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[EA]The Difficulty in the "Transgressive Seas" Explanation for Organically Enriched Rocks Is a Fundamental Problem with Applied Sequence Analysis, and it Is the Misunderstanding of the "Condensed Section"*

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Abstract

We are now aware that organically enriched rocks are formed during OAEs by large scale volcaniclastic deposition. The Cretaceous GOM Shelf Margin was overwhelmed by clastic deposition four times during OAEs and interpreted as evidence for sea level rise (Phelps, 2012). In the GOM, "Fifteen separate ashes {from the Yellowstone Plateau from 0.6 to 12 mya – DMP} have been documented. The paleo-ages of these ash beds are correlative with maximum flooding surfaces on sea-level curves." (Hanan et al, 1988). Geoscience has been interpreting altered ash deposition as evidence for sea level rise. Howell et al. (2018) returned to a "birthplace" of sequence stratigraphy and could not find evidence of sea level fall. "These observations indicate that a key aspect of the sequence stratigraphic model is not applicable in outcrops widely considered to be one of the type areas for sequence stratigraphic teaching and research." Sercombe (2009) observed high gamma ray 'hot' Eocene shales in southern deepwater GOM wells. They were deposited in water depths greater than 20,000' sstvd. "This forces the questioning of the association of 'hot' shales and maximum flooding surfaces." The condensed section and its association with the Maximum Flooding Surface has been misinterpreted. The description of a condensed section (see Loutit et al., 1988) is actually one of a volcanic ash fall event: (1) ash fall preserves a diverse fossil assemblage, (2) ash fall extends from offshore to onshore, (3) hiatuses associated with ash fall are documented in the Greenhorn Cyclothem, (4) hardgrounds are formed during the alteration of ash, (5) the authigenic minerals siderite and phosphorite include Fe and P, elements that Lee (2018) determined to be leached from ash shortly after deposition, (6) iridium anomalies are observed from Eocene explosive volcanism and, (7) bentonites are found in condensed sections. Condensed sections are those times when ash fall episodically dominates other sedimentary processes, not times when other sedimentation is redirected by sea level change. The condensed section does not imply a sea level high stand and has been misunderstood since it was described.

Introduction

When geoscientists encounter finer grained sediments in a stratigraphic section, they traditionally interpret those fine-grained sediments to be evidence of a low energy sediment distributary system. Commonly, that leads to an interpretation of a deeper water, lower energy, depositional environment. An observed transition from a higher energy regime to this lower energy regime is then interpreted to be a sea level transgression. But more often than not, when based on grain size of the sediment or on a transition from carbonate to clastic sedimentation, the interpretation of sea level transgression is not correct. These transitions at sedimentary basin-scale more often represent a series of volcanic ash fall events and not a sea level change event.

One source of the interpretation problem is with the "condensed section", which has been misinterpreted since its definition. All of the characteristics defining a condensed section would be expected from one or, more likely, a series of volcanic ash fall events. Eolian delivery of fine sediments can episodically overwhelm and dominate the extant distributary system energy regime.

Methods

A search of the published literature has identified data that supports the thesis that sizable, largely unrecognized volumes of volcanic ash has fallen episodically in earth's history. Part of this new paradigm is that volcanic ash is the driver for organically-enriched rock preservation (Zimmerle, 1985; Parker, 2017; Lee, et al., 2018; others). As part of the testing of the new paradigm, another look is needed at the condensed section, that time in sequence deposition that is currently believed to be causally related to organically-enriched rock formation and preservation. More specifically, is the condensed section a product of sea-level change, or is it evidence of a time when volcanic ash fall overwhelmed the existing depositional system?

Results

During the Cretaceous, the carbonate Commanchean Shelf Margin of the Gulf of Mexico was drowned in clastic deposition four times during Oceanic Anoxic Events (Phelps, 2012). These clastic drownings have been interpreted as evidence for transgressive seas. They correspond with the formation of organically enriched rocks. But we are now aware that organically enriched rocks are formed globally during OAEs by large scale volcaniclastic deposition, some associated with LIP emplacement, some by coincident arc volcanism. Should we not expect the Cretaceous shelf "drownings" to be evidence of large-scale ash-fall and the re-deposition of that ash fall? Are we misinterpreting large-scale deposition of altered volcanic tephra to be evidence of sea level transgression?

A problem with sea level change descriptions and their recognition becomes apparent in a study by Hanan et al., (1998). They analyzed Pb-Isotope signatures of volcanic glass shards from deepwater Gulf of Mexico (GOM) ash beds and state, "Fifteen separate ashes {from the Yellowstone Plateau from 0.6 to 12 mya – DMP} have been documented in our preliminary survey. We have determined the paleontological ages of these GOM ashes with industry micro-paleo reports. The paleo-ages of these ash beds appear to be correlative with the ages of maximum flooding surfaces on industry sea-level curves." Hanan et al. (1998) are therefore linking Yellowstone-sized volcanic eruptions to high stands of sea level, and to clastic ash deposition in the deepwater Gulf of Mexico. Why would Yellowstone volcanic tephra fall be coincident with sea level rise? Even if volcanism warmed the climate, melted the glaciers, and led to sea level rise, layers of Yellowstone volcanic tephra are not in the Gulf of Mexico because of oceanic transgression. Volcanic tephra falls where it falls, when it falls.

Did sea level rise four times in the Cretaceous coincident with OAEs (times of voluminous ash fall) and fifteen times more recently associated with Yellowstone ash fall? Once again, even if volcanism warmed the climate, melted glaciers, and led to global warming, ash volumes and layers are not in the Gulf of Mexico because sea level rose. They are there because they fell there, not because of any sea level change. There is a problem with what geoscience believes constitutes evidence for sea level change.

There are recent critics of the universal application of applied sequence analysis and corresponding sea level change. Recently, some researchers have had difficulty confirming the basic principles of sequence analysis after looking at some of the rocks from which the idea was developed. Howell et al. (2018) returned to the Book Cliffs of eastern Utah, one of the "birthplaces" of sequence stratigraphy, and re-examined the Cretaceous strata. Howell was surprised at not being able to find any evidence of sea level fall.

"The Book Cliffs of Central Utah have been a key testing ground for the concepts of high-resolution sequence stratigraphy since the early 1990's. The Book Cliffs are considered central to our understanding of the sequence stratigraphic paradigm. A core component of the sequence stratigraphic model is the implicit assumption of a rising and falling relative sea-level curve, with the occurrence of "sequence boundaries", formed during intervals of sea-level fall. These are primarily recognized by the presence of incised valleys and associated lowstand deposits basinward of the highstand shoreline." (Howell et al., 2018).

"The commonly accepted sequence stratigraphic model for the Santonian-Campanian section in the Book Cliffs recognizes up to ten high frequency sequence boundaries. Critical re-analysis of these indicates no conclusive stratigraphic evidence for any relative sea-level falls within these strata. The majority of "valley-fill" successions are filled with very large, single-story tidal macro-forms, that suggest a higher tidal range than is normally implied for the region but no evidence for falling base-level. The rare multi-story valley fills are interpreted to have formed during the vertical aggradation of raised peat-mires on the coastal plain during normal regression rather than stepped sea-level rise within a valley during transgression after sea-level fall. Previously documented "forced regressions" in the Book Cliffs are associated with a demonstrably rising shoreline trajectory. The major "sequence boundary" associated with the base of the Castlegate Formation is reinterpreted as the progradation of proximal facies belt in a major distributive fluvial system, enhanced by upstream uplift and tectonics, rather than sea-level fall. Furthermore, convolution of the known rates of subsidence with recent sea-level curves for the Campanian suggest that no relative sea-level falls would be expected, because the magnitude of falling sea-level was outpaced by the basin subsidence" (Howell et al., 2018).

Howell et al., (2018) concludes that, "These observations indicate that a key aspect of the sequence stratigraphic model is not applicable in outcrops that are widely considered to be one of the type areas for sequence stratigraphic teaching and research. This also has important implications for the use of the sequence stratigraphic approach during greenhouse times."

Other researchers have had difficulty forcing some Gulf of Mexico rocks into the sequence stratigraphic description of the maximum flooding surface. Sercombe et al. (2009) examined well data and wrote, "High gamma ray 'hot' Eocene shales were encountered in southern deepwater Gulf of Mexico wells. The two prominent shales were in the age range of 40 and 50 MYA. The shales were originally deposited in basin floor settings that palinspastically restore to water depths of greater than 20,000' sstvd {subsea total vertical depth – DMP}. The occurrence of 'hot' shales deposited at such water depths forces the questioning of the association of 'hot' shales and maximum flooding surfaces. The influence from eustatic sea level changes in very deep water would be minimal." (see Figure 1).

Discussion

Could there be something wrong with the principles on which sequence analysis is built? That appears to be the case. One universally accepted and applied tenet of sequence analysis is the condensed section and its association with the Maximum Flooding Surface. The following description of a condensed section is the classic one by Loutit et al. (1988). The two-paragraph description of a condensed section has been shortened from the Louitit et al. (1988) paper to include only the key characteristics for recognition of a condensed section.

"Condensed sections play a fundamental role in stratigraphic correlation, both regionally and globally. Condensed sections are thin marine stratigraphic units consisting of pelagic to hemipelagic sediments characterized by very low-sedimentation rates. Aerially, they are most extensive at the time of maximum regional transgression of the shoreline. Condensed sections are associated commonly with apparent marine hiatuses and often occur as thin, but continuous, zones of burrowed, slightly lithified beds (omission surfaces) or as marine hardgrounds. In addition, condensed sections may be characterized by abundant and diverse planktonic and benthic microfossil assemblages, authigenic minerals (such as glauconite, phosphorite, and siderite), organic matter, and bentonites, and may possess greater concentrations of platinum elements such as iridium."

"Accumulation of organic matter is preferentially controlled by sequence stratigraphy and relative sea level, where it strongly increases during periods of high sea level accompanied by a drastic decrease of conspicuous fluviatile-input. In other words, it is usually related to late stages of transgressive systems tracts and early highstand systems tracts during episode of maximum flooding of relative sea level (Vail et al., 1984; Loutit et al., 1988). As a result, condensed sections can be deposited around maximum flooding surfaces which are regarded as promising source rocks" (Loutit et al., 1988).

With knowledge accumulated since this description was written, we can identify the condensed section as a volcanic tephra fall event, and not a sea level change event (see Figure 2).

The key points of the description by Loutit et al. (1988) are that the condensed section is a thin stratigraphic unit that is aerially extensive during maximum transgression, commonly associated with marine hiatuses and thin, continuous zones of burrowed, slightly lithified beds, or as marine hardgrounds. Abundant and diverse planktonic and benthic fossils, authigenic minerals (such as glauconite, phosphorite, and siderite), organic matter, and bentonites and may contain platinum minerals such as iridium.

All of the key descriptive characteristics of the condensed section would be expected with a volcanic ash fall event. (1) A diverse assemblage of pelagic, hemipelagic, and benthic fossils would be expected as a part of the plankton bloom stimulated by ash fall (the driver for organically enriched rock formation). The Florissant Fossil beds of Colorado preserve detailed fossils with ash fall, as do nearly all other major Lagerstatten. (2) A maximum shoreward extent occurs during an ash fall event because it does not recognize the shoreline. (3) Hiatuses are documented within the transgressive, organically enriched facies (with abundant ash) in the Greenhorn Cyclothem (Glenister et al., 1985). Marine hardgrounds could be from calcite (Mahogany Marker Tuff) or chert (Wadia, 2007) formed during the alteration of ash. (4) The authigenic minerals siderite ($FeCO_3$) and phosphorite (P_2P_5) include Fe and P, mineral elements that Lee et al. (2018) determined to be leached from windblown ash during or shortly after deposition. Glauconite has indeterminate mineralogy, but its characteristics are controlled by the amount of expandable clays incorporated within (Triplehorn, 1966; Triplehorn and Bohor, 1983). Glauconite could essentially be an encapsulated bentonite. (5) It has been documented that "explosive volcanism in the Eocene resulted in significant iridium anomalies." (Schmitz et al., 1996). The key characteristics of the Loutit et al. (1988) description of a condensed section can be explained as a volcanic ash fall event.

The characteristics of condensed sections exist in water too deep to have been affected by sea level change (Sercombe et al., 2009). Hanan et al. (1998) identified ash fall events associated with Yellowstone eruptions that correspond fifteen times to industry sea level curves in the Gulf of Mexico implying that fine-grained deposits may regularly be interpreted as a sign of a transgression. The Cretaceous shelf margin in the GOM was drowned in clastics -- interpreted as evidence for transgression four times coincident with OAEs -- which are now known to be times large volcaniclastic deposition.

Conclusion

The perspective inherent in the Loutit et. al. (1988) condensed section description is this; that the constant background level of volcanic ash can cause ash to be a dominant form of sedimentation only when sea level change redirects other sedimentation elsewhere.

We now know that during Oceanic Anoxic Events, volcaniclastic sedimentation can episodically dominate other sediment distributary systems. At those times the GOM carbonate shelf margin was drowned in siliciclastics. We know that fifteen times ash linked to Yellowstone has been coincident with industry sea level curve transgressions, strongly implying that an increased volume of fine siliciclastic sediments is routinely interpreted to represent a sea level transgression.

Condensed sections are actually one, or a series of many, volcanic ash fall events; those times when ash fall episodically dominates other sedimentary processes, not times when other sedimentation is redirected by sea level change. The condensed section does not imply a sea level high and has been misunderstood since it was described.

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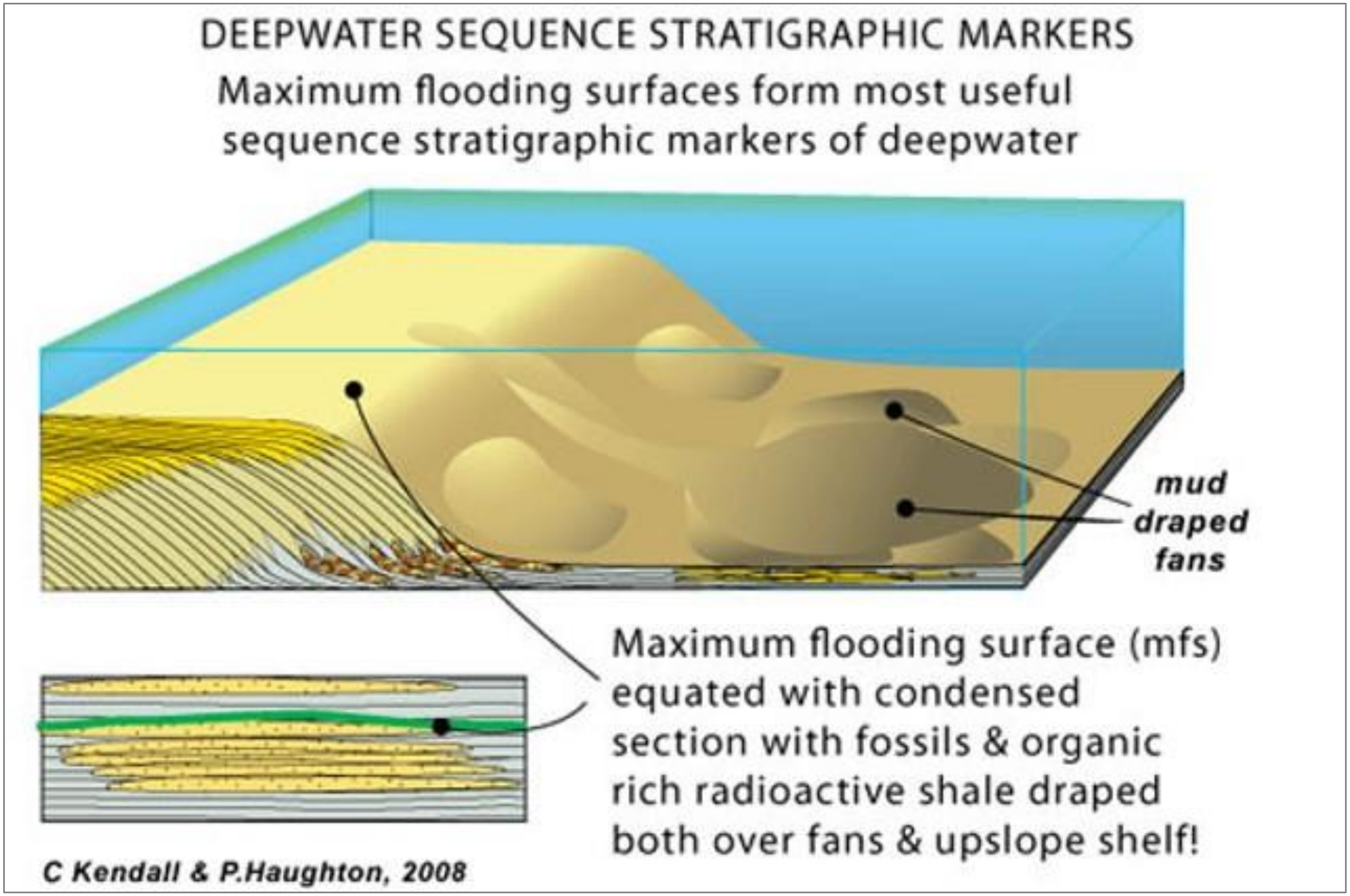

Figure 1. Traditional sequence analytical relationship between the condensed section, maximum flooding surface, preserved fossils, and organically enriched radiogenic sediments. The alternative interpretation presented here is that one, or a series of volcanic ash fall events is a better explanation for the "maximum flooding surface equated with condensed section". Zimmerle (1985), Parker (2017), Lee, et al., (2018), and others, recognized the role of volcanic ash in creating and preserving organically enriched rocks. Radiogenic shales have been shown to result from ash fall. Detailed fossil preservation is nearly always by ash fall as at the Florissant Fossil Beds of Colorado. The deposition of the condensed section in all water depths and more shoreward than other sequence boundaries is also consistent with one, or a series of, volcanic ash fall events.

Condensed Section Description (Loutit, T.S., Hardenbol, J., Vail, P.R., Baum, G.R., 1988)	**Volcanic Ash Fall Description** (Parker, 2019)
Bentonites	Bentonites are altered ash, condensed sections are ash fall events, not sea level change events (Parker, 2019)
Organic enrichment	Ash fertilizes primary production and alters to create transient sea floor anoxia to preserve organics (Parker, 2017)
Association with Maximum Flooding Surface	Ash fall does not recognize shoreline; extends from offshore to onshore (with likely interruption in surf zone)
Decrease in fluvial sediment input	Ash fall can dominate other sedimentation episodically without any necessity for redirection of fluvial deposition (as at OAEs)
Authigenic minerals – glauconite, phosphorite, siderite	Si (hardgrounds), P (phosphorite-5-20% P2O5), and Fe (siderite-FeCO3) among first minerals to separate from ash (Lee et al., 2018); no geoscience consensus on glauconite formation (Velde, B., 2003); likely volcanogenic also (Parker, 2019)
More platinum minerals such as iridium	Iridium concentrations elevated in basaltic and acid-mafic mineral assemblage ashes of Eocene age (Schmitz, B. et al., 1996)
Abundant, diverse planktonic and benthic microfossils	Ash fertilizes primary productivity and alters to preserve fossils (IF not thick, frequent, and long-lasting enough to contribute to extinctions as at OAEs)
Marine hiatuses	More hiatuses identified by Glenister et al. (1985) in ash-rich transgressive facies than ash-poor regressive facies Greenhorn Cyclothem
Marine "hardgrounds"	Descriptors of unconventional gas shales include alternation of "ductile" (more organic and clay rich) and "brittle" (more silica or calcite rich) layers (Slatt et al., 2011); organics and clay can be contributed from ash; silica and calcite can be contributed by ash.
Radiogenic minerals (potassium, uranium, thorium)	Uranium in Jurassic Morrison from ash; Eocene Gulf Coast uranium from ash; Eocene "hot shale" in Gulf deposited at 20K ft sstvd (Secombe et al, 2009) likely from ash; high gamma ray log value correlation with high TOC because of radiogenic minerals from ash (Parker, 2019)
	No consensus mechanism for condensed section formation (fast or slow sea level rise, sea level drop, global warming, global cooling all suggested (Baraboshkin, E. Yu, 2009)

Figure 2. Comparison of condensed section with volcanic tephra fall event.