Stratigraphy in the Oil Industry

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Stratigraphy and the oil industry are intricately intertwined, and have been so ever since the early days of the hydrocarbon exploitation. Stratigraphic understanding forms the basis for all upstream activity from basin exploration through field evaluation to reservoir development and production. Whilst the subject of stratigraphy in itself is fascinating and one that even non-earth scientists will have been in contact with when out and about in mountains, on beaches or even driving through road cuts (Figure 1), it is a subject that may well have remained firmly bedded in the ivory towers of academia if it were not for the petroleum industry. The overarching need of the petroleum industry to correlate between what are essentially 1-dimensional representations of stratigraphies (well-bores) is the driving force for the science.

Because of this need for stratigraphic understanding, the oil industry has been a key driver in the development of new, faster and higher resolution methods for establishing stratigraphic correlations. This 'end user' position that the oil industry occupies for the science is repaid many times over by the sheer amount of stratigraphic information supplied during a drilling campaign; information from enormous offshore basins such as the Gulf of Mexico or the NW Shelf of Australia would have likely never have seen the light of day if not for hydrocarbon exploration. Oil companies are also the source of much funding for academic development of stratigraphic thinking. The relationship between the oil industry and the science of stratigraphy is a very healthy one and is truly symbiotic.

The aim of this article is not to review stratigraphic methods, nor to provide a history of stratigraphy in the industry; good quality reviews are available elsewhere (e.g. Boggs, 1995; Catuneanu, 2006; Slatt, 2007; Ratcliffe and Zaitlin, 2010). Instead, this article examines why stratigraphic techniques that could be considered 'academic', suddenly (at least in geological terms) have become relatively widely used tools in the oil and gas industry. We also look briefly at where the industry may be turning next to find that much sought after product:- the cost effective, time efficient chronostratigraphically-grounded multi-well correlation.

Introduction

It is well known that the science of stratigraphy, the study of layered rocks (strata) which obey Steno's Law of Superposition (younger strata overlay older strata), has been studied for centuries, dating back to the work of William Smith and Georges Cuvier around the turn of the 17th Century (Winchester, 2002). The history of stratigraphic concepts and methods are summarised in numerous places, including the SEPM Strata web-site (http://www.sepmstrata.org/). However, as emphasised by Schoch (1989) in his textbook on stratigraphy, correlation is of 'overriding importance' to stratigraphy and the science would be reduced to the description of innumerable, localised successions of strata without it; an apposite statement about stratigraphy in the oil gas industry. Characterising single well-bores is of little importance, but being able extend that characterisation and place it in a time-context over an oil field or a prospective basin is without doubt the single most important building block for all later studies in hydrocarbon exploration.

"Standard" stratigraphic methods in the industry

Standard stratigraphic characterisation and correlation techniques in the oil and gas industry have been for decades, and still remain, seismic correlation and biostratigraphy. However, both come with limitations. While seismic correlation is clearly the most effective tool for regional correlations, it can lack sufficient resolution particularly in resolving the thickness and smaller scale architecture of strata. Acquisition of good quality seismic data can be hampered in many locations and the correlation aspects of seismic stratigraphy is in itself interpretative and susceptible to spurious hypotheses. Furthermore, there is always the need for hard and fast tie points derived directly from well-bores; even seismic interpreters need those well-bore data as anchor points. Commonly, the anchor points are supplied by wireline log data, but use of wireline logs for correlations takes us into the region of lithostratigraphy vs. chronostratigraphy and their relative merits in the oil and gas industry.

Biostratigraphy, which is undoubtedly the mainstay for producing chronostratigraphically significant correlations in the oil and gas industry, also has problems as a standalone chronostratigraphic tool. For example, in many depositional settings preservation potential is poor, facies variations can negate regional chronostratigraphic correlations or vertical resolution of time-significant species may be low. High resolution biostratigraphic correlations are often based on species acmes or abundances in a well-bore. While providing invaluable stratigraphic information, this approach is essentially reflecting changes in facies, i.e. lithostratigraphy.

Lithostratigraphy vs. chronostratigraphy in the oil industry

Until the development of sequence stratigraphy, correlation fell into two categories, namely

Fig. 1. Stratigraphic sections in cliffs and road cuttings are every day scenes that often go unnoticed.

lithostratigraphic and chronostratigraphic. During the early days of oil exploration, lithostratigraphic correlations were pretty much the norm and it is clear to see why (Figure 2) - constructing a lithostratigraphic correlation is 'simple'! However, in many examples of stratigraphy the 'simplest' explanation does not give the best model for 'reality' in stratigraphic correlations, a concept neatly demonstrated in one of the earliest chemostratigraphic papers by Pearce et al. (2005). Those authors demonstrated that a 'simple' wireline log correlation of the Schooner Formation in the Schooner Field in the North Sea produced a reservoir model that did not match production data, but that a revised correlation based on the then 'new' technique of chemostratigraphy produced a far better match to production data (Figure 3).

The development of sequence stratigraphy in the latter parts of the 20th century (e.g. Vail et al., 1977; Van Wagoner et al., 1990; Posmentier and Allen, 1999) clearly, demonstrated the need for recognition of chronostratigraphically significant events in well-bores. For example, once timelines are introduced into Figure 2 and a new correlation created, it becomes apparent that not only was the simple layer-cake correlation incorrect, but it would also provide a very poor representation of actual reservoir architecture.

Clearly, chronostratigraphic correlations are important to the oil and gas industry and therefore the question of how to get at the time lines (Figure 2) when dealing primarily with cuttings samples from well-bores requires consideration. This need has driven the development of 'new' techniques in the oil and gas industry, such as chemostratigraphy, palaeomagnetism, isotope stratigraphy, cyclostratigraphy, to name a few. The word new is in quotation marks because often the techniques have been used ad hoc, but only under certain conditions do they begin the rise to common language in the oil and gas industry.

Development of a new stratigraphic method

Because of the limitations in 'traditional' stratigraphic methods and the ever increasing need for faster, more cost effective and higher resolution chronostratigraphically-based correlations in the oil exploration game, it is hardly surprising that over the past 20 years there has been a proliferation of 'new' stratigraphic methods being applied to the oil and gas industry. Techniques that use changes in inorganic (elemental) geochemistry, magnetic properties, isotopic compositions (stable and radiogenic) and detailed mineralogy (clay and heavy minerals) are all now commonly used in the oil and gas industry.

One simplistic way look at the development of a technique or method is by the number of publications in a year that include the technique. So, for example, looking at publications that use the term 'sequence stratigraphy', it is evident that in the late 1970s it was not a term greatly used in the literature and even a decade after the pioneering paper of Vail et al (1977) there were still relatively few publications. The rapid proliferation in publications and acceleration of uptake of this technique was in the 1990s, when sequence stratigraphy became a standard methodology for oil industry stratigraphic correlations.

Looking at one of the current crop of 'new' stratigraphic tools in a similar manner, chemostratigraphy (and the authors make no bones that they chose this simply because it is close to their hearts) shows that throughout the 1980s and early 1990s there were few publications that talked about chemostratigraphy and those that did were un-related to the oil industry. From 2000, however, there was a rapid rise in the number of publications, with a 7-fold increase between 2000 and 2010. A large proportion of the 2000-2010 papers were related in some way to hydrocarbon exploration.

Why did chemostratigraphy 'suddenly' develop as a tool for correlation in the oil and gas industry? No single event typically sees a stratigraphic tool become a commonly used method in the oil and gas industry, several factors need to converge. During the 1990s and the early parts of the new millennium, exploration was very active in the Barren Red Measures of the Southern North Sea, which is a complex fluvial system in which biostratigraphic recovery was poor. At the same time, research was being published (Jarvis and Jarvis, 1992) using inductively coupled

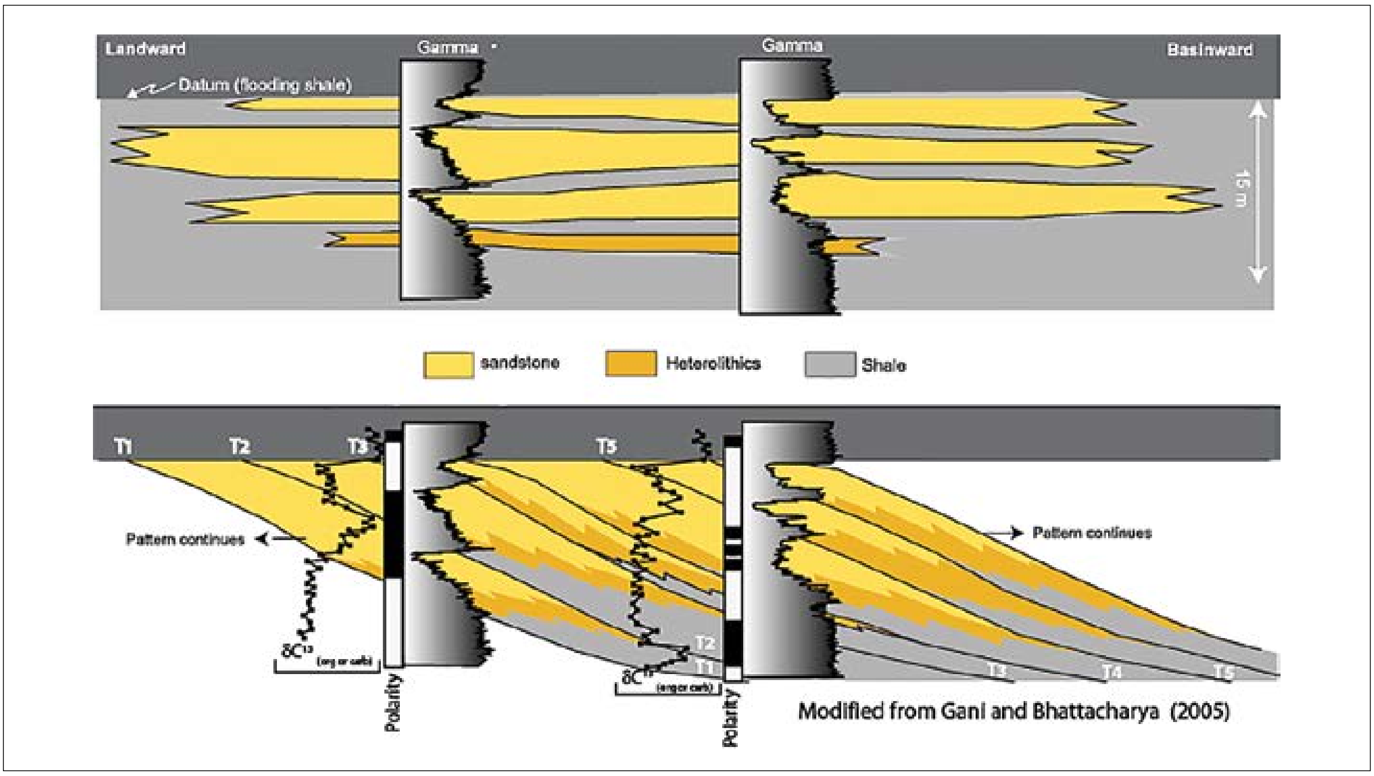

Fig. 2. A simplistic lithostratigraphic correlation that may result if only log data were available (top) and the chronstratigraphically-grounded correlation once stratigraphic techniques (in this case palaeomagnetism and d13C) are applied (bottom) provide time lines and a sequence stratigraphic approach can be taken.

plasma (ICP) technology to get a wide array of high quality elemental concentrations quickly and inexpensively from rock chips – including cuttings samples. This technological development fortuitously coincided with the demand for correlations based on novel techniques. At the present time, fuel to the development of the use of elemental data in the industry is now being provided by the rise in shale plays, which are often studied using their major and trace element chemistry (Ratcliffe et al., 2012 and references therein).

It is not always obvious if elemental chemostratigraphy can provide chronostratigraphic correlations or why it should (Ratcliffe et al., in press), but one technique that unequivocally does so is magnetostratigraphy. Magnetostratigraphic methods can be used to identify normal and reversed magnetism in sediments at the time they were deposited, thereby providing time-equivalent chrons that are unequivocally time equivalent events ('Polarity' in Figure 2). This tool has been applied in the oil and gas environment, but with varied success (e.g. Hauger and Van Veen, 1995; Turner and Bryant, 1995; Hailwood et al., 2010), primarily due to the apparent need for conventional core samples. However, even when core coverage is patchy, it is a powerful method to ascertain whether techniques such as chemostratigraphy or biostratigraphy are providing chronostratigraphic correlations. This approach was demonstrated in two papers published on the Mungaroo Formation at the APPEA 2010 50th Anniversary conference. Ratcliffe et al. (2010) defined a chemostratigraphic correlation for the Gorgon Field, which was used by Hailwood et al. (2010) to construct a composite palaeomagnetic reversal stratigraphy for the Mungaroo Formation (Figure 5). Armed with a composite for a given formation and the published global magnetic polarity timescale (GMPTS), it is possible to test the chronostratigraphic significance of more regional chemostratigraphic correlations, even when core is only available over relatively short sections, by ensuring that the correlation produced by matching normal and reversed polarities are commensurate with the proposed chemostratigraphic correlation scheme.

Stable isotope stratigraphy utilising carbon and oxygen isotopes, has been used as a stratigraphic tool for decades and increasingly $\delta^{13}C$ global excursions are being identified and tied to the Geological Time Scale (Saltzman and Thomas, 2012). Therefore, it would appear to be a stratigraphic method that is ideal for providing chronostratigraphic correlations, but has remained relatively underutilised by the oil and gas industry (Figure 6). Possibly, this has been due to the limitation of lithology; carbon and oxygen isotopes together can only be determined from carbonates, which outside a few geographic locations form a relatively minor part of the world's reserves. However, $\delta^{13}C_{org}$ can be determined from kerogen in organic mudrocks and this variable has been demonstrated to record global chronostratigraphic fluctuations. The importance of this protocol becomes apparent when it is realised that major fluctuations are to a large extent related to enhanced periods of organic matter burial, i.e. periods when high TOC shales can be expected to be found around the World, i.e. potential shale resource plays. $\delta^{13}C$ stratigraphy has the potential to provide chronostratigraphic correlations in shale plays and as such, it may well be the next big thing in hydrocarbon exploration.

Defining chronostratigraphic correlations

One major drawback with many stratigraphic techniques is their non-unique solutions. For example on Figure 2 two positive $\delta^{13}C$ excursions are depicted in the right-hand well, either of which could correlate to the single excursion in the left-hand well. Indeed if the upper excursion on the right is correlated, the lithostratigraphic correlation (upper part of Figure 2) could be interpreted to be chronostratigraphic. Similarly, matching reversal patterns, or faunal acmes or elemental concentrations are all non-unique and when used in isolation can potentially result in either incorrect or ambiguous correlations.

So, how best to define robust chronostratigraphic correlations? On Figure 2, when both rock reversal and $\delta^{13}C$ data are used, the correlation becomes unique. The younger $\delta^{13}C$ event in the right-hand well is associated with a normal chron, whereas the older $\delta^{13}C$ event is associated with a reversed chron. Therefore, by combing two non-unique solutions, a unique and chronostratigraphically correct correlation can be made.

In a nutshell, there is (at the moment) no single 'golden-spike technique' that can provide a unique and confident stratigraphic solution. However, the more stratigraphic data streams that are gathered and integrated, the greater the chances of finding

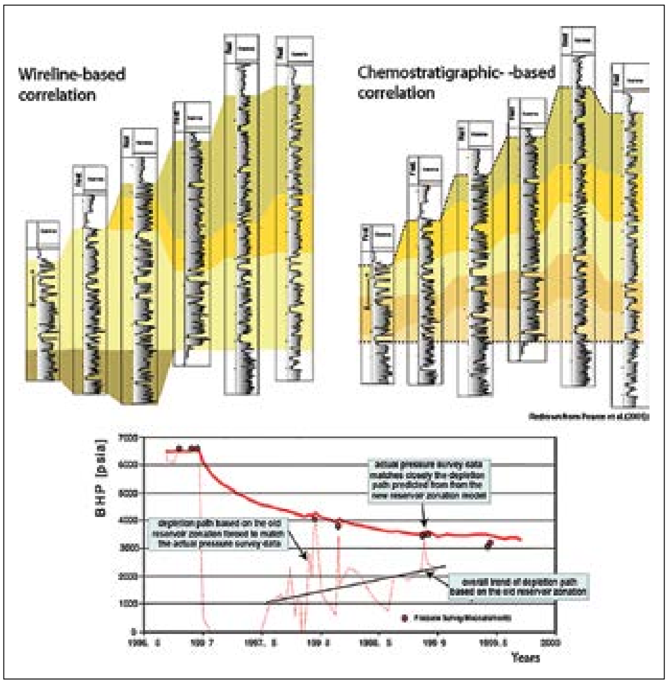

Fig. 3. Reservoir zonation prior to (left) and after (right) chemostratigraphic analysis. Lower figure shows pressure depletion in one well for entire reservoir.

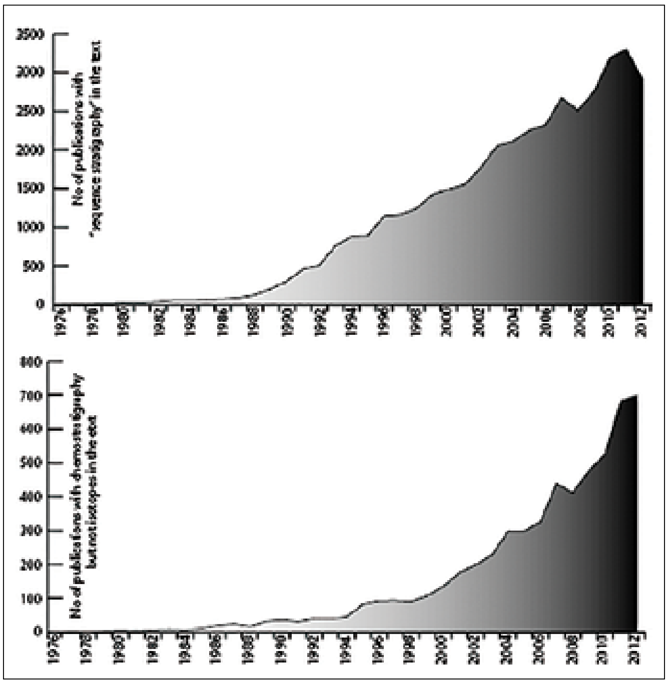

Fig. 4. Publications per year that include 'sequence stratigraphy' in the text (top) and include chemostratigraphy and petroleum (bottom) in the text. Data from Google Scholar.

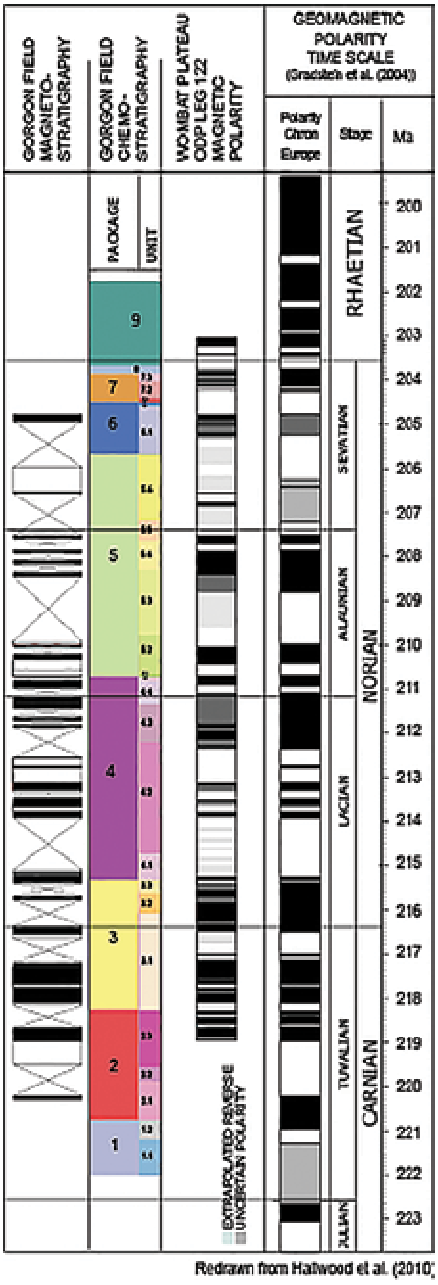

Fig. 5. Composite reversal stratigraphy in the Mungaroo Formation of the Gorgon Field achieved by integrating chemostratigraphy and palaeomagnetism data (Ratcliffe et al., 2010; Hailwood et al., 2010).

a unique and chronostratigraphically significant multi-well correlation. In other words, the oil and gas industry needs to take a holistic view of stratigraphy and move away from being reliant on any single stratigraphic technique. Being a stratigrapher, I think that makes for exciting times ahead!

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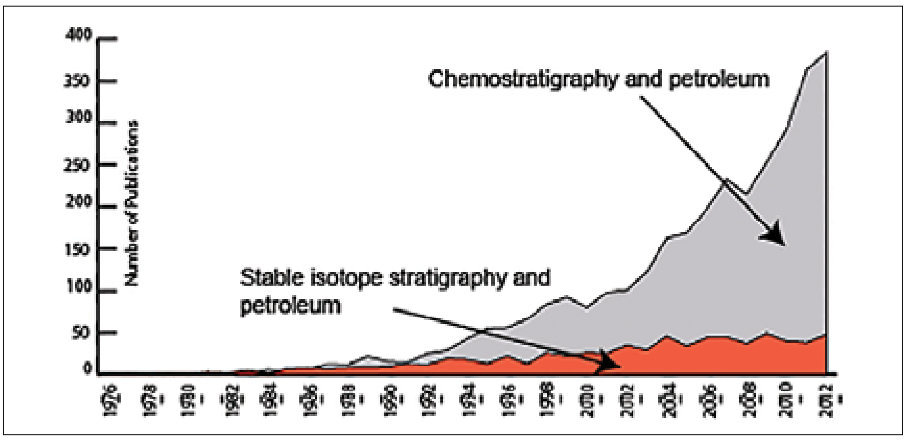

Fig. 6. Publications containing the words 'chemostratigraphy' and 'petroleum' (grey) and the words 'stable isotope stratigraphy' and 'petroleum' (red). Source – Google Scholar.