n/a		Carbonates	117 / 173 / 255	e.g. chalks, limestones, dolomites
n/a		Evaporites	248 / 200 / 238	e.g. halite, gypsum

Figure 126. The default fill colors, and explanation for grain size lithological qualifiers. At the current time these are not allocated a symbol ID.

CODE	EXPLANATION
1	Sandstone/conglomerate dominant
2	Sandstone with shale
3	Shale with sandstone
4	Shale
5	Clastics with some carbonate
6	Carbonate with some clastics
7	Pure carbonates

Table 2. The clastic-carbonate index of Ziegler et al (1985). Category 1 has been modified in this version to include sandstone dominant units as well as conglomerate-dominant systems as given the original version of the index.

ABBREVIATION	EXPLANATION
Clastic-Carbonate sediments	
C	Conglomerate
S	Sandstone
M	Mudstone, shale
L	Carbonate
Climatically significant sediments	
T	Tillite and glacio-marine beds
P	Peat, coal
D	Dolomite
G	Gypsum, anhydrite
H	Halite & bittern salts
E	Evaporites (G & H above)
R	Reefs
Oceanographically significant sediments	
Q	Bedded chert, radiolarite, diatomite
V	Phosphorite
W	Ferromanganese nodules & concretions
X	Limonite
Y	Chamosite
Z	Glauconite
Soils	
N	Non-marine, non-deposition
Acid-basic volcanic sequence	
K	Rhyolite, rhyodacite, trachyte, latite
A	Andesite, basaltic andesite, dacite
B	Basalt, phonolites, basanites, dolerite dykes (dikes)
Acid-basic intrusive sequence	
J	Granite, monozonite, adamellite, alkali granite
I	Granodiorite, diorite, albitic granite, tonalite
F	Foidite, foyaite, essexite, theralite, etc
"Cooling ages" on intrusive and metamorphic rocks	
U	Uplift & unroofing

Table 3. The basic lithological types used in regional paleography as described in Ziegler et al (1985)


Precambrian basement, Ontario, Canada

10. Metamorphic Petrology

10.1. Metamorphic rocks

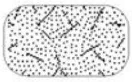
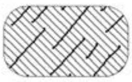
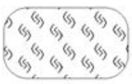
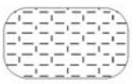
CODE	SYMBOL	DESCRIPTION	NOTES
L900		Metamorphic, undifferentiated	*Picture bitmap based on USGS 701*
L910		Quartzite	A non-foliated quartz-rich metamorphic rock formed from quartz-rich sandstone protoliths. The term metaquartzite is frequently applied to different metamorphic quartzite from sedimentary quartz-rich sandstones. *Picture bitmap based on USGS 702*
L920		Slate	A fine-grained, foliated metamorphic rock formed from metamorphism of fine-grained clastic protoliths (viz., shales or mudstones). The foliation need not represent the original bedding, but reflects the orientation of compressive stresses applied to the rock during metamorphism and the development of the 'slaty cleavage' *Picture bitmap based on USGS 703.*
L930		Schist	A medium-grained, foliated metamorphic rock. Formed at high temperatures (higher grade) than slate and phyllite). *Picture bitmap based on USGS 705*
L940		Gneiss	A coarse grained, foliated metamorphic rock formed at high temperatures and pressures. This includes orthogneiss (igneous protolith) and paragneiss (sedimentary protolith). *Picture bitmap by PJM based on USGS symbols.*
L950		Serpentine	An ultramafic rock that has undergone serpentinization, which combines hydration and low temperature metamorphism. *Picture bitmap based on USGS 710.*
L960		Marble	Metamorphosed carbonates comprised recrystallized carbonate minerals. Marbles may be foliated reflecting original lithological variations. *Picture bitmap constructed by PJM by modifying the carbonate indeterminate symbol.*

Figure 127. Fill patterns with their associated symbol codes and explanations for differentiating the major metamorphic rock petrologies.

Paleogene rippled sandstones. Tremp Basin, central Pyrenees

11. Geomorphological Features

The symbols in this category comprise features that either describe transport direction or the status of the palaeo-shorelines drawn onto the palaeogeographies. These are specifically designed for use with source-to-sink reconstructions. A wealth of other features can be added in the future.

The line symbols differ from point data, for example, wind and ocean current directions, bed shear stress, and paleocurrent directions tied to a specific outcrop or well datum, in that they are more generalized representations of transport direction. Mapping confidence is captured in the attribute table as with other databases, so 'generalized' does not necessarily mean imprecise. Vectors tied to point data, such as wells, relate to a specific point in time and space, such as a particular bed of rock or core.

SYMBOL	DESCRIPTION	RGB	LINE WEIGHT
TP110	Submarine transport direction	168 / 112 / 0	1.5 pt
TP110i	Submarine transport direction, inferred	215 / 194 / 158	1.5 pt dashed
TP120	Water transport direction	0 / 112 / 255	1.5 pt
TP120i	Water transport direction, inferred	115 / 178 / 255	1.5 pt dashed
TP130	Wind transport direction	255 / 255 / 0	1.5 pt
TP130i	Wind transport direction, inferred	255 / 255 / 190	1.5 pt dashed
TP140	Ice transport direction	197 / 0 / 255	1.5 pt
TP140i	Ice transport direction, inferred	255 / 190 / 232	1.5 pt dashed

Figure 128. Transport pathway line symbol set. Line symbols for sediment transport pathways by the general process used in the (paleo)drainage analysis and palaeogeographic mapping with their associated symbol codes. This figure includes the symbol id codes, RGB colors, and line weights. As with most symbology in our legends, the inferred representation of a line feature will generally have a lighter hue and be dashed. Observed paleocurrent directions from outcrop or well are also included in our databases, but on maps, are represented by arrows assigned to a point location.

SYMBOL	DESCRIPTION	RGB	LINE WEIGHT
GM500	Submarine canyon	137 / 68 / 68	3.0 pt
GM500i	Submarine canyon, inferred	137 / 68 / 68	3.0 pt dashed
GM100	Paleo-shoreline	0 / 112 / 255	1.8 pt
GM100i	Paleo-shoreline, inferred	0 / 92 / 230	1.8 pt dashed
GM120	Paleo-shoreline, maximum transgression	0 / 77 / 168	1.8 pt
GM120i	Paleo-shoreline, maximum transgression, inferred	0 / 88 / 168	1.8 pt dashed
GM130	Paleo-shoreline, maximum regression	115 / 178 / 255	1.8 pt
GM130i	Paleo-shoreline, maximum regression, inferred	115 / 178 / 255	1.8 pt dashed

Figure 129. Geomorphological line symbol set for paleoshorelines and canyons. This figure includes the symbol id codes, RGB colors, and line weights. Drainage and palaeo-drainage are represented by dashed red lines in some instances where white would not be clear. As with most symbology in our legends, the inferred representation of a line feature will be dashed.

SYMBOL	DESCRIPTION	RGB	LINE WEIGHT
GM600	River	0 / 112 / 255	1.2 pt
GM600i	River, inferred	0 / 112 / 255	1.2 pt dashed
GM650	paleo-River	0 / 197 / 255	1.2 pt
GM650i	paleo-River inferred	0 / 197 / 255	1.2 pt dashed
GM610	River trend	0 / 112 / 255	3.0 pt
GM610i	River trend, inferred	0 / 112 / 255	3.0 pt dashed
GM660	paleo-River trend	0 / 197 / 255	3.0 pt
GM660i	paleo-River trend, inferred	0 / 197 / 255	3.0 pt dashed
GM670	paleo-Drainage divide	255 / 255 / 255 or 255 / 0 / 0	3.0 pt
GM670i	paleo-Drainage divide, inferred	255 / 255 / 255 or 255 / 0 / 0	3.0 pt dashed

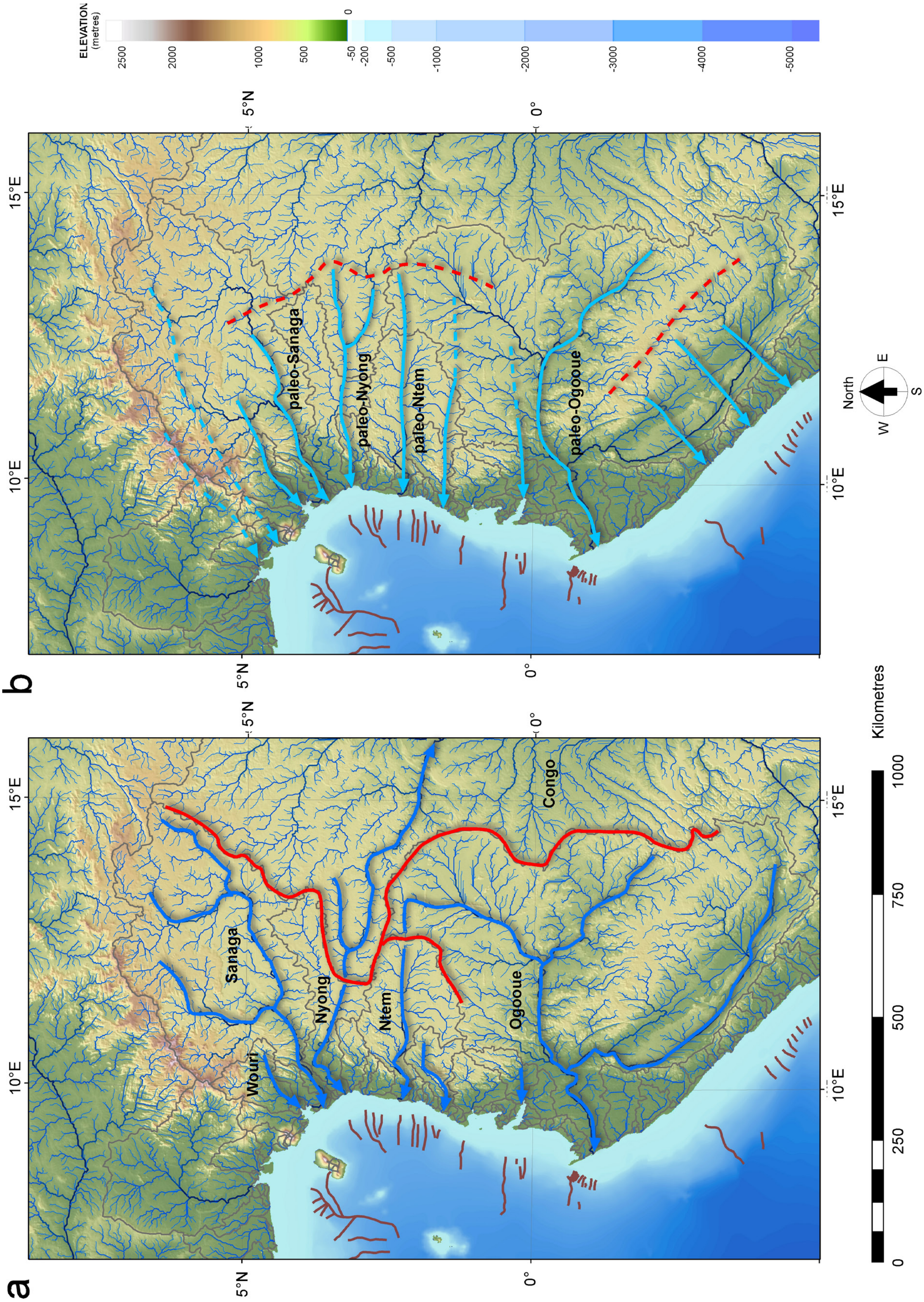
Figure 130. Geomorphological line symbol set for rivers and paleorivers. This figure includes the symbol id codes, RGB colors, and line weights. Drainage and palaeo-drainage are represented by dashed red lines in some instances where white would not be clear (e.g. on a white background). The river and paleoriver trends are the general patterns used to summarize networks in drainage analysis mapping. In contrast, the river and paleoriver lines are used for the actual or inferred position of these features. As with most symbology in our legends, the inferred representation of a line feature will be dashed.

Green River at Dinosaur National Monument, Carboniferous to Triassic section

SYMBOL	DESCRIPTION	RGB	LINE WEIGHT
1	Strahler order 1	0 / 112 / 255	0.8 pt
2	Strahler order 2	0 / 92 / 230	1.2 pt
3	Strahler order 3	0 / 80 / 230	1.3 pt
4	Strahler order 4	0 / 77 / 168	1.75 pt
5	Strahler order 5	0 / 38 / 115	1.8 pt
6	Strahler order 6	0 / 38 / 115	1.85 pt
7	Strahler order 7	0 / 38 / 115	1.9 pt
8	Strahler order 8	0 / 38 / 115	1.9 pt
9	Strahler order 9	0 / 38 / 115	1.9 pt
10	Strahler order 10	0 / 38 / 115	2.0 pt

Figure 131. The RGB color code and line width for the Strahler order line symbology used in our drainage analysis and shown in Figure 132.

Figure 132. Example of the application of the geomorphological symbol set for West Africa, as part of the drainage analysis results for major rivers from Cameroon to Congo (Markwick, 2019). (a) The main trends of the present-day rivers (dark blue lines) and drainage divides (red lines). Evidence for the reversed flow of the headwaters of the Nyong River, indicated by barbed confluences, is consistent with the capture of these headwaters by the Congo River due to the uplift of the Gabon craton. Similar evidence of capture is seen in the headwaters of the Ntem River, but in this case, capture is by the Ogooue River via the rapidly expanding Ivindo catchment. (b) The interpreted palaeo-drainage pattern indicated by analyzing the present-day drainage network patterns, indicators of flow change, incision patterns (using a high pass topographic filter), hypsometric curves (not shown here), river long profiles, geology, and structure. This is interpreted to represent the pre-Oligocene paleodrainage, on the basis that the uplift that has resulted in the interpreted changes is Oligo-Miocene in age. These results can then be added to the palaeogeographies for the pre-Oligocene and taken back to the last thermo-mechanical event.


a
b
Wouri
Sanaga
Nyong
Ntem
Ogooue
Congo
paleo-Sanaga
paleo-Nyong
paleo-Ntem
paleo-Ogooue
5°N
0°
10°E
15°E
ELEVATION
(metres)
2500
2000
1000
500
0
-50
-200
-500
-1000
-2000
-3000
-4000
-5000
Kilometres
0
250
500
750
1000
North
N
E
S
W

Juvenile alligators: Brazos Bend State Park, Texas.

12. Paleoclimatology: Climate Proxies

Most datasets that are plotted on paleogeography maps, such as wells in exploration, have their own suite of standard symbols. Others, such as climate proxies, do not. Since a major part of our research relates to the Earth system, especially paleoclimate modeling and analysis, we have included some of the climate proxy legends we use. These examples are based on those used in Markwick (2007).

ID	SYMBOL	DESCRIPTION	RGB	NOTES
n/a		Crocodylians	255 / 0 / 0	Crown group crocodilians, which includes living groups.
n/a		Crocodylomorphs	255 / 0 / 0 255 / 190 /190	Includes the broader groups related to crocodillians including groups that were traditionally referred as "Mesosuchians", "Protosuchians", "Thalattosuchians", "Notosuchians" and "*Sebecus*"
n/a		Turtles	0 / 112 / 255	All turtles. These also act as a taphonomic control for crocodilians.
n/a		Amphibians	56 / 168 / 0	All amphibians, indicative especially of hydrology
n/a		Dinosaurians	255 / 170 / 0	All dinosaurians.
n/a		Vertebrates, undifferentiated	225 / 225 / 225	All vertebrates, as a high-level taphonomic and sampling control.
n/a	C	Peats and coals	152 / 230 / 0	Peats, coals, brown coals, lignites
n/a	E	Evaporites	255 / 190 / 190	All evaporite deposits including halite, gypsum
n/a	R	Reefs	211 / 255 / 190	Biological reefs
n/a	T	Tillites	232 / 190 / 255	Diamictites with clear evidence of glacial deposition.
n/a	P	Phosphorites	190 / 232 / 255	Phosphorites as evidence of high productivity.

Figure 133. Symbol set used for climate proxies in Markwick (2007)

13. Topography and Bathymetry

Landscape information includes elevation (topography and bathymetry), rivers, lakes, cities, and other geographic features found in present-day reference atlases, such as the”Times Atlas” (Times Books 1988, 2014). For consistency, familiarity, and clarity, we follow the “Times Atlas” for elevation when using DEMs, and the default ESRI symbology sets for lakes and rivers.

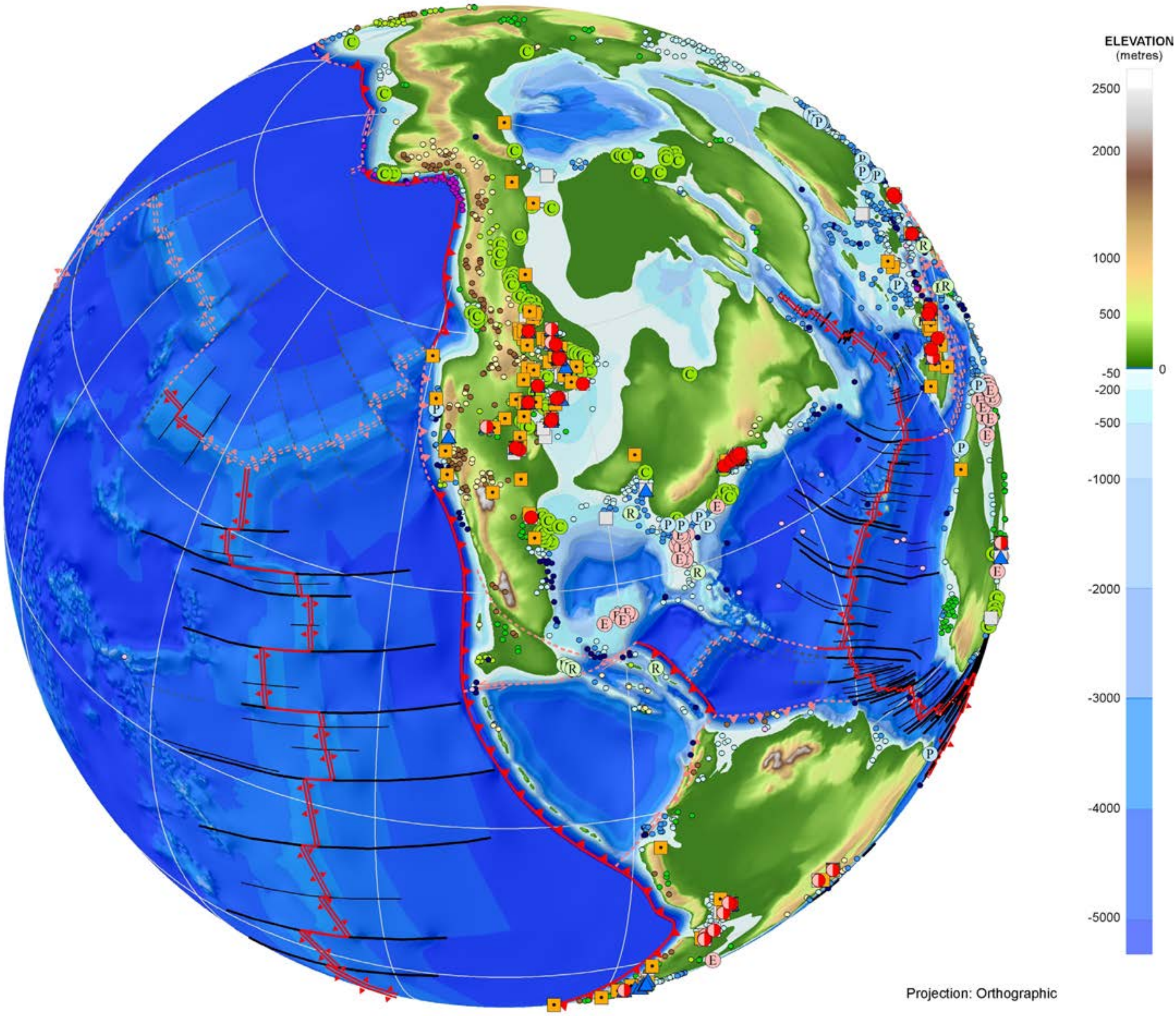


Figure 134. Climate proxies from the Maastrichtian database shown on the draft paleotopography and paleobathymetry of our Generation 3 Maastrichtian paleogeographic map (work in progress). This is also the dataset used in the cover image.

ELEVATION	SYMBOL	RGB	SYMBOL	RGB
	Topography		Ice-sheet Topography	
		255 / 255 / 255		255 / 255 / 255
5000				
		119 / 119 / 119		254 / 254 / 254
4000				
		164 / 164 / 164		253 / 249 / 254
3000				
		209 / 209 / 209		249 / 236 / 251
2000				
		218 / 210 / 125		249 / 223 / 253
1000				
		254 / 246 / 164		246 / 201 / 251
500				
		167 / 254 / 164		247 / 189 / 254
200				
		19 / 218 / 17		245 / 178 / 253
100				
		2 / 174 / 0		244 / 164 / 254
0				
		235 / 252 / 254	Ice-shelf	
-50				
		210 / 250 / 254		252 / 144 / 254
-200				
		160 / 240 / 254	Lakes	
-500				
		160 / 210 / 254		20 / 164 / 171
-1000				
		130 / 190 / 254		
-2000				
		100 / 160 / 254		
-3000				
		0 / 129 / 254		
-4000				
		0 / 70 / 254		
-5000				
		0 / 40 / 254		
-6000				
		15 / 0 / 189		

Figure 135. Elevational colors used for the standard paleogeographic topographic and bathymetric maps. This follows the methodologies and elevational breakdown described in Ziegler et al. (1985). Elevations are in meters.

ID	SYMBOL	TECTONIC ENVIRONMENT	RGB	ELEVATIONAL RANGE
n/a		Collisional	210 / 210 / 210	>4000 m
n/a		Andean-type	160 / 102 / 50	2000 - 4000 m
n/a		Rift shoulders	254 / 248 / 164	1000 - 2000 m
n/a		Inland plains	180 / 254 / 0	200 - 1000 m
n/a		Coastal plains	2 / 219 / 0	0 - 200 m
n/a		Inner shelves	194 / 251 / 254	0 - -50 m
n/a		Outer shelves	50 / 153 / 254	-50 - -200 m
n/a		Slope and rise	13 / 0 / 129	-200 - -4000 m
n/a		Abyssal plain	249 / 194 / 254	-4000 - -6000 m
n/a		Trenches	202 / 0 / 219	>-6000 m

Figure 136. Color symbols applied to the elevational ranges by tectonic environments described in Ziegler et al. (1985)

A hillshade is usually added for elevation-based datasets, generated in ArcGIS, with either an 80% or 90% transparency and black to white color ramp. This will depend on the spatial extent of the map. We recognize, however, that different users may have their own preferences.

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Appendix 1. Loading ArcGIS .style Files into ArcGIS Desktop and Pro

In our geospatial databases, each feature is related to the relevant symbol set stored in the .style file using a Symbol ID code. This code comprises a text field of 6 characters. Each code begins with a letter(s) that indicates the type of feature (e.g. structural, sedimentary, geomorphological), a numerical code that is unique for what the feature represents (e.g. normal fault, fluvial environment, canyon), and then a qualifier to show the state of that feature (viz., 'inferred', 'active', 'inactive') if this is appropriate.

The name of this Symbol ID field can vary because, in ArcGIS, the user will be asked what field contains the symbol code when linking to a .style file, so you can then choose the relevant field as long as the field format is compatible (a text field). However, we recommend that in their own databases, users keep this field name consistent; for example, "Symbol_ID" or "SYM_ID" are good standard field names and easily understood.

We provide two versions of the Paleogeography Map legend ArcGIS .style file, which can be downloaded from the Knowing Earth website (www.knowing.earth):

1. **Markwick2023_Paleogeography_legend.style** - This version includes the symbol ID and an associated description. It is the best version to use if you want to manually select a symbol that matches your own needs;
2. **Markwick2023_Paleogeography_Legend_labels_only.style** – This version only includes the symbol ID used in our databases. This can be used with the <Match to symbols in a style> option in the Layer Properties/Symbology/Categories dialogue box in ArcGIS ArcMap, to populate your symbol sets automatically. However, it will only work if you use the same symbol ID codes in your databases as described in this book. These IDs match the codes in our published databases.

Both style files should be compatible with ArcGIS Desktop versions 10.5 and later.

ESRI provides some excellent guides for loading .style files into ArcGIS on their website:

- ArcGIS Desktop: https://desktop.arcgis.com/en/arcmap/latest/extensions/task-assistant-manager/importing-styles-from-a-style-file.htm
- ArcGIS Pro : https://pro.arcgis.com/en/pro-app/latest/help/projects/connect-to-a-style.htm

Further information about the ESRI style files can be found at: http://desktop.arcgis.com/en/arcmap/latest/map/working-with-arcmap/using-symbols-and-styles.htm).


VEGETATED AREAS ON LESS STEEP SLOPE INTERPRETED AS FINER GRAINED
BEDDING WITHIN SANDSTONE BODIES

It’s time again to get out the pencil crayons!

About the Author

Dr. Paul Markwick

Paul is the CEO of Knowing Earth Limited, a Visiting Lecturer at the University of Leeds, and Visiting Research Fellow at the University of Bristol. He graduated from St. Edmund Hall, Oxford University, in 1987 and received his Ph.D. from the University of Chicago in 1996.

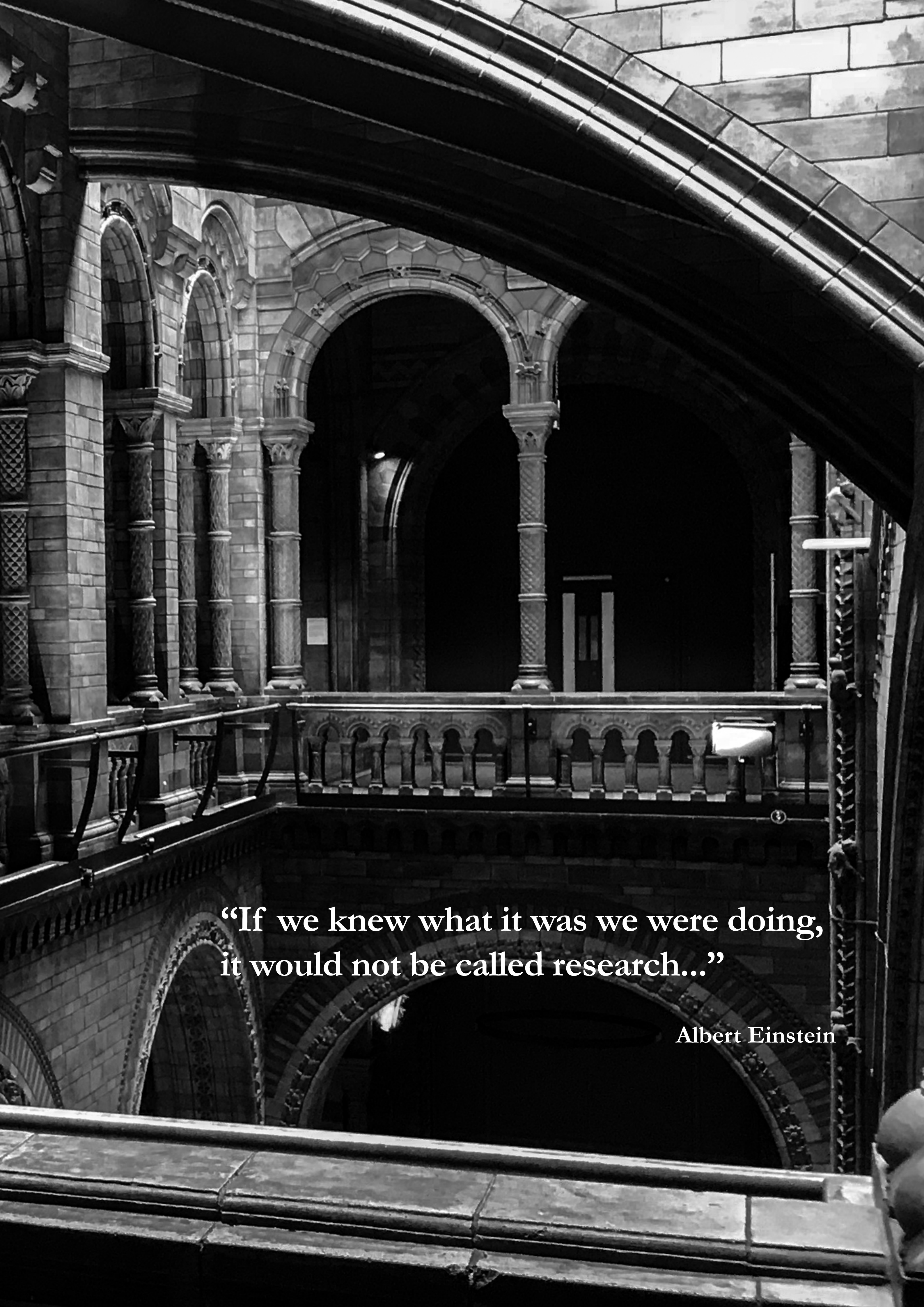
He worked for two years at BP's Research Centre in Sunbury-on-Thames before moving to Chicago, where Paul studied with Professor Fred Zeigler's "Paleogeographic Atlas Project" (PGAP). This was followed by a post-doctorate at the University of Reading, researching the mineral exploration significance of southern Africa's paleoclimatic and drainage evolution using computer-based climate models with Professor Paul Valdes. He then moved to Robertson Research International Limited, now part of CGG, as a Staff Petroleum Geologist, where he developed global predictive models of source and reservoir facies. In 2004 Paul moved to Getech Group plc to set up the Petroleum Systems Evaluation Group with Dr. John Jacques. From 2006 to 2017, Paul served on the Getech board overseeing the strategic technical direction, which saw the business transition and grow from an academic research group to a multi-million-pound company with four offices, 120 staff, and an international client base. During this time, Paul designed and developed the Globe suite of data and knowledge bases, drawing heavily on his own diverse research and exploration experience.

More recently Paul has taken his exploration experience and applied this to fields including the exploration for natural hydrogen and geothermal resources.

His active research interests include global tectonics, paleogeography, paleoclimatology, the history of geology, and depositional modeling. Paul is the author of over 100 published scientific papers and articles.

When he is not working, his hobbies include photography, hiking, producing educational videos, and learning Spanish.

See more of Paul's work at www.knowing.earth and www.palaeogeography.net


“If we knew what it was we were doing,
it would not be called research...”
Albert Einstein

Paleogeographic maps are common throughout the geological literature. They were first used in the 19th century as a means for managing and representing the complexity and diversity of geological information through time. But their full potential as a tool with which to solve problems in environmental science and resource exploration has rarely been realised. In most cases maps have been used only as backdrops to presentations.

The Knowing Earth Standard Legend for Paleogeography 2023 is designed to address this by providing geologists with a symbol set to aid them in building paleogeographic maps. It covers all of the key elements in the paleogeographic mapping workflow described in Markwick (2018) from crustal architecture, structural mapping and geodynamics through to depositional systems, drainage analysis and landscape dynamics.

www.knowing.earth