Wheeler's Confusion and the Seismic Revolution: How Geophysics Saved Stratigraphy

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ABSTRACT

The leading stratigrapher in his day was the late Harry Wheeler, who was one of the first stratigrapher's to use the term "sequence" to refer to unconformity-bounded rock units, although his concepts did not catch-on at the time because of an unwieldy insistence that all stratigraphic units be defined on the basis of arbitrary vertical cutoffs and diachronous facies boundaries. The net result was a nearly impenetrable proliferation of different names for the same genetic, correlative and descriptive lithofacies. Stratigraphy was largely phased out of University curricula and by the mid-1970's was replaced by an emphasis on process-based facies models and petrographic studies. The facies-oriented stratigraphic cross sections of the time bore little resemblance to real stratigraphic architecture and were not amenable to the analysis of reservoir-seal pairs, critical in delimiting flow units in subsurface reservoirs.

At around this time, Peter Vail, and other geophysical pioneers within the hydrocarbon industry, recognized that the stacking of offset seismic traces enhances the subtle, but nevertheless sharp and highly coherent lithological contrasts across beds. They also realized that seismic data was unable to image the arbitrary facies boundaries and imaginary arbitrary vertical cutoffs upon which so much lithostratigraphy was based. This led Peter Vail to make the revolutionary statement that "primary seismic reflections are generated by stratal surfaces which are chronostratigraphic, rather than by boundaries of arbitrarily defined lithostratigraphic units." Seismic data allowed geologists to observe unconformable lapout boundaries and to extend these into the areas where strata became conformable. This allowed a revolutionary reformatting and reevaluation of the stratigraphic record into sequences bounded by their unconformities and correlative conformities. This, in turn allowed for a vastly superior correlation of genetically related stratigraphic units and enabled a re-evaluation of the forcing parameters that control distribution of sediments both locally and globally. Reflection seismic data thus provided the key technological breakthrough that provided continuous cross sectional views of stratigraphic basin fills. This fresh approach has fundamentally revitalized the science of stratigraphy.

INTRODUCTION

Although there remains considerable debate as to the merits of sequence stratigraphy (Embry, 1995; Dickinson, 2003; Catuneanu et al, 2009; Bhattacharya, 2011), it is widely practiced, especially in the oil and gas industry (Miall, 2016). This paper addresses the question, what problem did sequence stratigraphy solve and why has it been so successful? We review lithostratigraphic practices prior to the advent of sequence stratigraphy, with an emphasis on fluvio-deltaic depositional systems, and show that they mostly failed to capture the complexity required to define reservoir-seal pairs in the oil and gas industry. Although it required the advent of seismic data before sequence concepts could be fully applied, , the proprietary nature of seismic data, a lack of rigorous scholarship in early publications, and an emphasis on eustasy versus tectonics, led to widespread skepticism and even derision by much of the academic community.

LITHOSTRATIGRAPHY IN CRISIS

The seeds of sequence stratigraphy, are as old as the science of stratigraphy itself (e.g. Chamberlain, 1889, 1909, Grabau, 1906, Blackwelder, 1909, and Barrell, 1912, 1917; see also review by Nystuen, 1998 and recent reviews by Miall, 2016). Sloss et al. (1949) introduced the preliminary concept of sequences as interregional rock units comprising assemblages of Formations and Groups bounded by objective recognizable horizons (commonly stratigraphic discontinuities) but without specific time significance. Harry Wheeler (1958 used the term "sequence" to formally describe unconformitybounded stratigraphic units however his sequences were defined by **arbitrary vertical cutoffs** at the point where the unconformity passed laterally into a correlative conformity. The adherence to the use of arbitrary cutoffs resulted in a confusing proliferation of sequences. Sloss (1963) defined the now well known continent-wide, unconformity-bounded tectono-stratigraphic units across North American, although his ideas were not fully appreciated when first published (Sloss, 1988, Van Wagoner et al., 1990).

What is sometimes forgotten, is that many formal lithostratigraphic units, were decidedly not chronostratigraphic. Lateral "contacts" between many formations were routinely defined by arbitrary vertical cutoffs, especially where inter-fingering occurred (Wheeler and Mallory, 1953; 1956) (Fig. 1a). The horizontal boundaries that defined the base and top of formations and members, in measured sections were also commonly arbitrarily defined, especially where contacts were gradational. The very concept of lithofacies was also fundamentally different in Wheeler's day (Fig. 1b), and was defined by the ratio of lithologies (e.g., sandstone, shale, limestone etc.) within gross stratigraphic units, that might include several formations, versus the environmental facies concept as practiced today.

The Blackhawk Mancos Dilemma

The problem of defining stratigraphic boundaries was a particularly acute problem in clastic wedges, such as are common in the Mesozoic successions of the Western Interior Seaway of North America (e.g. Fig. 2). One of the most important examples in sequence stratigraphy, involves the transition of the broadly fluvio-deltaic, coal-bearing Blackhawk Formation into the coeval marine Mancos Shale Formation in the Upper Cretaceous Book Cliffs successions of Utah (Fig. 2). The nature of this pinch-out involves several sandstone tongues (Young, 1955, 1957). In lithostratigraphic terms, where the sandstone members gradually overlie a shale, the base of the sandstone member is typically arbitrarily defined by the first thick sandstone above the underlying shale (e.g. Fig. 2A). Of course with these types of gradational interbedded facies, such as where the deltaic and shoreface sandstones overly prodelta and shelf shales, a thick sandstone bed in one locale might pass laterally into a much thinner siltier bed in a more distal position, and the formation contact would thus be arbitrarily picked at a higher and younger sandstone bed in a more distal location, resulting in a diachronous lithostratigraphic



Figure 1: Lithostratigraphic and facies concepts of Wheeler and Mallory (1956). A. Arbitrary vertical cutoffs are used to define lateral "contacts" between formations. The boundary between the Honaker and Maryville formations are defined by the pinchout of the Rogersville Shale Formation. B. Lithofacies are broadly defined by the average gross lithology across several formations and are also defined by arbitrary vertical boundaries. C. Broadly conformable lithostromes and highly diachronous lithosomes roughly correspond to modern usage of the lithofacies concept.

boundary (Fig. 2). Another problem is the separation of delta front sandstones and their co-eval, genetically related prodelta mudstones, into different lithostratigraphic units.

Young (1955, 1957), influenced by Krumbein and Sloss (1951) was one of the first to recognize the cyclic nature of this transition and shows a remarkably modern understanding of the stratigraphic relationships between the Blackhawk and Mancos formations (Fig. 2B). Despite Young's sophisticated stratigraphy, later work emphasized generalized environmental lithofacies depictions that failed to depict the interfingering nature of the various Blackhawk tongues (e.g. Van De Graaff, 1972; Fig. 2B).

Wheeler and Mallory (1953) specifically addressed the lithostratigraphic subdivision of the Book Cliffs section but suggested a confusing nomenclatural scheme, using arbitrary vertical cutoffs (Fig. 2A). Where sandstone tongues of the

Blackhawk extended into the Mancos Shale Formation, these sandstone tongues were assigned as members of the Blackhawk Formation. Correspondingly, the overlying shale tongue was also included as a member of the Blackhawk Formation, and was thus not treated as an extension of the Mancos Shale (Fig. 2A). The distal boundaries of these overlying "Blackhawk" shale members were defined by an arbitrary vertical line, drawn up from the tip of the pinchout of the underlying sandstone member. The net result was that the same rocks, with the same lithofacies, of the same biostratigraphic age were arbitrarily separated into different formations according to the pinch-out of different layers, stratigraphically above or below the particular stratigraphic unit of interest. Extended mapping of the overlying or underlying strata, or more detailed measured sections, that might have shown these strata to pinch-out farther into the basin than previously identified, could easily require the arbitrary vertical boundaries to shift, resulting in the names and positions of mapped formations or members to change. This problem instigated significant debate among stratigraphers, some of whom objected that these arbitrarily defined formations or members could not be distinguished in the field either biostratigraphically, or on the basis of lithology. Young (1955, 1957) pointed out the "cyclothemic" nature of these successions and maintained that the tongues of shale be included as part of the Mancos, rather than arbitrarily assigned to the Blackhawk Formation (Fig. 2B).

The End of Stratigraphy

The net result of the Wheeler and Mallory (1953) approach was a proliferation of different names for the same rocks that was ultimately confusing to all except those geologists deeply concerned with the rules of stratigraphic nomenclature. Anecdotal evidence suggests that many stratigraphy courses in the late 50's and early 60's focused on memorizing type sections, type fossils, and local stratigraphic schemes, versus understanding stratigraphic and



Figure 2: A. Lithostratigraphic subdivision of the Campanian Mesaverde Group strata of the Book Cliffs, Utab, using arbitrary cutoffs. Shale tongues are assigned to the Blackhawk
Formation, rather than the Mancos Formation. From Wheeler and Mallory (1953).
B. Dip-oriented cross section of the Campanian Book Cliffs strata showing clear interfingering of Blackhawk Formation sandstones with marine shales of the Mancos Formation. From Young (1955, 1957). C. Later depiction of the Book Cliffs from Van der Graaff (1972) de-emphasizes the cyclic nature of the Blackhawk Members. Zigzag, "shazam" lines are drawn, separating the fluvial Castlegate sandstones from the delta plain, shoreline, and delta-front lithofacies. This is a classic environmental lithofacies stratigraphic cross section, popular in the 70's and 80's. Despite the popularity of such depictions, the cross section ignores key surfaces, critical to define reservoirseal pairs, and provides no information about stratal geometries or lapout relationships.

sedimentological processes. In contempt, famed petrologist, Paul Krynine, was alleged to have declared that *"Stratigraphy is the complete triumph of* *terminology over facts and common sense.*" Whether or not the account of Krynine is apocryphal, the reality was that by the mid-70's, (around the time that the



Figure 3: Seismic line and facies interpretation shows that the clinoform seismic reflections cut obliquely across the lithostratigraphic base of defined formations. However, the tops of the formations are flooding surfaces that coincide and are concordant with the seismic reflections. Vail et al. (1977) used these observations to infer that the seismic reflections more closely approximated time surfaces, rather than arbitrary lithostratigraphic boundaries.

senior author was an undergraduate) stratigraphy was moribund and the emphasis in sedimentary geology courses became focused almost exclusively on process sedimentology, facies analysis, and petrographic description, versus stratigraphy.

Stratigraphic cross sections from the 70's and 80's are astoundingly "lithostratigraphic" and fail to capture the inter-tonguing and cyclic aspect of deposition (Fig. 2C), relying, rather, on gradational and arbitrarily defined "environmental" lithofacies boundaries, depicted as zigzagging "shazam" lines, as the basis for stratigraphic correlation, more akin to the "lithosomes" of Wheeler and Mallory (1956)(Fig. 1C).

In the 70's, a group of more forward thinking stratigraphers presented early versions of stratigraphic schemes that resembled modern sequence stratigraphy, such as the genetic increments of strata (GIS) of Busch (1971, 1974), the "depositional episodes" of Frazier (1974), and the correlations shown by Asquith (1970, 1974). These geologists ultimately influenced modern sequence stratigraphy (e.g. Galloway, 1989) as well as many in the petroleum business, but Busch was a consulting petroleum geologist in Tulsa, and Frazier worked at Exxon in Houston. Their work was largely ignored by the academic community and, in fact, Busch (1974), perhaps somewhat cynically, notes: "Very few textbook references appear in the bibliography because most of the ideas expressed here do not appear in such texts. "Busch did not think that standard academic textbooks of his day reflected state-of-the art stratigraphy. In defense of the academe, lack of access to proprietary core, well log, and of course seismic data, made them naturally cynical about any science based on data that could not be published, and this same concern, is still expressed in academic criticism of the modern

The **Sedimentary** Record

formulation of sequence stratigraphy (e.g. Walker, 1990; Miall, 1991; Miall and Miall, 2001; Dickinson, 2003).

At the same time, many academic sedimentologists were focused on extremely detailed analysis of 1D vertical sections, using the newly discovered sedimentary structures that appeared to hold the key to process-based paleoenvironmental facies analysis (e.g. Middleton, 1965; Reading, 1978; Walker, 1979), which in effect served as a new paradigm. Petrographic studies provided details on composition and diagenesis that were enormously useful for provenance analysis linked to the new theory of plate tectonics (e.g. Dickinson, 1970; Folk, 1974; Dickinson and Suczek, 1979). The outdated gross lithofacies concepts of Wheeler and Mallory (1956) were abandoned in favor of much more detailed approaches. In the process, stratigraphy appeared to have been forgotten and largely disappeared in the academe as reflected in the scarce reference to stratigraphy in the undergraduate textbooks that used by the senior author at that time (e.g., Blatt, Middleton and Murray, 1972, 1980).

HOW GEOPHYSICS SAVED STRATIGRAPHY

The abandonment and then resurrection of sequence stratigraphy invites the question, what was it that seismic data imaged that so many academic petrographers, lithostratigraphers and facies analysts failed to identify?

Following graduation in 1956 from Northwestern University, and heavily influenced by Bill Krumbein and Larry Sloss, Peter Vail eventually joined Exxon corporation (Mitchum, 1985). Vail recognized that Wheeler's timestratigraphic analytical approach and Sloss's sequence concepts, were superbly applicable to the analysis of proprietary seismic data (Vail et al., 1977). The basic concept that the stratigraphic record is built by a succession of beds, where the discontinuities are defined by lapout, as suggested by Grabau (1906), was readily applied to the interpretation of seismic data (Fig. 3). A primary assumption



Figure 4: Sequence stratigraphic interpretation of the Campanian Mesaverde Group in the Book Cliffs, Utah (from Hampson, 2005). The strata are subdivided into sequence sets, sequences and parasequences. Parasequences include both sandstone and marine shale facies. The emphasis is on correlative key surfaces, rather than diachronous lithofacies. Compare with figure 2.

was that seismic reflections are chronostratigraphic (Vail et al., 1977), an idea that has been heavily criticized (e.g. Dickinson, 2003).

An unique aspect of seismic data is that seismic lines are constructed by stacking of separate seismic traces of the same point in space taken at different angles. This stacking creates the multifold data that fundamentally enhances subtle but coherent stratigraphic boundaries, such as the contacts and surfaces between beds, bedsets, and parasequences, versus the arbitrary lithostratigraphic boundaries, as clearly stated by. "Primary seismic reflections are generated by stratal surfaces which are chronostratigraphic, rather than by boundaries of arbitrarily defined lithostratigraphic units", debunking much of the previous few decades of lithostratigraphic theory, Vail et al. (1977, 1987, Fig. 3)

Vail et al. (1977) originally defined lowstand and highstand sequences, which later became systems tract. The lowstand sequence was defined as a seismic package that is thickest in the basin and onlaps against the slope and lower part of the shelf. Highstand sequences are widespread on the shelf, thickest near the shelf edge, and prograde and downlap basinward. From the beginning, these terms referred to position on the shelf (geometry) not sea level.

Concomitant with the seismic analytic approach was the development of the hypothesis that seismic sequences were largely eustatic in origin (Vail et al., 1977; Haq et al., 1987). Thus the concept that global sea level changes largely controlled sequence development also became entrenched, albeit also heavily criticized (Miall and Miall, 2001).

Despite the criticism, recognition of these cyclic patterns were of prime importance to the oil and gas industry, as these cyclic units represent the basic building blocks in the deposition of reservoir-seal pairs (i.e. sands versus shales) and were thus critical in subsurface correlation and mapping (Van Wagoner, 1995). As discussed above, lithostratigraphic approaches, especially those schemes that used arbitrary cutoffs and gradational lithofacies boundaries as the prime means of subdividing stratigraphic successions (e.g., Fig 1 and 2C), were clearly of little value in defining basic reservoir compartments, as had long been understood by Busch (1971, 1974) and others.

From Seismic to Sequence Stratigraphy: A New Paradigm

The seismic revolution caused other researcher's at Exxon to completely reevaluate their approach to stratigraphy and correlation, especially as applied to higher resolution well log, core and outcrop data (e.g., Van Wagoner et al., 1990). They incorporated the ideas of Campbell (1967) Frazier (1974) and Busch (1971, 1974), but also incorporated process-based facies models as well as geomorphological insights (e.g. Posamentier and Vail, 1988; Posamentier et al., 1988;). Jervey, 1988 explained seismically resolvable stratal patterns by new accommodation models that quickly led to the realization that the sequence could be subdivided into smaller stratal units, ultimately called "systems tracts" (after Brown and Fisher, 1977).

The new formulation of sequence stratigraphy emphasized identification and correlation of bounding discontinuities using facies analysis. by identifying surfaces across which there was an abrupt change in depositional regime or overall facies trends, such as the flooding surfaces marked by marine shales sharply capping shallow marine upward coarsening facies successions (Fig. 4), or the observation of coarsegrained fluvial deposits erosively overlying more distal marine facies that typify sequence boundaries (Wilgus et al., 1988; Van Wagoner et al., 1990, Bhattacharya, 1993).

Van Wagoner (1995b), and many others (e.g., Kamola, and Van Wagoner, 1995; Pattison, 1995; O'Byrne and Flint, 1995, Taylor and Lovell, 1995; Hampson, 2000; Hampson and Howell, 2005; Pattison, 2010; Hampson et al., 2014) eventually presented a fully revised sequence stratigraphic interpretation of the Book Cliffs section referred to above, which solved the problem of different lithofacies of the same genetic unit being separated into different lithostratigraphic units (Fig. 4). Sequence stratigraphy (and allostratigraphy) allowed different lithofacies to be grouped into the same depositional system or systems tract, and used key bounding surfaces as the means

of separating stratigraphic units, rather than gradational, arbitrarily-defined facies boundaries.

Evolution of Sequence Stratigraphy

The new version of sequence stratigraphy divide sequences into component "parasequences" and "systems tracts" on the basis of key bounding surfaces and specific facies stacking patterns. However, many of the terms used to designate systems tracts and key surfaces belied the underlying assumption that eustasy, or at least relative sea level change, was the dominant control (e.g. lowstand, forced regressive, highstand, and transgressive systems tracts; flooding surfaces and transgressive surfaces). In the early publications (Vail et al., 1977) the sequence boundary was identified by onlap and downlap surfaces. The maximum flooding surface was identified as a downlap surface and based in part on observation of biostratigraphic condensed zones (Vail et al., 1984; Van Wagoner et al. 1988).

At the same time that one set of definitions was being proposed based on geometries, another school was developing in which systems tracts were related to sea level cycles. Mitchum (1977) defined the highstand as an interval of time during a cycle of relative change in sea level when sea level is above the shelf edge. Van Wagoner et al., (1987), in contrast, defined the highstand systems tract according to its geometric characteristics as commonly widespread on the shelf and characterized by aggradational to progradation vertical stacking of shoreline systems (parasequences). Van Wagoner (1987) also defined a Transgressive Systems Tract as characterized by one or more retrogradational parasequence sets, marked at the base by the transgressive surface and at the top by the downlap surface (maximum flooding surface). Systems tracts nomenclature thus represented confusing, non-parallel terms. Highstand and lowstand systems tracts referred to position on the shelf, but could also be construed as reflecting periods of sea-level stasis, the

transgressive systems tract specifically implies a shift in position of the shoreline, but a parallel construction, such as "midstand" was never considered

Van Wagoner (1995a), recognizing this dilemma, suggested that there were two emerging sequence stratigraphic paradigms, reflected in the confusing systems tract terminology, one based on designation of stratigraphic units based on their inferred mode of origin, which he called the "sealevel paradigm", versus an analytical approach based largely on observed facies stacking patterns and geometric relationships, which he termed the "rock paradigm". Helland-Hansen and Gjelberg (1994) recognized that facies stacking of shallow marine systems is fundamentally controlled by sea-level changes (be they eustatic or relative), and developed the useful concept of shoreline trajectory (Helland-Hansen and Martinsen, 1996). Neal and Abreu (2009) recently introduced the concept of scale-independent accommodation successions that also emphasizes stacking patterns of clinoforms in seismic data, extending and generalizing the concept of parasequence stacking patterns to all scales, and retreating from an emphasis on the sea-level dominated terminology of systems tracts.

Facies models concepts, although novel in the early 70's, also became less static and were re-formulated in the context of allogenic sea-level change (e.g. Walker and James, 1992), versus the largely autogenic concepts that prevailed in the initial formulation (Reading, 1978; Walker, 1979).

Ongoing Concerns in Sequence Stratigraphy

Some of the ongoing debates in sequence stratigraphy remain focused on whether the larger-scale geometric arrangements of strata are more or less important than the vertical facies trends (Embry, 2002). Fundamentally, in seismic data, lapout relationships are directly observed and geometric considerations are paramount, although lithologies must be interpreted and vertical resolution remains a problem. However, in well log cross sections,

or in other sparse data sets, such as isolated outcrop sections (e.g. stream cuts or roadcuts), although 1D vertical resolution is greatly improved, lapout relationships are rarely observed, and must be interpolated between 1D sections or wells (Bhattacharya, 2011). As a consequence, the conceptual framework of the interpreter will be key in making the correct correlations (e.g. Gani and Bhattacharya, 2005; Catuneanu et al., 2009). Facies considerations may help drive the correlation using sparse data. For example, measured sections may show several upward-coarsening parasequences that become thinner and muddier in more distal sections. The geologist may have to make an *a priori* assumption about whether strata form clinoforms, and at what angle, or remain parallel? Assumptions must commonly be made about how units are likely to correlate (i.e. dipping or layer-cake) as opposed to seismic data, where the geometries are observed directly. Because of the level of interpolation and interpretation involved, the practice of sequence stratigraphy using well log, core, and outcrop data may require model-driven *a priori* assumptions to be made. In addition, newer concerns are being raised regarding the time-stratigraphic relationships of key sequence stratigraphic surfaces (e.g., Strong and Paola, 2009; Bhattacharya, 2011, Holbrook and Bhattacharya, 2012; Blum et al., 2013).

Despite these provisos, it is clear that the application of older stratigraphic concepts to seismic data revolutionized and revitalized stratigraphy. The proliferation of seismic data in the late 70's demonstrated emphatically, that basin fill stratigraphic patterns could not be understood using the prevailing lithofacies concepts. The fact that lithofacies cross sections of the time (e.g. Figs. 1 and 2) failed to reproduce the kinds of stratal geometries seen in seismic data (Fig. 3) demonstrated the failure of the lithofacies approach in stratigraphic analysis. In all cases, it is key to recognize that sequence stratigraphy, at its heart, is the reordering, correlation, and sometimes renaming of stratigraphic units on the

basis of bounding discontinuities and their correlative surfaces, as opposed the arbitrary lithofacies—oriented approach using broad facies "shazams" or arbitrary cutoffs, such as was used in traditional lithostratigraphy. Without using a sequence stratigraphic approach, regardless of which school of sequence stratigraphy you prefer, it will be difficult to define reservoir-seal pairs and make accurate predictions about the updip and downdip limits of strata.

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STEPPE NEWS

STEPPE welcomes 2016 Fellow, Rachel Salter, from North Dakota State University. She is currently pursuing a dual doctoral degree at North Dakota State University in Evolutionary Biology and STEM Education. She will work to further develop education and outreach programs and materials focused on early career professionals, K-16 students and teachers. Keep your eyes open for her blog posts, etc. The STEPPE Fellowship program is generously supported by SEPM, The Paleontological Society, and the Geological Society of America.