



KNOWING.EARTH

2018



Just when you think you understand...

Zone of deformation and
mineralization associated with shear
in Devonian carbonates. Plan,
central Pyrenees.

The Knowing Earth Review 2018

EDITOR
Dr Paul Markwick

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To cite this work (Book): Markwick, Paul J.
2018. *The Knowing Earth Review 2018*. Knowing
Earth Limited, Otley, Yorkshire. 64pp.



COVER PHOTOGRAPH

The Claron Formation (Red Member), Cedar Breaks National Monument, Utah. The Claron Formation comprises alternating beds of sandy limestone and calcareous limestones with occasional beds of calcareous mudstone and conglomerate. Deposited in lacustrine and fluvial environments. The units are largely unfossiliferous which has led to problems in assigning a precise age. Generally given as Paleocene – Eocene, recent charophyte evidence points to a Ypresian age. The Claron Formation is equivalent to the Wasatch Formation.





Reconstructing the Past Understanding the Present Revealing the Future

Folded ribbon cherts of the Jurassic -
Cretaceous Franciscan Complex.
Conzelman Road, Mill Valley, California, USA



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Welcome to




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

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

The following short articles will give you a glimpse into this world. We hope you find these stimulating.

For further information please contact us or our academic partners.



Arro turbidites, Ainsa Basin. The main sandstone canyon fill is to the right of this outcrop. The whole section has been inverted during Middle Eocene deformation within the Ainsa Oblique Deformational Zone.

Editor's Letter

Part of geology's appeal is its breadth and diversity, bridging the divide between the humanities and the 'pure' sciences, borrowing elements from all. Whether we call ourselves 'geologists', 'Earth scientists' or 'geoscientists', the key to understanding the Earth is considering how all the components of the Earth system fit together, interact and evolve through time. But this breadth and diversity come at a cost and nowhere more so than when applied to oil and gas exploration.

I am not referring to the emotional costs of the frequent jibes from friends and colleagues about geologist's use of colouring pencils beyond the age of five, or why we have rocks and fossils on our every bookshelf, mantlepiece, and desk, or our predilection for the great outdoors, whatever the weather, in order to see, well, rocks...

The 'cost' I refer to is more fundamental. That if we are to fully understand the Earth system, especially enough to find and manage natural resources, requires a diversity of knowledge and understanding that has traditionally required an army of 'specialists'. This results in both a financial and logistical 'cost'. Specialists are expensive and fostering cross-discipline interaction not always easy.

How do we solve this dilemma? I wish I had all the answers. I don't. But based on 30 years in consultancy, academia and the majors, let me offer five of my learnings which I consider to be important, and which I think will help, especially at the current time.

1. Know your data

Well managed, standardized, data- and knowledge-bases make communication, access and analysis much more effective and efficient. The oil industry is the epitome

from current technological developments in areas such as machine learning and artificial intelligence (AI) to help us get more from the data.

That if we are to fully understand the Earth system, especially enough to find and manage natural resources, requires a diversity of knowledge and understanding that has traditionally required an army of 'specialists'.

of 'Big Data'. Harnessing the wealth of information within our corporate libraries and databases will help us get a better understanding of our exploration assets and through that minimize financial costs. This includes ensuring that all data has a full audit trail, is standardized and is digitally flexible – can be used in variety of software systems. This will then enable us to gain the most

2. Turn experience into workflows

Workflows provide the means of capturing expertise as a recipe for others to follow. This ensures that knowledge is not lost and facilitates training. This is all the more important after three awful years that have seen the departure of so much of our experience-base.

3. Consider the big picture

We live in an age of specialists. But solving exploration problems requires an understanding of how all the components in the system fit together. This needs people with broad backgrounds, who understand enough of the specialist vocabulary to recognize the key issues, sources of information, and potential caveats, and who know and can talk to the specialists and bring teams together.

This process can also be facilitated in (geological) exploration through the use of palaeogeography to act as a spatial and temporal context for curating, displaying and analyzing all the inputs into the Earth system; from tectonics through source-to-sink and basin analysis to palaeoclimate, weathering, erosion, to the retrodiction of source and reservoir distribution and quality.



"...or our predilection for the great outdoors, whatever the weather, in order to see, well, rocks..." In this case the Leeds MSc students preparing to sketch the seismic-scale features in the view behind them...

4. Talk to the experts

Most companies already have strong links with academic research groups, although support has been curtailed during the downturn. Sponsorship of research groups and supporting MSc and Ph.D. projects provide access to cutting-edge research,

At the end of the day, it's about finding answers through the exchange of ideas, experience, and knowledge. Most of all it's not being afraid to ask questions

whilst simultaneously identifying and training the next generation of explorationists. We need to find a way to foster this relationship further so that industry can more readily access scientific innovation and understanding, and in return, academics can gain greater access to the wealth of expertise and information within companies.

5. Share with the next generation

Training is often one of the first casualties of 'cost-saving' in any market downturn, and the last downturn has been no different. But it is essential to ensure that our teams are the best trained and that they are familiar with all the knowledge companies have gleaned

over decades and in some cases a century of exploration. Academia can help here, together with specialist training companies, but there is also an army of well-qualified, experience in recently retired industry staff who could be used to better prepare the next generation.

Why Knowing Earth?

This is where I have designed Knowing Earth to fit. By providing standardized, baseline data and knowledge bases to underpin your exploration research, to providing workflows, problem-solving and mentoring to understanding the big picture and how all the components interact and fit together. We are about facilitating communication between experts and building partnerships across Industry and Academia.

At the end of the day, it's about finding answers through the exchange of ideas, experience, and knowledge. Most of all it's not being afraid to ask questions.

It's time to get out the pencil crayons!

Paul Markwick
Yorkshire, 1 July 2018



Dr Paul Markwick, BA (Oxon), PhD (Chicago)

CEO Knowing Earth Limited
Visiting Lecturer, University of Leeds
Visiting Research Fellow, University of Bristol

ABOUT THE EDITOR

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

He worked for two years at BP's Research Centre in Sunbury-on-Thames before moving to Chicago, where Paul studied with Professor Fred Zeigler's oil industry sponsored Paleogeographic Atlas Project. This was followed by a post-doctorate at the University of Reading researching the exploration significance of the paleoclimatic and drainage evolution of southern Africa using computer-based climate models with Professor Paul Valdes. He then moved to Robertson Research International Limited, now part of CGG, as a Staff Petroleum

Geologist, where he developed global predictive models of source and reservoir facies. In 2004 Paul moved to Getech Group plc, to set-up the Petroleum Systems Evaluation Group with Dr John Jacques. From 2006 to 2017 Paul served on the Getech board overseeing the strategic technical direction, which saw the business transition and grow from an academic research group to a multi-million-pound company with four offices, 120 staff and an international client base.

His active research interests include global tectonics, palaeogeography, palaeoclimatology, the history of geology and depositional modelling. Paul is author of over 100 published scientific papers and articles. A new paper on "Palaeogeography in Exploration" is due to be published in July 2018.



Wasatch Range in northern Utah cut by a small N-S fault-bounded basin now occupied in part by the Mantua Reservoir. This view is looking south with Cambrian quartzites, oolitic limestones and shales forming the high ridge bounding the basin to the west (right in this picture).





The Precambrian Town Mountain Granite, Llano Uplift, Enchanted Rock State Natural Area, Texas. Basement outliers such as the Llano Uplift are frequently shown as positive features (above contemporary base-level) on palaeogeographic maps. But this is an over-simplification.



How the Paleogeographic Atlas Project Redefined Palaeogeographic Mapping and Big Data for Exploration

Fred Ziegler's Paleogeographic Atlas Project was something of an oasis in a building that might otherwise be described diplomatically as architecturally 'interesting'. If you have ever been to the Hinds building at The University of Chicago you will know what I mean. The office comprised a relatively large work area with three smaller annexes. Large wooden tables occupied the central space surrounded on all sides by shelves filled with books and papers arranged in alphabetical order, each paper in its own manila folder, each carefully recorded in a reference database, a stamp on its cover to indicate the basics of what it contained. From the resulting databases and atlases, Fred and his team reconstructed past landscapes as palaeogeographic maps, developing methods that still define much of how we do palaeogeography today. But the Atlas Project also showed how to build, manage and analyse large geological databases. With 'Big Data' now prevalent throughout our industry, it is timely to look back to Chicago for some guidance

Fred's own annexe was a windowless, brick-walled room, with old metal sinks along one side, but a hive of activity. The sound of

classical music could always be heard playing quietly in the background as Fred worked at his high table drawing maps or identifying

key references, which the work-study undergraduates would then find and record as data points in the already impressive



Navajo Sandstone, Canyon Overlook Trail, Zion National Park

lithofacies database.

This database underpinned all the palaeogeographic mapping and is still available online. As a further data management step, Fred would also record each data point by grid cell in large, physical data books that provided a quick indication of data coverage. These were the days before GIS and the internet, a computer world still dominated at Chicago by the Mac SE, now a museum piece. Plate modelling was carried out on an Evans and Sutherland workstation, the maps themselves laboriously drawn by hand or printed using grid point representations from the database.

What Fred and his Paleogeographic Atlas Project established was not only a workflow for palaeogeographic mapping, but also methodologies for managing, visualizing and analysing large datasets. Today we would refer to this as 'Big Data'. In many ways, this was the forte of the whole second floor in Hinds throughout the 1980s and 1990s. The quantitative analysis of large geological datasets of information to find patterns. The work of Jack Sepkoski (Sepkoski and Sheehan, 1983; Sepkoski and Raup, 1985), David Raup (Raup and

Sepkoski, 1984; Raup and Sepkoski, 1986), and David Jablonski (Jablonski, Flessa and Valentine, 1985; Jablonski and Bottjer, 1988) needs no introduction. Their analyses established our understanding of extinction and evolutionary patterns. Their quantitative methods have since been applied way beyond palaeontology and into investment banking and climate change.

an audit trail, but also a means of qualifying uncertainty. Fred's solutions were elegantly simple and described in a paper published in 1985 (Ziegler et al., 1985).

Constraining data confidence

The confidence schemes developed by Fred were simple for two reasons:

First, computer power at the time was

What Fred and his Paleogeographic Atlas Project established was not only a workflow for palaeogeographic mapping, but also methodologies for managing, visualizing and analysing large datasets. Today we would refer to this as 'Big Data'.

Fred Ziegler's group focussed on how to use large geological databases to constrain the depositional environments and elevation of past landscapes. The group was sponsored by oil and gas exploration companies and one thing these sponsors needed was to ensure they understood the basis for interpretations. That necessitated

limited and databases had to be frugal with field sizes;

Second, a database with a simple scheme was more likely to be populated than a complex one, especially given the vagaries of the geological record and heterogenic nature of the source data.

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CLIMATE
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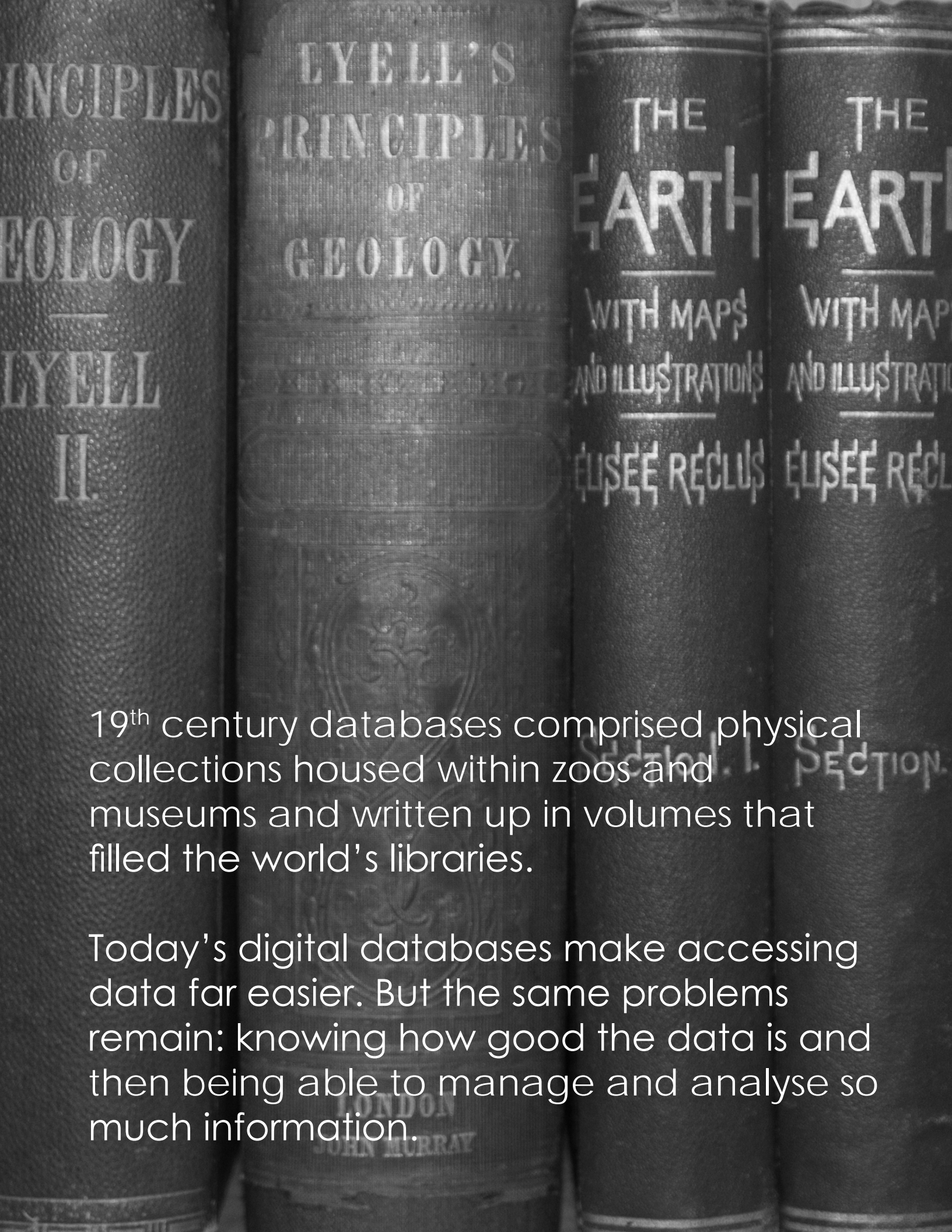
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19th century databases comprised physical collections housed within zoos and museums and written up in volumes that filled the world's libraries.

Today's digital databases make accessing data far easier. But the same problems remain: knowing how good the data is and then being able to manage and analyse so much information.

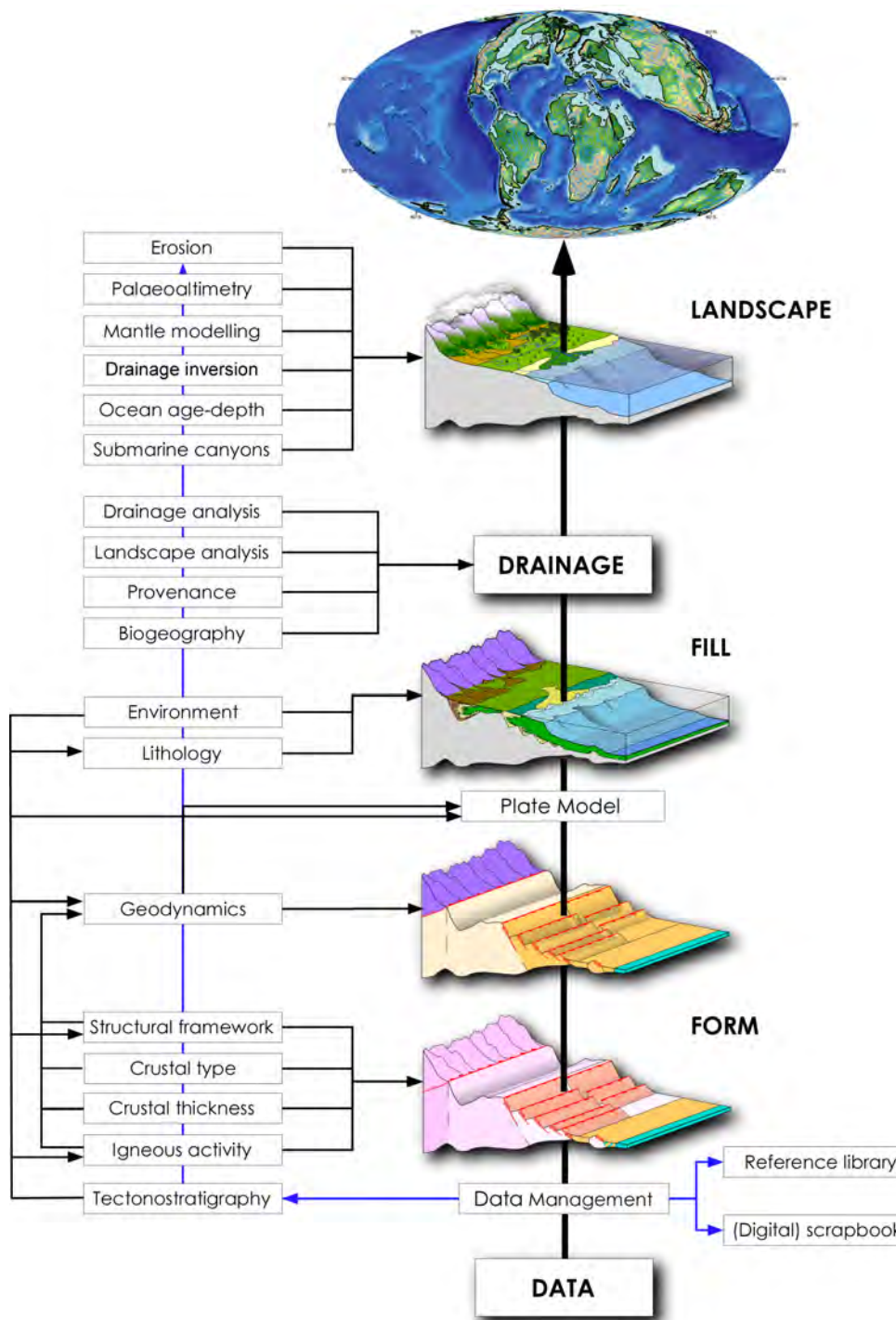


Figure 1. The palaeogeographic mapping workflow described in Markwick (2018). This follows the structure of the Earth by building up from the crustal architecture through the basin fill to drainage and landscape following ideas originally presented in the late 19th and early 20th centuries (Hunt, 1873; Schuchert, 1910; Schuchert, 1928; Ziegler et al., 1985). This builds from the underlying crustal architecture to reconstruct the basin and hinterland geometries, which then defines the accommodation space and source-to-sink stories. It is also a key input into the plate modelling. With the structural foundation in place, this is filled with the depositional environments and dominant lithologies. The palaeo-drainage is then added and with all the other components used to build the palaeo-landscape that acts as the boundary conditions for Earth system modelling. In reality, this is an iterative process. For clarity in this figure, only the top two levels of the workflow are shown. The block diagrams show how each stage of the workflow builds to form a hypothetical landscape.

This was summarized by Markwick and Lupia (2001) that “a database should be simple enough that it can be used, but comprehensive enough that it will be useful”.

But there was a third important reason for capturing as much information on data provenance and confidence and that related to the nature of the published record, which was not always forthcoming about specific data that might be essential for, say, building a palaeogeography map in a particular place at a particular time. A poorly constrained datapoint spatially and temporally might be the only data point for a specific problem. It was therefore key to record this but to also include all caveats. The user could then query the database for the resolution and data confidence appropriate for their own work.

In the databases of Markwick, additional qualifiers were used to define geographic precision (how precisely a feature was known to be located spatially; this was especially important in the days prior to use of GPS to locate data), and also the significance of data absence (when is a gap in the data significant

A database should be simple enough that it can be used, but comprehensive enough that it will be useful

or just a lack of data coverage).

It is also important that data should not be ‘altered’ on entry to fit an *a priori* bias. That can be done later in the analytical stage. If you have altered your data on entry then it is very difficult to get back to the original source if, as happens, your *a priori* view changes.

A palaeogeographic mapping workflow

The workflow outlined in Fred’s 1985 paper built on the earlier work of Hunt (1873), Willis (1909), Schuchert (1910; 1928) and Kay (1945). The focus was on tectonic reconstructions, especially the significance of true palinspastic restoration, and then how mapping depositional systems could be built up and with tectonics used to reconstruct palaeotopography and palaeobathymetry.

These methodologies, together with



A 19th century palaeogeography of the Eocene of NW Europe (Lyell 1837). Grey fill shows the extent of marine conditions.

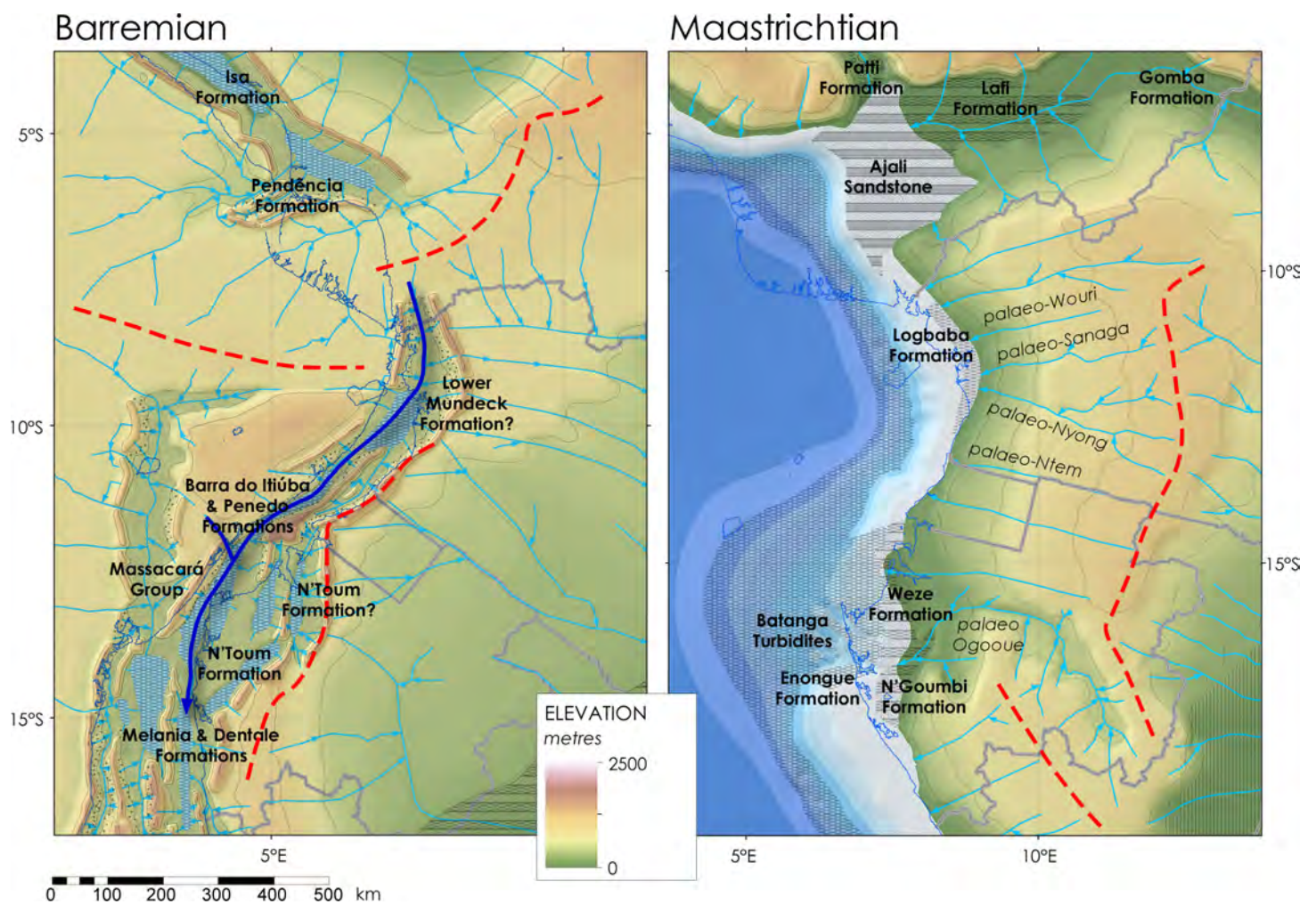


Figure 2. Drainage evolution of Cameroon to Congo during the Cretaceous. Barremian, syn-rift reconstruction of the palaeolandscape and palaeodrainage of the northern South Atlantic. The reconstruction of palaeo-rivers along each rift is conceptual with short-headed rivers draining into an axial trunk stream. Connectivity between individual rifts will evolve through time. The provenance of the Dentale Formation in the South Gabon Basin is equivocal but the source shown here (blue arrows) from the north is consistent with the conclusion of Hodgson (2014). The high porosity and permeability reflecting the consequences of longer distance reworking than would be expected were the sandstones sourced from adjacent rift shoulders. The map shows lakes more typical of the Melania Shale, which immediately underlies the Dentale sandstones. Maastrichtian palaeodrainage reconstruction showing the uplifted Gabon craton, probably in response to the Santonian Inversion. Elevations are nonetheless relatively subdued. At this time the Cuvette Centrale is shown as erosional (the sub-Paleocene unconformity of Sachse, Delvaux and Littke, 2012).



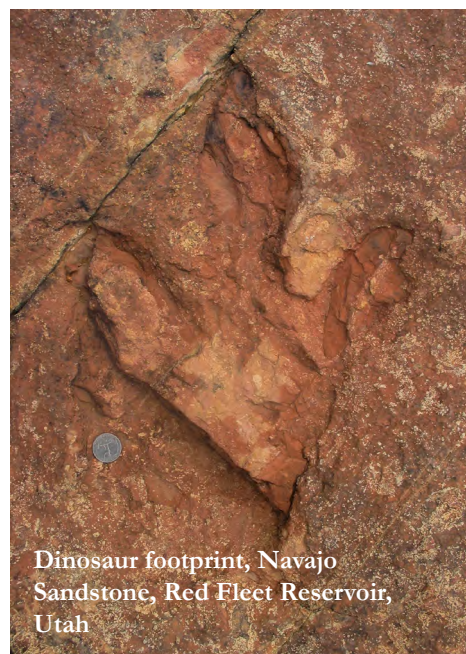
Triassic - Paleozoic section, Dinosaur National Monument, Utah. This was a frequent field base for the Chicago students taught by Fred Ziegler

the data audit techniques, were further developed by Fred's students. The most recent iteration of this workflow, based largely on Markwick and Valdes (2004) and Markwick (2018) is shown in Figure 1. This adds more detail to the crustal architecture following the workflow originally presented by Hunt (1873), in his first definition of palaeogeography and palaeodrainage. This workflow continues to follow the way the Earth builds the landscape from a definition of the crustal architecture (crustal type, geodynamics and structural framework) to placing depositional environments and from there the rivers and landscape (paleotopography and palaeobathymetry). This is an iterative process, but one that lends itself to increasingly levels of automation. This is an area of active research.

Although sadly the Paleogeographic

Atlas project fell into abeyance with Fred's retirement, and his former project office is now under different ownership, what we might refer to as the "Chicago School of Paleogeography" continues to influence palaeogeographic reconstruction and exploration across the world through Fred's students. I count myself fortunate to one of those inheritors of Fred's passion for palaeogeography and an interest in the full breadth of Earth science – the Big Picture.

Palaeogeography remains underutilized within our industry, and that is a great shame. At a time when we have lost so much of our experience, but have so much more data, where costs are critical, palaeogeography and its way of helping us problem solve in exploration are all the more important today, as it was in 1873 when Hunt first coined the term. ■



Dinosaur footprint, Navajo Sandstone, Red Fleet Reservoir, Utah



FURTHER INFORMATION

A paper on the history of palaeogeography and the methodologies discussed here is in press (Markwick, 2018)

A training course on the palaeogeographic methods and the palaeogeography workflow described in this article is available and can be adapted to your specific needs.

Palaeogeography as a service is available through Knowing Earth. This includes bespoke mapping solutions, multi-client atlases and development of your existing palaeogeographic assets.

Current academic research is in association with the universities of Leeds and Bristol

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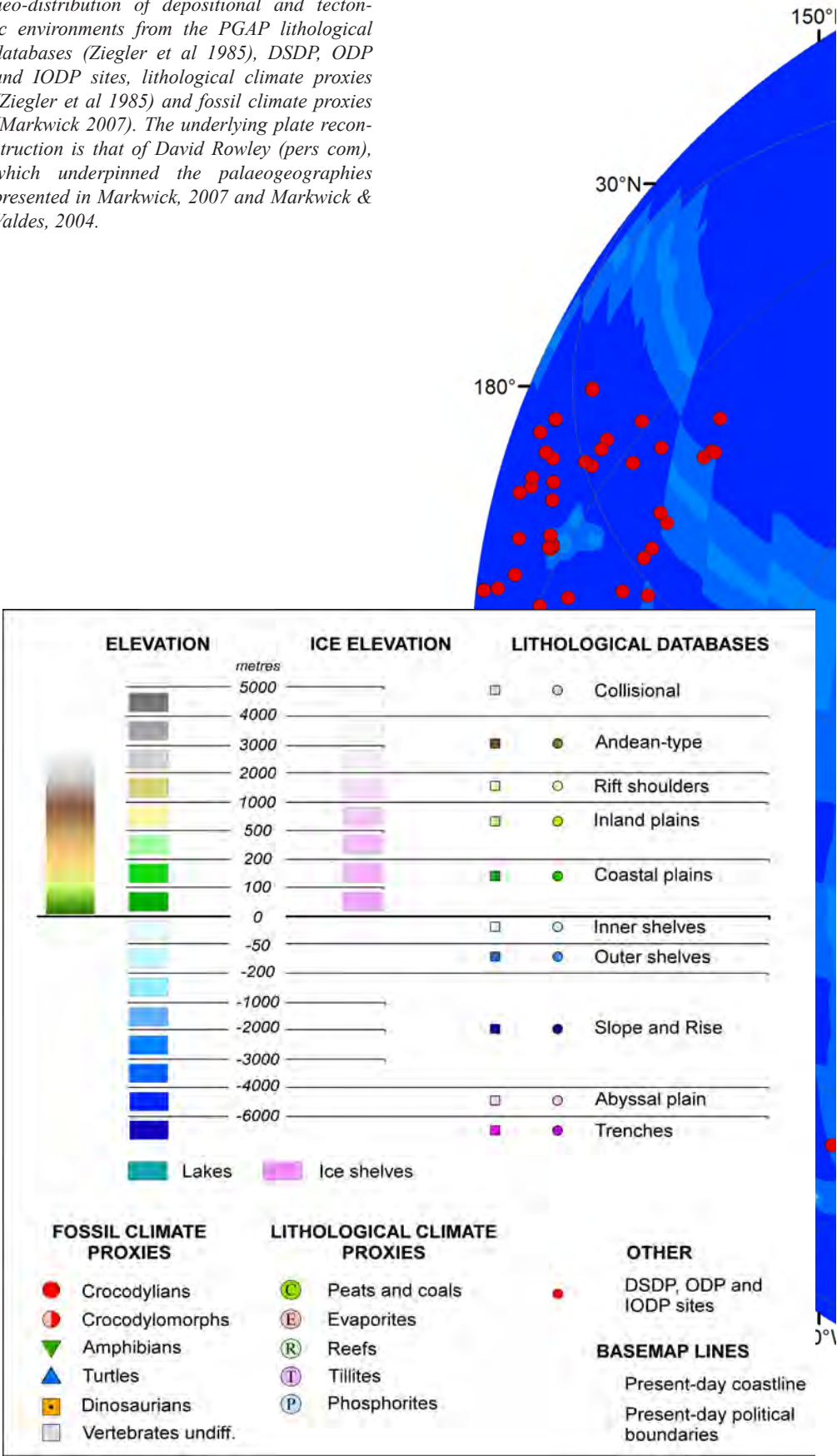
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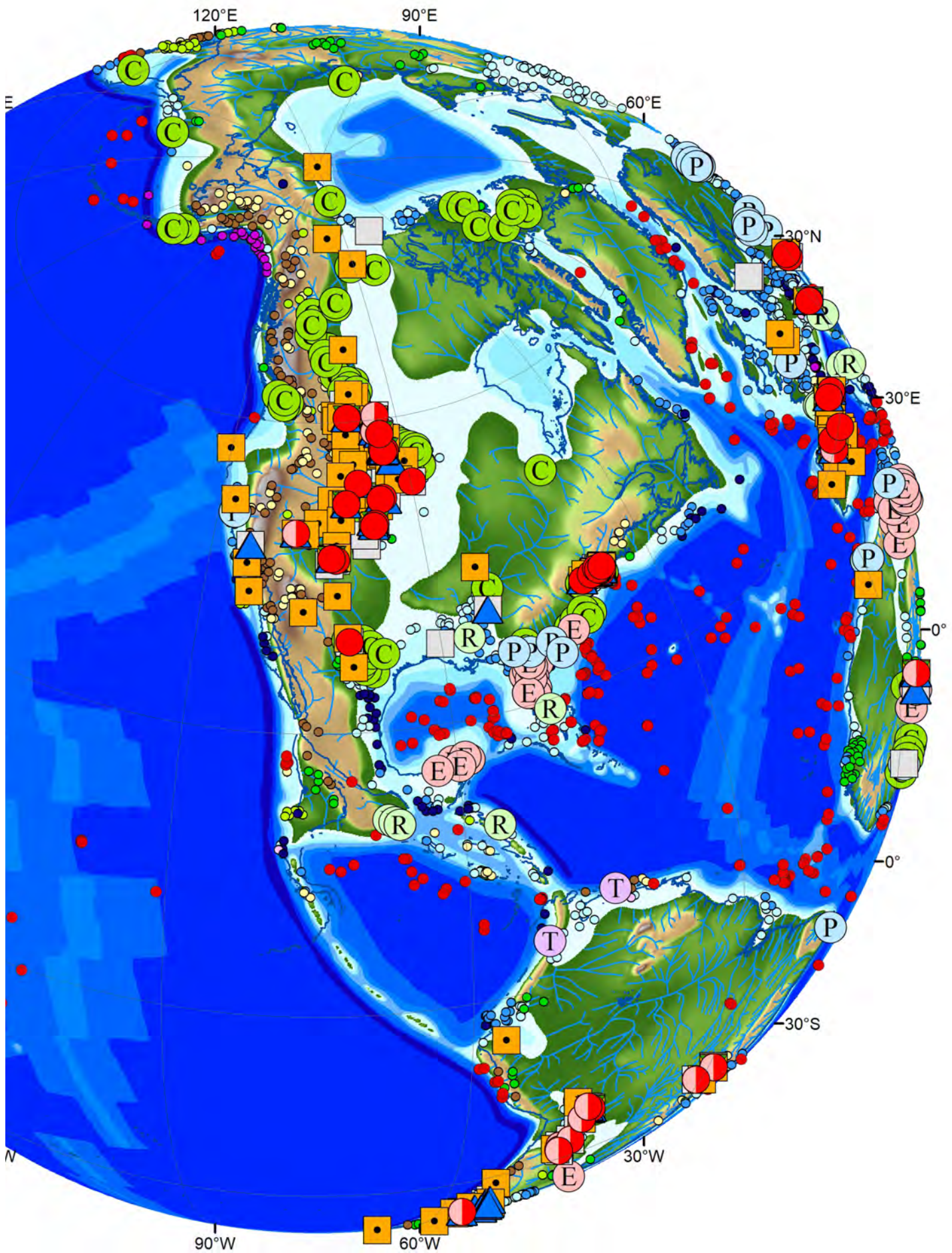
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Figure 3. Maastrichtian palaeogeography (Markwick & Valdes, 2004) showing the palaeo-distribution of depositional and tectonic environments from the PGAP lithological databases (Ziegler et al 1985), DSDP, ODP and IODP sites, lithological climate proxies (Ziegler et al 1985) and fossil climate proxies (Markwick 2007). The underlying plate reconstruction is that of David Rowley (pers com), which underpinned the palaeogeographies presented in Markwick, 2007 and Markwick & Valdes, 2004.







A major challenge in palaeogeographic mapping is how to represent the palaeolandscape when the record is missing. In this case a 'gap' of 100 million years in the story represented by the sub-Late Triassic unconformity.

The sub-Triassic (angular) unconformity, Friars Point, South Wales. Steeply dipping Carboniferous limestone overlain unconformably by Triassic fluvial conglomerates and sands.



Revealing the Earth's Architecture

When Thomas Sterry Hunt first coined the phrase “paleogeography” to describe the reconstruction of the Earth’s geography through time (Hunt, 1873), his workflow began with an understanding of what he referred to as the “architecture” of the Earth. By architecture, he was describing the Earth’s structural framework, crustal geometry and composition, and geodynamics, which today we define broadly within the concept of “Crustal Architecture”.





The Axial Zone at Plan de Larri, central Spanish Pyrenees. The view shows Cretaceous carbonates thrust up over Devonian carbonates (bottom right).

Getting the crustal architecture ‘right’ is not just important for palaeogeography, it is critical for exploration. It defines the geometry and evolution of accommodation space, the depositional environment, heat flow, the location and change in sediment input points, hinterland uplift (and thereby sediment production and supply, as well as

Getting the crustal architecture ‘right’ is not just important for palaeogeography, it is critical for exploration.

its effects on climate and circulation) and constrains the underlying plate model. The fundamental importance of the structural framework was not lost on Hunt himself as one of the first petroleum exploration geologists. Indeed, it was Hunt who recognized the relationship of anticlinal

complex this architecture can be and the processes responsible.

To fully understand the role of crustal architecture we need to break the problem into two main components: 1. mapping the observations; 2. the interpretation of the processes responsible for those observations.

1. Mapping the observations.

This includes mapping the structural framework, using primary data such as direct observations (Figure 1), satellite imagery (viz. Landsat) and other remote sensing datasets including potential fields (gravity and

of course, some element of interpretation at this stage, as we extend mapping beyond better-constrained areas. But the ‘risk’ (uncertainty) can be minimized by the use of analogues and the addition of more seismic and well information.

To then get at the processes responsible we need to map out one further ‘observational’ dataset, which is the geodynamic state of the crust. This records the nature and geometry of the last thermo-mechanical process to affect that area. This is a fundamental part of the palaeogeography workflow discussed in Markwick and Valdes (2004).

2. The interpretation of the processes responsible.

The interpretation of process involves investigating and understanding how the crust behaves and evolves, which leads us directly into restoration modelling, basin



Figure 1. Deformational zone within Devonian carbonates near Plan, central Pyrenees. This outcrop comprises evidence of multiple phases of deformation, from an original extensional geometry in the Devonian through multiple compressional intervals. This complex evolution is captured within a new global structural elements database by recording each event in a separate, related activation history table.

trapping to oil discoveries (Hunt, 1862) following the first oil discoveries in Ontario (1858) and Pennsylvanian (1859).

Over the last two decades, our understanding of crustal architecture has changed radically, especially on passive margins. This has been driven by the needs of deep-water exploration and the availability and interpretation of more and more seismic, especially the margin-scale lines such as the ION SPAN surveys (<https://www.iongeo.com/>). Within the last 10 years, the work of numerous authors, especially Manatschal and colleagues on the Iberian margin (Manatschal, Sutra and Péron-Pinvidic, 2010; Péron-Pinvidic and Manatschal, 2010), has shown just how

magnetics), as well as seismic. The structural framework partitions the crust, provides zones of weakness, and evidence (strain) with which to understand the evolution of the stress field driven by geodynamics and big picture global tectonics. In many areas the structure also dictates how the landscape

modelling and plate modelling. Mapping out the geodynamic state obviously gets us part of the way to addressing this, which is why we consider it to be so important, but process also requires a more in-depth understanding of the dynamics, including mantle dynamics, the plate (tectonically) driven contemporary

As Hunt recognized 150 years ago, to build a palaeogeography for exploration you first need to understand and build the architecture.

responds – drainage especially is frequently dictated by the geological structure. With this framework in place, the geometry of different crustal types can be captured, defined by thickness and petrology. There is,

stress field, and the interplay of these drivers with crustal rheology and inherited crustal fabrics. In a recent paper on the opening of the South Atlantic, Paton et al (2017) showed just how complex these relationships can

be with, in this case, inheritance attributed to early phases of rifting, but not the main phase. We can see this complexity in the East Africa Rift system forming today (Figure 3) with pre-existing weaknesses, such as Karoo fabrics or Precambrian shear zones and cratons dictating Late Cenozoic rift geometries in some parts of the system, but not all. For example, in central Tanzania, recent rifting cuts across cratonic basement with no apparent regard for pre-existing structure. How can the crust be so fickle? Well, of course, it isn't. Understanding why and how is the driver for this research.

Over the last 12 months, I have been focussing on the first part of this problem by designing and building new global databases, with their associated data management system and GIS symbology, to capture the observational information from which to build a better understanding of crustal architecture. This includes a new structural elements database (Figures 2 & 3), a new crustal types database, a new igneous features database and a new plate definitions database, which is being used to help constrain regional and global plate models. As part of my academic relationship with the Basin Structure Group at the University of Leeds these scientific databases will ultimately provide a global and regional context for the more detailed research of BSGs Ph.D.s and postdocs so that as more learnings are published, the databases can be updated and improved.

Partnerships with academic research groups are, in my view, key to our industry and are an essential part of the ethos of Knowing Earth. The Basin Structure Group at the University of Leeds led by Professor Douglas Paton (<https://bsg.leeds.ac.uk/>) is one of the leading groups in the world who are researching crustal architecture and they have an extensive publication record to prove it. By bringing together this cutting-edge research with my own expertise, especially the understanding of the broader palaeogeographic workflow, we can build a much better understanding of the Earth system.

To this end, we are now working together to develop two research initiatives at BSG. First, a portfolio of margin-scale transects to reveal the crustal architecture and its evolution over time. These will bring together the mapped structural framework, crustal composition and geometry, which are based on the interpretation of seismic,

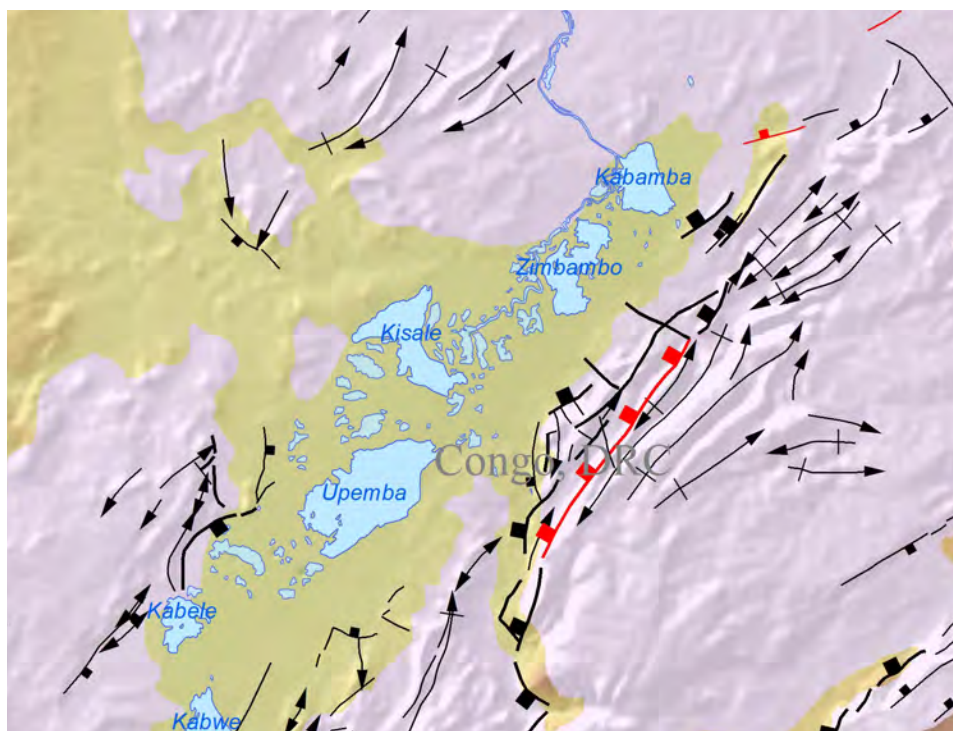


Figure 2. Detailed view of the East African Rift system in Congo DRC showing the level of detail of the mapping, including faults, folds and bedding.

well and potential fields data. The evolution of the crust along these transects will then be reconstructed using structural restoration and plate modelling. This then underpins reconstructions of the tectonostratigraphy and basin evolution (including basin modelling to identify the impact of the crustal architecture interpretations on petroleum systems and potential prospectivity). By design, these lines will also provide input into the evolution of accommodation space and hinterland uplift and geomorphology (the restoration of palaeolandscapes), as well as giving us a far greater degree of control on plate modelling, including deformable models. The resulting portfolio is, therefore,

more than just a database of geotransects, which are traditionally 2D representations of the crustal structure at a point in time, usually the present-day, and will help us better constrain how the crust behaves in 3D and 4D. Second, a reference library of analogues showing how different crustal architecture geometries look in seismic, gravity and magnetic data. Learnings from this can then be applied to less data-rich areas and hypotheses posed.

As Hunt recognized 150 years ago, to build a palaeogeography for exploration you first need to understand and build the architecture. ■

FURTHER INFORMATION

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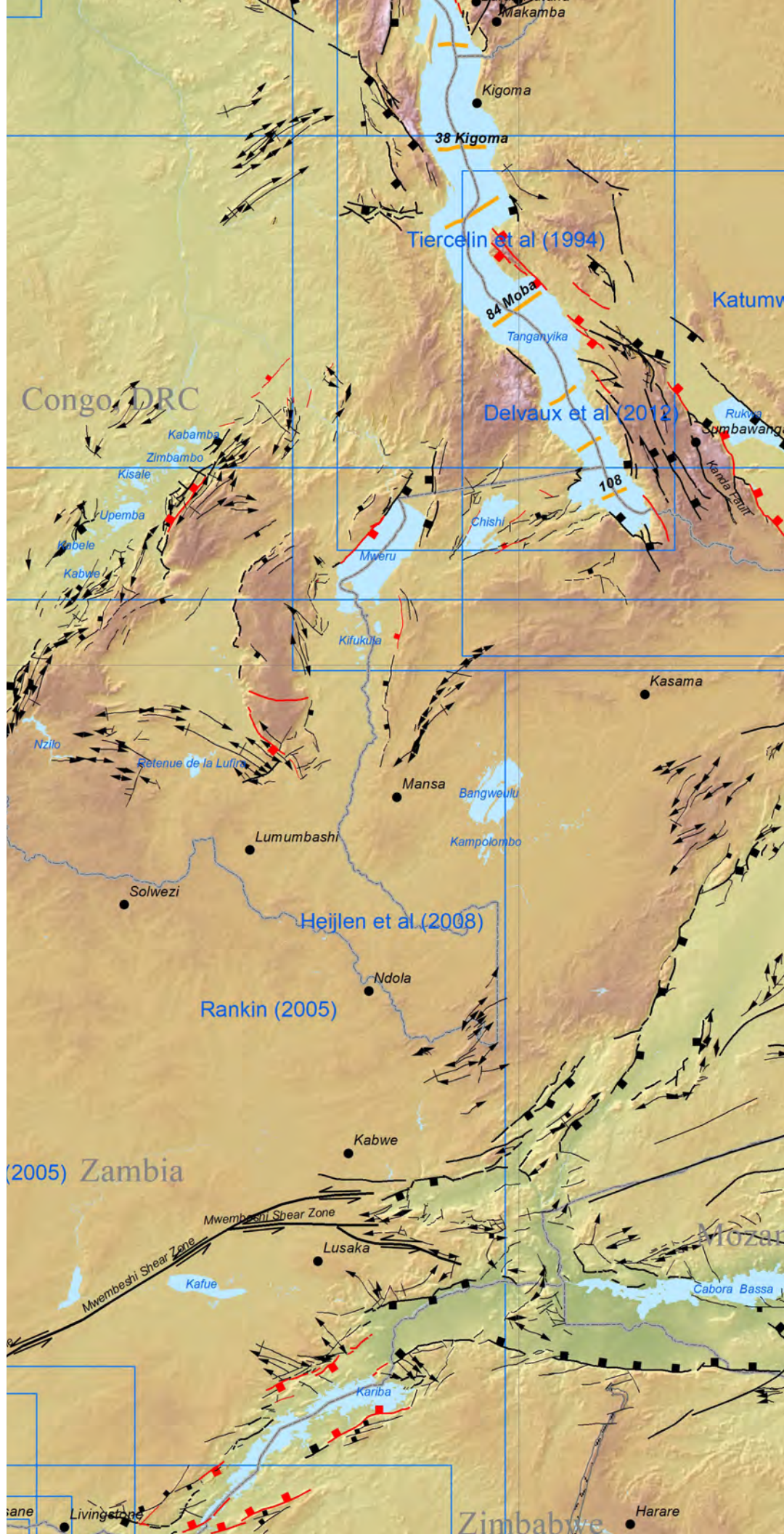
Figure 3. The structural elements database for East Africa showing the resolution onshore and offshore. All features include a comprehensive and fully referenced audit trail. The blue outlines show the footprint of the published sources used for the kinematic and geological attribution. Orange lines mark the location of seismic and section data within the databases.

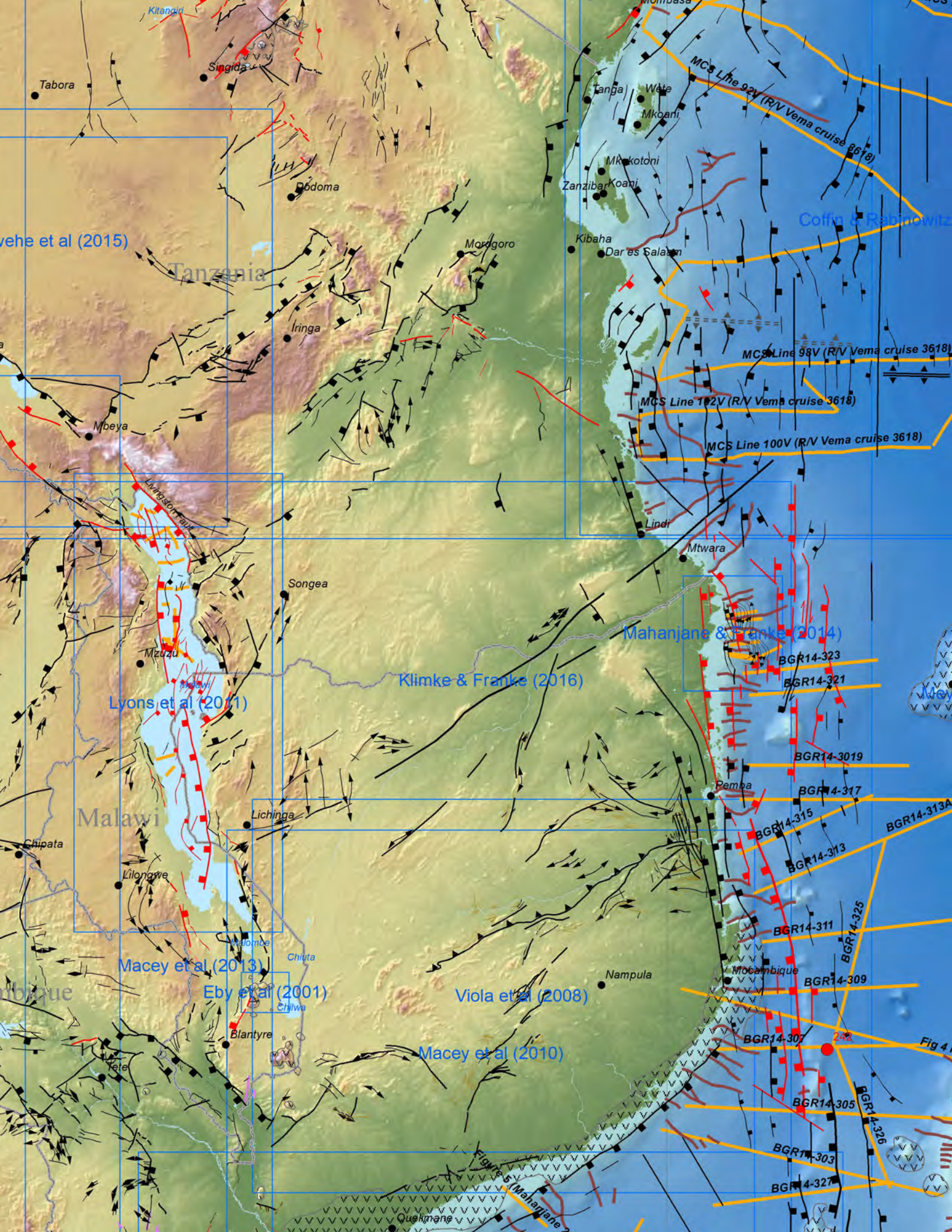
The related Igneous Elements database includes information on petrology, age and tectonic setting.

Activity at the present-day is based on published records and the NEIC-USGS seismicity database, which now spans over 40 years of records.

These features are a subset of the full, global databases that we are currently building.

The East African Rift (EAR) provides a well-defined source of analogues for examining initial rifting processes, as well, of course as exploration targets in its own right. In the area of Lake Mweru shown here, we can see evidence of pre-existing structure dictating rifts and in other areas the rifts cutting across the basement fabric. This reflects the interaction of the current stress field on the geology and how this is then accommodated as strain.







From Source to Sink: the Importance of Drainage Reconstruction

Source-to-sink has become a key concept in exploration, especially for understanding and predicting reservoir facies character and distribution. Source-to-sink follows the path of a particle from its formation through weathering in the basin hinterland, to burial and preservation in a sink area via erosion and transport (Martinsen et al., 2010; Somme et al., 2009). This is a complex journey that requires an understanding of a wide range of subjects from tectonics to climate, weathering and erosion, transport mechanisms and depositional systems.



The Valley of Desolation, Bolton Abbey Estate, Yorkshire. Pebble and cobble-dominated system with numerous knick-points and incised valleys consistent with active glacio-isostatic uplift.

A major part of the source-to-sink story is the reconstruction of the transport pathways, which in the terrestrial system is dominated by the reconstruction of palaeo-rivers (Figure 1). This is based on several lines of evidence (Figure 2); from analysis of present-day patterns – drainage network and landscape analysis – to the use of provenance data, palaeo-current indicators, palaeogeography and fish biogeography (Markwick and Valdes, 2004; Markwick, 2013).

In this article, the focus is on drainage network analysis, which establishes the hypotheses that are then tested by the geological record.

Drainage networks reflect two principal drivers, slope and geology (Twidale, 2004). In an area of homogenous geology (for example flat lying beds with no structural expression) drainages will respond primarily to the slope. This has been examined experimentally using sand tanks as well as field observations and has been discussed by numerous authors (see Schumm, Mosley and Weaver, 1987). At its simplest level, a tilting landscape will form a parallel drainage system, which will then switch to dendritic as the tilting slows or ceases. However, numerous studies show the importance of initial conditions in governing how a drainage will respond to tilting, so this ideal case will only apply in areas where the drainage is reset, for whatever reason, prior to uplift (e.g. an area transgressed by a lake or sea). A good example is seen in the southern Cuvette Centrale (Figure 3). This idea of resetting

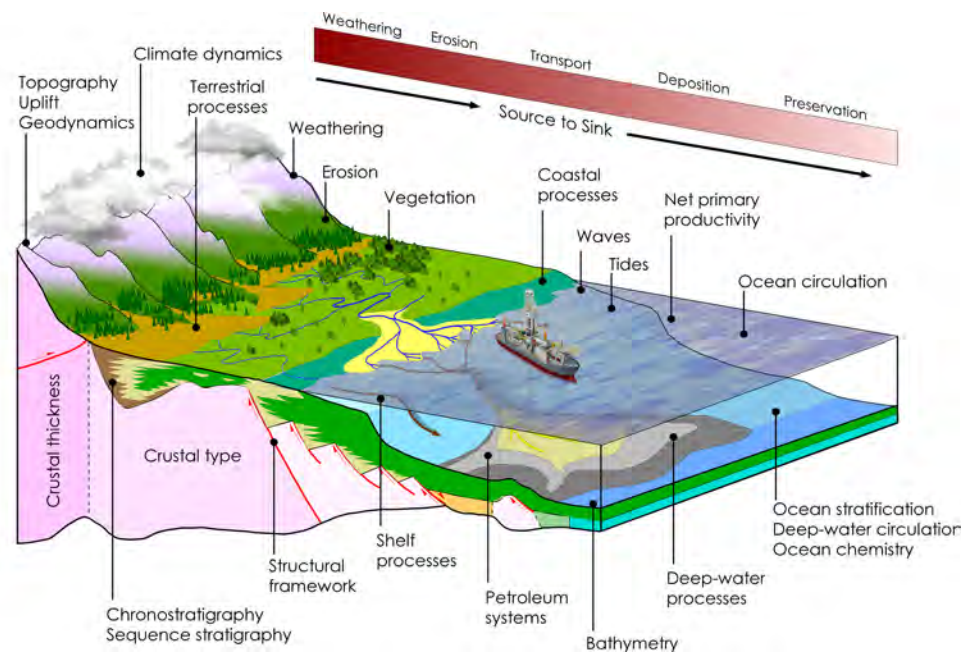


Figure 1. A block diagram of the paleogeographic workflow (Markwick, 2018) showing the importance of source-to-sink and its relationship to the hinterland and depositional systems.

the landscape is also true for volcanic areas, where extrusions can ‘wipe out’ existing drainage by infilling all valleys to spill point,

by the slope (Figure 4). But, in most cases, the geology has a much heavier influence with many major rivers dictated by tectonics,

Drainage networks reflect two principal drivers, slope and geology (Twidale, 2004)

for example, the Deccan Traps, or locally result in radial drainage patterns governed

such as the Niger, Amazon, and Ganges. On a more local scale, individual fault systems can dictate the paths of rivers, for example, the Ntem River in West Africa which flows along the Ntem Shear Zone.

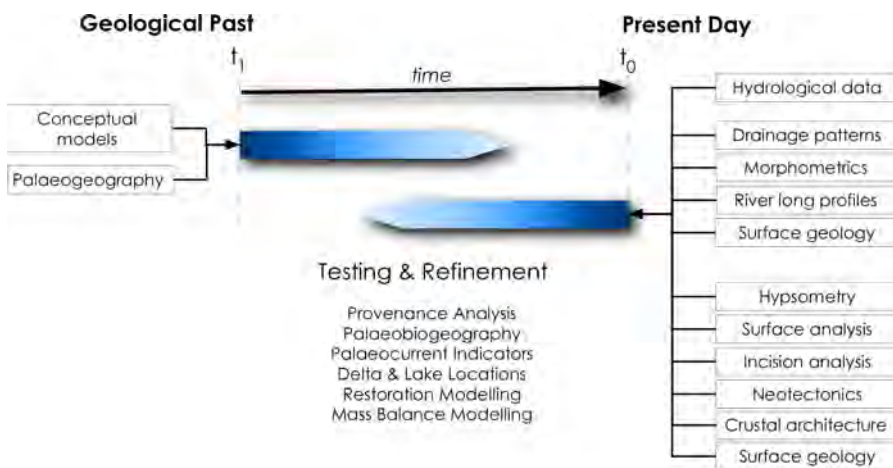


Figure 2. The workflow for reconstruction palaeo-river systems (from Markwick, 2018). There are a number of lines of evidence working backward and forwards in time that are combined to develop the drainage history. The resulting palaeo-river systems are amongst the more robust components of palaeogeography, not least because all hypotheses are explicitly testable.

Drainage network analysis, as applied to palaeogeography and exploration, examines the present-day drainage networks and landscapes in order to identify potential past changes in river systems. The applicability of analyzing the present-day to look for history is summarized nicely by Summerfield, ‘that drainage systems have a heritage rather than an origin...’ (Summerfield, 1991). Traditionally, network analysis includes identifying deviations to geomorphological ‘laws’ that were established in the 1960s by geomorphologists including Strahler (1952; 1957; 1964) and Horton (1932; 1945). Most of these ‘laws’ reflect simple geometric relationships that can be applied to other natural phenomena, for example, the number of stream segments of a

particular stream order (Strahler Order is the most commonly used) related to basin area. Deviations from these 'laws' are nonetheless useful in pointing the analyst to discrepancies that need an explanation and hypotheses about the evolution of the drainage network. Other analytical devices for drainage analysis include the drainage

'that drainage systems have a heritage rather than an origin...' (Summerfield, 1991)

network type (viz., parallel, dendritic, radial, etc.), confluence morphology (viz., barbs indicating flow reversals), river long-profiles and hypsometric curves.

Hypotheses generated from the network analysis can then be tested against provenance or related data. If the causal mechanism can be identified, and ideally an age of formation assigned to a particular drainage pattern, then this can be used to better constrain the drainage evolution.

Here are two examples:

Dated radial drainage, Phuoc Long volcanics, Lower Mekong River

Volcanics can reset the landscape due to the rate at which they change topography. This example from the southern Mekong River drainage system on the border of Vietnam and Cambodia (Figure 4) shows how in the workflow for palaeodrainage as part of palaeogeographic build, dated river patterns can be selected and eliminated for older reconstructions that predate the pattern 'event'. In this case the radial drainage is demonstrably linked to the Phuoc Long basalts, which are dated as 8 – 3.4 Ma.

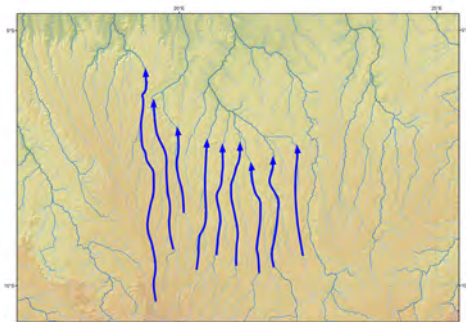


Figure 3. Parallel drainage in the southern Cuvette Centrale (Congo River drainage basin). Trends indicated by dark blue arrows.

Reversal of flow. The Nyong River, West Africa

This is a great example of flow reversal given that there are several lines of evidence all supporting the interpretation and because we have an indication of the timing. Figure 5 shows the network for the Nyong River generated from the SRTM30 radar-based

DEM. This has been checked against the DCW (Digital Chart of the World) blue line database for the area. Today, this river flows east into the Congo River, but the overall network pattern indicates westward flow with a confluence in a westward direction (towards the Atlantic). Looking more closely reveals barbed confluences along the southern tributary consistent with reversed flow but these are not seen in the northern tributary. Other evidence includes westward directed incision from the Congo River drainage basin (Cuvette Centrale) shown clearly using the high pass topographic filter (Markwick and Lefterov, 2008) consistent with a capture history by the Congo River. The timing of this capture is associated with uplift of the area as indicated by the long profiles and hypsometric curves with the pre-existing (inherited) landscape represented by shallow concave up profiles in both graphs now raised almost 1000 m. Most researchers assign this large-scale uplift to a mantle-effect of Oligocene or more likely Miocene age. So, by removing the capture and reconstructing the rivers

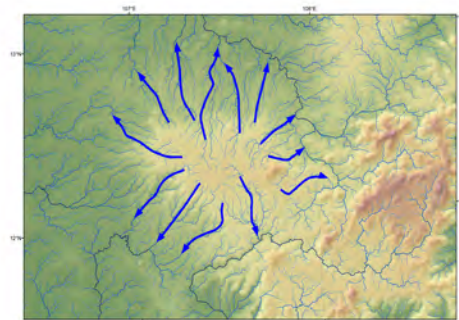


Figure 4. Radial drainage caused by an eruption of the Phuoc Long basaltic lavas near the Vietnam-Cambodia border. Trends are indicated by dark blue arrows. By dating the cause of the radial drainage, the volcanism, this can be then eliminated from consideration in older timeslices and the pre-existing drainage patterns extracted.

systems by inverting the analysis we can reconstruct what would, at first pass, be considered the Oligocene (pre-uplift) drainage configuration. In this case part of a series of narrow east to west draining river systems with a north-south drainage divide close to the eastern edge of the Gabon craton.

Once the drainage history is established this can be reconstructed onto palaeogeographic maps and used to investigate potential clastic composition and erodibility (Figure 6).

The further back in time we reconstruct, the less that history is preserved in the present-day landscape and the less drainage network analysis can provide information about palaeo-rivers. This varies depending on the stratigraphic and tectonic activity of the area studied, with some parts of Africa purported preserving early Mesozoic landscapes (King, 1950; Partridge and Maud, 1987), but active tectonic areas such as SE Asia having a record that may be only Cenozoic or younger. In NW Europe, the record of rivers in areas that were flooded during the Cretaceous and early Cenozoic may similarly be young – transgressions tend to reset the drainage networks.

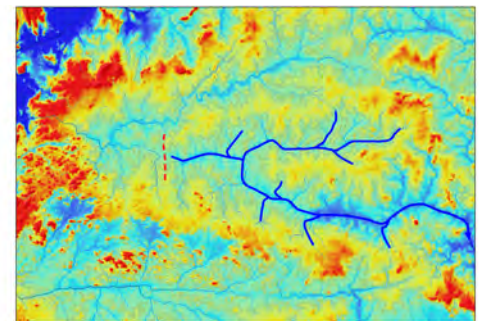
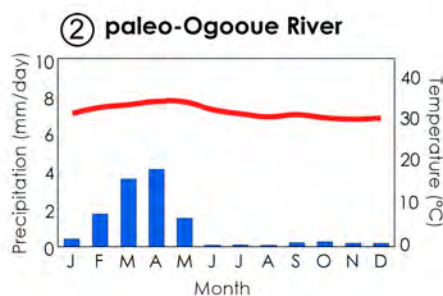
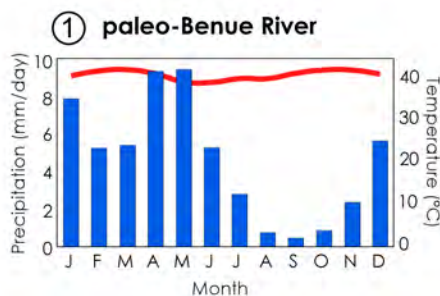
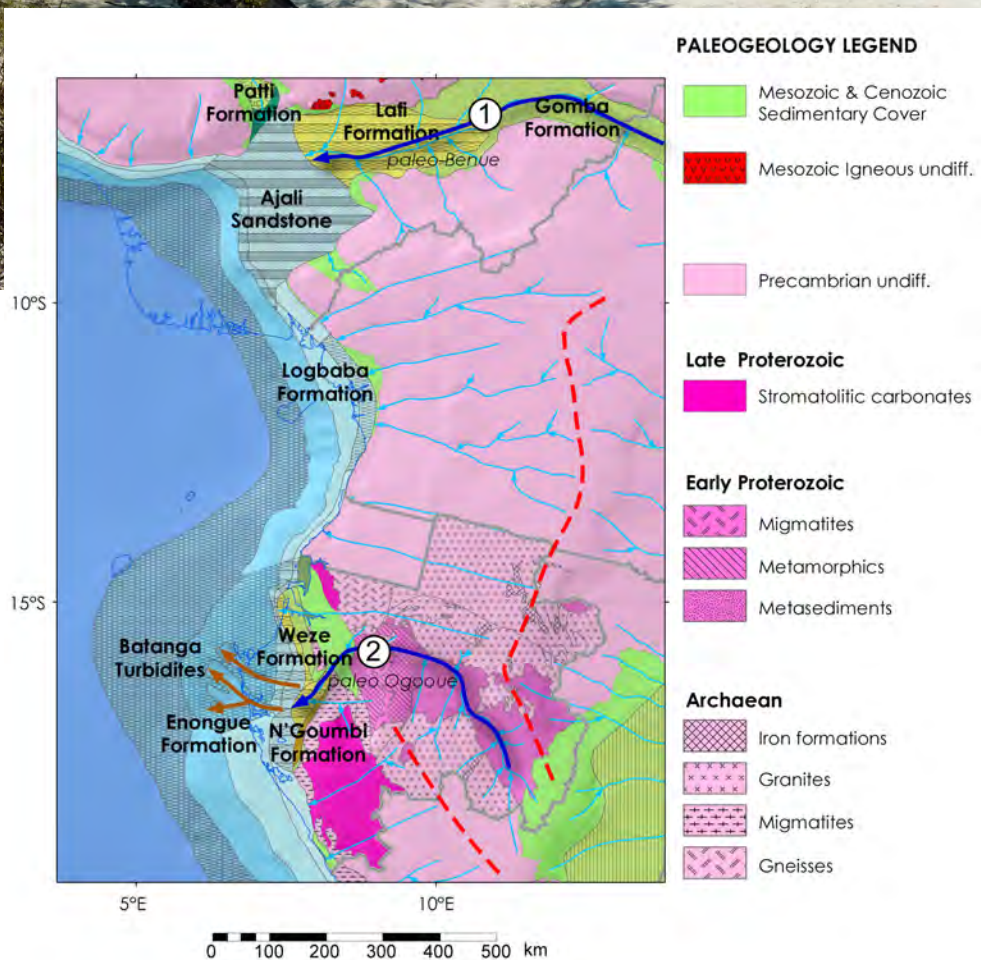


Figure 5. Nyong River. West Africa. Evidence of reversed flow is indicated by the confluence direction and especially the barbed confluences on the southern tributary, which now forms the major trunk stream of an eastward flowing Nyong River. The underlying grid represents a high pass filter through the topography which picks out areas of high incision in the darker blue colours. Note how in the Nyong River these dark blues propagate westward from the Congo River consistent with the capture story. Dark blue arrows show the flow trend within the network. The red dashed line shows the position of the present-day drainage divide. The hypothesis is that at some point in the past the river flowed across this divide and into the Atlantic.



Although focussed on reconstructing the distribution of clastics, reconstructed palaeodrainage can also be used to gain insights on source facies distribution and character: nutrients from rivers can affect local productivity, freshwater discharge can result in (especially seasonal) water column stratification and anoxia, or conversely clastics from rivers can dilute organic carbon accumulations and source rock quality.

The reconstruction of palaeo-rivers is a powerful, and essential workflow in exploration, with drainage network analysis as one part of that workflow. ■

Figure 6. With the palaeo-river systems reconstructed, additional datasets can be used to examine the hinterland. Bedrock geology for the Late Cretaceous to provide an indication of the nature of the underlying substrate that could be weathered and eroded to be transported into the Gabon Basin. The palaeoclimate (graphs 1 and 2) can be used to analyse weathering potential as well as transport mechanism (viz., flash floods). In this case Gabon in the Late Cretaceous sat on the boundary between the contemporary ITCZ (Inter-tropical convergence zone) dominated by Ever Wet conditions, and the arid zones to the south. This has important implications for the character of the derived sediment.



Village Creek, near Village Creek State Park, Texas. A sand-rich system flowing across the broad fluvial plain along the northern margin of the Gulf of Mexico.

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FURTHER INFORMATION

This article is taken partly from Markwick & Valdes (2004) and Markwick (2018). An online presentation by the author with a fuller set of examples for West Africa is available at <http://www.findingpetroleum.com/video/Getech/Paul-Markwick/1105.aspx>

I am currently working up new and revised drainage analyses for Africa, South America, North America and SE Asia. Derivative materials are available.

A training course on drainage analysis is available on request. For details please contact me at contact@knowing.earth

Modelling the Earth System for Exploration: why some Models *are* Useful

"All models are wrong, but some are useful"

George Box (Box and Draper, 1987)

George Box's quote has become something of a cliché and one I have frequently heard when promoting the use of climate and lithofacies models in exploration over the past 20 years. Though the usual riposte I receive is with an emphasis on "*all models are wrong*". The scepticism levelled especially at climate modelling has many 'justifications': "*models are not data*", "*there are too many uncertainties*", "*yesterday's weather forecast was wrong so how can I believe a climate model?*", "*climate change is not real, so the models must be wrong*", "*models are models*". Followed by the frequent question "*do you have any seismic?*".



Now, I like seismic as much as the next exploration geologist, and I admit that a glimpse into the ION library at AAPG reminds me of what is exciting about geology. But climate models are also very powerful tools for investigating the Earth system if you know how to use them and understand what they are designed to do and not to do.

Running a climate model and interpreting the results is no different than running any model for exploration, whether this is a reservoir or basin model with which we all seem much more comfortable. And just as you would not base your drilling decision on a single reservoir simulation, the same is true for using climate models. It is about assessing (geological) risk by investigating the sensitivity of the system using experiments.

Models, by definition, are representations of a system based on our knowledge of that system. Since that knowledge changes as we learn more, so models also develop.

Earth System models are based on physics and largely dictated by physical laws that have been with us since Newton. The 'uncertainties' stem from parameterizations within the models, which are the representations of processes that we either do not yet fully understand, yet, (viz., clouds) or which are beyond the resolution of the model (viz., individual storms). For models of the geological past, we have the additional uncertainties in the boundary conditions which are prescribed by the modeller: the palaeogeography, atmospheric chemistry, orbital configurations. There are also the intrinsic variabilities that reflect temporal resolution. These uncertainties and variabilities are well documented and have been investigated in both the present day and deep time and so the sensitivity of models to these

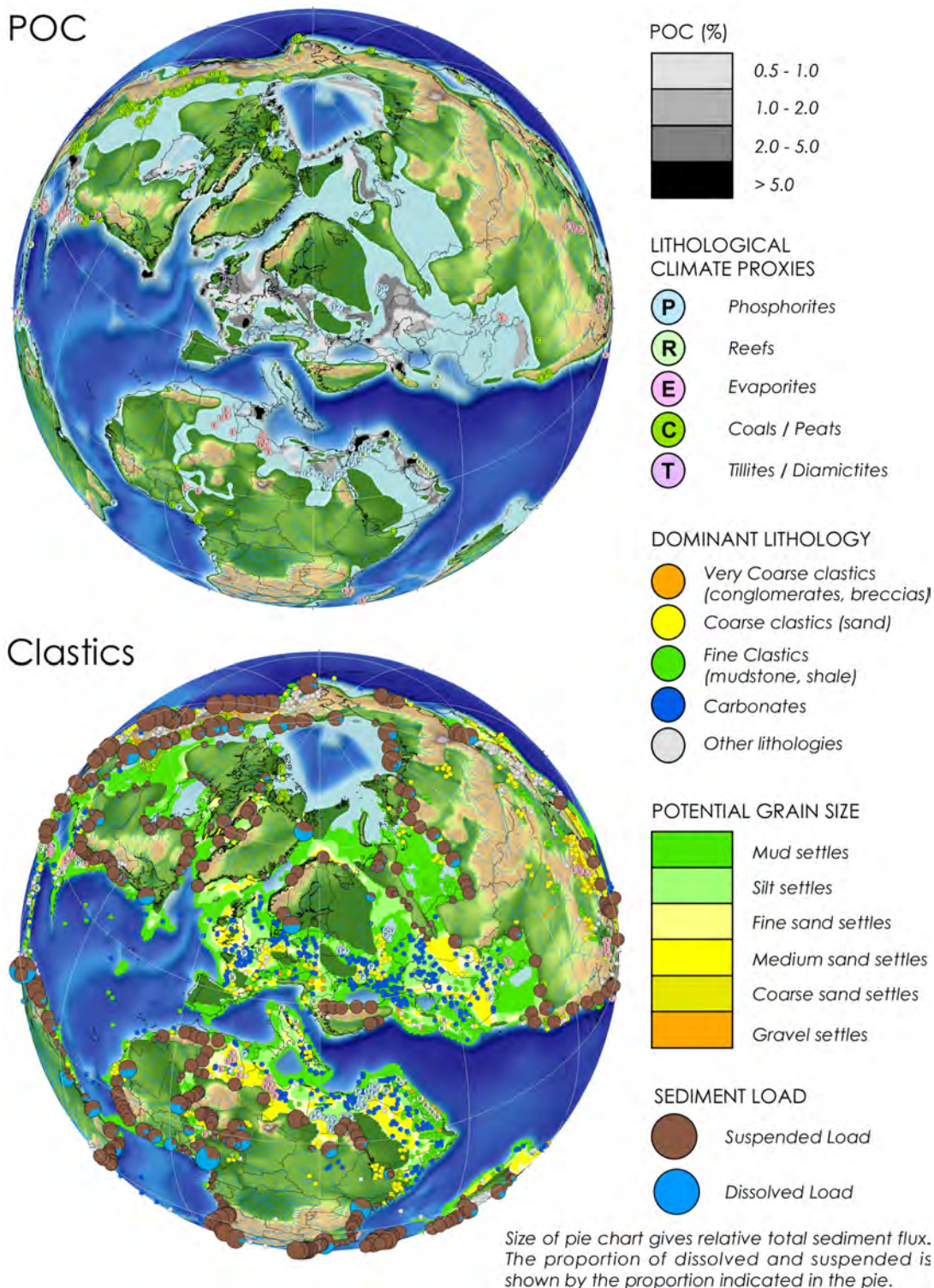


Figure 1. (From Markwick, 2018) Lithofacies retrodiction results for the Maastrichtian. (a) Particulate Organic Matter (POC%); (b) potential clastic grain size determined by motion on the shelf. In this example, it is assumed that clastics of the right grain size are available to be moved, but this can be further investigated by the output of transport part of the models. Relative calculated sediment flux values are shown by pie charts for each mapped palaeo-river using empirical equations based on published databases (Hovius and Leeder, 1998; Markwick et al., 2006; Meybeck, 1976; Milliman and Syvitski, 1994). Lithological data and climate proxies from the Paleogeographic Atlas Project (Ziegler et al., 1985; Ziegler et al., 2003) are shown to illustrate the density of data used to test and refine both the lithofacies retrodiction and Earth system models. This example only shows the results of one experiment.

factors is tractable at some level. Through data-model comparisons, it is also relatively well known how different models behave and for which modelled variables we can have the greatest or least confidence in the absolute values, at a given resolution. Again, this can be and is accounted for when model results are applied to exploration problems.

Models, by definition, are representations of a system based on our knowledge of that system. Since that knowledge changes as we learn more, so models also develop

In exploration, Earth system models are most commonly used to retrodict the inputs to processes that affect depositional systems (retrodiction is the act of ‘predicting’ past events or phenomena). The first applications in the 1980s used parametric climate models to reconstruct atmospheric circulation and together with palaeogeography to identify margins with ocean upwelling systems that could be sites of high net primary productivity and net export carbon (Parrish, 1982; Parrish and Curtis, 1982). Although the relationship between upwelling and net export carbon at the sea floor has since been shown to be much more complex, this work drove much of the initial interest in using climate models in exploration (see Summerhayes, 2015). Coincidentally, this is also how I began my interest and career in palaeoclimatology, Earth system modelling, and exploration, as an intern running computerized versions of Judy

Parrish’s parametric models (Scotese and Summerhayes, 1986) to predict upwelling at BPs Research Centre in the mid- 1980s (Miller, 1989). Since the 1980s, climate model results have been applied to other processes and problems, from bottom water temperatures for input into basin modelling to ocean, tide and waves models to investigate

submarine sedimentary transport and coastal morphology (especially important for reservoir systems). Much of this work has been integrated within what has been termed lithofacies models or Lithofacies Retrodiction (Prediction) Models that use the output of Earth system models together with palaeogeography to predict the

remains underutilized. The question is ‘why?’

I do not think that this is due to an inherent bias against models in general. We use reservoir and basin models in exploration, after all. To me, the explanation lies more in the way Earth system models have been applied in exploration with little or no support to help users understand what they can do with the results and how far to believe them. As a ‘black box’. The upshot is that when retrodictions (or predictions) do not appear to match observations the reaction has been to throw out everything in frustration.

So, how can we help and encourage the effective use Earth system modeling in exploration?

First, by seeing Earth system modelling for what it is, a tool, one of many in the explorationist’s toolkit.

Second, by using Earth system modelling in the same way other models are used, with multiple experiments to assess model

...within exploration, the starting point is to focus on understanding the system being modelled. This will help identify where the Earth system models might be most useful.

distribution of different lithofacies based on the processes responsible. An example of the output of a simple lithofacies model (Markwick, 2018) is shown in Figure 1.

The list of potential applications is extensive. And yet, Earth system modeling

sensitivity and thereby define uncertainty and variability.

Third, by introducing exploration geologists to, at least, the basic ‘vocabulary’ of Earth system models and how they can be applied to solving exploration problems.

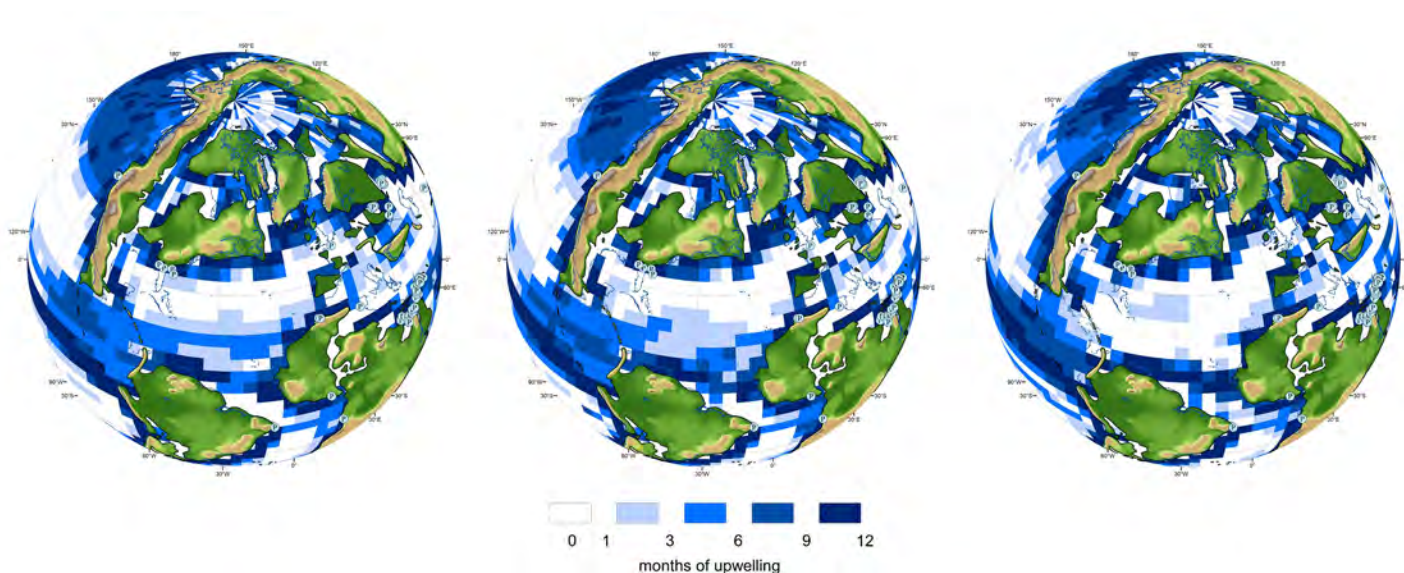


Figure 2. The number of months of upwelling in each model grid cell for three Maastrichtian scenarios. From left to right representing the following change in atmospheric chemistry: 2x, 3x and 4x pre-industrial CO₂ concentrations.



Fourth, and most importantly, to ensure that explorationists are provided with support when faced with the huge volumes of Earth system modelling results they can now access so that they can get the most from what they have.

In practice, within exploration, the starting point is to focus on understanding the system being modelled. This will help identify where the Earth system models might be most useful. Most commonly, though not exclusively, this will be in retrodicting the character, timing and extent of depositional systems, especially those responsible for the key play elements of source and reservoir facies. From 30 years of experience, a good way to approach this, and to ensure that all the components needed to be considered, are considered, is to start with the ‘big picture’. Use a regional palaeogeography to plot out your existing geological data assets, knowledge, wells etc., and use this to then identify what questions to ask. This does require an understanding of the depositional systems and what drives them, for which there is an inexhaustible literature. Don’t start with the model results for the grid cell that immediately overlaps with your asset, and especially don’t get too

focused on the results of a specific variable.

Once you know the questions then you can use model experiments to assess the sensitivity of the system to model or boundary condition uncertainty and especially to inherent geological variability. In the past, the use of Earth system modelling experiments has been limited by the complexity of climate models themselves, which required the use of high-end supercomputers, which made them expensive to run. Consequently, there was a reticence to run multiple scenarios given the expense, which meant that model use was very much a case of “light blue touch paper and stand well back”. That has changed. First through the development of faster models, suited to running ‘what if’ scenarios; though this does come at the price of accuracy. Second, more powerful computing systems, especially parallel systems. Third a growing portfolio of published and unpublished model results that can be drawn on to answer questions on model veracity, sensitivity and variability.

In fact, model experiments can also help identify the questions you need to solve in the first place, for example by identifying the key processes to be considered, which

factors are important (whether primary or secondary drivers), and which variables have no bearing on the question you are addressing. This is where recent developments in AI (Artificial Intelligence), especially machine learning, can be applied to quickly look at all potential relationships in model output (the volume of model output usually makes this prohibitive if done manually). The impact of each identified key driver in a system can then be assessed through a systematic matrix of experiments to investigate the sensitivity of the system to changes in, for example, palaeogeography, atmospheric chemistry, or orbital parameters. In Figure 2 a sensitivity experiment for the Late Cretaceous (Maastrichtian) used different atmospheric CO₂ concentrations to examine the impact on source facies deposition. In this case, focusing on marine upwelling, the results showed some change in the geographic distribution of upwelling systems in each scenario, but the major change was in seasonality of upwelling intensity. Since it is the seasonality that impacts export carbon production, this is important for understanding source rock depositional systems.

Another approach is to investigate the



Kimmeridge Clay Formation, Kimmeridge Bay, Dorset The initial use of Earth system modelling in exploration was driven by the retrodiction of source rocks using the modelled distribution of ocean upwelling as a potential proxy for areas of high productivity. In reality the relationship between upwelling, export carbon production and source rocks is more complex.

system through ‘what if’ scenarios. These are more targeted and require a deeper understanding of the system being modelled. A real-world example from the Cretaceous Wessex Basin of southern England

analogues. There is a voluminous literature on model sensitivity and data-model evaluation that can be accessed to provide background. You can use this as a guide to what might happen in your basin or asset

think of how rainfall can change in the UK because it is an island – but the patterns of high and low rainfall are generally useable. Again, don’t be drawn too literally by the absolute values.

some models are useful

would be to ask what inputs or boundary conditions need to be changed in order to switch from chalk deposition to Plenus Marl deposition and a concomitant increase in TOC (Total Organic Carbon). This could then be extended to the Kimmeridge Clay to see if the changes are the same as those responsible for switching between high TOC calcareous shale and the coccolith-rich white stone bands. If this well-documented system can be understood and retrodicted, then that understanding can be used to improve the understanding of the geological risk elsewhere.

If your budgets are limited, and you have access to only one suite of model results (i.e. one result per timeslice) all is not lost. You can assess system variability and uncertainty in three low-cost ways:

(a) Published data-model experiments as

given specified changes. For example, if you increase CO₂ in the atmosphere (or any greenhouse gas) the result of most published research is increased global temperatures but also a greatly intensified hydrological system. From the published literature, you will also get a sense of how individual variables respond. As a basic guide to sensitivities, consider the following: atmospheric circulation is relatively robust, especially the large-scale circulation; temperature values are generally reliable, but they are sensitive to atmospheric chemistry (note that in most cases temperature patterns remain largely consistent– which areas are warmer or colder than others in a particular time), and locally to the palaeoelevation (remember that the average lapse rate, which is the change in temperature with elevation, is today about 6.5°C / km); precipitation is highly susceptible to local conditions –

(b) Use different timeslices as a guide to sensitivity. Another way of understanding model sensitivity in the absence of multiple runs for a single timeslice is to look at how different variables vary over time for different geographies (different timeslices). This can help give you a clue for how variables may respond in your timeslice of interest, especially to different geographies. Again there is a growing literature on this that is readily available (Lunt et al., 2016).

(c) Present-day. Look at how different examples of a depositional (or other) system behave in different parts of the world today, with different inputs.

Earth system modelling is one tool in the explorationists toolbox and certainly one to consider in your exploration workflow. It is one that is relatively inexpensive given the insights it can provide, but only when used correctly and not as a black box.

In my experience, “Some [models] are useful”. ■

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Crocodilains past. Jaw of fossil crocodilian. Early Eocene. Washakie Formation, Washakie Basin, Wyoming.

FURTHER INFORMATION


For specialist expertise on climate modelling and for sponsorship opportunities please contact our academic partners in the BRIDGE group at the University of Bristol

Web: <http://www.bristol.ac.uk/geography/research/bridge/>

E-mail: P.J.Valdes@bristol.ac.uk or D.J.Lunt@bristol.ac.uk

For training courses on the application of Earth system modelling in exploration contact me at paul.markwick@knowing.earth. These can be adapted to your specific needs.

Knowing Earth staff and our academic partners are available for bespoke consultancy. This includes support for all companies (service and operators) using Earth system modelling in their exploration workflows.



A key part of testing climate models for deep time is the record of geological climate proxies. Testing requires the use of multiple proxies with the climate space of each constrained quantitatively.

Crocodylians present. Alligator,
Brazos Bend State Park, Texas.

Vegetation is a frequently forgotten component of the sediment supply story. It acts as a weathering mechanism, stabilises landscapes, provides terrestrial nutrients and carbon back into the system, and can affect local and regional climate through albedo and hydrological changes.





The Chevin Forest, Otley, Yorkshire.
Palaeo-vegetation cover is now an output
of many Earth system models to be used
in solving exploration problems

So much to take in...





...the need to bring it all together

The view north from the Castle of Samitier looking across the Ainsa Basin. Ainsa lies at the northern end of the Mediano Reservoir. The mountains in the background comprise the Axial Zone.

Sandstone turbidite, Ainsa Quarry,
central Pyrenees



Bringing it all Together: the View from the Field

The 11th century Castillo de Samitier sits precariously upon a Paleocene limestone ridge some 450 metres high above the Río Cinca that winds its way south through the gorge below. All that remains of the ‘castle’ is a small chapel, the Ermita de San Emeterio y San Celedonio, and a single defensive tower, a second having long since fallen into the narrow gorge below. From the castle, you can see in one view how tectonics, landscape, climate, deposition interacted some 50 million years ago, and how they interact today. The view is breath-taking, but highlights a problem, there is simply so much to take in.

This has been a constant theme of this magazine, the breadth and diversity of the Earth system and the need to understand all aspects of this system to be able to fully understand any one component, especially when applied to exploration.

Here in the Pyrenees, the logistical reality of this problem is all too apparent.

We could, say, concentrate our attention on just the structural story, the uplift of the north-south orientated Mediano Anticline to our right and how this relates to an overall east-west orientated Pyrenean compressional system. Alternatively, we might want to focus on the depositional setting and reservoir characteristics (porosity, permeability, and inter-connectivity) of the deep water turbidite story, and how this might be applied to exploration targets around the world. Or we may be interested in the evolutionary history of Alveolinid forams (Figure 1), which comprise the carbonates just below the summit here. Or how vegetation affects sediment supply to the rivers and what this might tell us about how sediment supply today, but also in the Eocene.

Or... any number of interesting, but diverse topics.

This is why most field trips to the Pyrenees focus on a single, specific topic. This is largely unavoidable given time constraints. But, in doing so, just as in exploration, we miss a large part of the story and risk not understanding the significance of each component.

So how do we address this dilemma? How do we bring everything together without it becoming unmanageable?

Using palaeogeography as a context within which to investigate and understand how all the components in the system interact is one

powerful part of the solution (Markwick, 2018). How we make this happen is nowhere more clearly shown than in how we approach field geology. This is summarised below as 10 headlines based on the approach used by Douglas Paton and myself to teach our MSc field geology course in the central Pyrenees.

1. Stand back and look at the big picture.

The first step is to understand the context, in time and space. In the field, this means sitting with a sketchbook on a hill or other vantage point looking at the literal ‘big picture’, before rushing to look at the details of grain size, permeability, porosity or sedimentary structures at a roadside exposure.

The sketchbook is essential (yes, back to the colouring pencils) because sketching the view gives you two things:

- it helps you observe and record what you see (rather than what you think you should see)
- time to think.

In the office, the equivalent is to research the regional context of your asset or area of interest by pulling together regional geological studies and data, which are widely available, and through this to identify the key questions and uncertainties.

2. Differentiate between observations and interpretations

Observations are the data. What you see and record. Interpretations are what you make from those observations. With more data, your interpretations may change, and you will need to ensure that you have notes that help you explain why. In the office, the same applies – don’t be biased by the first paper you read. What do the data (observations)

say to you?

3. Know where and when you are

In the field knowing where and when you are is critical. It may be that the stratigraphic scheme for your asset is not perfect, and certainly here in the Pyrenees the stratigraphy is in many places equivocal, but it provides a starting point, a temporal context for understanding how the observations fit together in time. In the Pyrenees we do this by referring frequently to poster-sized geology maps and chronostratigraphies that are fixed with magnets to the sides of the mini-buses. In the office, GIS makes knowing where you and your data are even easier or should do. But the stratigraphies can still be problematic and may change with more temporal information, but you need to have some temporal framework to start with.

4. Know the vocabulary

One of the barriers to understanding the Earth system is the specialist vocabulary of each different area of expertise. In my experience, you do not need to be an expert in every field, but you do need to know the language. A review paper and summary figures (for instance Figure 1 in the source-to-sink article) will help. This can be made as simple or complex as time, or necessity requires. This is much easier to visualize in the field by observing what processes are operating and how they interact today within a particular view.

5. Pose hypotheses and build models

Use the primary observations of process and products (the rocks) to pose multiple working hypotheses. From these hypotheses build a model. This is the representation of



Figure 1. From the large-scale to the small. The challenge is to build a story that takes in all the aspects of what we see. Shallow marine Early Eocene *Alveolina*-rich limestone now sitting at 835m above today's sea-level, just below the Castle of Samitier. How do we get from shallow marine to almost 1 km elevation in 55 million years?

your understanding of the system based on what you know at that point in time.

6. Visualize the system

Geology is a very visual science. Whilst the field sketch captures observations, sketches or annotated photos can be used to illustrate your hypotheses and resulting model. Those of you who have been taught by Douglas will be familiar with his predilection for block diagrams and sections drawn at outcrop onto laminated posters that pull together all your observations drawn out of you through various questions. These are a great visual aid, especially as they build through time.

Back in the office you can build a palaeogeography to capture the diversity and complexity of what you see (Figure 2). We can add or subtract observations, interpretations, and processes all within the same spatial context and see how these evolve and interact through time.

Today, with GIS and other spatial database systems, this process is made much easier, assuming that you already have your data management system in place and all the collateral ready to go.

At Knowing Earth we have built a GIS legend which is available to the community to standardize this visualization.

7. Test your hypotheses and model(s)

Visualizing the models also helps in assessing whether they are realistic. If it looks wrong, it probably is! But by starting with the big picture you can identify the key locations in your view that you now need to visit to test your hypotheses and models. In the field, this means driving to specific outcrops which can then be examined and measured in more detail. In the office, this will be through the addition of data, which means that testing is frequently an additional cost. But by starting with the big picture these costs are

to play and prospect scales. Sub-seismic scale observations, for example, are critical to understanding, in order that they can be anticipated in exploration settings.

9. Tell the story

At the end of the day, we, as geologists, are Earth historians reconstructing the story of the past. We are storytellers. Through these stories, we can build an understanding and from these insights.

What is the geological story we can see from the Castle of Samitier? To tell the story for one moment in time, the view

To understand the Earth system first stand back and look at the big picture.

mitigated because understanding the system and looking at the regional context allows us to be more focused on where the new data is needed.

8. Know what scale

Moving from big picture views to outcrop brings in the issue of scale. In the field, this provides a useful teaching tool for differentiating what we would expect to see in, say, a seismic line, rather than a core or wireline log. And how in turn this relates to exploration at regional to basin

has been captured as a late Ypresian (Early Eocene) palaeogeography map (Figure 2) which is reconstructed to represent the maximum progradation of the Montanyana Delta system represented by the Castissent Sandstone in the Tremp Basin, passing west through the Charo Canyon (Millington and Clark, 1995) and associated Arro sandstone turbidites in the Ainsa Basin, and ultimately the distal fan complexes at Broto in the Jaca Basin. This map resolution is getting closer to a 'moment in time' ala Kay (1945). The stratigraphic scheme used

here is that of E.B. Amorós (unpub. Ph.D. thesis Universitat de Barcelona, 2013). For those of you familiar with the turbidites at Ainsa, yes, they themselves are early Lutetian (Middle Eocene) and part of a complex deformational story that befalls this area after the Castissent and which gives rise to the north-south orientated Mediano Anticline that now dominates the view.

In this case, the palaeogeography (Figure 2) shows clearly the relationship of the uplifting Montsec thrust to deflect originally southward flowing rivers west towards the deeper parts of the foreland basin. These thrust-related uplifts also provide sediments to the system. As the mountains uplift, they act as barriers along which precipitation is focussed. Stratigraphically the transition from the Late Cretaceous to the Eocene shows a change from an arid, semi-arid climate (the Garumnian red beds) to wetter conditions. The Early Eocene warm phases are intervals with an intensification of the hydrological system which is superimposed on this local change. The Castissent Sandstone (Montañana Group) (Figure 3) comprises often poorly sorted (Figure 4), sheet sands with erosional bases cutting large channels in the landscape and interpreted as flood-related (Mutti et al., 2000; Ramacha et al., 2011). The transport distances from the hinterland are relatively short, which can affect the potential for reworking and sorting, and from this the porosity and permeability of the resulting deep-water sandstone turbidites. Debrisites amongst the Arro turbidites (pers. obs.) indicate gravity failure along the shelf margin, consistent with seismicity and/or climate (floods).

This is of course only part of the story. There is more to come.

10. Retell that story and develop analogue libraries

A final important part of our field trips is to get the MSc students to present what they have seen. The results each year are impressive, given that the students generally only have an hour or two to prepare. This is then a means of demonstrating understanding, refining models and abandoning those hypotheses that do not work. It is also about working in teams but presenting individually. As such it is great training for exploration.

In a broader context, this is also about building up knowledge and understanding to provide a library of field analogues to

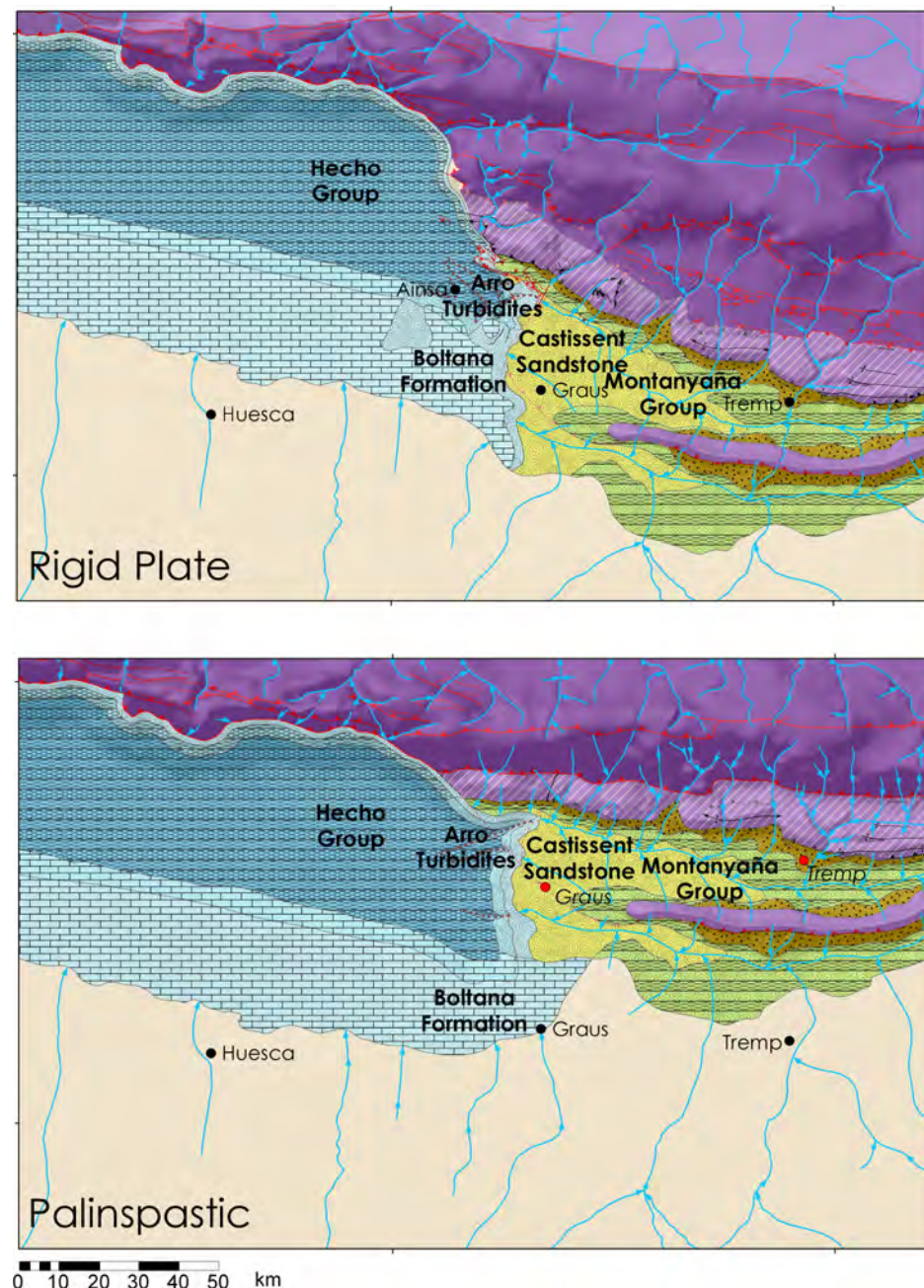


Figure 2. The late Ypresian palaeogeography of the central Pyrenees showing the results for a rigid plate (Top) and palinspastic (Bottom) solution and how this affects the overall geometry of the basin and its relationship to the sediment source areas. Image based on Markwick (2018)

take back to the office and then apply to any other part of the world where we are not able to sit on a hill and take in the big picture and then test at the outcrop. Here in the central Pyrenees, the story we build and the learnings we gain around the formation of the deep-water turbidites in the Early and Middle Eocene can be applied to the deep-water plays of Gabon or Angola or any number of frontier areas and through that reduce geological risk.

The view from the field provides a reminder of how we can understand the Earth system in order to solve geological

problems in exploration.

It is about first standing back and looking at the big picture. Understanding all the components and how they interact.

Of then focussing on the details to test hypotheses and gain greater understanding.

It is about visualization, about asking questions and more importantly knowing which questions to ask.

In many ways, this was the driver for palaeogeography as originally envisaged by Hunt (1873). It is also the geology that most of us signed up to. ■



Figure 3. Sheet-sandstones forming part of the Castissent Formation.

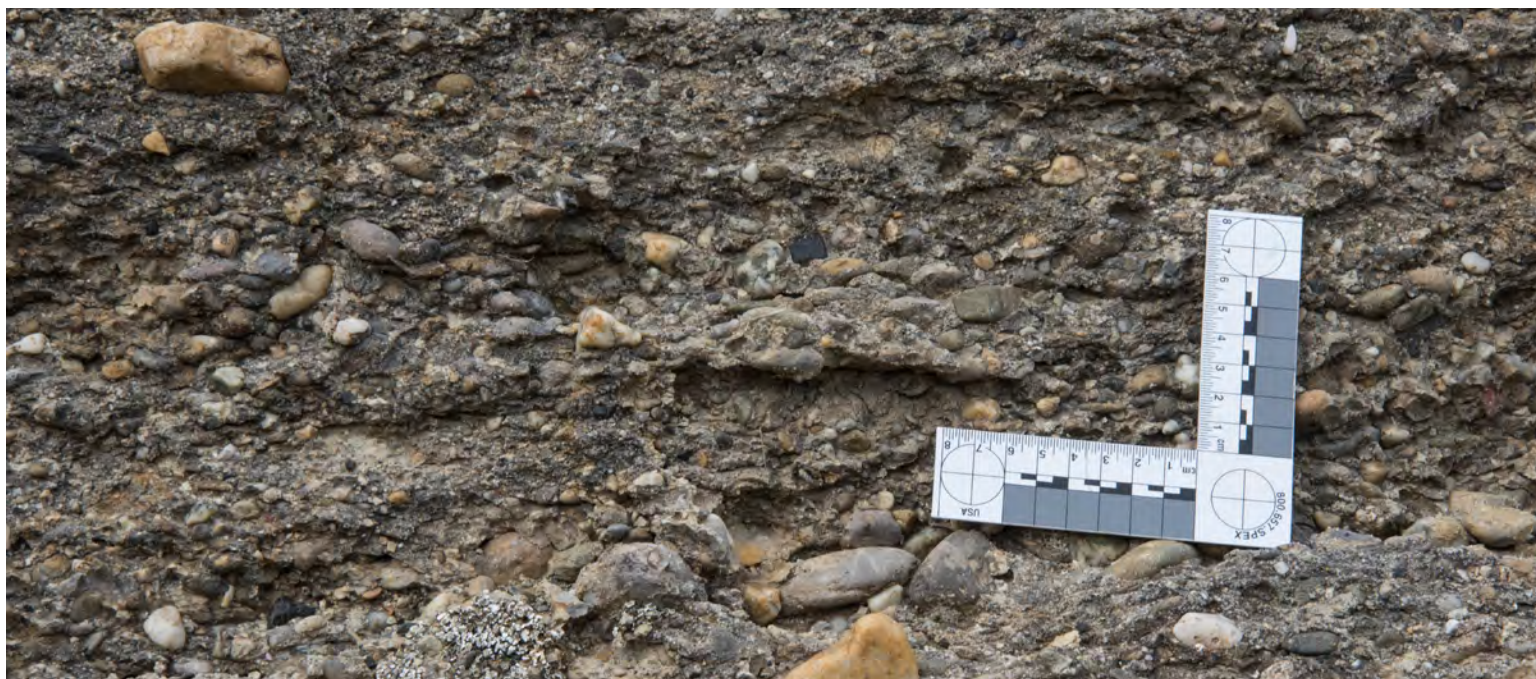


Figure 4. Poorly sorted, cross-bedded gravels and conglomerates comprising parts of the Castissent Formation and interpreted as flood-related deposition.

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FURTHER INFORMATION

If you would be interested in a field course in the central Pyrenees focussed on either basin structure and / or the palaeogeography workflow discussed here, please contact either myself at paul.markwick@knowingearth or Professor Douglas Paton at the University of Leeds, D.A.Paton@leeds.ac.uk.



At the end of the source-to-sink story
lie the distal turbidites at Broto.



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



Iron-stained sandstone within the
Bathonian Forest Marble Formation,
Great Oolite Group, Fault Corner,
Dorset, southern England.



Creating a Legend

Maps are a means of visualizing spatial information. As such, they need a map legend that conveys that information through colour or ornamentation as simply and clearly as possible. In geology, there is a long tradition of colouring and coloured maps, with ‘relatively’ standardized symbologies for chronostratigraphy (geological time), structural elements and lithologies.

The legend described here has been produced by Knowing Earth and is designed to cover all the elements in the palaeogeographic workflow described in Markwick (2018) and reproduced in part in this publication. It includes symbolizations for structural and tectonic elements, lithologies, crustal types and processes, thermo-mechanical state and depositional systems.

This legend is being made freely available to the geological community including academia and industry to facilitate standardization and communication within the field.

Comments or suggestions for additions or modifications to the legend are welcome. ■

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SYMBOL	DESCRIPTION
E170	Delta top, undiff.
E172	Delta top, tide-dominated
E174	Delta top, wave-dominated
E176	Delta top, fluvial-dominated
E181	Estuary, undiff.
E182	Estuary, tide-dominated
E183	Estuary, wave-dominated
E180	Coastal
E190	Supratidal
E185	Barrier
E184	Strand plain
E186	Lagoon
E187	Tidal flat

Figure 1. Legend for coastal depositional environments. The range of environments reflects those environments that can be recognized from the geological record and which have exploration significance.

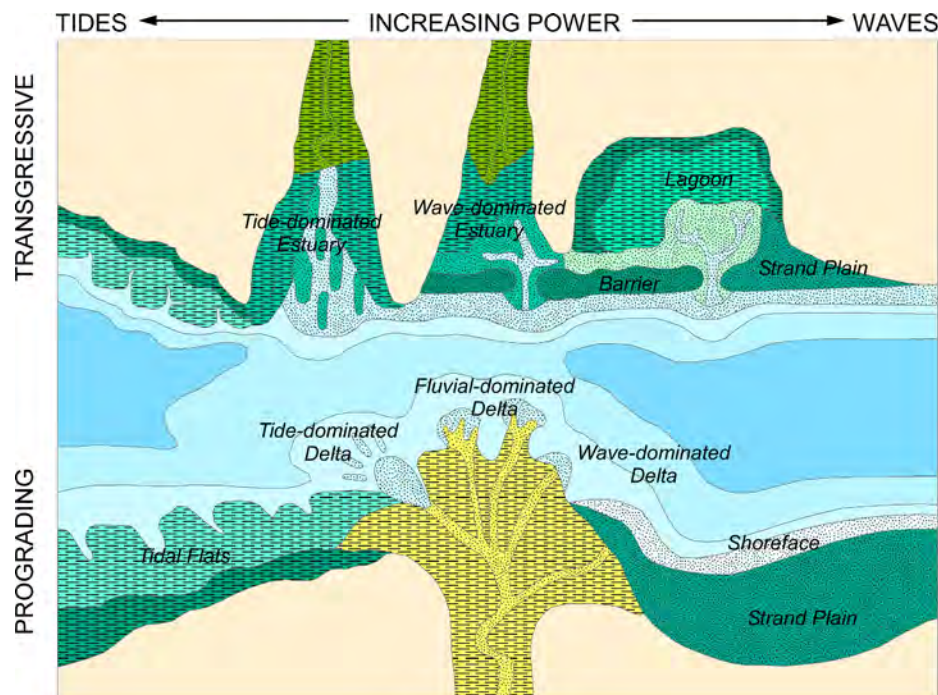


Figure 2. The legend applied to the coastal classification scheme of Boyd et al (1992)

FURTHER INFORMATION

The legend is available from the following websites:

Supplementary material for Markwick (2018): <http://journals.cambridge.org/geo>

Digital explanatory notes and ArcGIS style files: www.knowing.earth


Digital explanatory notes and ArcGIS style files: www.palaeogeography.net

A printed version of the explanatory notes and legend are available on request.



What untold story lies hidden in the rocks?

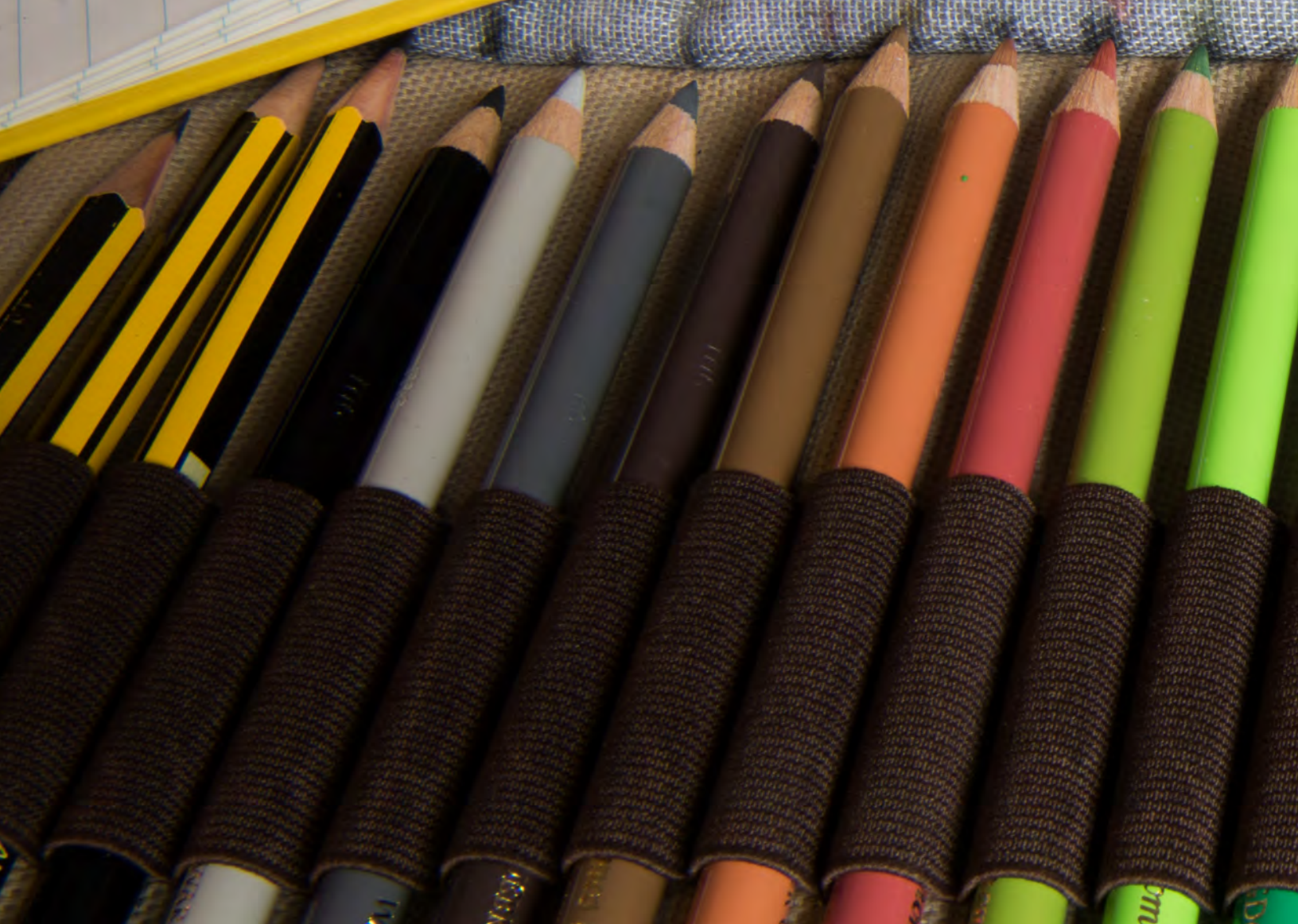




View looking north from Port de la
Creu de Perves into the Axial Zone,
central Pyrenees



Let us help you unravel that story
From the big picture, through to basin,
prospect and outcrop





It's time to get out the pencil crayons!

Further Information

Knowing Earth is about building partnerships and ensuring that all members have a common suite of baseline databases with which to build understanding. For further information, whether commercial or academic, please contact myself or my colleagues.



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This site provides an overview of who Knowing Earth are and their goals, including active research, products and services.



Basin Structure Group (BSG), University of Leeds

Professor Douglas Paton

Website: <https://bsg.leeds.ac.uk/>

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Access to structural and tectonic data is available to sponsors of BSG. This is an academic research group focussed on understanding the evolution of basins and its applications in exploration.



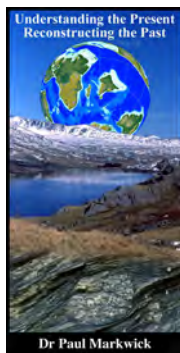
BRIDGE, University of Bristol

Professors Paul Valdes and Dan Lunt.

Website: <http://www.bristol.ac.uk/geography/research/bridge/>

E-mail: P.J.Valdes@bristol.ac.uk or D.J.Lunt@bristol.ac.uk

The Bristol group are leaders in the use of Earth system modelling for deep-time palaeoclimatology and have worked with many exploration service companies and majors.




Paul Markwick's research

Dr Paul Markwick

Website: www.palaeogeography.net

This website includes information on Paul's past and active research, including links to available publications



“It seems to me that the natural world is the greatest source of excitement; the greatest source of visual beauty; the greatest source of intellectual interest. It is the greatest source of so much in life that makes life worth living.”

Sir David Attenborough

www.knowing.earth