Paleogeography in Exploration: Lessons from the Past for the Next Generation of Explorers

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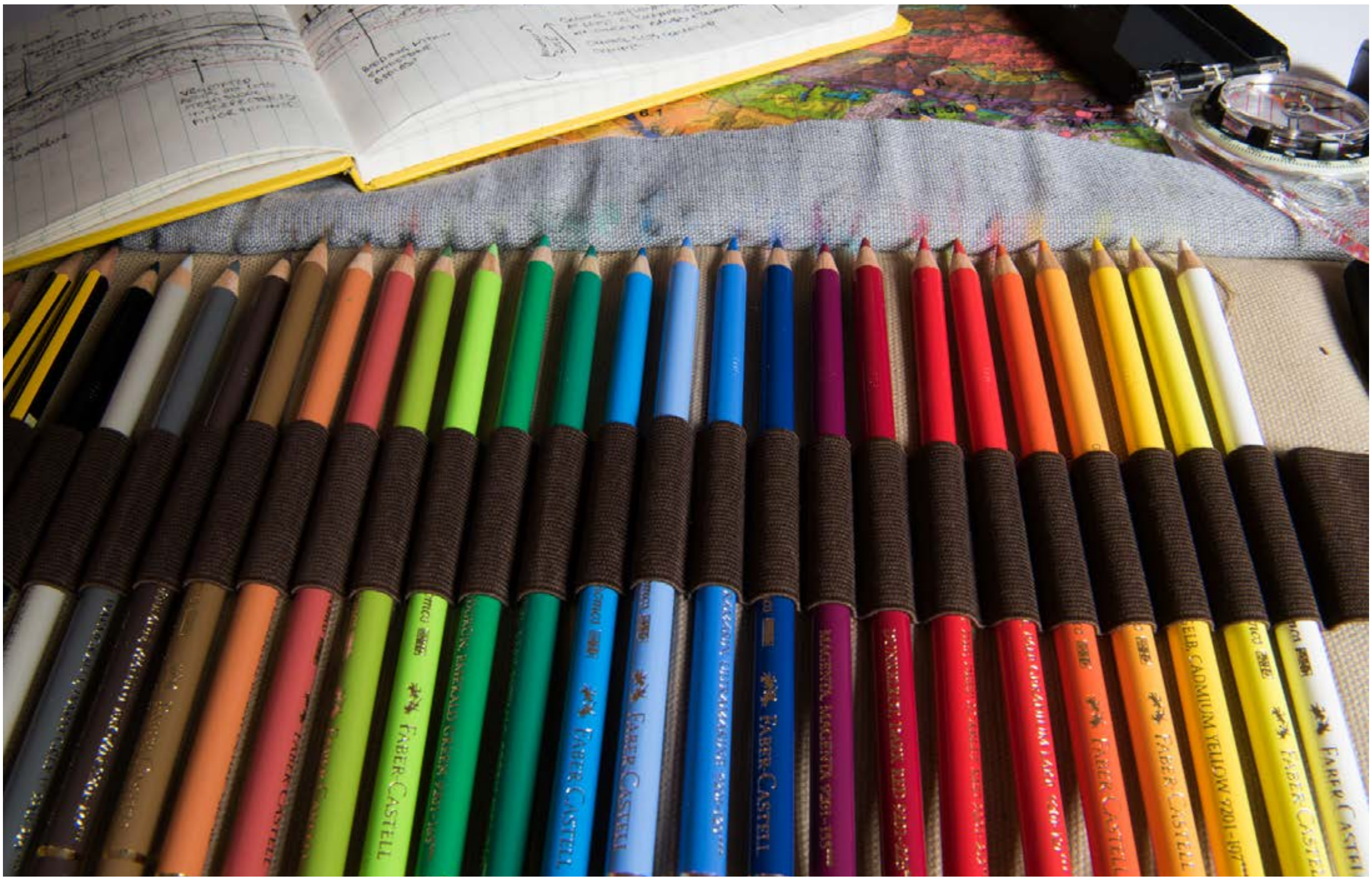

There is something about colored pencil crayons that we, as geologists, find impossible to resist. From geological maps to field sketches, to interpreting seismic on those never-ending rolls of paper taped to the longest corridor wall we can find. What more could any geologist want?

This is a source of much mirth amongst my non-geological friends and concern amongst management especially those having just purchased the latest expensive software.

Our need for powerful software, paper, and colored pencils reflects a fundamental problem in geology and especially exploration: how to manage, analyze and visualize the diversity and wealth of information required to solve exploration problems.

Figure 1. The nature of the problem: There is so much to take in. The view from the Castillo de Samitier north towards Ainsa.

There is simply so much to take in.

I am reminded of this each spring when Douglas Paton and I take the Leeds MSc "Structural Geology with Geophysics" students out to the central Pyrenees. This is an area familiar to many of you and highly recommended to those of you yet to visit.

As we look out from the Castillo de Samitier with the students, geological notebooks in hand, the challenge is always the same: how far should we, can we, 'stray' away from teaching only the structural geology?

If we only focus on the structures, we miss drawing student attention to the important interactions between deformation and the evolution of the turbidite transport pathways; something they will need to know if they ever look at deep-water West Africa or Equatorial South America. To fully understand those pathways requires knowledge of hinterland evolution and the whole source-to-sink story, a story that is heavily dictated by not only tectonic uplift, landscape dynamics, and drainage network evolution, but vegetation cover, bedrock and climate and how these impact weathering and erosion. When we talk about the contemporary climate, what climate? The 'background', 'average' (whatever that means) climate? Or a really 'bad day' in the Eocene? - the Castissent flood events of (Marzo, Nijman and Puigdefabregas, 1988; Mutti et al., 2000), and what does that do to submarine-channel architecture downstream and the interconnectivity, porosity, and permeability of potential reservoirs?...

...and suddenly we find ourselves discussing regional paleogeography, Earth System modeling, the PETM (Paleocene Eocene Thermal Maximum), the importance of extreme events, ala Derek Ager's catastrophic uniformitarianism (Ager, 1984; Ager, 1993) and plate tectonics, and we have lost most of the day and possibly our audience...

There is simply so much to take in.

So, what do we do?

Focus just on the structures? That is the MSc course title after all.

Or do we bring in the other parts of the story - the bigger picture?

The answer is, of course, the latter, and the reason is obvious.

To solve geological problems in exploration we need to consider all the components.

Explorationists, and therefore our students, need to know enough of the vocabulary of each part of the Earth system to know what questions to ask, where to look for answers, and how the components fit together to dictate source rock geometry and character, trap formation and timing, reservoir quality and all the other plethora of geological risks they will need to assess as explorationists.

Paleogeography as a solution

This is not a new problem. 200 years ago, the early geologists were faced with the same challenge, how to manage, analyze and visualize the rapidly expanding observations accumulating in the databases of the time – the world's libraries and museums.

One solution was to map out (in color of course) the accumulated knowledge on reconstructions of the past distribution of land and sea such as those of Elie de Beaumont in France and Charles Lyell in Britain (Lyell, 1837). For the first time here were representations of what the Earth looked like in the geological past. But by the 1870s it was clear that more was needed, especially following the Pennsylvanian (1859) and Ontario (1858) discoveries and the birth of oil exploration (Sorenson, 2007).

It was one of the first petroleum geologists, Thomas Sterry Hunt, who saw the value of paleogeography in exploration, and who, in 1873, first coined the term 'paleogeography' (Hunt, 1873). Hunt had worked in the Ontario discoveries (Hunt, 1862) and was one of several geologists who had simultaneously recognized the importance of anticlinal traps. It is probably this structural experience that led Hunt to realize that in order to reconstruct paleogeography (past landscapes) you first need to understand the underlying "architecture of the Earth", the crustal architecture on which the landscapes are formed.

Despite the obvious benefits of mapping structural evolution and depositional systems spatially in geological time, Hunt's ideas were not immediately utilized. It is true, that over the following three decades there were a large number of paleogeographic maps drawn. From Alfred John Jukes-Brown's Building of the British Isles (Jukes-Browne, 1888), in which he showed paleorivers, albeit only on a few maps, and somewhat schematically, to James Dana's first maps of North American paleogeography (Dana, 1863). By 1900 Albert August Cochon de Lapparent (Lapparent, 1900) felt confident enough to draw the first series of global paleogeographies, including a best guess at what was happening in the Atlantic and Pacific. But in all these cases the maps were still land-sea maps.

It was to be in Germany that geologists finally started to bring together crustal architecture and paleogeography as Hunt had originally advocated over 30 years before. From Franz Kossmat's geological history of land and sea distributions (Kossmat, 1908), albeit heavy on text and light on maps, to Theodor Ardlts 'Handbuch der Palaeogeographie' (Arldt, 1917). But, with Alfred Wegener (Wegener, 1912), the potential to put together continental drift, palaeobiogeography, crustal architecture and Earth structure within paleogeography, seemed within reach. Indeed all of these elements were discussed in a single book by Edgar Dacqué in 1915 (Dacqué, 1915). The consequence should have been the first atlases of paleogeographies on plate reconstructions. "Should have been," that is. Unfortunately, 1914-18 was a terrible time to be a German scientist trying to promote ideas to American and European audiences. And so, as a sad consequence of contemporary politics, there was no atlas, and development stopped and much of this literature was largely forgotten.

Or rather, almost forgotten.

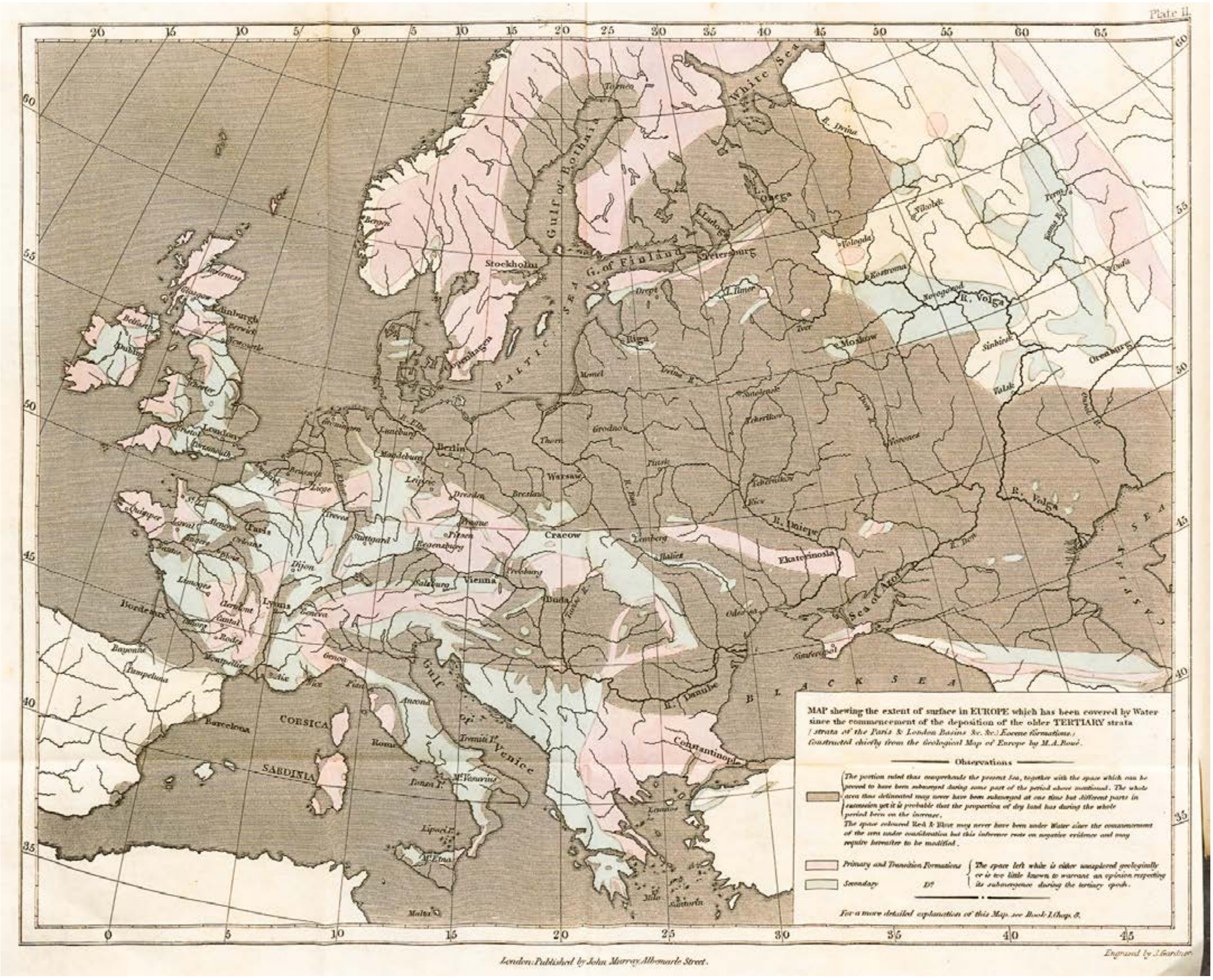

Figure 2. Lyell's 1837 land-sea map of the Tertiary of NW Europe

The Yale View of Paleogeography

When in 1904 Charles Schuchert joined the faculty at Yale as Professor of Paleontology he was faced with a problem, how to teach the breadth of geology. His solution was to use paleogeographic maps to show how the Earth had changed over time. It was to become a life-long passion.

Schuchert knew the German work (his parents were German émigrés) and he was well versed in the 19th and early 20th-century geological literature, including that of Hunt. He was also a colleague of Joseph Barrell, one of the founders of modern stratigraphy. Consequently, Schuchert not only took Hunt's workflow, but also emphasized the importance of constraining time. For Schuchert, a paleogeographic map representing a large geological interval, such as the whole Cretaceous, was meaningless, given the major changes that occurred over even the shortest of geological intervals.

The resulting paleogeographic atlas of North America, first published in 1910, comprised 60 maps at much higher detail than before and set the tone for paleogeographic research for the rest of the 20th century. Considered together with paleo-climatology and -oceanography these paleogeographies could provide information on depositional systems. When this was linked with structure (it was Schuchert who first stressed the importance of understanding deformation by palinspastically reconstructing the past geography - deformable plates to you and me) this integrated view could have huge benefits for petroleum exploration (Schuchert, 1919).

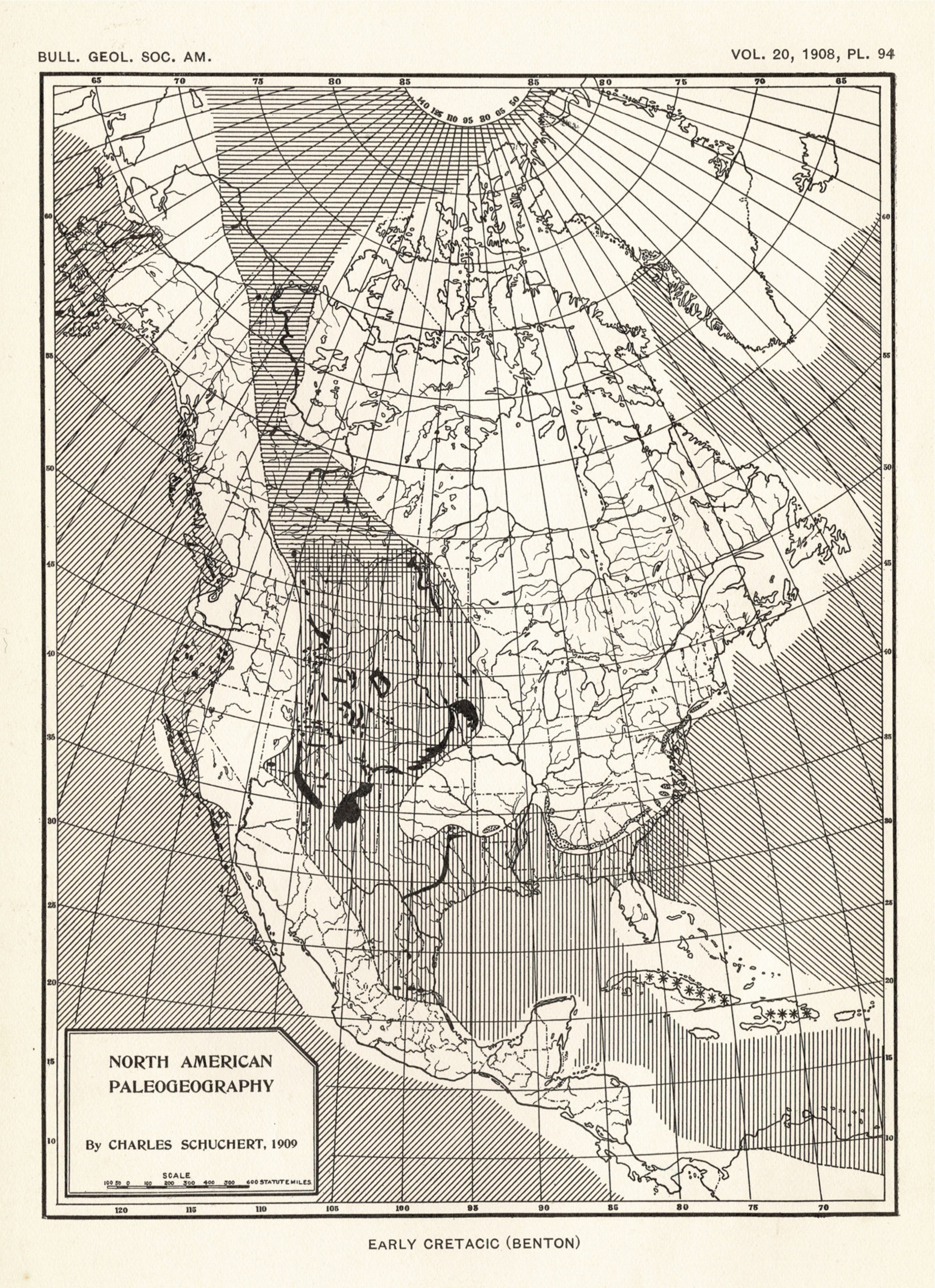

Figure 3. Charles Schuchert's paleogeographic map of the Turonian of North America

Missed Opportunities and Continued Frustration

And yet, 25 years after Schuchert's first maps, we find another petroleum geologist, John Emery Adams (1943), lamenting that paleogeography was still underutilized in the industry. Yes, there were more maps being drawn, but these were mostly local in extent, and more often than not more facies map than paleogeography. The standout exception was the work of Alexander Du Toit, another geologist familiar with the German literature and especially Wegener's work. He had put all the components together to generate the first paleogeographic reconstruction of Gondwana back in 1937 (Du Toit, 1937) having already published a restored fit for South America and Africa (Du Toit and Reed, 1927). But hey, he was in South Africa and what did he know? Quite a lot as it turned out. But in North America and Europe little was done.

Adams suggested three reasons:

1. Paleogeography maps take a long time to build
2. We rarely have the temporal resolution required
3. Paleogeography maps are never finished.

Having spent my career building paleogeographic maps, I empathize with Adams's frustration.

And yet, here was a great exploration opportunity, as Adams realized. Because if you put paleogeography together with reconstructions of climate and oceanography you could potentially predict source and reservoir facies, and what a great exploration advantage that would provide.

Plate Tectonics and the penny drops

Adams was to include some of these ideas in his eulithogeologic maps, which were very much a precursor to the play concept.

The importance of bringing paleogeography together with depositional systems, structure, paleo-climatology, and -oceanography was further developed by Marshall Kay a few years later (Kay, 1945).

But, it was to be another 30 years before the Industry realized what they had been missing when suddenly all the pieces fell into place, metaphorically and, as it happened, literally. This was the advent of plate tectonics. What the German workers had recognized and discussed at the turn of the century, now had observational support and a unifying mechanism (Heezen, 1960; Heirtzler, Pichon and Baron, 1966; Hess, 1962; Vine and Matthews, 1963; Wilson, 1963; Wilson, 1965).

Suddenly, geologists were rushing to plot their exploration data on the new plate reconstructions, together with paleo-coastlines and land-sea distributions. The result was an explosion in paleogeographic research with companies either generating their own maps internally or working with research groups to do so.

It was the late 1970s and exploration following the oil crisis of 1973 was in full swing. Great... But these were still land-sea maps (coastlines), and there was an increasing problem of how to deal with all the new data, especially now that this had to be rotated onto plate reconstructions which multiplied the volume of data created by orders of magnitude.

Paleogeography, Computers and big data in the Windy City

The Hinds Laboratory, home to the Department of the Geophysical Sciences at The University of Chicago, is one of those architectural 'wonders' that wins awards for architecture, and everyone 'wonders' why. In the 1970s and 1980s, the second floor was home to the leading figures in quantitative paleontology. Nothing short of the analysis of the entire fossil record. Big data indeed. The result was the discovery of the five great mass extinctions (Raup and Sepkoski, 1984; Sepkoski and Raup, 1985).

In another corner of the second floor, Fred Ziegler was also manipulating large datasets using early computer systems, this time to build paleogeographic maps (Ziegler et al., 1985).

Fred's background, like Schuchert's, was Paleozoic paleobiology, especially the use of fossil assemblages to reconstruct paleobathymetry. It was to be this interest that was to differentiate the Paleogeographic Atlas Project and the students it spawned. Because Fred's maps included reconstructions of paleo-bathymetry and paleo-elevation – the paleo-landscape. Schuchert had talked about this, and indeed there had been attempts to show paleolandscapes such as that of Pepper et al (1954), but those of the Atlas project were systematically constructed based on the underlying tectonics. They were also global in extent, constrained in time to stage level (probably the highest realistic resolution at a global scale), and took some account of palinspastic changes following the work of Kay (Kay, 1945) and Schuchert.

Fred's work had three immediate consequences.

First, the reconstruction of landscapes was key to understanding depositional systems because it was on these paleo-landscapes that the rock record was built. A particle sees topography, rivers, and oceans. It does not see mantle convection or hyper-extension, at least not directly. Weathering and erosion, transport, and ultimately deposition are a function of what happens at the surface.

Second, if you could model depositional systems, then you could model source, reservoir and seal facies, as Adams had suggested back in 1943. This led Judy Parrish, another of Fred's students, to take the new paleogeographies, use these as the boundary conditions for her parametric climate modeling and then to take the results to retrodict (predict past events) the distribution of ocean upwelling and through this the areas of potential organic carbon accumulation - source facies (Parrish, 1982; Parrish and Curtis, 1982).

The third consequence was data management. Underpinning the new atlases of paleogeography were some of the first computer-based geological research databases. What Fred and his students realized as they built these was the need to better 'know' the data itself, specifically its provenance and reliability. 'Big Data' can be

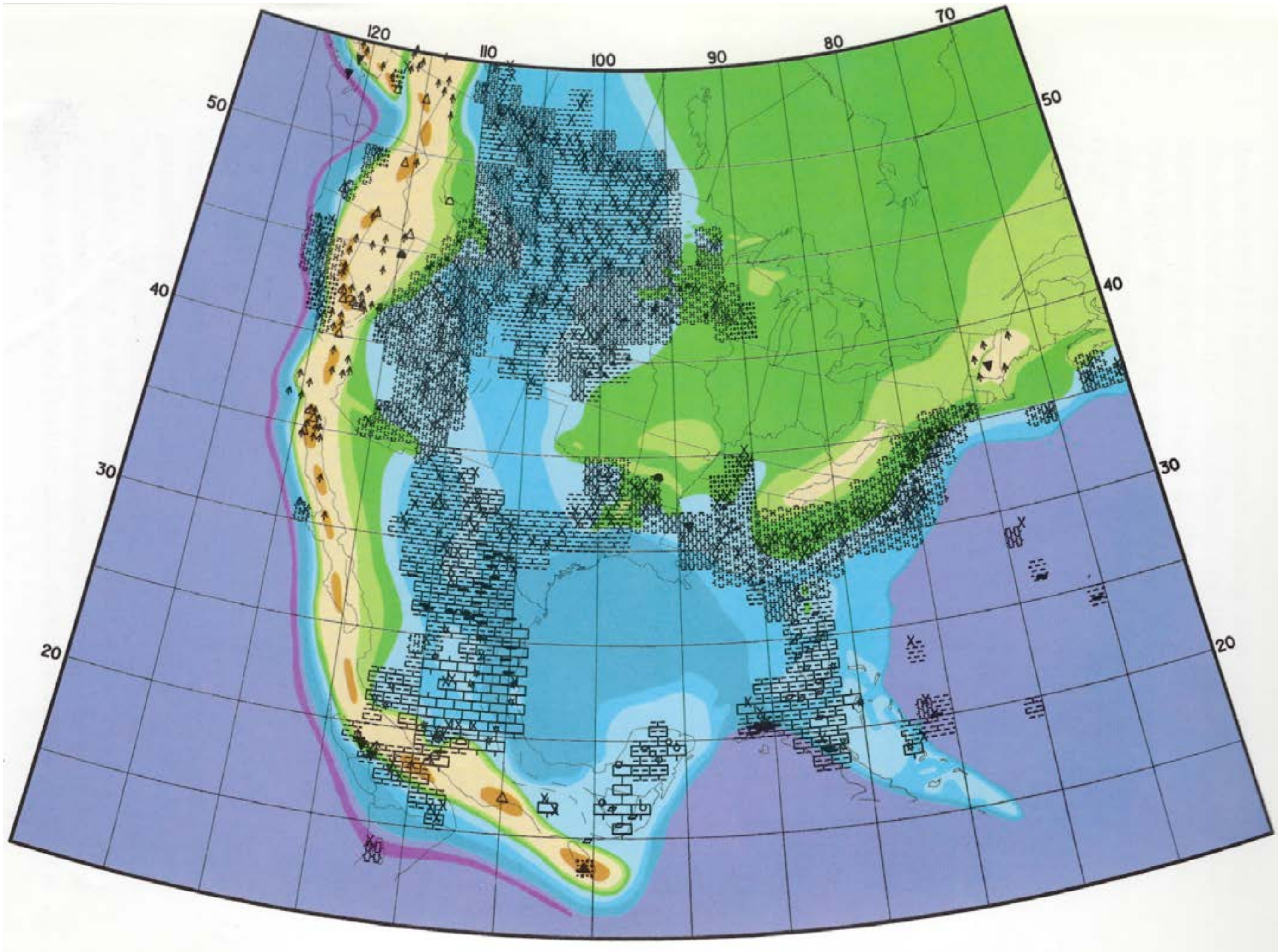

Figure 4. Fred Zieglers Cenomanian map of North America. The use of computer databases and representation of paleotopography and paleobathymetry

a very powerful resource, but only if the data is well-constrained. Unconstrained data is simply big bad data and that is worthless.

What Fred did was to find ways to qualify data quality and mapping confidence and provide an audit trail for interpretations. The confidence schemes Fred derived were simple (Ziegler et al., 1985), a categorization of 1-5 where "1" indicated caution and "5" represented the highest confidence. But that simplicity ensured clarity and, more importantly, that the databases would be populated. As Markwick and Lupia later wrote, having worked with Fred, "A database must be simple enough to be used, but comprehensive enough to be useful" (Markwick and Lupia, 2001). The Atlas Projects databases were then linked to the source data through a reference code to computerized reference database with physical copies of all papers stored alphabetically on shelves around the walls of Fred's workroom.

Where next?

Today, 50 years after plate tectonics, and 150 after Hunt, we are spoiled for choice by the plethora of maps that are readily available online such as those of Chris Scotese and the beautiful photoshopped images of Ron Blakey, which adorn many of the posters and presentations at AAPG each year.

The ideas of Hunt, Schuchert, Adams, Kay, and especially Ziegler have been developed and expanded, not least by Fred's students, including Chris Scotese, who has perhaps done more than anyone else over the last 40 years to promote paleogeography. My own small contribution has been to build on Fred's methods to improve paleogeographic boundary conditions for climate modeling (Markwick and Valdes, 2004), further developing the mapping workflow (Markwick, 2019) and then applying these methods to exploration through the development of the lithofacies prediction methodologies that ultimately became CGG Robertson' Merlin and Getech's Globe products, both of which used detailed global paleogeographies and Earth system models to retrodict depositional systems, as Adams had advocated back in the 1940s.

And yet, like Adams back in 1943, it feels that despite all this progress, for most explorationists paleogeographies are still only seen as backdrop images for presentations and montages rather than a key exploration tool. That is a great shame.

It is time to get out the colored pencils …

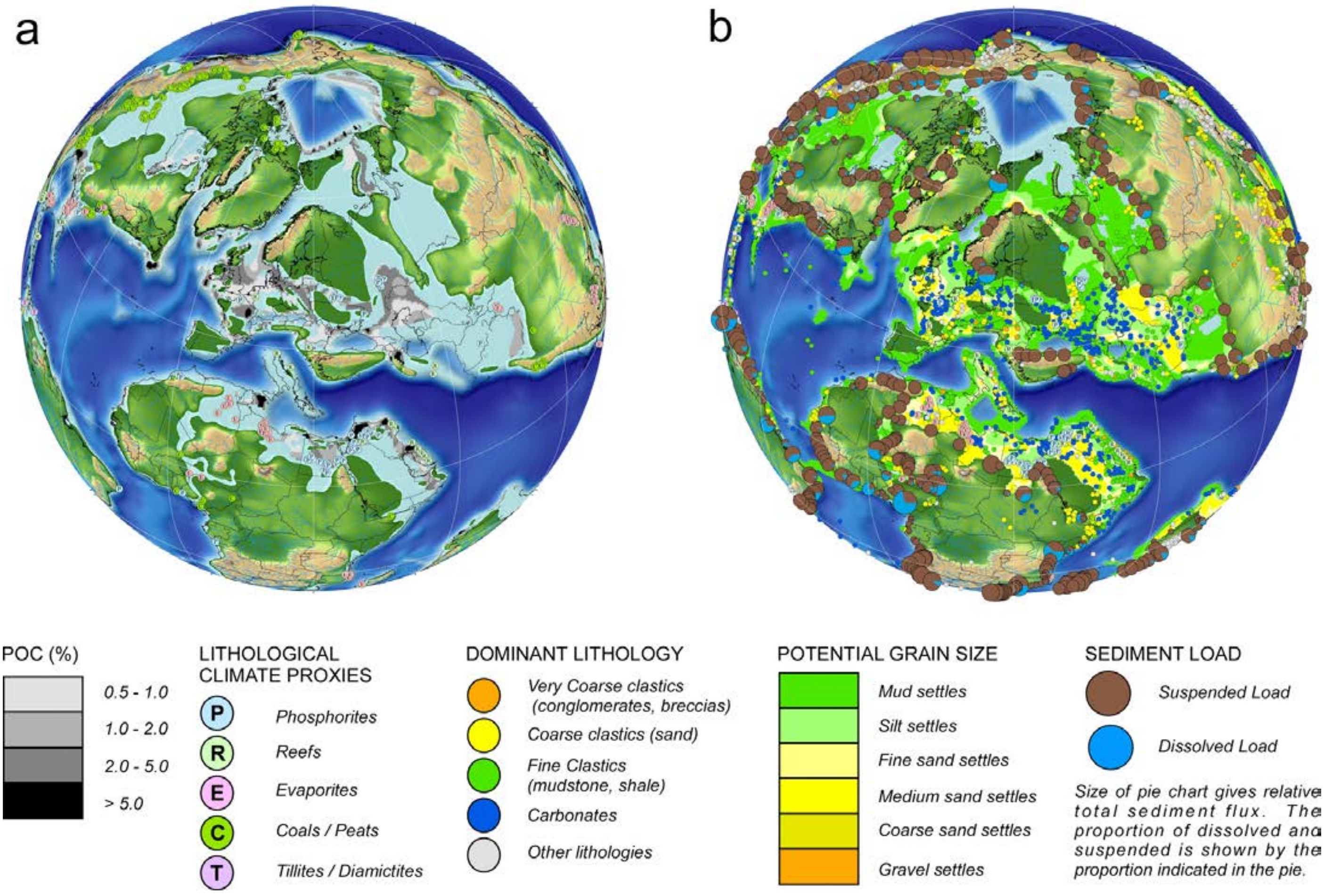

Figure 5. As Hunt, Schuchert, Adams, and Ziegler had all recognized, the greatest potential of paleogeography as an exploration tool has always been the ability to represent, analyze and understand all the components in the system. In this example to then use these to retrodict organic carbon and clastics for any time interval.

Acknowledgments

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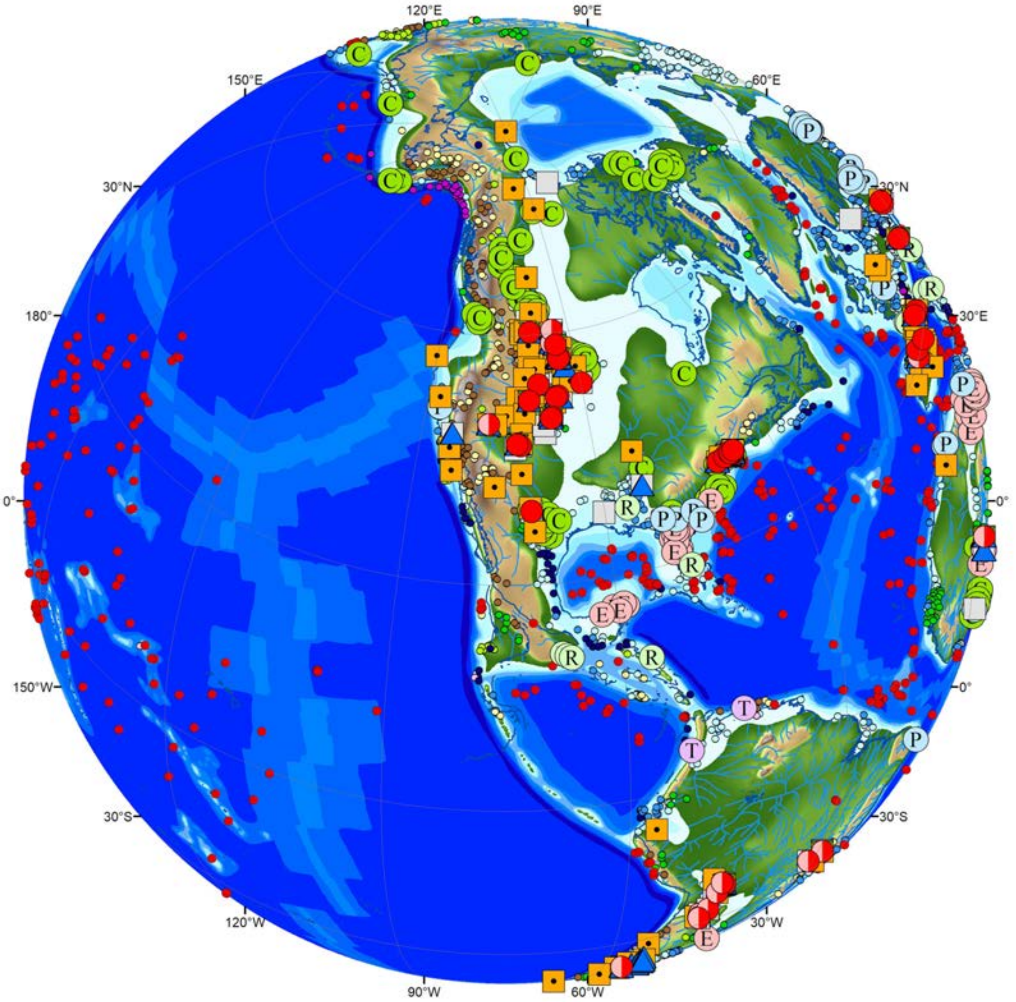

The Maastrichtian world. Based on Markwick and Valdes (2004)

About the author

Paul is 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 Ph.D. from The University of Chicago in 1996.

He worked for two years at BP's Research Centre in Sunbury-on-Thames before moving to Chicago, where Paul studied with Professor Fred Zeigler's 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 the author of over 100 published scientific papers and articles.

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