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Atlas of Global Palaeogeography: Vol. 2
Cretaceous

Users' Guide to Palaeogeography

G1526

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Executive Summary

Getech's *Atlas of Global Palaeogeography: Vol. 2, Cretaceous* is the second volume of global palaeogeographic maps that show the evolving landscape, tectonics and gross depositional environments (GDEs) for 12 timeslices in the Cretaceous (Table 1.1). Each atlas is presented at a scale of 1:20,000,000, with a precision of 1:5,000,000. All mapped interpretations are provided digitally in ArcGIS™, and all atlases are supplied with the underlying bibliography, methodologies and location of data points. Volume 2 palaeogeographies are underpinned by Getech's *Global Plate Model* v.2 (Getech, 2013).

Era	Period	Epoch	Stage (Gradstein et al., 2004)	Recon Age Ogg et al. (2008) (Gradstein et al., 2004)
MESOZOIC Mz	CRETACEOUS K	UPPER K_2	*Maastrichtian* 70.6–65.5 Maa	67.809 (67.809)
			Campanian 83.5–70.6 Cmp	79.543 (79.543)
			Santonian 85.8–83.5 San	84.000 (84.000)
			Coniacian 88.6–85.8 Con	87.550 (87.550)
			Turonian 93.6–88.6 Tur	91.400 (91.400)
			Cenomanian 99.6–93.6 Cen	96.550 (96.550)
		LOWER K_1	*Albian* 112.0–99.6 Alb	105.800 (105.800)

			Aptian 125.0–112.0 Apt	118.500 (118.500)
			Barremian 130.0–125.0 Brm	127.240 (127.240)
			Hauterivian 133.9–130.0 Hau	135.690 (135.690)
			Valanginian 140.2–133.9 Vlg	137.600 (137.600)
			Berriasian 145.5–140.2 Ber	144.040 (144.040)

Table 1.1: Summary and reconstruction ages for each stage map in the Atlas of Global Palaeogeography: Vol. 2, Cretaceous.

The atlases are designed to be a flexible exploration tool. They can be used as a digital reference framework with which to investigate specific exploration problems (e.g. source to sink relationships, tectonic timing and regime); they can also be modified and supplemented by clients within their own organisations to produce results that fit their specific needs and knowledge base.

This atlas forms part of Getech's core *Globe* programme deliverables. The maps achieve four key exploration objectives:

1. Defining the underlying tectonic framework
2. The generation of a series of palaeolandscape maps to show evolving source to sink relationships
3. A spatial context for understanding exploration data
4. To provide boundary conditions for advanced Earth System Modelling

Objective 1: defining the underlying tectonic framework

The maps define the spatial and temporal tectonic framework in which all exploration areas fit. This provides valuable information on the timing, nature and extent of tectonic events on a global scale that can affect basin development and history. Potential heat-flow variations, the original juxtaposition of play elements and possible extensions to plays, an understanding of the causes and relationships of hinterland uplift and its relation to denudation and sediment supply, can also be deduced from the information the maps provide.

Objective 2: the generation of a series of palaeolandscape maps to show evolving source to sink relationships

Each stage includes a reconstruction of the palaeolandscape to show transport pathways, which provides an explicit, and testable, representation of contemporary source to sink relationships. When combined with palaeogeology and palaeoclimatology, these results can help explorationists understand the nature, flux and timing of clastic supply.

Objective 3: a spatial context for understanding exploration data

The maps can be used as the spatial context for plotting and interrogating any digital exploration data for specified time intervals; this allows explorationists to investigate the processes responsible for mapped plays and their potential extensions. The palaeoenvironmental maps also provide analogues for understanding new areas.

Objective 4: to provide boundary conditions for advanced Earth System Modelling

The palaeogeographies form the boundary conditions for a complementary suite of atlases of Earth System Model results (palaeoclimatology, palaeoceanography, palaeovegetation). These provide additional, quantitative information on the processes responsible for source, reservoir and seal facies formation and character, which can be used to assess frontier areas or other regions with sparse data coverage.

CHAPTER 1

Introduction

1 Introduction

Palaeogeography is the study of the past spatial differentiation of the Earth's surface and includes features such as elevation, climate, vegetation, depositional systems and environments. Palaeogeographic maps are often used to provide a backdrop for showing the distribution of geological data, but they can also provide insights into an array of fields, including source to sink relationships, crustal types and the potential viability of a petroleum system. Palaeogeographic maps may also be used to provide insights into processes which affect hydrocarbon prospectivity through depositional and tectonic systems, e.g. identifying areas where there could be clastic poisoning on a potential source rock. Boundary conditions for Earth System Models can be created from palaeogeographic maps; they include climate, oceans, waves, tides, vegetation, weathering, and other surface processes. These are increasingly being used as an exploration tool to predict lithofacies distribution. The maps can also be taken further; for instance, they can be used as a starting point to make quantitative calculations of sediment fluxes and denudation rates through time.

Each stage is represented by a single timeslice map comprising the following reconstructed information:

- Principal structural and tectonic elements
- Tectonophysiographic terranes (areas above contemporary base-level defined by the last thermo-mechanical regime to affect them)
- Gross depositional environments (GDEs)
- Base-level
- Principal lithologies
- Palaeoriver systems (drainage basins, trunk streams and outfall locations)
- Palaeotopography and palaeobathymetry (as palaeo-DEMs)
- Palaeoshoreline variation (highstand and lowstand)

The Cretaceous, comprising 12 timeslices (Table 1.1), is mapped onto Getech's *Global Plate Model v.2* and is therefore compatible with all other products using this version of the plate model. This information can be found within the metadata provided in the GIS products.

1.1 Study Aims and Objectives

The principal aim of the Atlases of Global Palaeogeographies is to provide explorationists with a digital tool for understanding and evaluating their exploration targets within a spatial and temporal framework.

To achieve this we set ourselves the following specific objectives:

1. To generate a series of detailed (1:20,000,000) global maps to represent the following in a simple, but comprehensive, way:

    i. Tectonic setting and history

    ii. Structural and tectonic elements

    iii. Gross depositional environments (GDEs)

    iv. Source to sink relationships

    v. Intra stage sea level variations

    vi. Palaeotopography

    vii. Palaeodrainage (rivers and basins)

    viii. Palaeobathymetry

    ix. Underlying data

    x. Mapping confidence

2. That these maps are digital so that they can easily be modified in the future by either clients (by using their own data) or Getech to facilitate improvements as new data and hypotheses arise.

3. That all interpretations have a paper trail, so that interpretations can be checked.

4. That existing hypotheses and interpretations are reviewed as part of the mapping process, and in turn these are systematically recorded.

5. That the maps form part of a continuous range of scaled solutions and can fit with more detailed, regional maps provided as part of Getech's *Regional Reports*.

6. That maps are versioned so that users know the vintage of the map and what plate model it is based on.

7. That the palaeogeographies provide information for enhancing the underlying plate model.

8. That the databases built during this project conform to a systematic data model which means that the data and interpretations can be applied with confidence across all Getech's products and services.

9. That the results form robust boundary conditions for use in the latest coupled ocean-atmosphere and Earth system models, the results of which can be used in conjunction with the palaeogeographic and landscape reconstructions to add additional tools for explorationists.

10. That these maps provide the Industry with a reference set of global palaeogeographic maps for every stage in the volumes mapped, with which to show the evolving landscape through geological time.

1.2 Study Workflow

Global palaeogeographies synthesize the current available knowledge of global tectonics, depositional environments, stratigraphy and landscape evolution onto a 1:20,000,000 scale map. This requires a large, dedicated team of experts who can integrate across many scientific disciplines at a variety of scales: global, regional and local. At the same time, the maps have to be drawn with an understanding of who will use them and how they will be used, which may be varied. Moreover, this has to be iterative with each volume of the palaeogeographic maps being instrumental in improving the plate model.

An explanation of the technical methodologies used to construct the maps is presented in Chapter 2 of this report. The general workflow is summarised as follows:

1. Start-up

This the logistical set-up stage for the project and mapping. All data are stored and captured in ArcGIS™ and other databases. This is an ongoing process throughout the study.

2. Plate Model Review

The plate model underpins all of the mapping. Getech's original Cenozoic and Cretaceous palaeogeographic atlases were mapped on Getech's *Global Plate Model v.1*, which incorporated fully-reviewed existing plate models and results from Getech's *Regional Reports* on structures and tectonics. *Regional Reports* included Southeast Asia and Southern Asia, Circum-Arctic, East Africa, Equatorial Atlantic and South Atlantic.

Getech's *Global Plate Model v.2* is a global update of Getech's *Global Plate Model v.1*; it extends to the beginning of the Jurassic and incorporates feedback and improved regional understanding from the Cretaceous and Cenozoic mapping process, updates to Getech's Global Structural Data Layer and other *Regional Reports*. This report accompanies version 2 of Getech's *Atlas of Global Palaeogeography: Vol. 2, Cretaceous*, which contains the original data layers and new layers (fully attributed data points, regional text and polygons) updated onto Getech's *Global Plate Model v.2*. This is to ensure globally consistent tectonic and environmental interpretations from the Jurassic to the Present Day.

Beyond Getech's *Global Plate Model v.2*, the model has since been updated to introduce more detailed attribution, as well as to reflect further insights from Getech *Regional Reports*, feedback from the Jurassic mapping process and extension of the model to the beginning of the Permian; these updates included modifications to tectonic plate geometries, relative motions and appearance ages. The Getech *Global Plate Model v.3* is the version of the plate model that supersedes Getech's *Global Plate Model v.2*; this version has provided the basis for the Permian and Triassic palaeogeographic mapping.

Oceanic ages have also recently been globally re-evaluated to incorporate recent updates to Getech's magnetic pick database; this re-evaluation inherently resulted in minor modifications to the *Global Plate Model*. Consequently, Getech's most recent plate model is *Global Plate Model v.4*; this version provides the basis for 1:5,000,000 scale palaeogeographic mapping as part of the second subsription of the *Globe* programme.

3. Data Access

Initial searches are of Getech's own databases, with a more detailed literature review that includes third party data sets. New information is then databased and updated through the life of the study as new findings are discovered. All information is also synthesised in stratigraphic and tectonic datasheets that provide a stage by stage summary of the key events for each geographic area. In addition, key figures are captured and filed in scrapbooks, which provide a ready source of information during the mapping phase. These methods are largely based on working practices established by Professor Alfred Ziegler's Paleogeographic Atlas Project at the University of Chicago.

4. Basemaps

All geological and cultural data are rotated using the plate model to generate the initial basemaps. As this is an iterative process, this may be repeated numerous times as the plate model is modified.

5. Structural and Tectonic Framework

The structural framework, which is based on the 1:10,000,000 rotated Present Day mapped structural databases and plate model, is then modified for each timeslice according to the information recorded in the activation summary table.

6. Palaeoenvironmental Mapping

The main phase of mapping comprises the compilation of GDEs, tectonophysiographic terranes and principal lithologies. These are drawn by hand onto the hardcopy basemaps, following methods outlined in Ziegler (1985). To ensure continuity, features are mapped through time sequentially, rather than completing each timeslice in isolation. To facilitate this mapping, teams are divided by geographic area, of which there are 16 for the Cretaceous mapping. Laurasian areas are North America, Caribbean, Europe, Western Tethys, Circum Arctic, Russia, Central Asia, the Far East and Southeast Asia. Gondwanan mapping areas are South America, Antarctica, Africa, Southern Asia, Australia, New Zealand and the Southwest Pacific. The remaining major ocean areas are mapped separately. These areas are then digitised into a GIS geodatabase. Scrapbooks, datasheets, databases and reference databases (Getech's *knowledge database*) are populated during compilation.

7. Editing and Peer Review

Throughout the project, interaction and testing is facilitated through project meetings, discussions and collaborative working within a single workroom. In addition, external experts are brought in to act as peer reviewers. Conference presentations of selected, specific results are also used to gain valuable external input in order to fine tune results.

8. Compilation of Palaeorivers

The palaeorivers and related palaeodrainage basins are compiled based on existing Getech work on drainage analysis, as well as new hypotheses using the palaeogeographic maps themselves. These are a critical input for Earth System Models that utilise the palaeogeography maps as boundary conditions.

9. Palaeotopography

The palaeotopography is driven by two complementary data sets: the Present Day elevation, which is rotated back through time as a guide, and the palaeoenvironmental and tectonic mapping. Contours are constructed for each time interval and the results are modified based on assessments of known geology and continuity between timeslices. These are then converted to palaeo-DEMs, following the methods outlined by Markwick and Valdes (2004), which also take account of the mapped palaeorivers and lakes. This is done within ArcGIS™. Results are then tested for sequential timeslices.

10. Palaeobathymetry

The palaeobathymetry of the deep ocean is calculated using both a modified version of the Müller et al. (2008) ocean-age data grid and the ocean-depth equations of Stein and Stein (1992). Additions are made based on the identification of the age and extent of ocean floor volcanics (including seamounts and Large Igneous Provinces: LIPS).

11. Final Review and Production

External editing occurs throughout the entirety of the project, with a final review QC stage before production.

1.3 Deliverables

1.3.1 Digital Deliverables

- A4 users' guide (PDF)
- ArcGIS™ project comprising:
    - Cultural data:
        - Rotated cities
        - Rotated country boundaries (2007)
        - Rotated coastline
        - Rotated data Points (from Getech Wells and Outcrop database)
    - Base-level:
        - Palaeo-base-level
    - Palaeogeography:
        - Major structural and tectonic elements
        - Lithologies
        - Depositional environments and tectonophysiographic terranes
        - Regional text polygons with accompanying PDFs
    - Palaeotopography:
        - Palaeorivers
        - Palaeodrainage basins
        - Palaeonodes
        - Lowstand shoreline
        - Highstand shoreline
        - Highstand lowstand difference
        - Palaeo-DEM contours (land)
        - Palaeo-DEM hillshade (land)
        - Palaeo-DEM (land)
        - Palaeo-DEM contours (ocean)
        - Palaeo-DEM hillshade (ocean)
        - Palaeo-DEM (ocean)

For consistency, all ArcGISTM data layers are supplied in the same coordinate system with complete attribution:

Projection: Geographic

Ellipsoid: WGS84

1.4 Staffing

This study represents the combined efforts of a diverse team of Getech geoscientists and external advisors. It also builds on the work of other Getech staff on related projects, especially those which form part of Getech's Global Tectonics Programme.

Technical Development	Mr Simon Campbell
Project Managers	Dr Amanda Galsworthy Miss Lauren Raynham
Client Manager	Mrs Francesca Newton
Peer Reviewers and Advisors	Mr Simon Campbell Prof. Bill Fitches Dr Christopher Green Dr Paul Markwick Dr Andrew Quallington Dr Richard Tyson
Plate Modellers	Miss Dorothea Eue Dr Sheona Masterton Dr Peter Webb
Structural Geologists	Miss Catherine Hill Dr David Sagi Miss Jade Roland-Warden Mrs Laura Wilson
Mapping Geologists	Mr Robert Bailiff Ms Kate Benny Mr James Coombe Dr Laura Duthie Mr Simon Jackson Mr Michael Lawson

	Mr Tom Rorks Mr Michael Sturla Mr David Tierney Mr Henry Wareham Mr Tom Wiggins
Palaeo-drainage Specialists	Mr James Martin Mrs Laura Wilson
Geodynamicists	Dr Abigail Redmile
GIS	Mr Antoni Alcaraz Mr Richard Howe Mr Neil Wrobel
External Editor	Prof. Bill Fitches
Internal Editor	Miss Katie Spike
Report / Production	Mr Michael Benson Mr Peter Birch Mr David Blackledge Miss Helen Chambers Mrs Sarah Wilkinson
Databasing Manager	Miss Gemma Scougal
Databasing Support Staff	Mrs Marie-Anne Benson Miss Emma Edgecombe Mr Tom Hopkins-Flanagan Mr Rowan Gill Mr Andrew Kilpatrick

1.5 Future Work

In the new subscription phase of *Globe*, Getech is mapping all completed volumes (Permian to Cenozoic) on Getech's *Global Plate Model v.4* at a 1:5,000,000 mapping scale using Getech's 1:1,000,000 structural data set and a revised, more comphrensive legend. A new and improved DEM method has been also been developed. Concurrently there will be new and updated datalayers; these are stand-alone products which can also be rotated back with the plate model to help constrain environments. Getech will also continue building on the following datalayers: global source rocks through time; atlases of climate, ocean, vegetation, tides and waves model results; global layers, and other thematic layers (including global reservoirs through time). For further details of this new phase of *Globe*, please contact Paul Carey using the contact details supplied on the front page. Delivery is region by region, starting with North America, South America and Africa.

We always welcome suggestions for additional deliverables that can be incorporated within this programme. We continue to research the methods and workflows to find ways of improving results, so that we can understand exactly how the landscape and tectonics have changed through time, which affects basin evolution, the sediment source to sink relationships and hydrocarbon prospectivity.

CHAPTER 2

Methods

2 Methods

Palaeogeographic mapping involves five main stages: structural mapping (Figure 2.1B), plate modelling (Figure 2.1C), GDE mapping (Figure 2.1D), drainage analysis and digital elevation modelling (Figure 2.1E). The methods used are based on those of the Chicago Method (Scotese 2008). Present Day structural coverage, in most areas, defines the plate polygons and sub-plates. These structures are picked using a combination of digital elevation data (Shuttle Radar Topography Mission: SRTM) and Getech's own extensive gravity (Figure 2.1A) and magnetic data using ArcGIS™, and are cross referenced against data accessed in critically reviewed published literature. Using the plate model, the structural coverage, the points database and other relevant geological data are rotated onto the appropriate timeslices and used to constrain the depositional environments. It is often at the mapping stage when iterations are made to either the plate model and/or the structural data set. The mapped GDEs, along with rotated drainage networks and provenance analysis, are used to constrain the palaeorivers. The Present Day drainage network has a greater influence over the drainage interpretation on younger timeslices. The palaeo-DEMs for both onshore and offshore use the palaeogeographies and drainage to guide the contours. As with the drainage analysis, the palaeo-DEMs use rotated Present Daycontours as a guide. The further back in time the reconstructions are, the less useful the Present Day contours; in which case a combination of geochemical analyses, such as Apatite-Fission Track APFT data and Present Day analogues, are used to determine elevation.

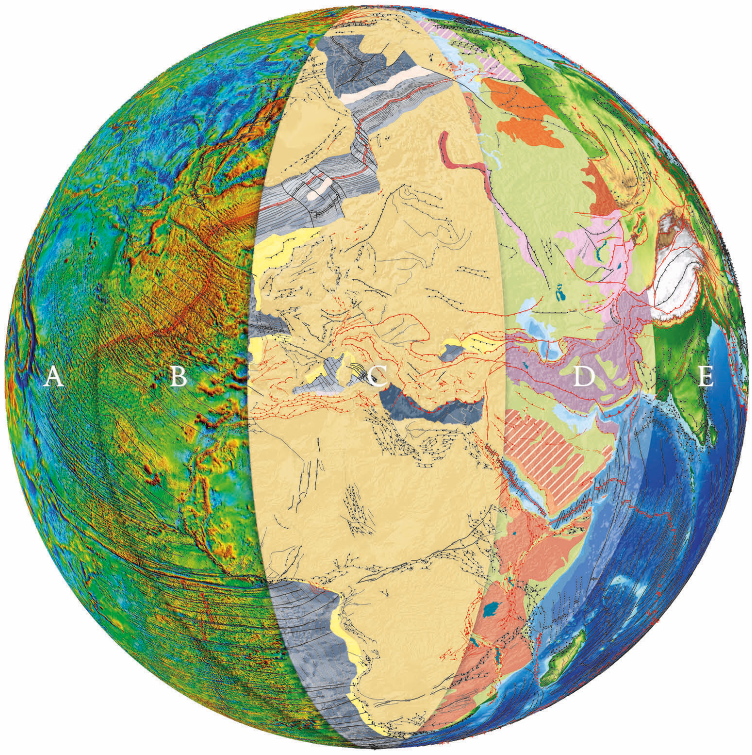


Figure 2.1: *A graphical representation of the workflow which represents the layers from which the palaeogeographies are built up within Globe.*

A) potential fields data set. B) potential fields is used to pick lineaments for a global structural coverage. C) structures define the boundaries for the plate polygons and terranes. D) using the plate model and interpreted structures, environments and lithologies are mapped. E) environments are boundaries used by drainage and DEMs for both onshore and offshore.

2.1 Temporal Grain

The initial difficulty is defining the precise geological times in which to construct the maps. Conceptually, a palaeogeographic map should represent the geography at a specific moment in time. However, this is rarely possible because of the heterogeneous nature of the geological record. As the spatial extent of a map increases, so does the temporal grain, which is also a function of uncertainty in age dating and correlation. Additionally, the dating and correlation errors are not uniform across the globe. Consequently, the term *timeslice* has been used, which suggests a broader temporal range than a single plane (Figure 2.2). This is a good pragmatic solution that maximises the available data; if the data were to be limited to localities with well-constrained ages, then this would limit the data set available, and over large spatial areas, this would limit mapping coverage. To account for these uncertainties, the quoted age assignment for each data point is included as an attribute, which means that the viewer can use this to understand mapping fidelity and resolution.

This precision is good for the designed frontier exploration applications of the maps. However, to understand the finer-scale variations necessary to evaluate a prospect, a more focussed, detailed map is required.

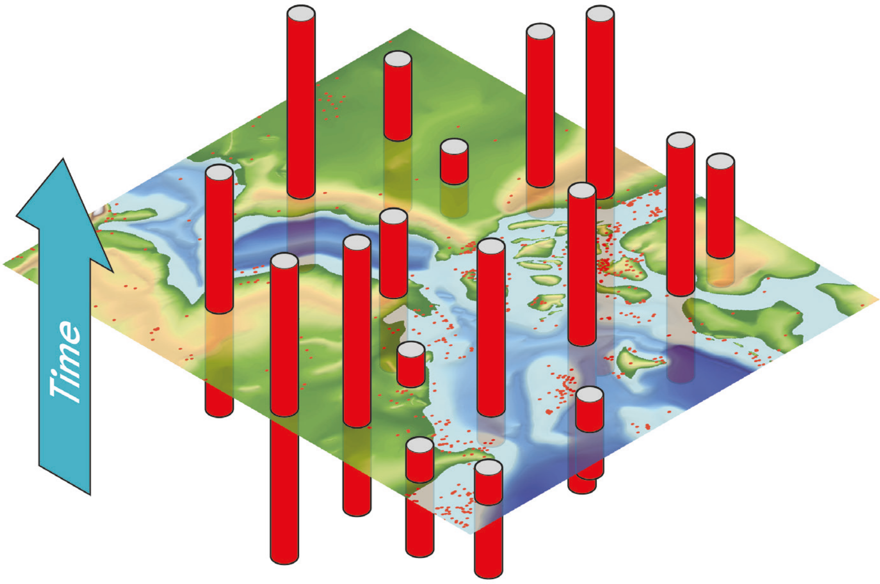


Figure 2.2: *The red cylinders represent the temporal grain of data used to construct a timeslice map (Markwick and Valdes, 2004).*

The data used in the construction of a palaeogeographic map represent a variety of reliabilities and resolutions. Each data point is placed on the map and is assumed to represent a single observation. However, the time presented by each locality varies, due in part to dating and correlation uncertainties. Consequently, the recorded information for a locality actually represents the full length of red cylinders. For example, the map might show sandstones for a particular formation at a particular locality which is dated as Kimmeridgian–Tithonian. The conceptual *time-plane* cuts this unit at some point within this section, although the poorly resolved dates mean that it is impossible to say exactly where. The more points there are, the greater the uncertainty, which means that there is no guarantee that two adjacent data points plotted on a map actually co-occurred.

2.2 Base-level

Base-level (Barrell 745-904; Wheeler 599-610; Figure 2.3) is the conceptual surface in the landscape representing a balance between net erosion and net deposition; this is essentially the equilibrium, or graded profile of fluvial geomorphologists. Following on from Markwick and Valdes (2004), we have used this concept to map the distribution of contemporary sediment source and sink areas for each timeslice map. This provides a direct link between elevation and the underlying tectonics (which are responsible for the distribution of accommodation space and areas of relative uplift above base-level).

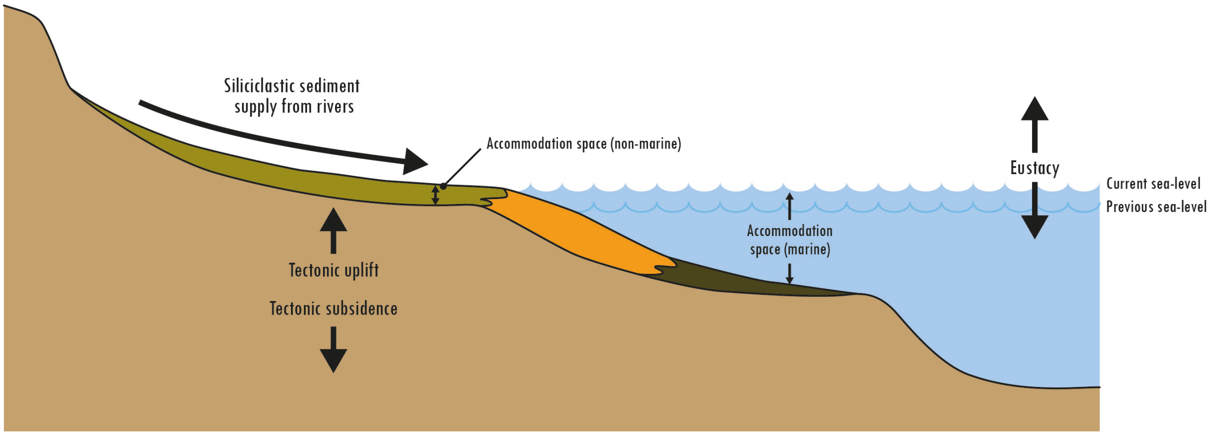


Figure 2.3: *The Getech palaeogeographies are constructed around the representation of the distribution of contemporary (at the time of the timeslice map) base-level, the contemporary landscape (elevation and bathymetry), base-level and accommodation space within this landscape, and the representation of the landscape through the mapping of the palaeoenvironments and lithologies (areas below contemporary base-level) and tectonophysiographic terrane (areas above contemporary base-level).*

2.3 Storing Data

2.3.1 Wells and Outcrop Database

Getech has developed its own corporate database which is used to store all point type data. It is continually populated and consequently, the data points received by clients as part of their *Globe* subscription are the absolute minimum Getech has used to help constrain these palaeogeographies. These points include confidence information relating to spatial and dating information. At any time the database can be downloaded from our central SDE server into ArcGIS™ as a layer with the key attributes. The data points give a spatial precision of a point as well as being linked to a tops data set, which includes lithogical and environmental information, and other key information about that particular geological unit.

2.3.2 Datasheets

Datasheets are internal documents containing information on each mapped area over the whole geological timescale. These files also contain key images found for the region of interest. This is a vital way of keeping all the critically evaluated, validated and relevant information relating to a geological region in one searchable reference document. These datasheets are actively updated and populated with new data, allowing us to continuously revaluate the entire region. If new data changes our understanding of an area, then the paleaogepgraphic atlases are updated at the next available opportunity and provided to clients as versioned updates.

2.3.3 Refcite

Getech has developed its own referencing system, so that it is more user friendly and focused to what we do as a company. This has allowed users to place and search data in the most convenient way possible, and ensures that all references are readily accessible.

2.3.4 Location Lines Database

All line-based reference data are stored in an ArcGIS™ geodatabase. Line data includes the following:

- chronostratigraphic section lines
- structural/crustal model cross-section lines
- seismic lines (both interpreted and uninterpreted lines)
- 2D profile lines
- play cartoon lines
- well correlation profiles

2.3.5 OneNote and Evernote

Microsoft OneNote is used as a collaborative workspace in which the plate modelling team store notes, ideas and technical information. Combined with the ability to tag important information, link to reference literature and organise notebooks according to geographic regions and other key subject categories, this software provides a useful environment for the electronic compilation of information and knowledge. This system is currently being migrated onto Evernote.

2.4 Plate Modelling

A plate model is a representation of the motion of tectonic plates across Earth's surface over geological time. Plate models can be classed as either rigid or deformable, with the latter allowing for changes in the shape of terranes associated with deformation over geological time. The Earth's surface is divided into tectonic plates which have unique geological histories; these are represented within the plate model as plate polygons and are mapped using Getech's potential field and structural data, SRTM data and peer-reviewed literature. Each plate polygon has associated attribution, such as plate name, crustal type, appearance age and key references. Several plate polygons may share a common tectonic history and together they make up a single tectonic plate. Within the plate model, the polygons which form each tectonic plate are assigned a plate ID number. For example, in our plate model, all plate polygons (including both oceanic and continental polygons) that form the northwest African Plate have a plate ID of 7701.

Relative motion between tectonic plate pairs (represented by different plate IDs) is then constrained using a variety of evidence, including structural relationships and trends, isochron locations (where palaeo-oceanic crust still exists), palaeomagnetism, fossil distributions and published tectonic solutions. These motions are represented in the plate model as Euler poles: a finite rotation about a fixed point on Earth's surface. Addition of these rotations forms a complex hierarchy (Figure 2.4) that allows the reconstruction of any tectonic plate within the model at any given reconstruction age relative to a fixed reference frame; our default reference frame is Earth's spin axis.

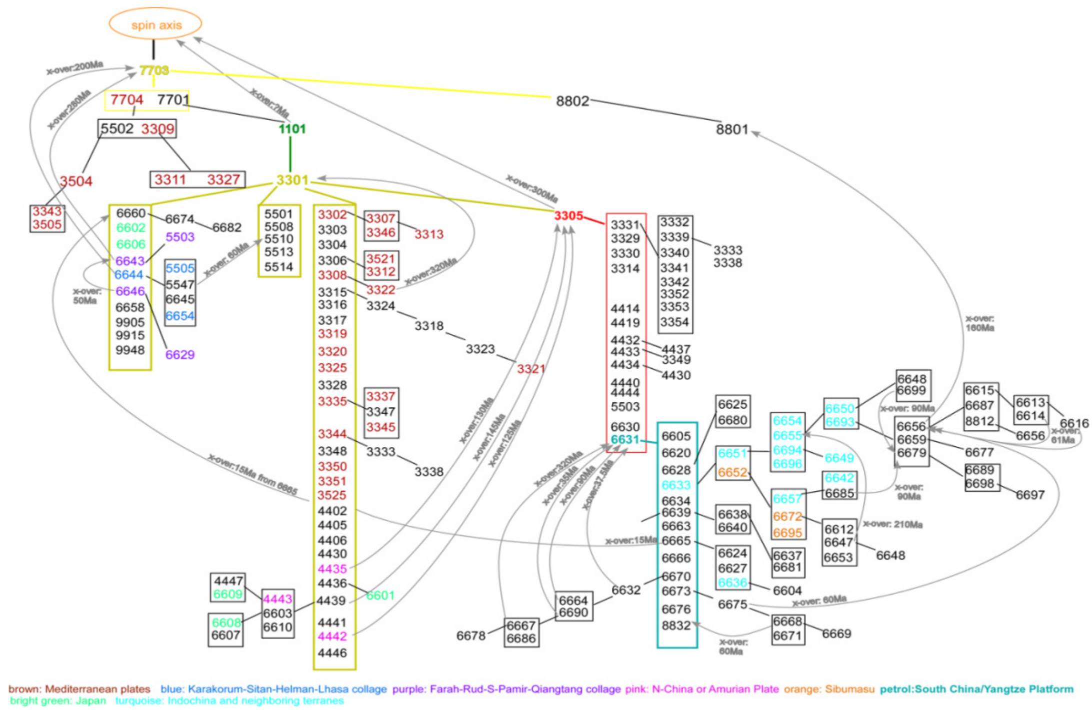


Figure 2.4: *An example dendogram of the complex plate hierarchy that exists within the Getech Global Plate Model. Each number represents a unique tectonic plate (coloured by Present Day regions), and arrows point towards the parent plate in each plate pair. Earth's spin axis is at the top of the hierarchy, providing the absolute fixed reference frame in the plate model.*

Getech uses both PaleoGIS and GPlates software packages for developing and testing the tectonic reconstructions used to develop our *Global Plate Model*. The model comprises a global plate polygon set (which represents defined tectonic plates) and associated plate rotation parameters (which describe relative motion between terranes). Both of these aspects of the plate model are supported by additional information in the form of GIS attribution and plate motion explanations.

As Getech uses a rigid plate model, it shows the shape of tectonic terranes as they are at Present Day, instead of changing shape to reflect deformation over geological time. Extension and shortening are represented in plate reconstructions as overlaps and gaps, respectively. For example, a volcanic arc that has experienced subsequent oroclinal folding (Figure 2.5) will exhibit its Present Day shape, after folding has occurred; for reconstructions prior to the onset of folding, the original (pre-deformation) shape of the arc must be represented by appropriate space around the Present Day terrane shape. An alternative way of representing such deformation would be to break the terrane into smaller pieces and introduce relative motion between each segment; we generally do not favour this approach because it is not necessarily tectonically meaningful on the scale of our global model.

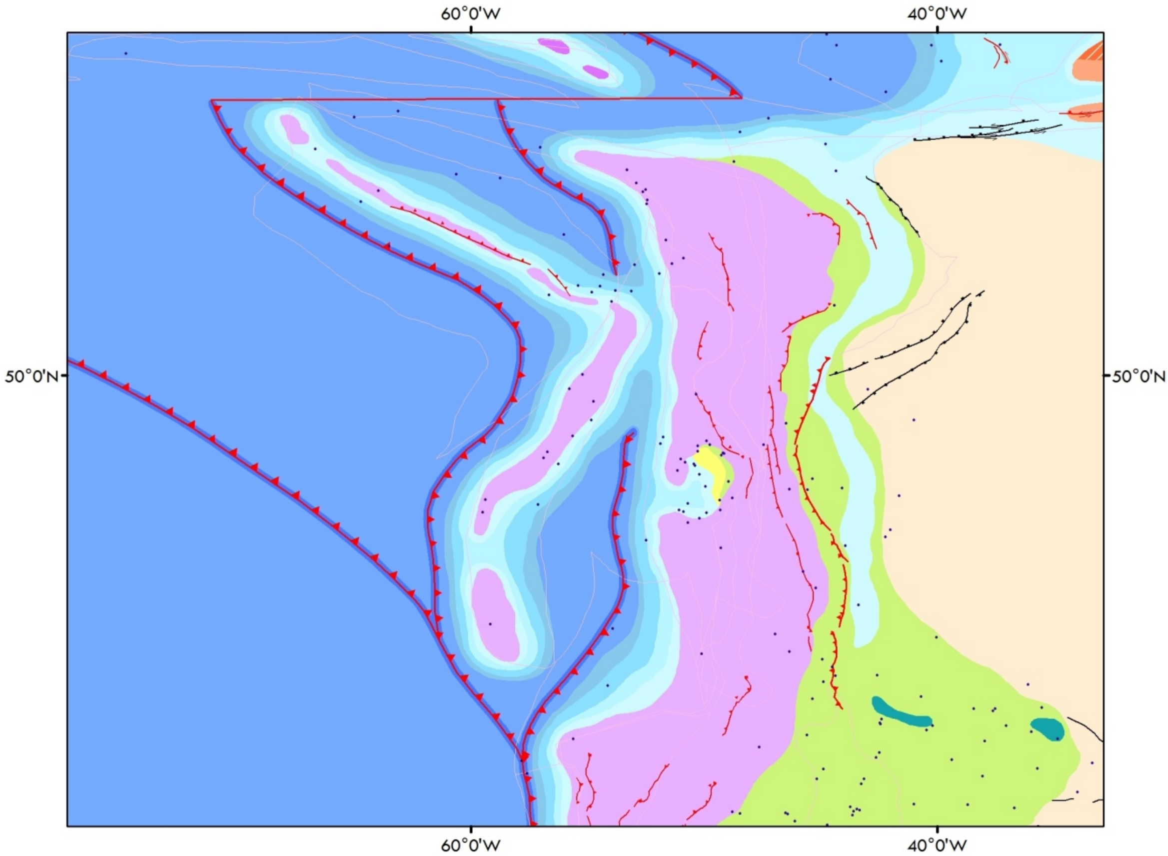


Figure 2.5: *The subduction zone on the left of this image would have been a different shape in the past but represents the Present Day geometry after deformation due to being mapped on a rigid plate model.*

The use of a rigid plate model inherently limits the ability to perform palinspastic reconstructions; for example, the rotational pivot point for the Mongol-Okhotsk has been constrained by the westernmost extent of the exposed ophiolites along the Mongol-Okhotsk Suture Zone. This is located relatively close to where the Songpan-Ganzi Ocean closed, which causes a spatial problem for the closure of this ocean (Figure 2.6), with the result being exaggerated shortening. However, the prospect of implementing a globally accurate deformable plate model is currently unrealistic within the plate modelling community. For the *Atlas of Global Palaeogeography: Vol. 2, Cretaceous,* problematic areas have been highlighted with accompanying notes in the form of hyperlinks which are present within the GIS product. These documents explain the limitations of the rigid plate model and how they have been resolved on our maps.

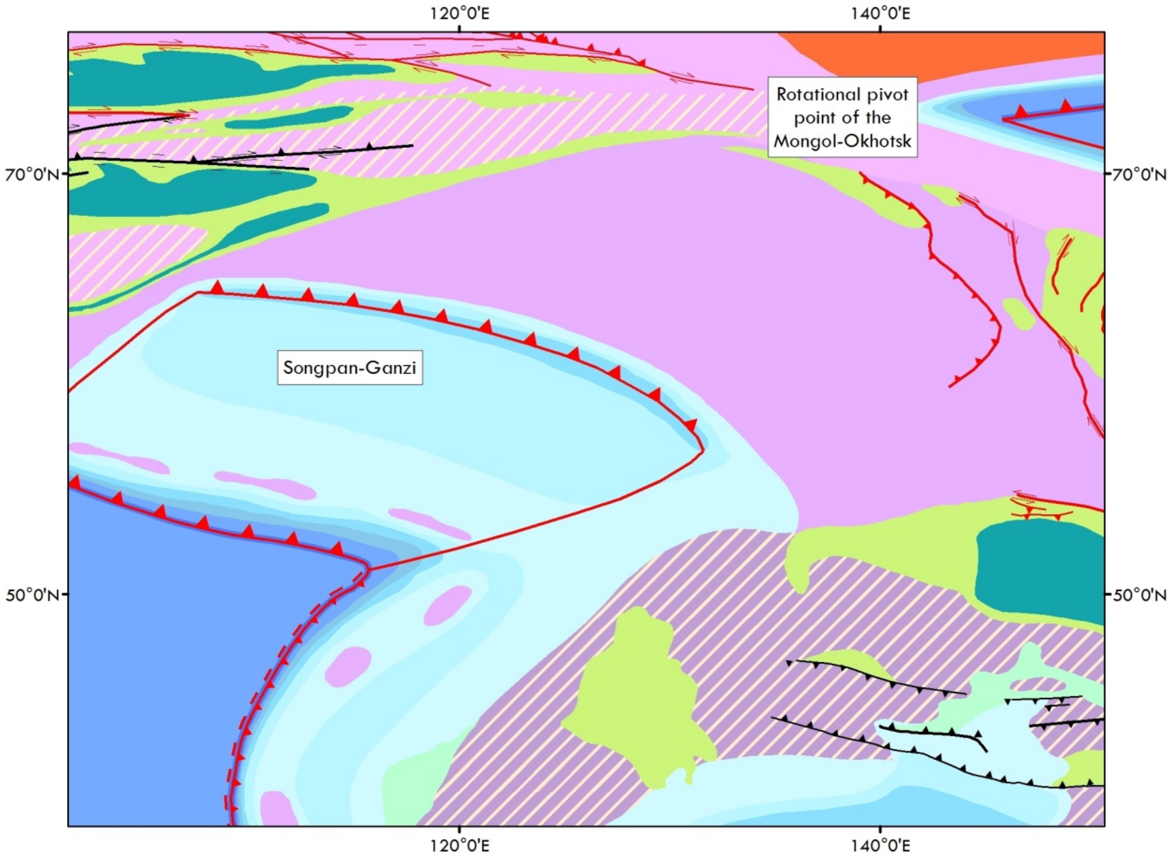


Figure 2.6: Inherent spatial problems associated with the use of a rigid plate model result in the overestimation of shortening in the Songpan-Ganzi area after the collision and docking of Qiangtang at approximately 190 Ma. Problematic areas such as this are identified and described in the regional text documents.

Constraints within the plate model include the availability of peer-reviewed literature on a regional scale, data availability and the requirement to generate a globally self-consistent tectonic solution. However, the plate modelling undergoes rigorous tests within Getech as it underpins all studies, with iterations stemming from palaeogeographic mapping and *Regional Reports* on structures and tectonics.

2.5 Structural Coverage

Understanding the kinematics of plate dynamics, basin styles and the juxtaposition of terranes is built on the understanding of the interactions between structures. Lineaments are drawn in ArcGIS™ using potential field (different derivatives of gravity and magnetics), DEM and Landsat data. By analysis of critically reviewed public-domain data and other studies, these lineaments are assigned a kinematic attribution for Present Day. The structures are thoroughly researched with full attribute (Figure 2.7) information logged relating to their geological history. This information includes sense of movement through time, interval dates of activation and inactivation throughout geological time, and first appearance age of the fault. The Present Day structures are used to help define the plate boundaries. The structures are also rotated to specific timeslices and assigned the correct kinematics for that age. Included in the structural data sets are the results of Getech's past *Regional Reports on* structural and tectonic evolution. Similarly, results from all future *Regional Reports on* structural and tectonic evolution will feed back into the *Globe* database through updates.

Structure ID	Description	CSID	First Appearance	First App	Dating Reliability	Country	Basin Name	Explanation	Compiler
1262	Active Normal Fault, Certain	B1100	Late Jurassic (Kimmeridgian)	155.7	Secondary information	Sudan	White Nile Rift	BAFA, ISO, Tilt	CJH
1263	Active Normal Fault, Certain	B1100	Late Jurassic (Kimmeridgian)	155.7	Secondary information	Sudan	White Nile Rift	BAFA, ISO, Tilt	CJH
1264	Active Normal Fault, Certain	B1100	Late Jurassic (Kimmeridgian)	155.7	Secondary information	Sudan	White Nile Rift	BAFA, ISO, Tilt	CJH
1265	Active Normal Fault, Certain	B1100	Late Jurassic (Kimmeridgian)	155.7	Secondary information	Sudan	White Nile Rift	BAFA, ISO, Tilt	CJH
1266	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Mozambique (off	Rovuma	GETECH Interpretation: gravity d	ed: DAS (*
1267	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Mozambique (off	Rovuma	GETECH Interpretation: gravity d	ed: DAS (*
1268	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Mozambique (off	Mozambique	GETECH Interpretation: gravity d	ed: DAS (*
1269	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Mozambique (off	Rovuma	GETECH Interpretation: gravity d	ed: DAS (*
1270	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Mozambique (off	Rovuma	GETECH Interpretation: gravity d	ed: DAS (*
1271	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Madagascar (off	Morondava	GETECH Interpretation: gravity d	ed: DAS (*
1272	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Madagascar (off	Morondava	GETECH Interpretation: gravity d	ed: DAS (*
1273	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Madagascar (off	Morondava	GETECH Interpretation: GETECH	ed: DAS (*
1274	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Mozambique (off	Mozambique	GETECH Interpretation: gravity d	ed: DAS (*
1275	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Mozambique (off	Mozambique	GETECH Interpretation: GETECH	ed: DAS (*
1276	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Mozambique (off	Mozambique	GETECH Interpretation: GETECH	ed: DAS (*
1277	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Mozambique (off	Mozambique	GETECH Interpretation: gravity d	ed: DAS (*
1279	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Madagascar (off	Mozambique	GETECH Interpretation: gravity d	ed: DAS (*
1280	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Madagascar (off	Mozambique	GETECH Interpretation: gravity d	ed: DAS (*
1281	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Madagascar (off	Mozambique	GETECH Interpretation: GETECH	ed: DAS (*
1282	Active Right-Lateral Transten	B1126	Bathonian	166	Secondary information	Madagascar (off	Morondava	GETECH Interpretation: gravity d	ed: DAS (*

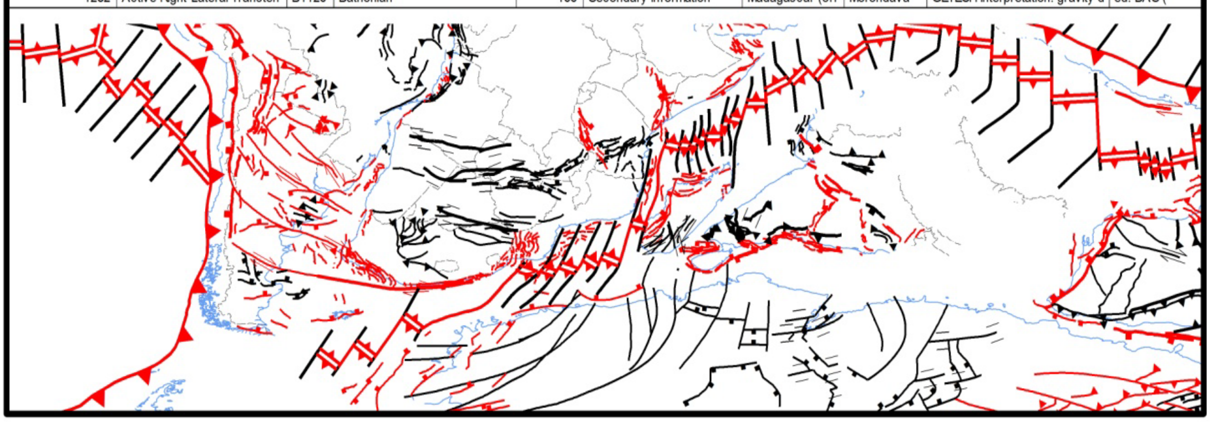


Figure 2.7: *Picking out lineaments from the potential field data gives the location and extent of these features, while extensive literature reviews elucidate the kinematic history. This information is stored in attribute tables within ArcGIS™.*

The global structural coverage is compiled at a scale of 1:10,000,000, which is at a higher resolution than the global palaeogeographies (1:20,000,000). As an example, Figure 2.8, which is at a scale of 1:5,000,000, shows the thicker black line from the global mapping coverage at 1:10,000,000, while the thinner black lineaments are taken from Getech's *Equatorial Atlantic Tectonic Elements Regional Report* (completed 2013) which was mapped at a scale of 1:1,000,000 (this data set is also supplied as a Present Day layer as part of the *Globe* programme). This example clearly illustrates structures from both scales and shows that the fundamental difference in resolution does not compromise understanding of the overall trend and is much more suitable for mapping at 1:20,000,000. This example is from the Transbrasiliano Lineament, a shear zone located in South America.

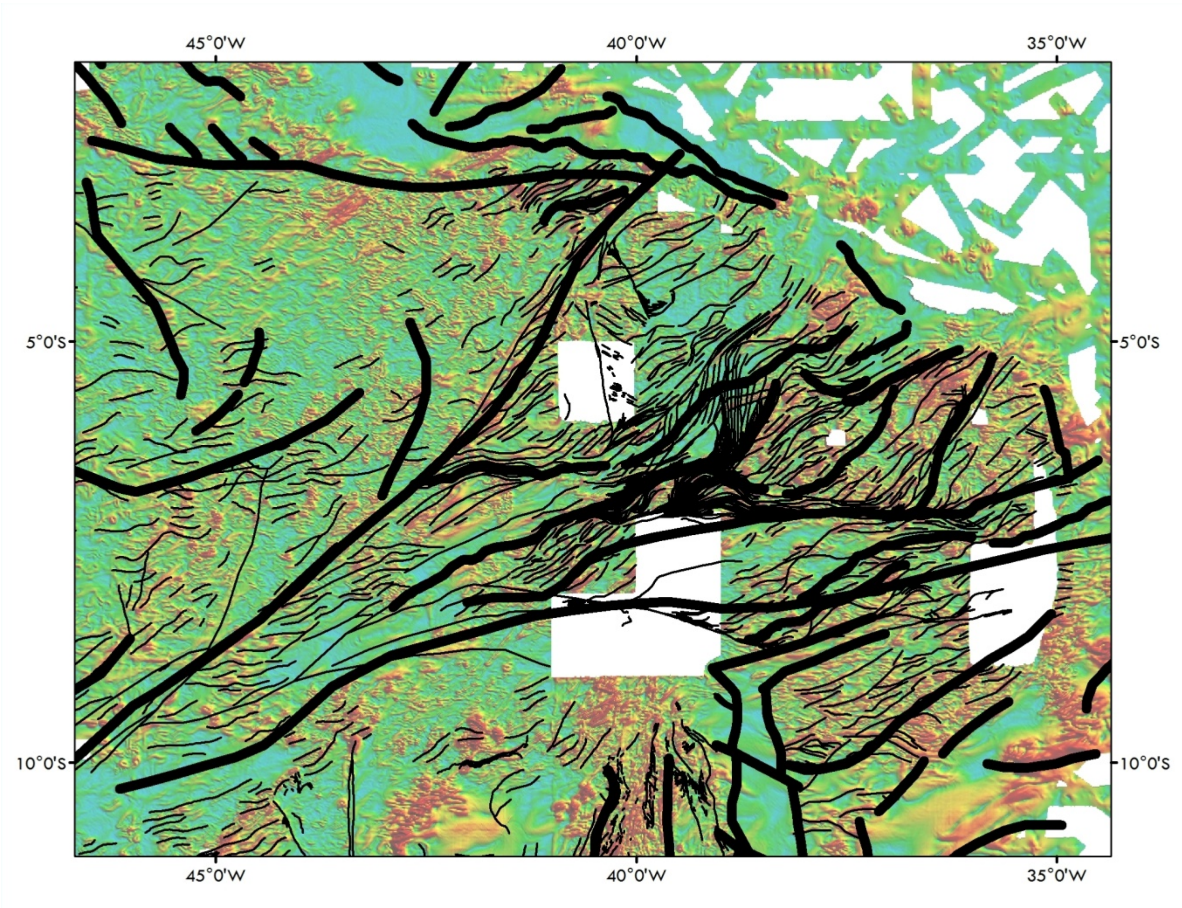


Figure 2.8: *The Transbrasiliano Fault shown (at 1:1,000,000) in two data sets mapped at different scales. The thick lines are from Getech's 1:10,000,000 scale global database, and the thin lines are from the 1:1,000,000 database. Scale is critical and depends on the true application. In both cases, the database comes with a comprehensive attribute and audit trail.*

As with all structures, thrust fronts are mapped in their Present Day location and are rotated to previous timeslices. The rotation process causes faults to fragment when they are located on two differing terranes, in which case they are duplicated on each plate. In the case of collisional boundaries, the remaining structure is the one that is located on the hanging wall. Where structures are split across strike-slip boundaries, the structures are reconnected. The complication for intra-plate compressional systems is that they migrate through time which cannot be directly represented in a rigid plate model. Constraining the exact extent and timing of the movement of these types of faults is difficult. Topographical data may help with the initial interpretation; however, this will not indicate any of the timings of when the thrust front moved forward. Using estimations of shortening (which involves fieldwork, structural modelling and, if possible, sedimentological evidence) could indicate the movement of the fault through time. At 1:20,000,000 the position of the thrust front would not be sufficiently accurate and furthermore, this would be prohibitively time consuming for every fault. Figure 2.9 is an example of where gravity (Getech Global Gravity ISO v.2011; isostatic anomalies) data highlights a thrust front in Arabia. The position of this thrust front has not been modified through time for the reasons outlined above.

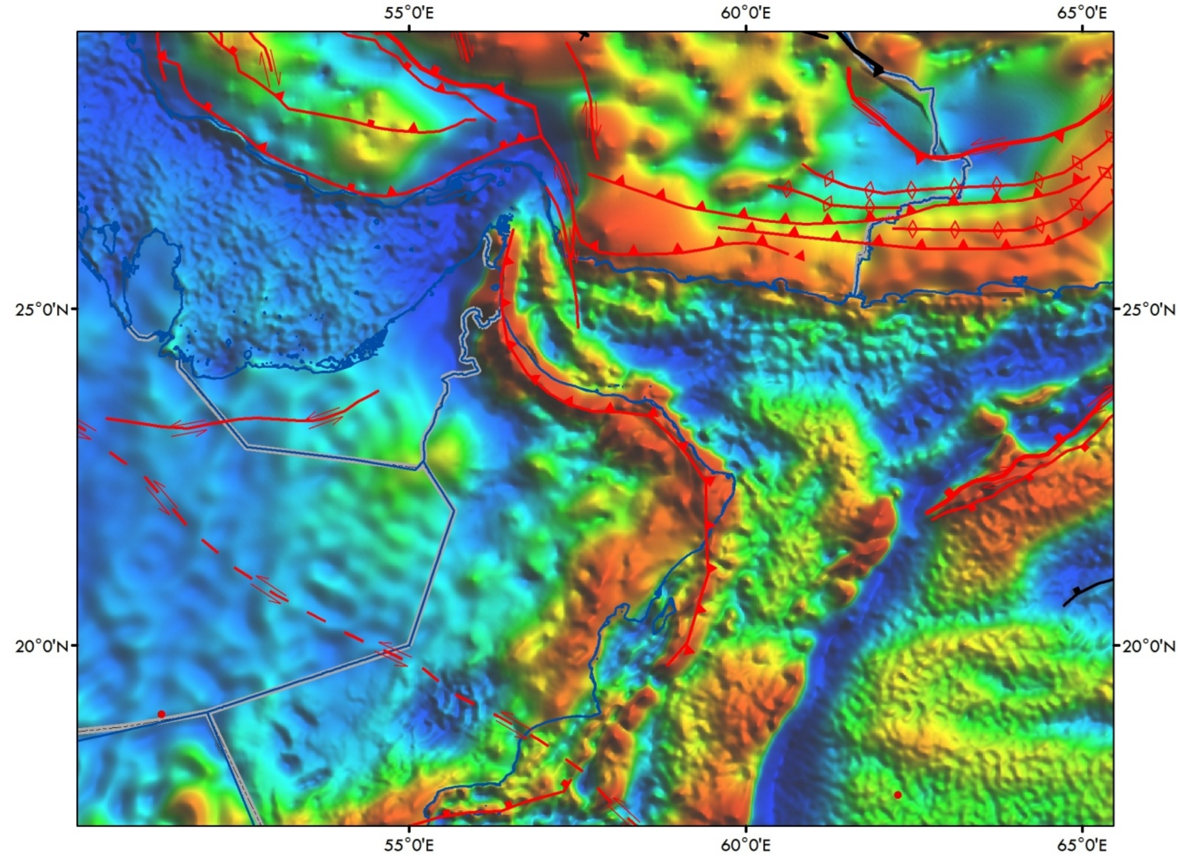


Figure 2.9: *Present Day location of the thrust front on the Arabian Peninsula. The fault is located in the same place throughout time in Getech's maps with respect to this continental block.*

2.5.1 Oceanic Structures Older Than the Crust

Much of the Cretacous oceanic crust has been lost through subduction, with the exception of (often contentious) small fragments of trapped oceanic crust. In order to map the Cretaceous ocean structures, this study uses the flowlines tool in GPlates to track the motion between pairs of plates. The flowlines are then plotted on our maps as transform faults. This assumes three things: even spreading and subduction rates, that the conjugate margins between a spreading centre are either both active or both passive and, lastly, that the location of the spreading centre remains an equal distance from the conjugate margins. When one margin is active and the other is passive, the transform faults on the passive margin side are traced through from the map of the previous (older) stage. If the ocean is closing, the spreading centre is placed at the end of the transform fault drawn from the passive margin side. The active margin transform fault is then traced through from where the passive margin transform fault hits the spreading centre to where it hits the subduction zone. If the ocean is opening, then the transform on the active and passive margins is traced through from the previous (older) map. A continuation of the transform will be drawn in this space, and the spreading centre is plotted in this gap with a 2:1 ratio biased towards the passive margin in order to show that the spreading centre is moving towards the subduction zone as the plate is being consumed. This ratio is an approximate igure based on the difference between the average rates of spreading and subduction.

The time taken for newly produced crust to reach abyssal depths is calculated using the following equation,

$$t = (\frac{\mathrm{d} - 2600}{365})^2 \qquad \text{Equation 2.1}$$

Where:

d = distance in metres

and t = time in million years (Stein and Stein, 1992).

The boundary between rise and abyssal plain is set at 4,000 m below sea level. Using the above equation, choosing d = 4,000 m means it takes crust produced at the ridge 14.7 million years to sink to abyssal depths. We use the 14.7 million year interval to define the boundary between ridge and abyssal plain environments, and to map the width of the ridges formed at spreading centres.

When both margins are passive we have been able to calculate the age of the oceanic crust as it moves away from the mid-ocean ridge using GPlates. When one or both of the margins are active this is not possible. If previously the active margins were passive, we assume that the spreading rate has remained constant and the ridge remains the same width. In all likelihood, spreading and therefore the width of the ridge are more likely to increase owing to the addition of slab pull force acting on the subducting plate; however, we have no way of calculating the slab pull force and the effect it has on the plate. When we are not able to pin any constraints on the spreading rates between plates, such as in the Pacific, we have taken the average width of the rise from Present Dayanalogues.

2.6 Palaeogeographic Mapping

The palaeogeographies are excellent tools for evaluating the temporal and spatial juxtaposition and extension of GDEs beyond areas of available data. Tectonic regimes can also be elucidated in terms of extent and the dynamic regime within a visual context. The palaeogeographic maps therefore integrate tectonics with surface processes by the representation of contemporary base-level, enabling the representation of a landscape.

Basemaps (Figure 2.10) are created using the plate model and contain rotated structural coverage, grids, time-specific geology and data points. Data points are obtained from Getech's own Wells and Outcrops database, which records lithological and depositional information (see section 2.2), plus additional third party data sets (e.g. ODP, DSDP, IODP and Chicago Lithofacies Database). The population of this database is actively ongoing, although for each atlas most of the information is recorded in the early stages of the mapping process. Useful images such as seismic lines, cross-sections, chronostratigraphies, facies and geological maps are also incorporated into databases and scrap-books, and georeferenced if possible. Environments and lithologies are drawn onto these basemaps, with ArcGIS™ used to capture and attribute the reconstructions in one feature class using Getech's own legend (see Figure 2.18).

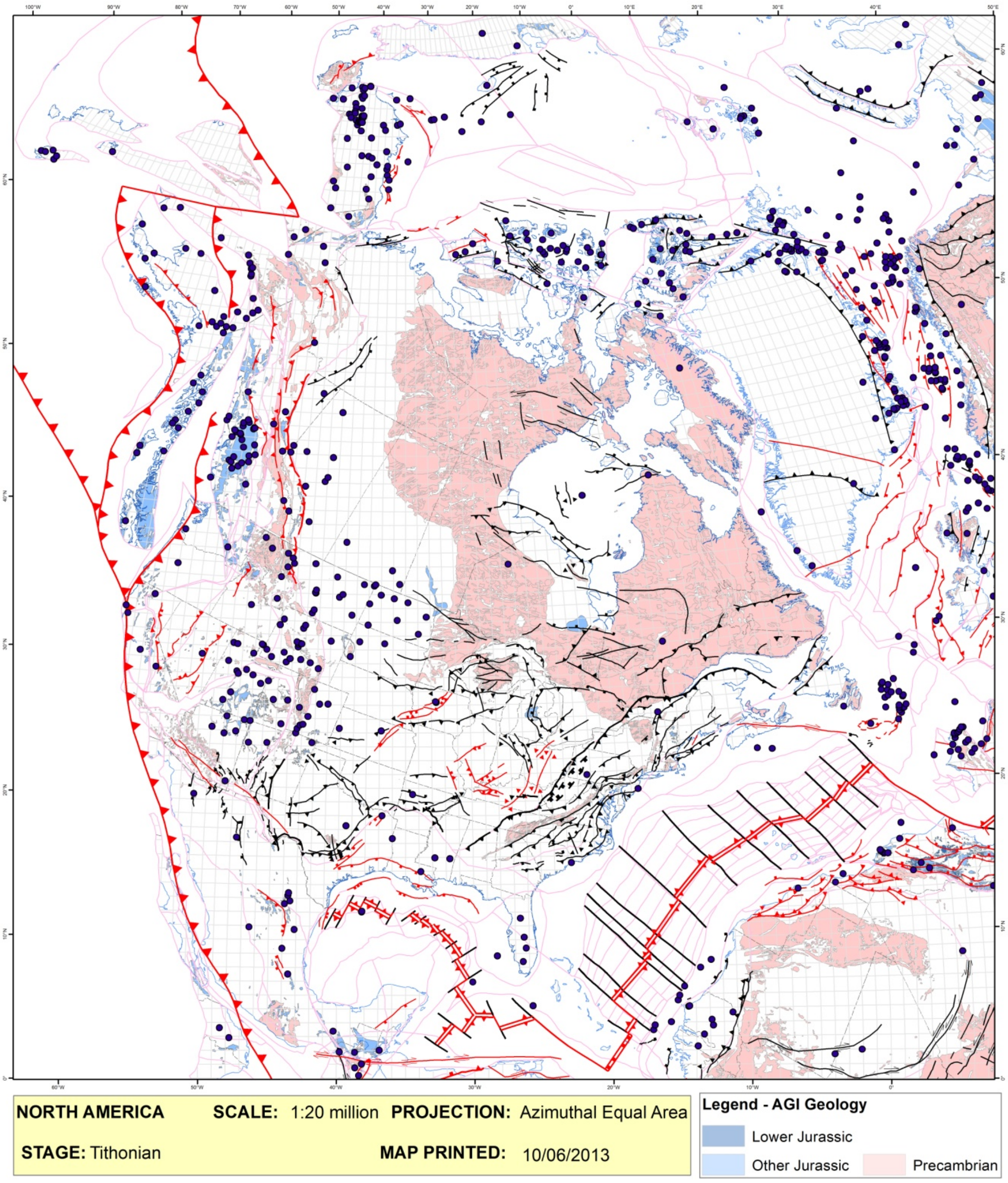


Figure 2.10: *An example of the rotated basemaps onto which the gross depositional environments and tectonophysiographic terranes are mapped. These contain rotated plate polygons, a 1:10,000,000 scale structural data set, data points, geological information and cultural data (coastlines, country boundaries and cities).*

Drawing on reconstructed maps is a key stage in the palaeogeographic mapping process owing to the interdisciplinary nature of this project, bringing the structures, GDEs, tectonophysiographic terranes and plate modelling together. At this point, gaps and inconsistencies in data and differing interpretations and ideas are highlighted and addressed. These iterations are a key stage of the project to ensure that all the different disciplines are considered in a consistent and coherent interpretation.

2.6.1 Tectonophysiographic Terranes

Tectonophysiographic terranes are related to a specific tectonic regime defined by a series of mantle and crustal processes or driving geodynamic forces. Tectonic uplifts are separated into variations of both horizontal and vertical uplift. Apart from where terranes are mapped as actively uplifting, areas above base-level (tectonophysiographic terranes) are mapped and coded so that the last uplift mechanism in the local area is accounted for. This is until the time period in which the last uplift mechanism took place more than 300 million years prior to the timeslice being mapped; in these cases the areas are considered anorogenic.

Compressional tectonophysiographic terranes are dominated by converging, horizontal stresses and can be subdivided into three broad categories differentiated by crustal types:

- Ocean-ocean: subduction of oceanic crust beneath oceanic crust and the formation of intra-oceanic island arc/back-arc complexes.
- Ocean-continent: subduction of oceanic crust beneath continental crust and the formation of Andean type orogens.
- Continent-continent: collision of continental crust with continental crust and the formation of major orogens such as the Himalayas.

There are also two additional tectonophysiographic terranes that are classed as compressional settings, areas of compression undifferentiated and areas influenced by far-field effects.

Active extensional settings are areas of the Earth's crust where horizontal stresses are tensional and the formation of intra-cratonic rifts is ongoing. These may be associated with rift flank uplift. Continental rifting often develops in areas where plumes and their associated large igneous provinces (LIPs) are present. A Present Day example of ongoing, active intra-continental rifting is the East African Rift System. There are two evolutionary pathways that extensional settings can follow after initial tensional stresses are removed: continental splitting can either stop completely and a failed rift develops, or extension continues and eventually creates a passive margin.

Active thermal anomalies refer to settings that are the result of mantle (plume) processes and are often associated with extrusive expression as LIPs. For first order constraints, plume settings are sub-divided into the following;

- Isolated intraplate islands (hotspots)
- Oceanic plateaus (*offshore* LIPs)
- Plume setting on continental crust with LIPs

For oceanic islands and seamounts, Present Day examples of intraplate plume impact on oceanic crust are the Hawaiian Chain and the Canary Islands. Mantle plumes and LIPs are intimately connected and rarely occur separately. For intracratonic plume settings with associated LIPs, a Present Day analogue is northeast Africa where the Afar Plume is currently impacting the base of the African Plate and generating surface uplift and the Ethiopian flood basalts. Plume-related surface uplift has a predominantly long wavelength geometry. Plume activity is one of the hardest regimes to delimit owing to the differing tectonic response within varying crustal types. For instance, a mantle plume emplaced under oceanic crust has island chains associated with it, whereas the plume under South Africa has elevated much of the southern part of the African continent. The crustal response to a plume will be a complex interdependent relationship of crustal thickness, density, weak zones and size of the plume. Additionally, there will be subtle uplift on the flanks of the plume that may not have volcanics or major clastic inputs within basins associated with it, but have a minor positive topographic effect.

The main problems encountered when mapping tectonophysiographic terranes are the extent to which an area was affected by and (if any) subsequent tectonic overprinting. Greece for example, has undergone several tectonic phases, and regions that are in close proximity today were once spread over different tectonic plates and vast oceans in the past. During the Jurassic, Present Day Greece was spread across the Adria/Apulia Plate, Hellenides and Dinarides Plate, Pindos Ocean, Pelagonia Plate, Vardar Ocean and Rhodope-Dacia Plate. Subsequently, the closures of the Vardar Ocean in the latest Cretaceous and the the Pindos Ocean in the Eocene have caused multiple compressional phases and periods of thrusting and overthrusting. The region also saw further compression following the collision of Africa with Europe and the formation of the Hellenic Arc. In more recent times, Greece has become a region of extension behind the Hellenic Arc.

2.6.2 Gross Depositional Environments

Gross depositional environments (GDEs) combine the depositional environment and the lithology deposited. For the global palaeogeographies these are separated into the following sections:

1) Continental: which includes alluvial, fluvial, flood plains, aeolian and swamps (not differentiated on global maps, but are differentiated in *Regional Reports* at 1:5,000,000 (or finer scales) and will be in the next phase of *Globe*)
2) Lacustrine
3) Delta top
4) Transitional: which includes coastal, sabkhas, lagoons, mangroves, saltmarshes, etc. (not differentiated on global maps but are differentiated in *Regional Reports* at 1:5,000,000 (or finer scales) and will be in the next phase of *Globe*)
5) Marine environments: shallow shelf (<50 m), deep shelf (50–200 m), continental slope (200–2,000 m) and rise (2,000–4,000 m), abyssal plain (4,000–6,000 m), deep ocean (>6,000 m) and trenches (unlike all the other marine environments, the latter is a function of subduction and not depth)

The main limitation to GDE mapping is data availability. Depending on the region being mapped this can be due to the following issues:

- Lack of access to sub-crop or outcrop data, for instance, Greenland or Antarctica owing to the ice cover, or Siberia owing to the remoteness of the area Older or terrestrial deposits can be problematic due to a lack of reliably dated fossils, e.g. long-lived redbeds without volcanic intrusions or lakes to constrain these units
- Political reasons or areas that have been under conflict

Additionally, comparing basin-scale with regional interpretations can highlight inconsistent, conflicting data or possible misinterpretations with surrounding areas. Spatial and temporal variations within data points can sometimes be misleading. This is usually a consequence of defining a timeslice (see Section 2.1 on Temporal Grain), although it can also be related to mapping scale. This also means that in some cases, known source rocks, for instance, may not be mapped as they cover short timespans related to the time mapped and thus are not the dominant lithology and/or environment. The staff at Getech come from differing scientific spheres which allows the input of different perspectives into problematic areas and concludes with interpretations that always honour the available data.

2.6.3 Palaeobathymetry

The palaeobathymetry is constructed in several ways. Continental shelves, shelf break and intrashelf bathymetry are based on available seismic, lithological and palaeontological information. Oceanic crust is derived by following the age-depth equations of Stein and Stein (1992; equations 2.2 and 2.3) using Present Day ocean bathymetry (Jones, 2008) and the ocean age grid of Müller et al. (1997), with corrections for sediment cover, sea level changes and the intrusion history of oceanic seamounts (Markwick and Valdes, 2004).

For crust younger than 20 Myr:

$$d = 2600 + 365\sqrt{t}$$ Equation 2.2

For crust older than or equal to 20 Myr:

$$d = 5651 - 2473\exp(-0.0278t)$$ Equation 2.3

where t is the age of crust in millions of years and d is the depth in metres.

The results are then rotated into their palaeopositions and compared with other palaeobathymetric data, including seismic data, information from DSDP, ODP and IODP cores and other wells. For areas of no well-dated ocean crust (e.g the Arctic Basin), or older time periods for which ocean crust is no longer preserved, age-depth calculations are applied to modelled synthetic isochrons based on the conceptual plate model for each area. The methods used to calculate ocean spreading form part of the palaeobathymetry work.

2.6.4 Shoreline Variation

All volumes within these atlases are mapped at maximum deposition which is usually represented by the highstand sea level. Getech also provides a polyline representing the lowstand sea level and a polygon representing the difference between the lowstand and highstand. Mapping the lowstand is highly data dependant and consequently the polylines have been categorised into three different types of data: certain, inferred and uncertain. The latter category is highly speculative, but is supplied to enable a continual global polyline. Data comes from seismic, chronostratigraphies, geological maps, outcrop and subcrop data, facies maps and fossil records where possible. In many cases, the highstand and lowstand will not differ; this is because at this scale (1:20,000,000) there is not a significant variation either due to localised sea level variations or tectonic controls.

2.7 Drainage Analysis

Overlaying the rotated Present Day river network on the mapped GDEs and tectonophysiographic terranes indicates past relationships between, relative drainage basin size, current outlet points, sediment source locations and flow directions. This is used in conjunction with published provenance analysis. The geologically younger the map, the more valuable the rotated drainage networks are. Changes in river drainage at this scale are only expected if there is a significant alteration in the palaeoenvironments, sediment sources or sea level.

Drainage analysis is the part of the workflow designed to reconstruct transport pathways between sediment source and sink areas. This workflow includes drainage network analysis (Present Day: identifying potential changes that can then be tested against geological observations), geomorphological analysis (looking at the relationship between geomorphological patterns in the landscape and tectonics and surface processes), palaeogeographic mapping and provenance analysis (Figure 2.11). The tectonophysiographic terranes give information on the characteristics of the river such as length which is based on Present Day analogues (Figure 2.11; right). Short-headed rivers tend to develop in actively uplifting areas where there is not enough time or land area to allow the system to develop; these rivers are common in rifts. Long rivers are usually observed in less active tectonic environments or anorogenic land where there has been more time for a system to develop. Although there are exceptions to this, e.g. the Ganges or the Mekong.

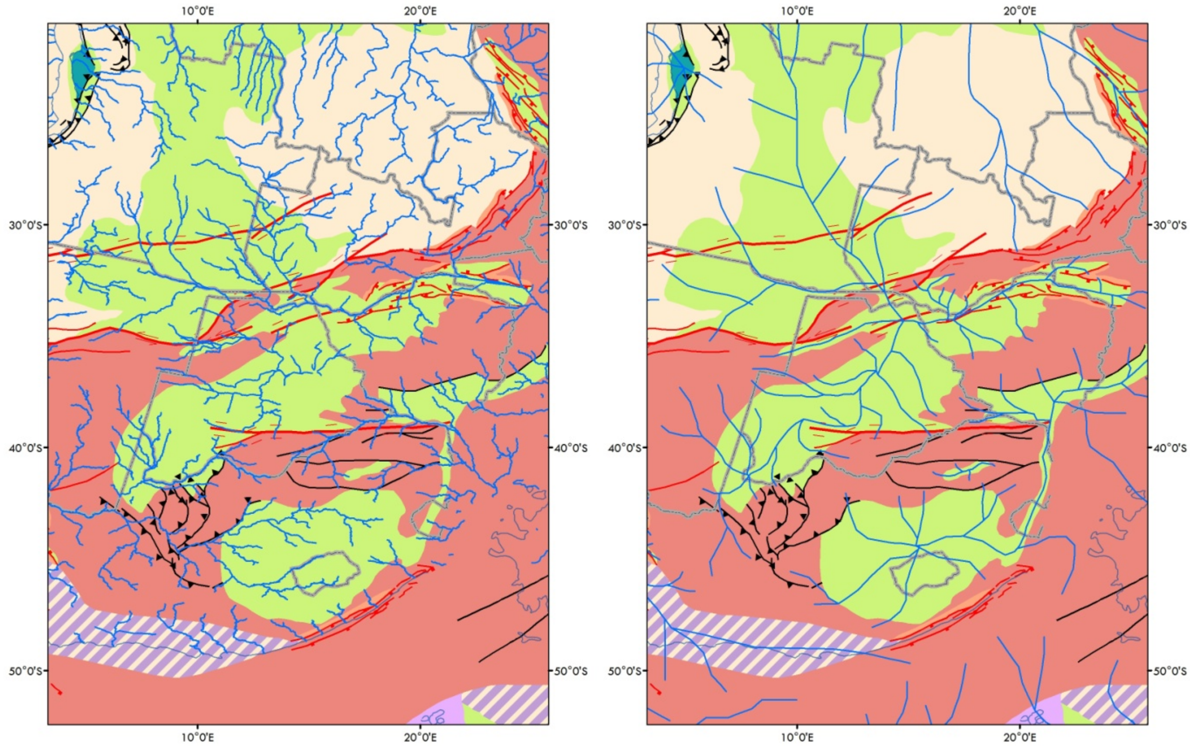


Figure 2.11 Rotated Present Day drainage network with palaeoenvironments (left) and reconstructed palaeodrainage (right) for the Hettangian.

Drainage patterns are assumed to remain constant until subjected to a change in one of the following:

- Regional base-level change due to:
  - Large-scale tectonics (uplift or subsidence)
  - Mantle processes (dynamic topography)
  - Sea level
- Local tectonics
  - Small-scale uplifts causing diversion (depend on rate of uplift and river erosion)
  - Small-scale mantle-related uplifts (100–200-km wavelength)
  - Individual volcanic eruptions leading to diversion/deflection of river systems (e.g. diversion of the Middle Mekong)
- Climate
  - Change in weathering patterns and erosion, leading to increased erosion and ultimately capture events
  - Flood events
  - Natural damming (e.g. landslips or alluvial fan development blocking drainage and causing diversions)

Drainage basins are mapped in order to help compartmentalise the landscape for use in the creation of the palaeo-DEMs. Comparing the rotated changes in both drainage basins and river networks provides insights into the changes of sediment flux in a given area. Additionally, a river extension feature class is created at the same time, which extends the rivers to the lowstand shoreline.

2.8 DEM Mapping

Palaeo-DEMs represent the Earth's topography during a geological period of time. Present Day topography has an intrinsic relationship with the underlying tectonic regime as tectonics and surface processes are ultimately the driving forces of elevation. Topography can be viewed as the product of the interaction of tectonic processes and surface processes striving to achieve equilibrium. Tectonic processes influence the rate of rock uplift such that if they increase without surface process, then surface elevation will also increase; therefore, tectonic processes are predominantly topographic builders. Surface processes include weathering, erosion, transport and removal of eroded material to more distal locations. If surface processes operate in the absence of any rock uplift, surface elevation must decrease; surface processes are therefore predominantly topographic reducers. Both tectonic and surface processes rarely operate separately and are instead intrinsically coupled. It is the interaction between them which defines surface elevation and shapes the landscape. In a sense, these surface processes (mainly denudation) and their interactions with tectonic processes can be viewed as two competing groups of processes, with topography as the interface between them.

For Present Day, the highest elevations are dominated by areas where tectonic processes either outpace or balance surface processes, and the lowest elevations are in areas where either surface processes outpace tectonic processes or both groups of processes are very low. This relationship forms the basis for Getech's conceptual model for palaeotopographic reconstruction. If the assumption is made that tectonic processes and surface processes operate in a similar manner in the past, then the landscapes they produce should also be similar. This assumption allows a direct link between tectonics in a particular region in the geological past and the inferred palaeotopography that should be present in this region, without the need for any prior detailed knowledge of past surface processes.

2.8.1 The Getech Model for an Idealised Tectonic Cycle

Both the classical conceptual models and the processes-focussed models (in Bullet al., 1992; Davies, 1899; Hack, 1960; King, 1967; Penck, 1953) form the initial basis for Getech's framework for its own model of landscape evolution (Figure 2.12). This follows an idealised tectonic cycle (Figure 2.13), which has the same broad characteristics for both compressional settings and mantle anomaly settings. Although the idealised tectonic cycle can be applied to any regime, it is perhaps easier to visualise the cycle for an orogenic setting, which is outlined below.

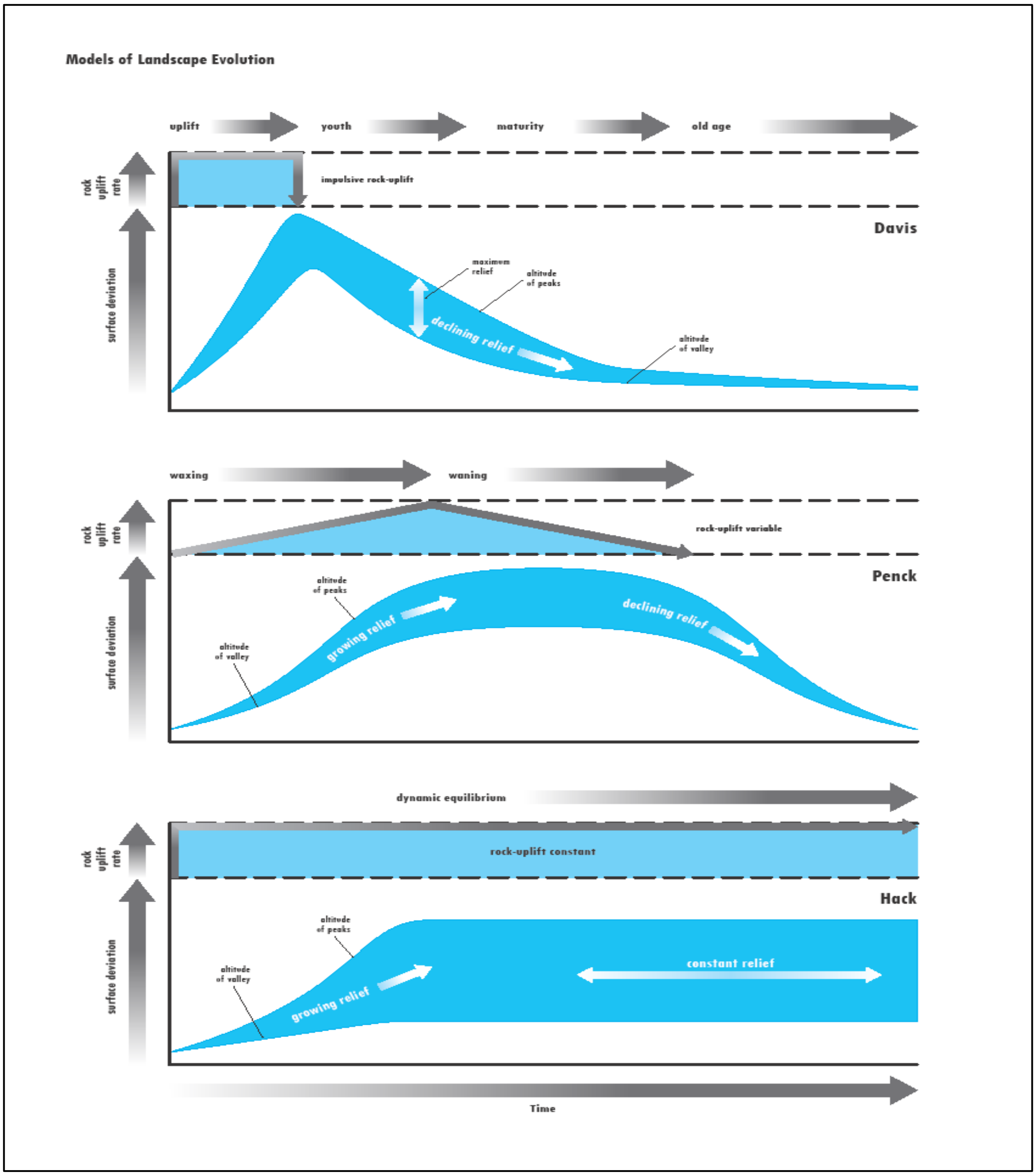


Figure 2.12: Conceptual models for landscape evolution.

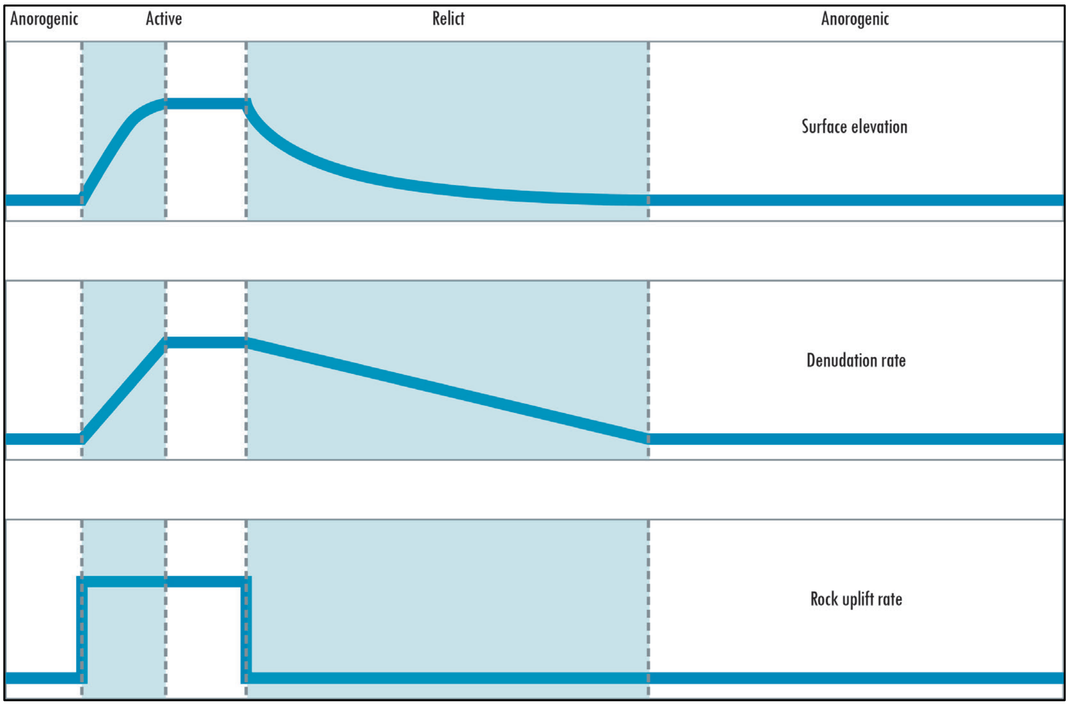


Figure 2.13: Idealised Getech model for a simple orogenic cycle.

Phase 1 – Orogenic growth

The initial low-relief, low-elevation landscape experiences tectonic compression, which thickens the crust and upper mantle and generates rock uplift. Initially, the rate of rock uplift may be insufficient to trigger a denudational response, and surface elevation will increase unhindered at the same rate as rock uplift. At a threshold elevation, denudation will be triggered and will begin to increase, which is effectively trying to reduce the elevation of the orogen. Therefore, denudation subsequently moderates rock uplift, reducing the rate of surface uplift. Phase 1 terminates when the rate of rock uplift is matched by the rate of denudation and surface elevation stabilises (total response time).

The timing and magnitude of surface uplift during orogenic growth is critical when attempting palaeotopographic reconstructions. Long-term rock uplift rates and denudation rates of mountain belts have been quoted as being between 200 and 1,000 m/Myr (Gleadow and Brown, 2000; Clark and Jäger, 1969; Mehta, 1980; Schaer et al., 1975). Furthermore, numerical modelling experiments predict that steady-state equilibrium between rock uplift and denudation (i.e the response time) will occur after ~1–10 Myr for typical crustal convergence rates and crustal thicknesses (Willett 1999; Allen 2008). Using these constraints, Figure 2.14 highlights the maximum surface elevations obtained for a range of rock uplift and denudation rates for different relaxation times.

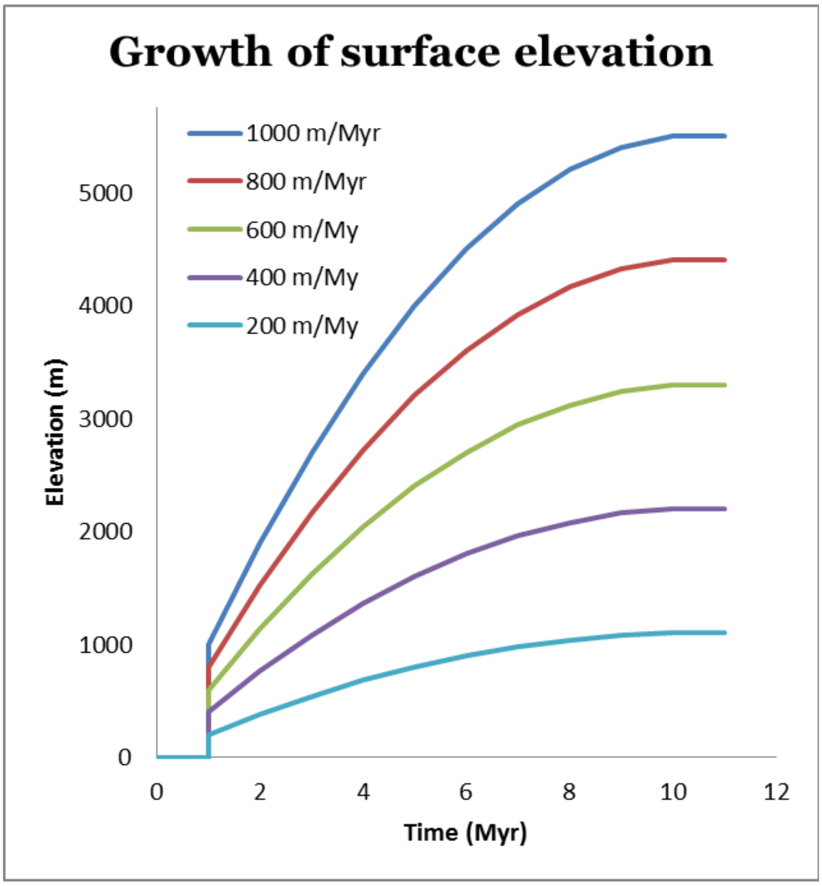


Figure 2.14: Relationship between surface elevation growth and time for different rock uplift and denudation rates. For a 10 Myr total response time, higher rates of rock uplift and denudation result in higher surface elevation.

Constraining the rate of rock uplift, the rate of denudation and the response time is problematic even for orogens that are currently active and well-studied. Attempting to constrain these parameters for ancient orogens is even more complex, and in many cases there is simply no information. The timing of the response is 10^7 years, which compares favourably with independent numerical models (Allen, 2008; Willett, 1999;). Rates of rock uplift and denudation of 1,000 m/Myr (comparable to most major orogens) will yield maximum surface elevations of ~5,000 m. This value compares favourably with the average maximum elevations of Present Day analogues (Figure 2.15).

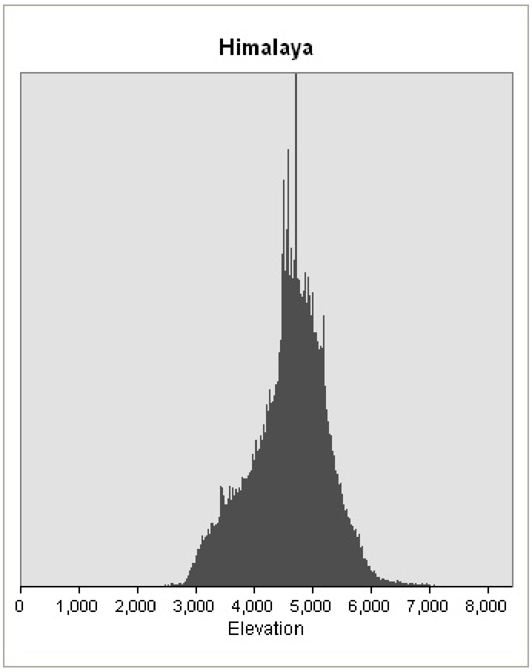


Figure 2.15: Left – SRTM topography for the Himalayas. Right – Histogram of elevation range for the Himalayas.

Phase 2 – Steady-state active orogen

Rock uplift is matched by denudation, and the orogen is in dynamic equilibrium. This phase is analogous to Getech's active tectonophysiographic terranes and defines the period when an orogen has attained its maximum surface elevation. During steady-state, there is still ongoing rock uplift and ongoing denudation (recorded within sediment flux, geochronometers and thermochronometers), but the surface elevation or topography remains unchanged.

The Himalayas and the Southern Alps of New Zealand are two examples of active orogens considered to be in a steady-state. The surface elevation of these orogens is no longer changing, and rock uplift is balanced by denudation. The Himalayas are believed to have had a total of 20-25 km of rock uplift (Summerfield 1991), whereas the Southern Alps have had a total of 15-25 km of rock uplift (Tippett and Hovius 2000). This is crucial when considering the relationship between surface elevation and the potential for generating sediment. During steady-state, surface elevation remains unchanged, but vast quantities of sediment can still be generated from ongoing rock uplift and denudation. It is only when tectonic processes diminish or cease entirely that denudation can outpace tectonic uplift and surface elevation will begin to decrease.

Phase 3 – Orogenic decay

When the tectonic regime changes and active compressional forces cease, the steady-state topography previously established can no longer be maintained and the maximum surface elevation of the orogen will begin to decay. This could be considered analogous to Davies' (1899) concept of a more mature, cyclic landscape developing after an initial period of rejuvenated uplift. However, Hacks' (1960) concept of dynamic equilibrium could also be applied as an alternative model: viewing the landscape as being once again in a state of disequilibrium with the prevailing conditions. The decay of the orogen is no more than the landscape adjusting to this new set of conditions where tectonic uplift is now absent. The decay phase corresponds to Getech's relict tectonophysiographic terranes.

The rate at which the maximum surface elevation decreases will depend on three factors: the decay rate of rock uplift as orogenisis ceases, the decay rate of denudation as the orogen is lowered, and the moderating effects of denudational isostasy. The denudation rate is thought to decrease with decreasing elevation (Ruxton and McDougall 1967; Ohmori 2000; Pinet and Souriau 1988), decreasing slope angle and decreasing relief (Ahnert, 1970; Burbank, 2012; Montgomery and Brandon, 2002). Both numerical modelling using these relationships (Beaumont et al., 2000) and field observations (Schumm and Rea, 1995) indicate that the denudational response and also the rate of surface lowering will approximate an exponential decay curve. It is this exponential decay curve that forms the basis for the rate of decrease in maximum surface elevation modelled for tectonophysiographic terranes as they become progressively more relict. As the relict orogen is denuded, the removal of material at the surface will elicit an isostatic response which will further moderate and extend this exponential decay curve (see Figure 2.12).

Elevation is one component that is common to most of the algorithms developed to establish what causes variations in denudation rates. Pinet and Souriau (1988) demonstrated that Present Day erosion rates seem to increase at a linear rate with an increase in elevation (Equation 2.4). The higher the initial elevation, the greater the erosion rate will be and the elevated area will be lowered more rapidly. As the elevation decreases so will the erosion rate, creating an exponential decay of surface lowering. Although there are caveats to this study and more complex relationships for variations in denudation rate have been developed, this study serves as a useful foundation. The relationship is defined as follows (Pinet and Souriau, 1988):

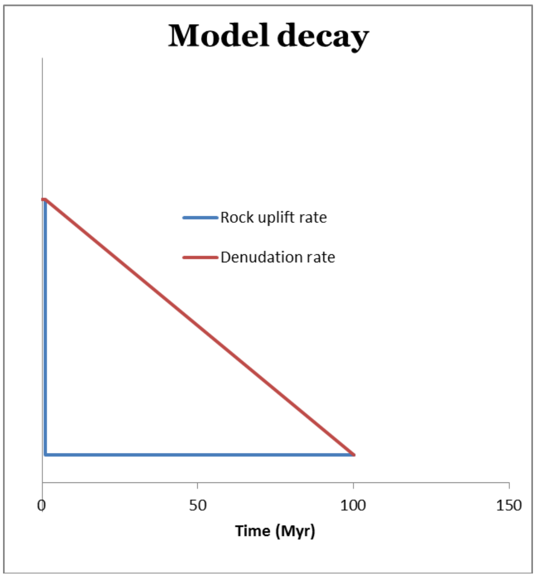
$$(m/10^3\ yr) = 61 \times 10^{-6}\ H\ (m) \qquad \text{Equation 2.4}$$

Where m is meters and H is height.

Using this relationship, the erosion rate at 5,000 m (Himalayan-type orogen) is 305 m/Myr. The exponential decay in elevation with time can then be calculated (Figure 2.16, red line). After only ~50 Myr the relict orogen has been completely eroded. This is extremely rapid, partly because Present Day erosion rates are likely to be unrealistic, but also because the impacts of denudational isostasy and bedrock composition have not been taken into account. As rock is removed from the orogen, the crustal column will have to isostatically adjust through isostatically induced rock uplift. The effect of erosional isostasy will be to moderate the rate at which the orogen is lowered because greater volumes of rock will have to be removed as more rock is fed through the orogen during isostatic rebound. Using a simple Airy type isostatic adjustment (Equation 2.5), the exponential decay of an orogen with an initial elevation of 5,000 m can be adjusted (Figure 2.16, blue line).

$$h_u = \frac{h_r (\rho_m - \rho_c)}{\rho_c} \qquad \text{Equation 2.5}$$

Where h_u is the thickness of the uplifted crust, h_r is the thickness of the crustal column between a fixed datum and the root, and ρ_c and ρ_m are the crust and mantle density, respectively.



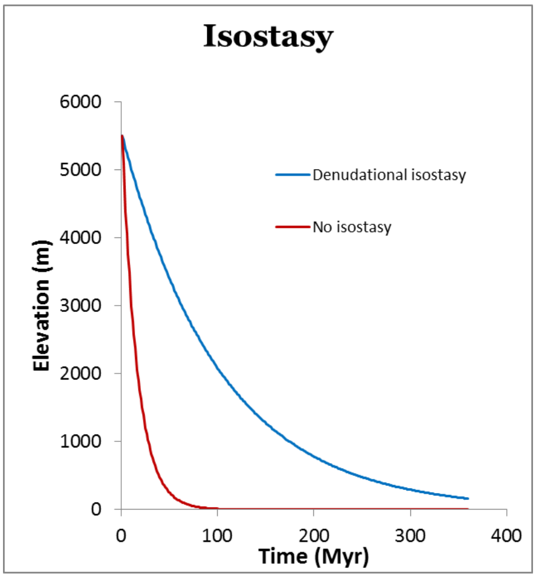


Figure 2.16: Left – simple model for orogenic decay with a step-wise decrease in rock uplift accompanied by a linear decrease in denudation rate. Right – modelled change in elevation with time for a scenario without isostasy and one with isostasy.

The elevations of Present Day analogues for both active and relict orogens of known age can be extracted from SRTM data in a manner similar to that explained above for the Himalayas. The elevation decay curve that best fits the SRTM data is for erosion rates of 300 m/Myr (Figure 2.17). Interestingly, the real data indicate that relict orogens appear to stabilise at a surface elevation of ~1,200 m after 200 Myr, and no further surface lowering occurs.

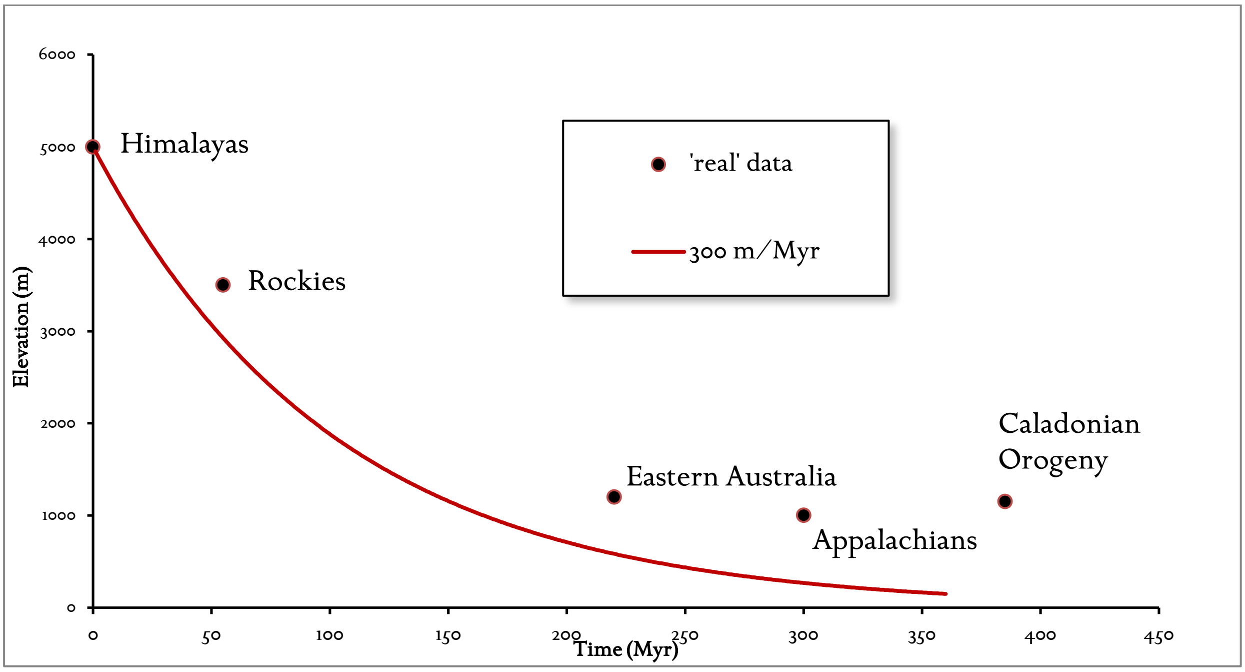


Figure 2.17: Relationship between decay of elevation and time for 300 m/Myr. This initial denudation rate provides the best fit decay of surface elevation for a selection of real data.

Phase 4 – Anorogenic landscape

Given sufficient time, denudation, even with the moderating effects of isostasy, will eventually reduce the relict orogen to a low-relief, low-elevation landscape. This landscape will be dominated by depositional processes and low rates of denudation. The surface elevation of this landscape will depend in part on the thickness of the crust and upper mantle, the underlying geology and the erosivity of the climate. Thick, strong crust and upper mantle will remain more elevated than thin, weak crust and upper mantle. Resistant geology and/or a weakly erosive climate will result in sluggish denudation as decay rates approach low values. Even given sufficient time, it may be that rates become so low that the landscape effectively *freezes* and inertia prevents surface lowering to equilibrium conditions.

2.8.2 Active and Relict Compressional Settings

Active compressional settings comprise tectonophysiographic terranes that are dominated by converging, horizontal stresses, which are assumed to be either increasing in elevation (during phase 1) or in a steady-state (during phase 2). Areas of compression with unknown causes and areas influenced by far-field effects are difficult to relate to specific elevation ranges owing largely to a lack of suitable Present Day analogues and difficulty to distinguish unknown mechanisms of compression.

Relict tectonophysiographic terranes for compressional settings initially have the same maximum elevations as their active counterparts. These maximum elevations then progressively decrease. This decrease takes into account the moderating effect of erosional isostasy, realistic long-term erosion rates, an exponential decay of surface elevation with time and stabilisation of relict terranes after 200 Myr.

2.8.3 Active and Relict Extensional Settings

As with active compressional settings, Present Dayanalogues prove valuable in establishing the pattern and magnitude of elevation over these features. A Present Day example of ongoing active intra-continental rifting is the East African Rift System. To extract accurate Present Day elevations that are solely related to active rifting is challenging because any elevation that is related to plume-impact processes must first be removed. This is achieved by filtering out all long-wavelength plume-related topography prior to extracting the rift elevations.

There are two evolutionary pathways that extensional settings can follow after initial tensional stresses are removed: continental splitting can either stop completely and a failed rift develops, or extension continues which eventually creates a passive margin. There are no suitable Present Day analogues of failed rifts; however, because these regions are elevated, it may be assumed that the decay in surface elevation will occur in a manner similar to the decay of a relict orogeny. There are Present Day analogues for passive margins, and although not explicitly a tectonophysiographic terrane within Getech, they encompass large segments of continental margins and must be included in palaeotopographic reconstructions

2.8.4 Active and Relict Thermal Anomalies

Thermal anomalies refer to settings that are the result of mantle (plume) processes and they are often associated extrusive expression as LIPs. In reality, constraining both the range of elevation and the elevation change with time for areas of the crust that have experienced plume impact is far more complex and is likely to be a combination of transient uplift (thermomechanical, secondary convection and lateral heat transport; Steckler 1985; Steckler et al., 1988), permanent uplift (lithospheric thinning, lithospheric stretching and magmatic underplating; Cox, 1993; McKenzie, 1978) and emplacement of LIPs. Furthermore, the magnitude of surface uplift will also be affected by the initial topographic conditions prior to plume impact. Consequently, first-order constraints for the surface elevation of areas influenced by plume impact are largely based on Getech's conceptual model which has been further modified for Present Day examples and model predictions.

For intracratonic plume settings with associated LIPs a suitable Present Day analogue is northeast Africa where the Afar Plume is currently impacting the base of the African Plate, generating surface uplift and the Ethiopian flood basalts. The maximum amount of dynamic plume-related uplift predicted from diapiric models is between 500 and 1,500 m (Campbell, 2005; Saunders et al., 2007). The magnitude of dynamic plume uplift is of a similar magnitude to Iceland (~2,000 m) and Hawaii (1,200 m; Jones et al., 2001; Sleep, 1988). Plume-related surface uplift has a predominantly long-wavelength geometry; therefore, prior to extracting Present Day surface elevations, the short-wavelength component is removed.

The decay in surface elevation of a region previously affected by onshore plume impact can be viewed in a manner similar to relict compressional settings. There are two key factors that influence the rate of decay in surface elevation for a plume setting: the rate of thermal decay of the plume itself and the decay in surface elevation as a result of erosion. The thermal decay of plumes occurs within the first 60–70 Myr after plume impact ceases (Richards et al., 1989). During the first 50 Myr after a plume has terminated, surface elevation will decrease rapidly due to both the thermal contraction of the waning plume and the high rates of erosion because the region will have had a high initial surface elevation. After 50 Myr, the rate of reduction in surface elevation will decrease less rapidly as the thermal contraction of the plume is completed and erosion rates are reduced at lower elevations.

2.8.5 Onshore Depositional Settings

Onshore depositional settings are regions where deposition exceeds erosion and includes transitional, deltaic and continental settings. Present Day analogues include large interior continental plains, large drainage basins, deltas and coastal strips. Accordingly, Present Day analogues of these environmental settings are used to define the elevation ranges of these features. For palaeotopographic reconstruction, large regions in the interior of continents and areas dominated by large fluvial systems have elevations similar to Present Day: between 0 and 300 m. All coastal, transitional and deltaic environments have elevations that do not exceed 50 m. Areas that are subsequently flooded during transgressions have low elevations when they are exposed during regressions.

2.8.6 Workflow for DEM Reconstructions

If tectonic processes and surface processes operate in a similar manner in the geological past, then the topography they produce should also be similar to their Present Day equivalents. This assumption allows a direct link between palaeotectonics and the inferred palaeotopography that should be present in this region, without the need for any prior detailed knowledge of palaeosurface processes. This concept forms the initial basis for Getech's reconstruction of palaeotopography. Such an approach elaborates on the established methods of Markwick and Valdes (2004), in which elevations are derived for tectonophysiographic terranes by analogy with Present Day elevation ranges. An important distinction between the methods of Markwick and Valdes (2004) and the current Getech methodology is a more rigorous treatment of the interaction between tectonics and surface processes within a conceptual landscape evolutionary framework.

The logistics of topographic reconstruction in ArcGIS™ follows two paths: plate reconstruction of the Present Day elevation grid, which is then manipulated through time, or the generation of contours for each timeslice based on tectonics. The former approach becomes more dominant further back in geological time, but the end product of both reconstructions is the generation of elevations in raster format or palaeo digital elevation models (palaeo-DEMs).

The key information for the generation of contours is the predominant tectonic regimes for each region of the globe for each timeslice. This information is already available in the form of palaeoenvironments which effectively represent the tectonic histories for each region. These tectonic histories are then used to establish maximum elevations for each region for each timeslice. The maximum elevations (Table 2.1) are tabulated with adjacent timeslices to insure consistency and to create a temporal series of elevations representing topographic development for each region.

The next phase of palaeo-DEM generation involves manual data capture of contours in ArcGIS^{TM} to represent the maximum elevations that have been assigned for each region. These contours are individually attributed feature class polylines that are digitised along major watersheds and palaeoenvironment boundaries. The positions of major watersheds are constrained using the palaeorivers for each timeslice. The palaeorivers also form a key data set used in the modelling to aid in the creation of a hydrologically correct palaeo-DEM. A final data set required for the modelling is the location and extent of palaeolakes. Palaeolakes are required to locally flatten the DEM to better represent the topography in these areas.

Further modifications are made to the contour data set to account for areas that become transgressed in younger timeslices. The elevations of these areas are kept lower than the typical conceptual framework would suggest, creating topography that can subsequently flood without requiring unrealistic elevation changes. The geometry and positions of completed contour data sets are also compared to adjacent timeslices to ensure that the resultant generated topography also has a consistent geometry.

The contours, rivers and lakes data sets are modelled simultaneously within an iterative, finite difference interpolation programme integrated into ArcGIS^{TM}. This programme is particularly adept at handling contoured data (the primary constraining input) and river data. The result of the interpolation is a hydrologically correct DEM that is capable of realistically accommodating abrupt changes in topography over relatively small spatial scales. This interpolation process is far from perfect, particularly while attempting to model topography over geological timescales where creating well-constrained, detailed contour data are both challenging and time consuming. Consequently, several iterations are usually required to adequately remove artificial and unrepresentative *artefacts* created during the interpolation process. If necessary, the palaeo-DEMs are modified to better account for regional data that contradicts our conceptual model. The objective is to produce a series of palaeo-DEMs that suitably mirror the underlying tectonics, with elevation ranges that are geologically reasonable within a landscape development framework.

ACTIVE		RELICT (0–50 Myr)		RELICT (50–100 Myr)		RELICT (100–200 Myr)		RELICT (>200 Myr)	
CODE	MAX (m)	CODE	MAX (m)	CODE	MAX (m)	CODE	MAX (m)	CODE	MAX (m)
1100	5,000	1,108	3,500	1,106	2,000	1,104	1,000	1,102	500
1110	4,000	1,118	3,000	1,116	2,000	1,114	1,000	1,112	500
1120	0–2,000	1,128	1,750	1,126	1,500	1,124	1,000	1,122	500
1130	2,000	1,138	1,750	1,136	1,500	1,134	1,000	1,132	500
1140	2,000	1,148	1,750	1,146	1,500	1,144	1,000	1,142	500
1200	1,000	1,208	750	1,206	500	1,204	400	1,202	300
1300	2,000	1,308	1,500	1,306	1,000	1,304	750	1,302	500
1310	2,000	1,318	1,500	1,316	1,000	1,304	750	1,312	500

Table 2.1 The maximum elevations of tectonophysiographic terranes currently adopted for Getech's palaeotopographic reconstructions. These maximum elevations take into account the moderating effect of erosional isostasy, realistic long-term erosion rates, modelling results and data from Present Day analogues.

2.9 Getech GIS Mapping Legend

All of Getech's palaeogeography maps are compiled in ArcGIS™, using our own comprehensive ArcGIS™-based map legend. This legend includes representations of the underlying structural and tectonic elements, palaeoenvironments, tectonophysiographic terranes and lithologies (Figure 2.18), together with cultural information (coastlines and country boundaries) and data constraints (points, lines, etc.).

Figure 2.18: Getech's GIS legend.

2.10 Glossary and Structural Mapping Confidence Information

Terms	Acronym	Definition
Appearance Age	–	Represents the first appearance age of a tectonic terrane within the plate model. Commonly given as basement age in continental crust.
Base-level	–	The conceptual surface in the landscape representing a balance between net erosion and net deposition; this is essentially the equilibrium or graded profile of fluvial geomorphologists.
Euler Pole	–	A pivot about which any given point is moved relative to another across the surface of a sphere in order to represent their relative motions.
Euler Rotation	–	Mathematical representation of the motion of a given point on Earth's surface about a fixed semi-axis (the Euler pole), by a finite angle.
Feature Class	–	"In ArcGIS, a collection of geographic features with the same geometry type (such as point, line or polygon), the same attributes, and the same spatial reference. Feature classes can be stored in geodatabases, shapefiles, coverages or other data formats. Feature classes allow homogeneous features to be grouped into a single unit for data storage purposes. For example, highways, primary roads, and secondary roads can be grouped into a line feature class named "roads." In a geodatabase, feature classes can also store annotation and dimensions."
Gross Depositional Environment	GDE	The area in the environment that is below base-level and represents a region of net deposition.
Highstand	HS	The interval of time during cycles of sea level change in which the sea level is at its highest point in a given area.
Layer File	–	"In ArcGIS, a file with a .lyr extension that stores the path to a source data set and other layer properties, including symbology."
Lowstand	LS	The interval of time during cycles of sea level change in which the sea level is at its lowest point in a given area.
Plate Code	–	A numerical identifier of tectonic plates that is used to describe relative plate motions within the model.

Plate Hierarchy	–	A plate model comprises Euler rotations of any given tectonic plate relative to a fixed reference plate; this reference plate, in turn, moves relative to another. A plate hierarchy is used to describe the complex interactions of several plate pairs within an absolute reference frame, such as Earth's spin axis.
Plate Polygon	–	A conceptual sub-division of Earth's surface that represents a continental tectonic terrane or an oceanic segment defined by structural elements and age constraints.
Polygons	–	"On a map, a closed shape defined by a connected sequence of x,y coordinate pairs, where the first and last coordinate pair are the same and all other pairs are unique."
Polylines	–	"In ArcGIS software, a shape defined by one or more paths, in which a path is a series of connected segments. If a polyline has more than one path (a multipart polyline), the paths may either branch or be discontinuous. "
Reference Frame (plate modelling)	–	A conceptual fixed co-ordinate system, to which all Euler rotations are relative. An *absolute* reference frame is the fixed co-ordinate system beyond which no further relative motion exists (e.g. Earth's spin axis).
Tectonic Plate	–	Sub-division of Earth's lithosphere with a unique tectonic motion history, made up of one or more tectonic terrane.
Tectonic Terrane	–	A tectonic plate of sub-division thereof that exhibits a unique geological history.
Tectonophysiographic Terrane	TPT	This represents areas above base-level and is related to a specific tectonic regime defined by a series of mantle and crustal processes or driving geodynamic forces.

NB: all GIS definitions in inverted commas are taken from the ESRI's online dictionary.

MAPPING CONFIDENCE		
Confidence	Summary	Structural Element Mapping
5	No changes expected	Features with defined kinematics based on interpretation of high-resolution primary data (including Landsat, high-resolution gravity, high-resolution magnetics, SRTM, etc.) constrained by additional information from multiple other independent sources, including seismic and/or publications and our own direct observations (field work and/or good seismic).
4	Minor changes possible	Features with defined kinematics based on interpretation of high-resolution primary data (including Landsat, high-resolution gravity, high-resolution magnetics, SRTM, etc.) constrained by additional information from multiple other independent sources, including seismic and/or publications.
3	Changes probable	Features with defined or definable (e.g. can include "*fault indeterminate*") kinematics based on interpretation of primary data (including Landsat, gravity, magnetics, SRTM, etc.) with or without supporting published information (viz., features that we believe are correct, but which lack additional, independent corroboration). May include features that would otherwise be Category 4 but for resolution issues (e.g. based on satellite gravity with 20-km resolution, so exact position uncertain).
2	Changes expected	Lineaments/discontinuities with no defined kinematics, which have been identified from primary data (including gravity, magnetics, Landsat and SRTM data). These would be category D features in our structure classification. Features with kinematics, but where placement or kinematics are equivocal or uncertain (these would otherwise be Category 3). This can include features where the signature is more subtle in the primary data, causing concern.
1	Revision and testing required	Features taken from publications, but with no supporting information from primary data sources; viz., georeferenced figure only.
0	Revision and testing essential	Source unknown. This information is internal only as more supporting data are required.

AGE CONFIDENCE

This shows the definitions for age confidence based on the source of the age assignment. This is modified from the scheme developed by the Paleogeographic Atlas Project (Ziegler et al., 1985).

Confidence	Explanation
I	Absolute Age. Ar-Ar or other precise radiometric age determination giving absolute age for crust and giving clear evidence of appearance age
II	Magnetostratigraphy. Magnetostratigraphic assignment; chrons recognized
IIa	Isochron, observed. Age assignment based on mapped isochron or magnetic pick (oceans only)
IIb	Isochron, interpolated. Age assignment based on interpolated (pseudo or synthetic) isochron (oceans only)
IIc	Isochron, 3rd party. Age assignment based on 3rd party isochron which has not been corroborated by Getech staff (oceans only)
III	Biostratigraphy. Biostratigraphic information for overlying rocks indicating minimum age for underlying crust
IV	Geological Inference. Correlation with an area with more precise information
V	Secondary information. Date from other authors, but without explanation of methods used
G	Estimated.

CHAPTER 3

Data Manipulation with ArcGIS™

3 Using ArcGIS™

3.1 Basics in ArcGIS™

Getech provide digital data in ESRI native formats for use within the ArcGIS™ suite. This section aims to guide the reader through some of the data's basic functionality within ArcMap™ and ArcCatalog™.

3.1.1 Symbology in ArcGIS™

As a standard part of the *Globe* deliverables, Getech has set up default ESRI map document (MXD) files containing relevant data for each respective timeslice. They will typically contain a data frame that displays the data in WGS84 and North and South Polar projections. Each individual data set is symbolised according to the Getech legend, which is achieved by individually coding every feature with a unique code(s).

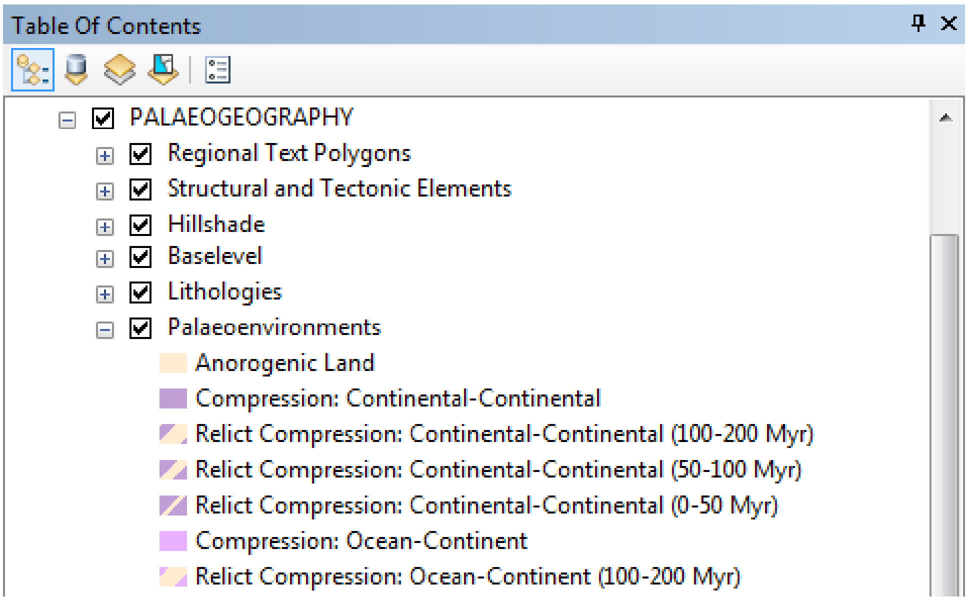


Figure 3.1: Table of Contents in ArcGIS™.

The symbology governed by our legend is not hard coded to the features within the MXDs which are provided by Getech, and therefore can be symbolised in multiple ways. Any layer can be symbolised by any of the other attributes associated with the features contained within that layer through the **Symbology** tab found in the **Layer Properties** dialogue box (which can be displayed by double-clicking on any layer in the **Table of Contents** window).

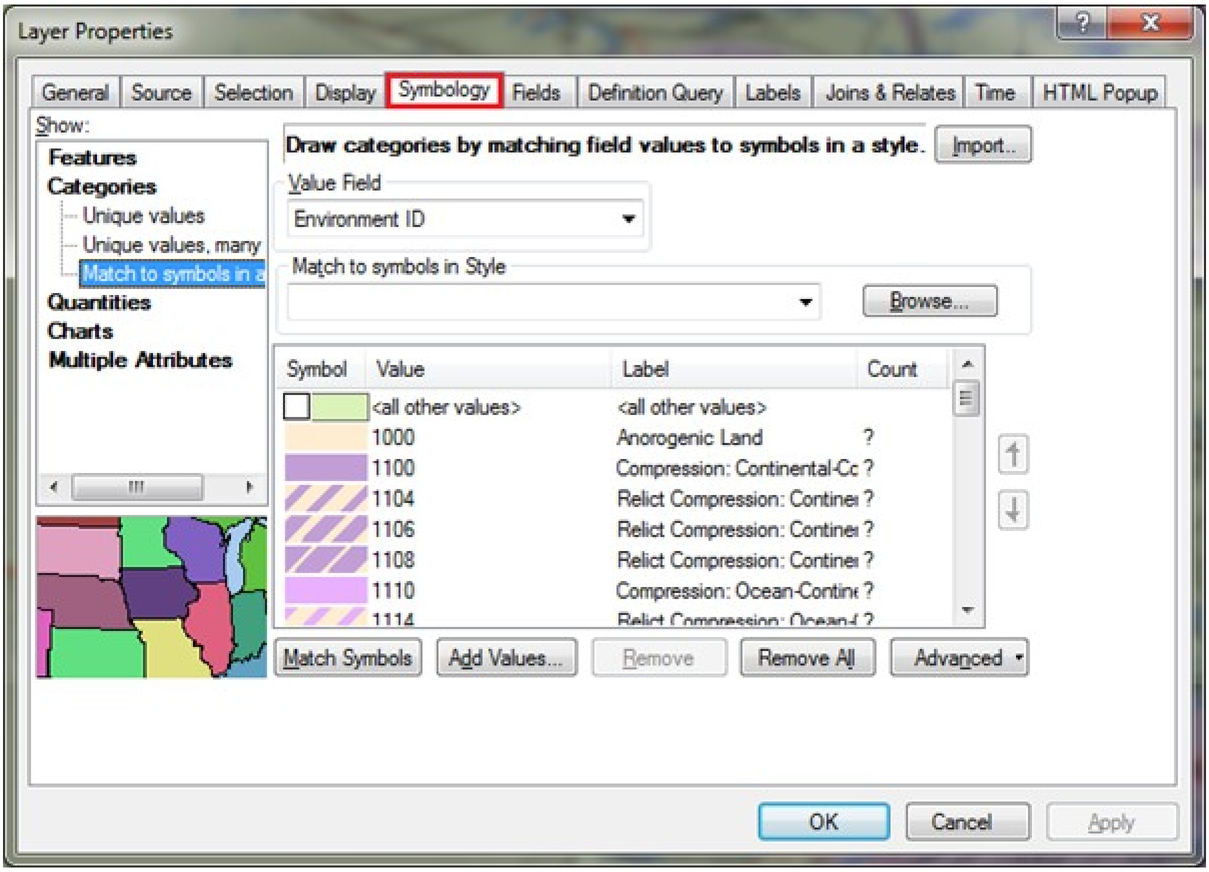


Figure 3.2: Symbology in ArcGIS™.

Examples of this can be found within all our volumes of the Global Palaeogeography MXDs for the feature class named GDE_Terranes, which includes information for palaeoenvironments, lithology and base-level. The MXD points to this data source three times, but each layer is symbolised differently based on attribution, i.e. EnvSID, LithSID or BASELEVEL. This is implemented as standard in Getech's default MXDs.

Getech anticipate that its clients may wish to alter and customise symbology based on their own preferences, and therefore encourage them to explore the possibilities that ArcMap™ provides. As already mentioned, ArcGIS™ symbology is associated with an individual MXD rather than with the data itself, and so the data integrity will not be affected by any symbology experimentation. More detailed information of symbology options can be found on ESRI's website as indicated below:

http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/About_displaying_layers/00s50000001s000000

Below is an example of the symbolised layers which are included by default in some of the *Globe* MXD deliverables:

Crustal type	Depositional environments
Structural and tectonic elements	Biomass and vegetation zones
Lithology type	Palaeovegetation
Shoreline confidence	Basin type
Sedimentary and depositional types	Geological qualifiers
Uplift types	Confidence polygons

3.1.2 Querying Data

ArcMap™ provides the functionality to interrogate the data displayed within an MXD through the use of querying. Definition Queries further enhance data's usability; they make use of SQL (Structured Query Language) to direct the software to display particular data. For example, a Definition Query could be applied to Getech's palaeoenvironments layer to ensure that only those environments classified as Extension were displayed. The **Definition Query** tab can again be found in the **Layer Properties** dialogue box. Clicking on the **Query Builder** button will launch a window to help you construct your query.

Firstly, add the layer that you are interested in to the query from the list. From our example you would double-click ENV_DESCRIPT. Next you need to add an operator, which in this case is the equals sign (=). Finally, you need to tell the software what you want environment description to equal. A list of all the attributes contained in the layer can be generated by clicking the **Get Unique Values** button. Simply select **Extension** from the list by double-clicking it, and your query would be complete and look like the example shown below (Figure 3.3).

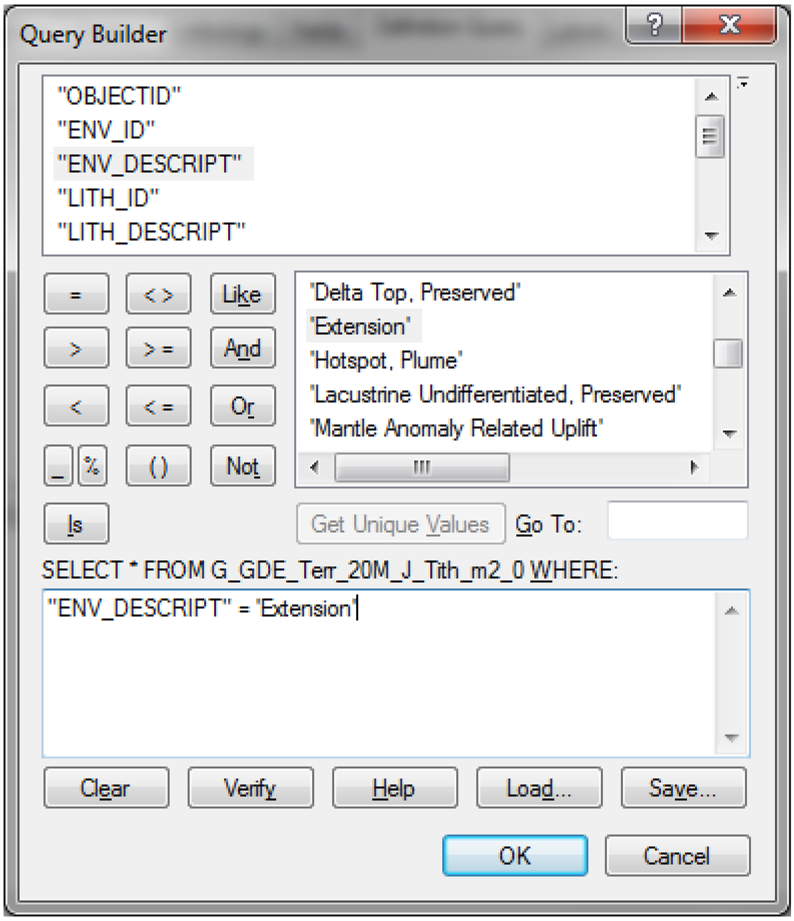


Figure 3.3: *Building queries in ArcGIS™.*

Any query can be tested for validity by clicking the **Verify** button. If the query works, click **OK** on the **Query Builder** window and **OK** on the **Layer Properties** dialogue box, which implements the query. The layer in question will now only display data that matches the query. The process can be undone by deleting the query from the **Layer Properties** dialogue box.

A similar process is used by Getech prior to reconstructing the structures and the wells and outcrops database for a particular timeslice using PaleoGIS. That is, features are queried by age to ensure that only the structures and data points which are relevant to a particular timeslice are selected and thus rotated.

More detailed information on **Definition Queries** and their use can be found on ESRI's website as indicated below:

http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//00s50000002z000000

3.1.3 Extracting Data Sets (regional)

At various points it can be useful to extract subsets of data from Getech's global coverage. In a similar way to **Definition Queries**, ArcMap™ can export a selection of data to a brand new data set. For example, if you wished to extract only the structures in a particular region or structures which contain a particular attribute.

To export just the features in a particular region, you would simply zoom to the region you were interested in. Right-click on the layer that you wish to extract the data from, and select **Data** followed by **Export Data**.

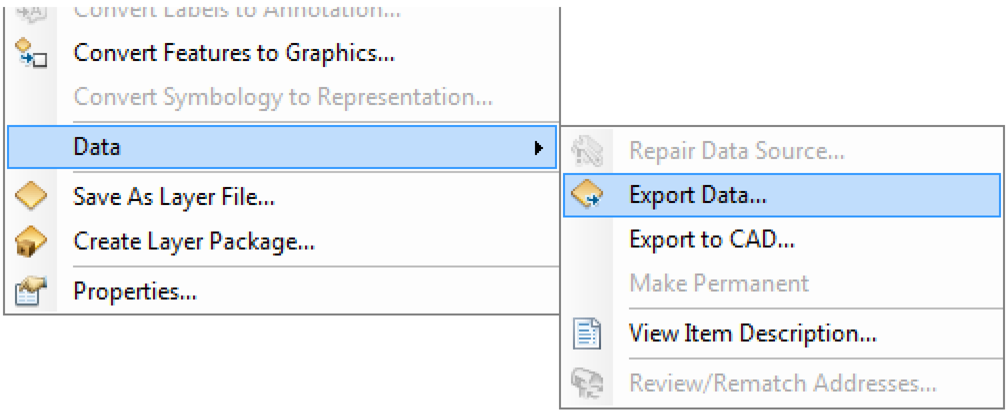


Figure 3.4: Exporting data.

A dialogue box will then appear with options for the export. Ensure that the drop-down menu next to **Export:** is set to **All features in View Extent**, and choose where to save your data. To export features based on an attribute selection, you first need to create the selection. Choose **Selection** from the top menu and **Select By Attributes** from the drop-down list.

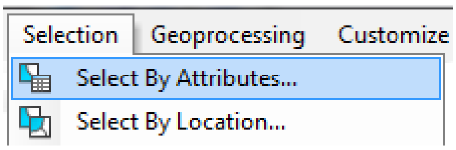


Figure 3.5: Selecting by attributes.

You will be presented with a dialogue box not dissimilar from the Query Builder used in Section 3.1.2.

If you wanted to only export the structures with a category of A (Transregional and Basin defining), you would need to ensure that the correct layer was selected in the **Layer** drop-down menu, and your query would look like the one below:

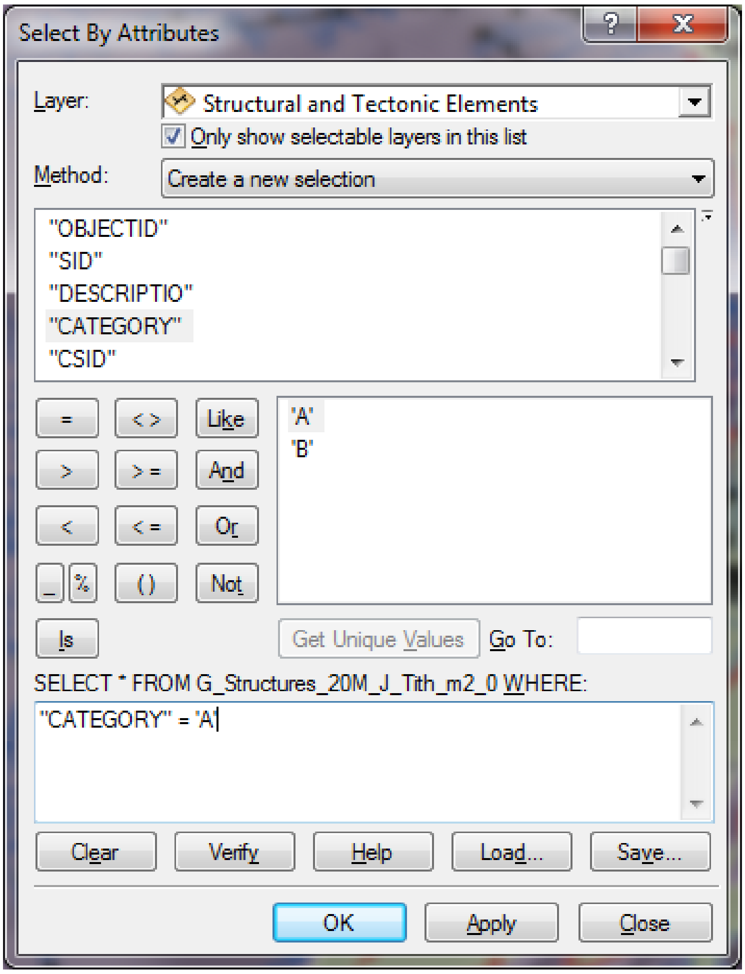


Figure 3.6: Selecting by attributes.

Click **OK** and your selection will be highlighted in blue. You can then follow the same path to export the data as previously, but ensuring that the **Selected Features** option is selected from the **Export** drop-down menu.

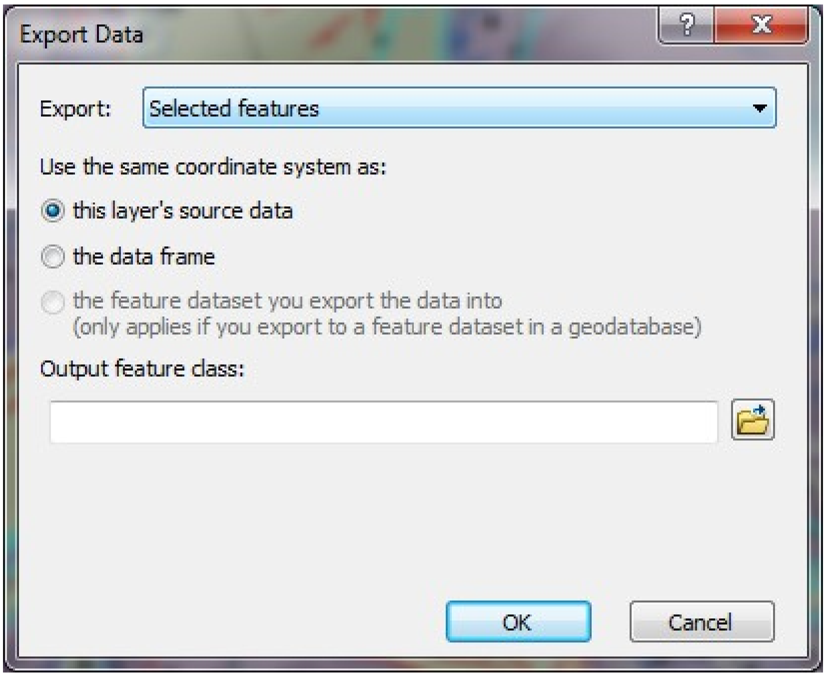


Figure 3.7: *Exporting data.*

More detailed information on exporting data from ArcMap™ and selecting by attributes can be found on ESRI's website as indicated below:

http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//00s50000000t000000
http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//00s500000021000000

3.1.4 Exporting Data (images)

Individual maps and images can quickly and easily be created from Getech's default MXDs through the use of ArcMap™'s **Layout View** and **Export Map** functions. This ensures full control over image quality and features, such as image resolution and scale.

In order to access layout view, you simply need to choose **View** from the top menu and select **Layout View** from the drop-down menu.

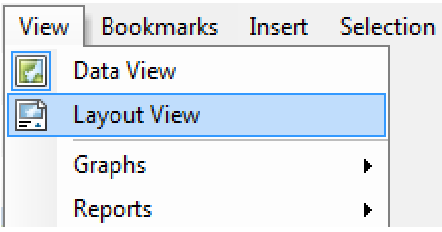


Figure 3.8: Exporting data for images.

Layout View can be considered similar to Page Layout or Print Preview in many word processing packages. All the standard tools from Data View also work within Layout View, ensuring you can zoom to and find the relevant area you wish to capture as an image or map. The Draw Toolbar is also useful should you wish to add text, titles, etc. to your image/map.

Once you are happy with the layout, select **Export Map** from the **File** dropdown menu at the top of your screen. You will then be presented with a range of export and format options for your exported image/map.

More detailed information on page layouts and exporting images can be found on ESRI's website as indicated below:

http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//00s900000007000000

http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/Exporting_your_map/00sm00000004000000

3.1.5 Accessing Getech Data Independently

The data provided by Getech as part of *Globe* can be used independently of the default MXDs we provide. On every client disc there is a geodatabase, which is broken down into feature data sets by timeslice and projection. The geodatabase contain all of the unsymbolised feature class data. This can be accessed and previewed through ArcCatalog™ (ESRI's default file management system).

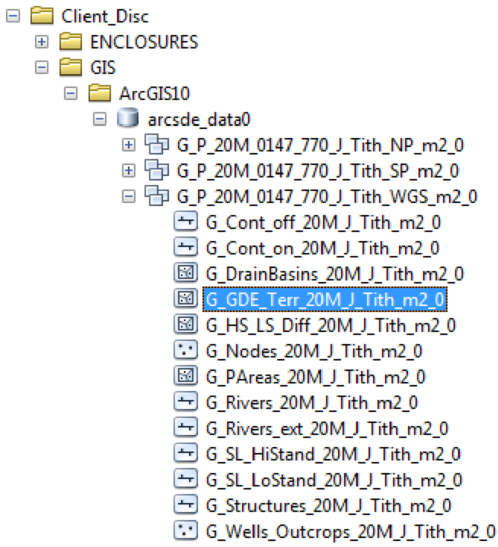


Figure 3.9: Globe data management system.

ESRI's naming system only allows for a certain character limit, and as a result the feature class names are often abbreviated. However, every feature class is populated with metadata, which can be viewed by clicking the **Description** tab at the top of the right-hand preview window within ArcCatalog™; this is populated with a full feature class name, useful tags (should the feature class be added to a database), a summary, a description, credits, use limitations and a preview image of the data.

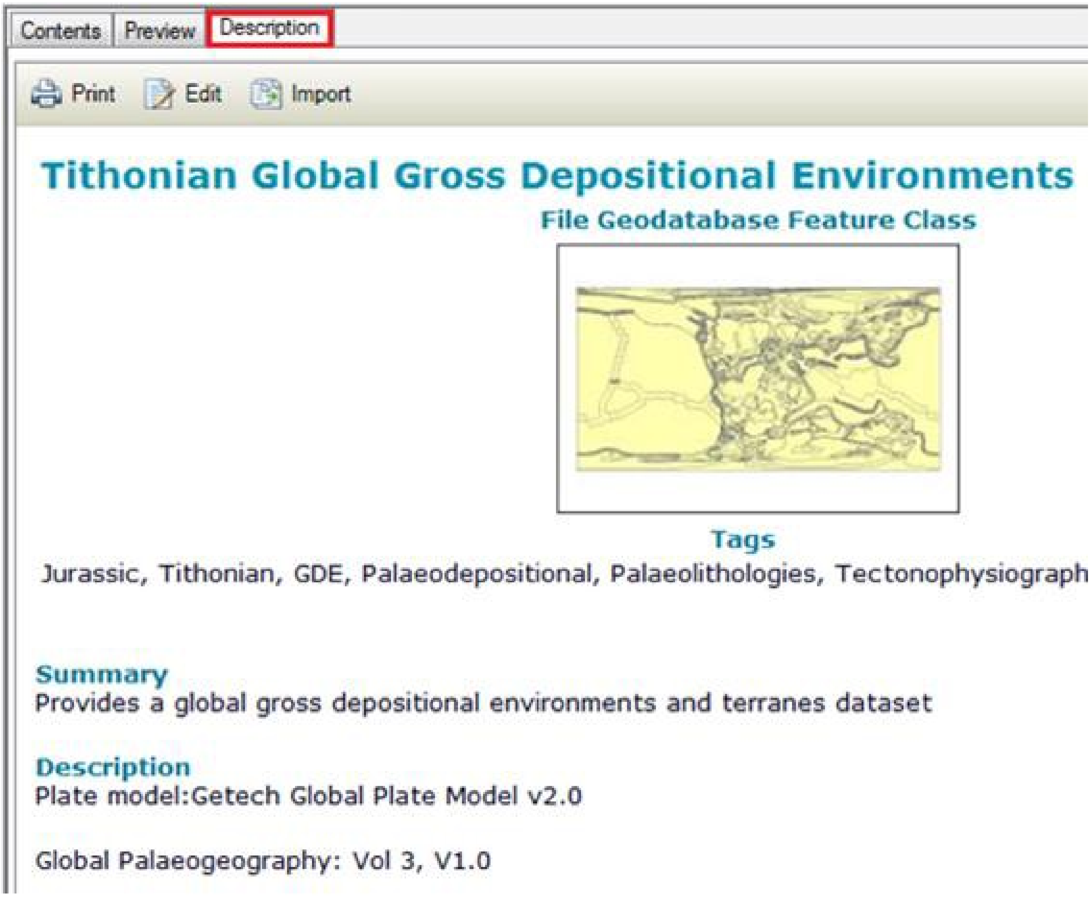


Figure 3.10: *Metadata.*

Every feature class within the geodatabase can be dragged and dropped from ArcCatalog™ into a new or existing ArcMap™ document, allowing the user the opportunity to query and/or symbolise the data in any way they wish.

More detailed information on ArcCatalog™ and metadata can be found on ESRI's website as indicated below:

http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/What_is_ArcCatalog/006m00000069000000/

http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//003t00000001000000

3.2 Wells and Outcrops Database

3.2.1 Overview

Getech's Wells and Outcrops Database is a spatial database which is designed to store all types of geological data recorded by Getech. The database has two forms: a Points Form which records the type of data and its spatial location, including precision, and a Tops Form which records stratigraphic, lithological and depositional information, as well as missing sections (erosional or non-depositional). Other tables are also in development to link the tops to information such as geochemistry and palaeoclimatology. The presence of the different data sets allows for a *one to many relationship* between points locations and tops data.

3.2.2 Wells and Outcrops in ArcGIS™

Users of *Globe* receive location points for each stage in every volume of the Global Palaeogeographies with a tops table; this is easily related in ArcGIS™, so that all points show the geological information associated with that point for a particular geological timeslice. Getech's default MXDs are already *related* between points locations and tops. The temporal uncertainty will show some tops covering the whole of a particular time period (e.g. the Cretaceous), while for others, it may be more limited to a stage (e.g. the Hauterivian).

3.2.3 How to Relate Points Locations and Tops

If the user wishes to interrogate the wells and outcrops data outside of the default Getech MXDs, the relationship held between the two must be reconfigured. This is a relatively simple process in ArcMap™.

Firstly, add both the **G_Wells_Outcrops_20M** points feature class and **G_Tops_20M** geodatabase table to a blank ArcMap™ document. Right-click on the points layer in the **Table Of Contents** window and select **Joins and Relates** and **Relate** from the drop-down menu(s).

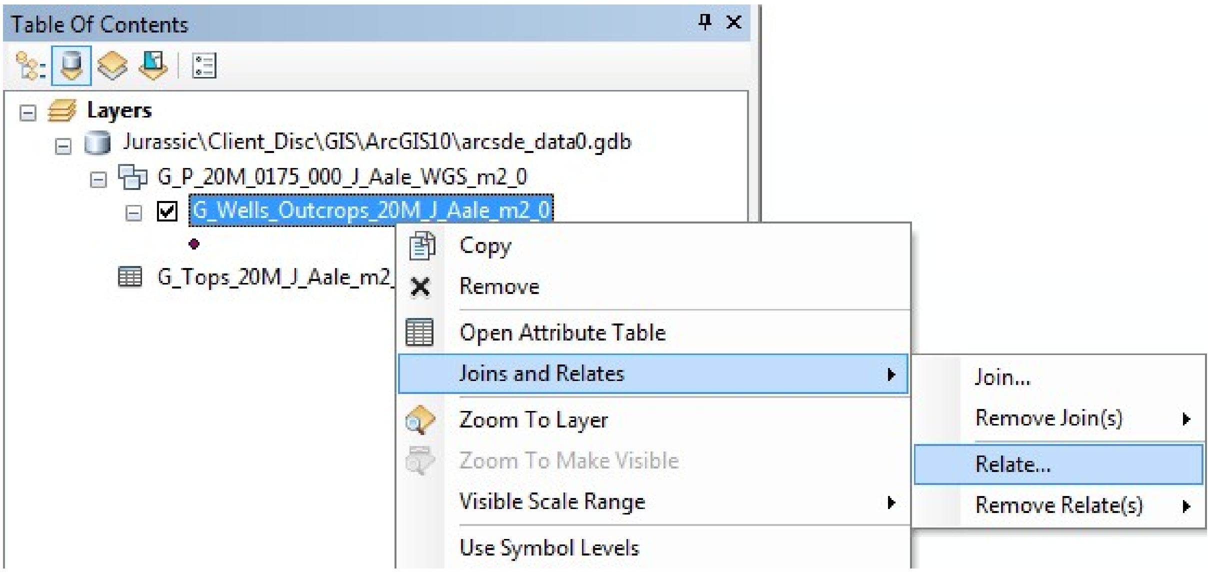


Figure 3.11: *Relating data.*

You will be presented with the **Relate** dialogue box. Ensure the dialogue box is set up like the example shown below, with the corresponding WID fields being selected.

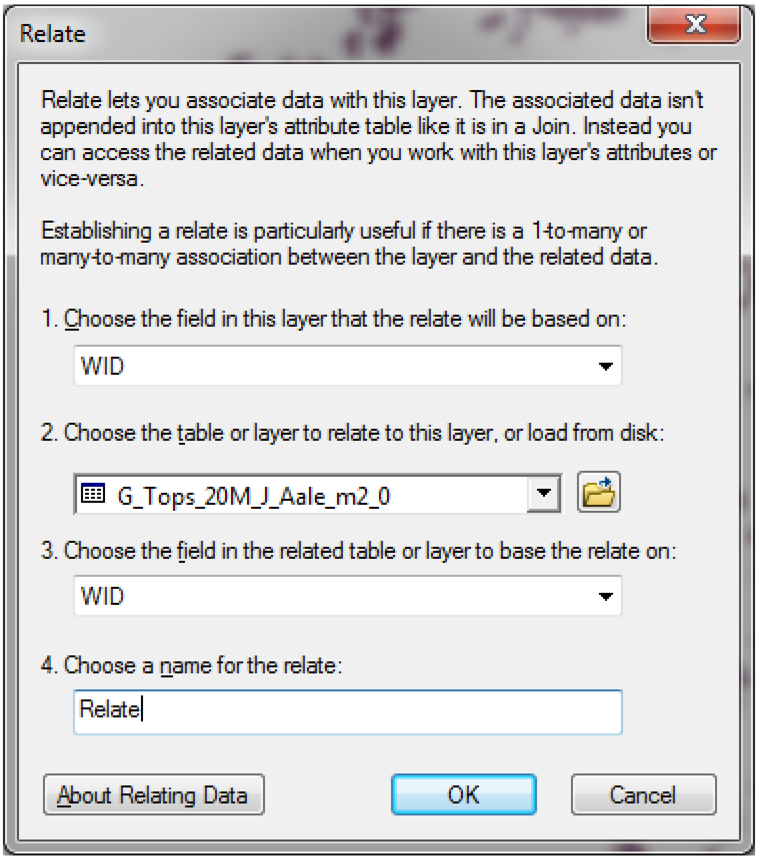


Figure 3.12: *Relating data.*

Click **OK** and the relate will have been created. This is now set up in this MXD only. To see the effect of the relate, you can interrogate the points layer on screen using the **Identify** option from the **Tools** toolbar (clicking on a point will show you the information for it and then each top related to it below).

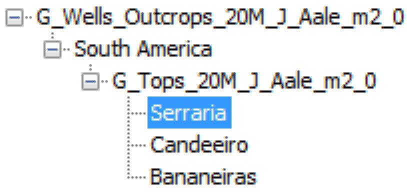


Figure 3.13: *Accessing attribute information.*

Alternatively, you can open the entire **Attribute** table, highlight any number of records and then view the related information by selecting the **Related Table** button at the top of the window.

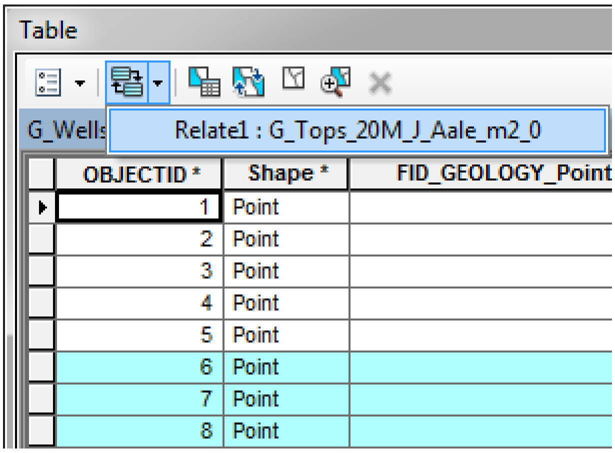


Figure 3.14: *Accessing attribute information.*

More detailed information on performing relates can be found on ESRI's website as indicated below:

http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/About_joining_and_relating_tables/005s0000002n000000/

3.3 Manipulating Data With PaleoGIS

PaleoGIS is a third party extension to ArcGIS™ (created by the Rothwell Group) that enables the user to incorporate geological time into GIS. With PaleoGIS, the user can visualise data in a palaeographic context. Getech use PaleoGIS to help build custom plate models and to reconstruct (and un-reconstruct) data to and from geological timeslices.

3.3.1 Reconstructing Data

In order to reconstruct data, the user requires the PaleoGIS extension to ArcMap™ to be enabled and a valid plate model to be loaded. The data to be rotated can then be added to ArcMap™ and a rotation age entered in the **Age (Ma):** box of the PaleoGIS toolbar.

Figure 3.15: Reconstructing data.

PaleoGIS will then perform an intersect operation between the data to be rotated and the plate polygons which make up the plate model. Using the associated rotation files held within the plate model reconstructs the data to the requested age.

The automatic nature of the reconstruction process means that an expert review of the rotated data is required post-reconstruction.

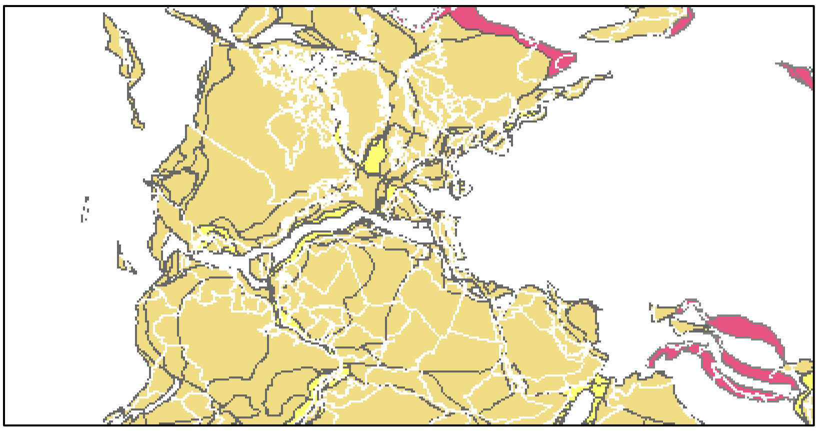


Figure 3.16: Reconstructing data.

3.3.2 Un-reconstructing Data

PaleoGIS also offers the ability to un-reconstruct data back to Present Day. Getech provides un-reconstructed data for each of the timeslices in the volumes it delivers.

The un-reconstruction process in PaleoGIS is also a relatively simple operation. Once again a valid plate model must have been loaded. The plate model can then be reconstructed to the ages of the data (which are to be un-reconstructed). Once the reconstruction has taken place, the data in question can be added to the same ArcMap™ document.

Right-click on the newly added layer and select the **PaleoGIS** option, followed by **Un-Reconstruct**. The process will now run in reverse and rotate the data back to Present Day.

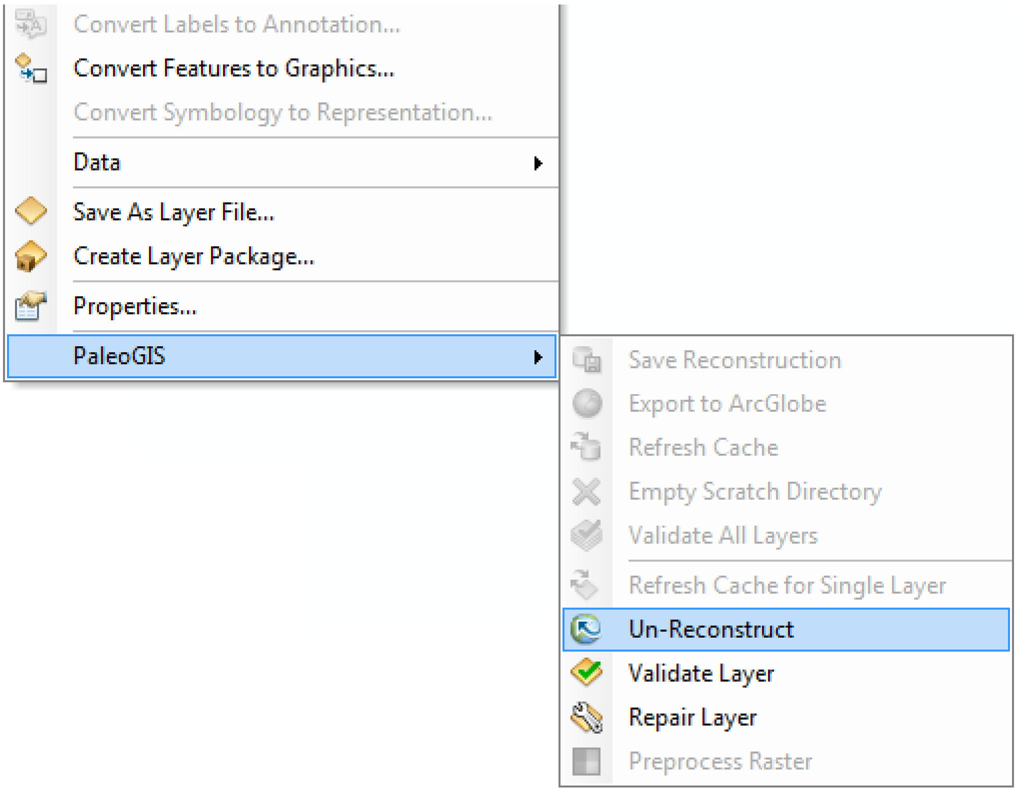


Figure 3.17: Un-r econstructing data.

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