Stratigraphic Emmental – Finding the Holes

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Summary

Detailed correlation of mudstone-dominated, mid-Cretaceous successions in Alberta and BC has revealed a wealth of erosion surfaces, more-or less subtle, that record relative sea-level changes, both of tectonic and eustatic origin. Where rock units have been beveled off, or pinch out, on a regional (~ 1000 km) scale, broad tectonic tilting is implied, perhaps coupled with eustatic change. Regional tilting may be best explained by the formation of flexural moats adjacent to actively-thickening portions of the orogen, whereas peripheral up-warps a few hundred kilometers distant accumulated condensed facies, such as thin ooidal ironstone and bioclastic lags that can represent 0.7 to 1 myr. Very detailed correlation of offshore mudstone successions reveals localized (50-150 km) regions of both uplift and subsidence across which strata thicken, thin, and are beveled off. Local offset on sub-Mesozoic structures is postulated to have caused this 'lumpy mattress' style of subsidence. Integration of allo-, bio-, and carbon-isotope stratigraphy allows long-distance correlation of depositional sequences. Upper Turonian and Lower Coniacian sequences in the Cardium and Muskiki formations range in duration from ~ 400 kyr to ~30 kyr, and can be correlated from Alberta to Europe. Stratal geometry and facies offsets can be explained by about 15 to 20 m of eustatic change; this amplitude implies a combination of aquifer- and glacio-eustatic control. Apparently monotonous marine mudstone of the Lower Cenomanian Westgate alloformation, deposited in the proximal foredeep, is punctuated by a thin rooted paleosol and 3 cm coal bed. This unequivocal evidence of subaerial emergence implies that this 'offshore mudstone' accumulated in shallower water, and closer to shore, than the facies would at first suggest. Slightly deeper transgressive erosion would easily disguise other subaerial disconformities, which is a slightly disturbing thought! Derek Ager's contention that the stratigraphic record may comprise 'more gap than record' may, at least in the shallow-marine realm, be close to the truth!

Introduction

In 1985, I was a keen young post-doc, house-sitting for Gerry and Muriel Middleton while they were on sabbatical in the south of France. For a week in the winter of '85, Gerry stayed with my wife and I while he was back home on McMaster business. I had just returned from a trip to the Calgary core research centre – and was telling Gerry, in breathless tones, how "...I had logged a lot of Cardium cores, and that I knew just where I was going to find the pebble beds and sequence boundaries in each core". Gerry looked at me, and, smiling seraphically, said: "Well, if you knew what you were going to find, then you would most assuredly find it". That rather took the wind out of my sails.

My students and I have spent the last 38 years examining the Cretaceous stratigraphy of Western Canada. We did not know what we were going to find. Our objective has been pretty much the same, regardless of which unit we examined: Look carefully at the outcrop sections, correlate to the nearest well logs, and then correlate bounding surfaces regionally, but also in detail. How is the stratigraphy put together, layer by layer? Can we distinguish eustatic and tectonic controls on accommodation? The process of 'just looking carefully' – both at the local detail of outcrop and core, and at the regional stratal architecture, has turned up a wealth of evidence for gaps in the stratigraphic record. In this talk, I will review some of my favourite examples of Stratigraphic Emmental.

Regional to inter-basinal tectonic + eustatic holes > 1000 km extent

Coniacian Example: The bulk of the Coniacian rocks in Alberta and British Columbia comprise a ~3 Myr transgressive-regressive succession, lithostratigraphically assigned to the Muskiki and Marshybank formations. These are neither source nor reservoir rocks, and hence are little-studied. The Muskiki and Marshybank are primarily mudstones and siltstones in Alberta, but the Marshybank includes nearshore sandstones in the west. The top of the Marshybank, generally marking the Coniacian-Santonian boundary, is marked by a chert pebble bed that records a regional, if not global lowstand. An allostratigraphic framework developed from outcrop and wireline log data (Plint et al. 2017), provides a high-resolution physical framework of 24 regionally-mapped allostratigraphic units within which the stratigraphic distribution of Inoceramid bivalves (Walaszczyk et al. 2017), and Scaphitid ammonites (Landman et al. 2017), was analyzed. This approach showed that the first occurrences of various Inoceramid and ammonite species exactly coincided with specific marine flooding surfaces; surfaces that could be independently traced in wireline logs for at least 750 km along the western margin of the basin. The biotic speciation events and the sea-level changes that formed the flooding surfaces were essentially synchronous, and could be treated as time lines. This new integrated stratigraphy showed that the thickness of lower, middle and upper Coniacian rocks changed dramatically along a 750 km strike transect of the basin. Flexural subsidence of the foredeep was non-uniform in both space and time, interpreted to reflect localized loading in response to spatially non-uniform thickening of the deformed belt. The most dramatic finding was that Upper Coniacian rocks fill a depocentre in the north, and pinch out to zero in the south, primarily as a result of truncation or non-deposition along an unconformity. Once the stratal geometry had been established, it immediately became clear why upper Coniacian rocks, representing ~ 1 myr, are absent over southern Alberta, with only scraps preserved in Montana. The missing 1 myr is represented by a few decimeters of ooidal pebbly ironstone, resting on a burrowed disconformity. In Montana, this bed is the MacGowan Concretionary Bed, that is mapped over the NW part of that state (Cobban et al. 2005).

Santonian Example: Santonian rocks of the Wapiabi Formation, dominantly mudstones, form an eastward-thinning wedge, typical of an actively-subsiding flexural foredeep. Three major packages, each a maximum of about 100 m thick and each representing ~ 700 kyr, are mapped in outcrop and subsurface along the foredeep (Hu and Plint, 2009; Ibrahim, 2018). The lowest package maintains an approximately uniform thickness for ~ 1000 km along strike. In contrast, package two thins to zero towards the south whereas package three thins to zero towards the north. In the south, what does the missing 700 kyr look like at the boundary between the first and third packages? To address this question, well logs were correlated to outcrop on Highwood River. There, a detailed sedimentological log, coupled with an outcrop gamma-ray log, allowed outcrop stratigraphy to be correlated with confidence to the wireline logs. In the 350 m thick outcrop section there is a unique, 2 m thick interval of siltstone, packed with inoceramid bivalves and oysters. That shell-rich package correlates exactly with the 'missing unit 2' and represents ~700 kyr of extremely slow deposition and storm-related reworking on the up-warped periphery of the depocentre.

Cenomanian Example: Lower Cenomanian rocks of the upper part of the Fort St John Group are dominated by organic-rich mudstones and claystones and occupy the foredeep in NE British Columbia. Allostratigraphic correlation of this mudstone package from BC eastward into Alberta (Roca et al. 2008; Angiel and Plint, 2022) shows that it correlates with the lithostratigraphic Fish Scales Formation. In Alberta and Saskatchewan, the Fish Scales Formation is ~ 5 to 20 m thick and has a sharp erosional base overlain by a highly radioactive phosphatic lag – the well-known 'Base Fish' log marker of industry. Traced westward into Alberta, the Fish Scales alloformation thickens to as much as 400 m. There, multiple zones of mudstone, rich in phosphatic fish debris can be recognized. These radioactive zones converge eastward across BC through onlap onto a master surface termed BFSM, to form a single, highly radioactive interval in Alberta. The BFSM surface is recognized at outcrop along the Peace River in BC as an erosion surface with a veneer, typically only 1 cm thick, of chert pebbles. These extra-basinal pebbles, immediately under- and over-lain by dark, unbioturbated marine mudstone, record a period of subaerial exposure, accompanied by fluvial supply of gravel to the lowstand shoreline. Mapped westward to the BC Foothills, the BFSM surface is identified in Hasler Creek, where it is underlain by a lenticular body of conglomerate, 15 m thick, with large-scale accretion surfaces. This is a huge gravel point bar of a river that was feeding sediment to the lowstand shoreline. The non-depositional hiatus due to the eastward onlap of mud, coupled with non-deposition and erosion across much of the basin at the BFSM lowstand, resulted in a composite hiatus at the base of the Fish Scales Formation as seen in Alberta (on the forebulge), that represents > 300 m of rock in the west, and probably well in excess of 1 myr.

Sub-regional tectonic holes – the Lumpy Mattress model.

Coniacian example: In addition to the major tectonically-related beveling unconformity at the top (described above), the Coniacian (Muskiki-Marshybank) mudstones in the subsurface of west-central Alberta are partitioned by numerous, minor flooding surfaces. Extremely detailed correlation of those surfaces by Beth Hooper (PhD, 2019) revealed complex thickening and thinning of five main packages, bounded by erosion surfaces. Although an isopach map of the *entire* Coniacian package shows simple westward thickening into the foredeep, the five component units, each bounded by beveling surfaces, show that accommodation was very non-uniform, with 'holes' and 'highs' developing well outboard from the foredeep, on length scales of 50-150 km. Former 'highs' became 'holes' on a timescale of < ~500 kyr. These localized zones of uplift and subsidence strongly suggest localized tectonic control by structure in the underlying rocks. So far, we have been unable to link mapped isopach features to publicly-documented basement structure, so the specific cause of the 'Lumpy Mattress' stratigraphy remains enigmatic.

Eustatic holes of inter-basinal extent – the Cardium Formation

Turonian-Coniacian examples: Biostratigraphy was integrated into the three-dimensional allostratigraphic framework for the Upper Turonian-Lower Coniacian Cardium Formation (Plint et al. 1986; Shank and Plint, 2013; Walaszczyk et al. 2014). These data were then combined with carbon-isotope stratigraphy, which, collectively, allowed sequence boundaries in Alberta to be correlated with those in coeval rocks of the Bohemian Basin of the Czech Republic (Plint et al. 2021). In the Upper Turonian, transgressive-regressive sequences of 400 and 100 ky periodicities could be correlated, whereas in the Lower Coniacian, sequences of as little as 30 kyr could be correlated with a high degree of confidence, using the refined inoceramid biostratigraphy. Eustatic sea-level changes of the order of 15 to 20 m were inferred from both the Alberta and Bohemian basins. An astronomically-tuned timescale suggests that the stratigraphic holes associated with the Coniacian sequence boundaries might be of the order to 10 kyr or less; Turonian hiatuses might be somewhat longer. Aquifer + thermal eustasy has most recently been estimated to contribute no more than 10 m to Cretaceous eustatic change (Simmons et al. 2020). The conservative estimates of 15-20 m of eustatic change from both Alberta and Bohemia implies some other mechanism was also involved in controlling sea-level on these Milankovitch timescales: glacio-eustasy could be the culprit.

Lower Coniacian Example, Muskiki Formation: *Inoceramus gibbosus* is present in only a few localities in Europe and defines the uppermost zone of the Lower Coniacian (Walaszczyk et al. 2017). The *I. gibbosus* Zone is absent over most of Europe, and has not been found in the US portion of the Cretaceous Western Interior. However, *I. gibbosus* was found through several tens of meters of the lower Muskiki Formation in Alberta, the top of the Zone being marked by a sharp erosion surface, termed CS4, that is mantled by a few millimeters of chert pebbles and granules (Plint et al. 2017; Walaszczyk et al. 2017). Immediately above surface CS4 appear inoceramids of the genus *Volviceramus*, marking the base of the Middle Coniacian. It would appear that the rocks of the *I. gibbosus* Zone were preserved in western Alberta because of a high accommodation rate in the foredeep, whereas other, less rapidly subsiding areas in North America and Europe were subject to erosion or non-deposition as a result of a late Early Coniacian eustatic lowstand. This hiatus probably spans tens of kyr.

Lower Coniacian – the Muskiki CS1 surface: About 10-20 m above the base of the Muskiki Formation (i.e. above Cardium alloformation, surface E7), is an erosion surface, termed CS1 that caps a subtle, upward-shoaling succession. CS1 has a patchy chert pebble lag, from millimeters to a few centimeters thick. The CS1 surface has been mapped for > 1000 km along the Rocky Mountain Foothills of Alberta and BC (Plint, 1990; Plint et al. 2017). Outcrop shows that a granule conglomerate on CS1 is molded into isolated granule wave ripples, between which, the erosion surface is devoid of coarse grains. Depending on exposure extent, it is therefore quite possible to miss the critical extra-basinal lag. Applying the same logic to other surfaces with extra-basinal lags, it seems reasonable to infer that surface CS1 was once subaerially-exposed, when gravel was delivered by rivers, despite the fact that the sediment above and below CS1 is a marine mudstone or siltstone, and there is no evidence of shoreface deposits, roots or pedogenesis. Is surface CS1, like CS4 that caps the *gibbosus* Zone, also a global eustatic unconformity? In fact, the Coniacian rocks are punctuated by 23, regionally-mappable surfaces that resemble CS4 and CS1, some of which have extra-basinal pebble lags, whereas others have intraclastic lags. Some surfaces separate widely-correlatable biozones. Is it unreasonable to attribute *all 23* Coniacian surfaces to high-frequency eustatic cycles, with 23 events within ~ 3 myr? That is a lot of holes.

Unexpected subaerial surfaces in marine strata

A 100 m thick succession of apparently 'offshore' marine mudstone and siltstone comprises the Lower Cenomanian Westgate alloformation, which in this example, is exposed in the proximal foredeep, where accommodation rate was high. Subtle, siltier-upward cycles, 5-10 m thick are typical. Some 45 m above the base of the Westgate, sandwiched between grey marine mudstones, is a 10 cm thick rooted siltstone, overlain by a 3 cm, *in-situ* coal (Angiel and Plint, 2022). Marine mudstone sharply overlies the coal. This most unexpected facies indicates that an 'offshore' mudstone became subaerially-emergent, allowing plants to root and peat to develop, before being transgressed. It seems unlikely that eustatic fall would have exceeded ~ 20 m, and given the foredeep setting, short-lived uplift seems unlikely. We are forced to conclude that the 'offshore' mudstone facies was deposited in shallow water, easily rendered emergent by minor eustatic fall. If ravinement had wholly removed the 3 cm coal, then this subaerial disconformity would easily be overlooked! In the same mudstone succession occur several erosion surfaces mantled with coarse sand to granule veneers a few millimeters to a few centimeters thick. *Skolithos* occur within, and penetrate below these coarse lag beds. These anomalously coarse-grained beds also probably indicate episodes of subaerial exposure, sediment bypass and/or erosion during sea-level lowstand.

Conclusions

Detailed correlation of mudstone-dominated, mid-Cretaceous successions in Alberta and BC has shown that subtle bounding surfaces can record important relative sea-level changes. The presence of extra-basinal lags lying on rocks lacking such clasts is strong evidence that the pebbles were fluvially-supplied when the surface was subaerially-emergent, despite the absence of recognizably shallow-water or terrestrial sediments. Rarely, a 'smoking gun' in the form of a conglomerate-filled channel, feeding the lowstand shoreline, can be found, as is the case with surface BFSM in the Fish Scales alloformation.

Other erosion surfaces mark the boundaries of molluscan biozones, such as seen in the Cardium Formation, and in the Muskiki Formation at surface CS4, the latter defining the top of the *I. gibbosus* Zone. These surfaces, on biostratigraphic evidence, are readily correlated from Alberta to Europe, implying an eustatic origin. Eustatic change of no more than about 20 m seems to be adequate to explain the observed stratal geometry and facies offsets.

Where rock units can be shown to have been beveled off, or pinch out, on a regional (~ 1000 km) scale, then broad tectonic tilting is implied, perhaps coupled with eustatic change. Regional tilting may be best explained by flexural subsidence around actively-thickening portions of the orogen that produced arcuate depocentres adjacent to them. The up-warped periphery of each depocenter records a depositional hiatus. In the case of the Coniacian, an extensive, decimeter-thick ooidal ironstone records about 1 myr of non-deposition/erosion across SW Alberta and NW Montana. In the Santonian, a 2 m thick siltstone, exposed at Highwood River, is packed with bivalve shells and represents extreme condensation on a peripheral up-warp. The bioclastic unit is equivalent to ~ 100 m of mudstone that accumulated over ~700 kyr in the middle of the depocentre, some 600 km to the NW.

Evidence of much more localized differential subsidence and uplift is provided by offshore mudstone of the Coniacian, deposited on a low-gradient ramp. Subtle beveling unconformities, of limited lateral extent (~ 50-150 km), and truncating ~10-20 m of section, show that subsidence was spatially non-uniform. Erosional beveling is attributed to wave scour in shallow water: there is no clear evidence of subaerial exposure. The beveling unconformities may represent several tens to several hundred kyr hiatuses. Although it has not been possible to link the regions of uplift and subsidence to known sub-Mesozoic structures, some form of differential subsidence across fault-bounded basement blocks might provide an explanation.

Apparently monotonous marine mudstone of the Lower Cenomanian Westgate alloformation, deposited in the proximal foredeep, is punctuated by a thin rooted paleosol and 3 cm coal bed. This is unequivocal evidence of subaerial emergence, despite the lack of evidence of progressive shallowing below the coal. In the same section, coarse sand to granule veneers cap erosion surfaces within mudstone successions, and also appear to indicate periods of emergence. This evidence of repeated emergence suggests that this 'offshore mudstone' accumulated in shallower water, and closer to shore, than the facies would at first suggest.

This variety of well-constrained evidence for 'Stratigraphic Emmental' provides dramatic support for Ager's (1973) contention that the stratigraphic record may comprise 'more gap than record'. In at least the shallow-marine realm, this appears to be true!

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