Allostratigraphy, paleogeography and subsidence in a syn-tectonic wedge: Harmon and Cadotte alloformations (Middle Albian), Alberta & B.C.

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Summary

Detailed subsurface correlation, linked to outcrop sections, allows both the sedimentology and regional stratal geometry of the Middle Albian Harmon and Cadotte alloformations to be determined. The mudstone-dominated Harmon alloformation forms a pronounced wedge that thins from > 145m in the west to 5 m in the NE over ~ 300 km. The Harmon is interpreted to record a time of rapid flexural subsidence in the foredeep. In contrast, the overlying, sandstone-dominated Cadotte alloformation has a much less pronounced wedge shape, and thins from 85 to 18 m over ~ 300 km. The more tabular geometry of the Cadotte is interpreted to record less pronounced asymmetrical flexural subsidence. In an attempt to quantify the physical controls on observed stratal geometry, the modeling program *tao* was employed. The *tao* program uses a finite-difference method to calculate the deflection of the lithosphere, and thereby allows tectonic, eustatic and sedimentary processes to be linked at varying spatial and temporal scales.

Introduction

The purpose of this study is to establish a high-resolution regional allostratigraphic framework for the informal, middle Albian Harmon and Cadotte alloformations (Buckley & Plint, 2013; Henderson & Plint, in review). Allostratigraphy provides the basis for analysis of i) stratal architecture, ii) paleogeography, iii) subsidence patterns and iv) provides the 'ground truth' against which to test numerical simulations of subsidence and stratal architecture.

The flexural subsidence of foreland basins has been modelled in many studies (e.g. Beaumont, 1981, Jordan, 1981; Jordan and Flemings 1991; Sinclair et al. 1991; Johnson and Beaumont, 1995; Gaspar-Escribano et a. 2001; Carrapa and Garcia-Castellanos et al. 2005). In most studies, the model output has not been closely tied to detailed, 'real world' stratal architecture defined in regional wireline log cross-sections. We used the program *tao* (Garcia-Castellanos et al. 1998) as a means to model the observed stratal geometry, with the aim of isolating the various factors (tectonic, sediment and water loads, eustasy), that may have controlled the stratal architecture of the Harmon and Cadotte members.

Stratigraphy

The stratigraphy of the Harmon and Cadotte alloformations was studied using a database of ~1360 gamma ray and resistivity log pairs distributed over ~70,000 km^2 . A succession of allomembers, bounded by regionally-mappable marine flooding/transgressive surfaces and/or thick regional bentonites, were correlated through a grid of 40 cross-sections (Buckley, 2011; Buckley & Plint, 2013; Henderson & Plint, in review). Eighteen outcrop sections and 21 cores provided lithological detail in the Rocky Mountain Foothills and in the Peace River valley.

The base of the Harmon alloformation is marked by a regional transgressive surface termed HE0 above the Spirit River Formation (and equivalent Gates Formation in outcrop); the Spirit River Fm.

represents coastal plain, shallow marine to shoreface environments. The Harmon alloformation is dominated by weakly- to strongly-bioturbated marine mudstone; the unit becomes increasingly rich in silt and very fine sand in the proximal (western) part of the foredeep in British Columbia. In the far east and north, the Harmon is primarily a claystone to silty claystone. Traced to the south, the Harmon alloformation becomes locally sandy, with clean sandstone units ~1-3 m thick capping sandier-upward successions. This sand-rich facies is interpreted to represent nearshore deposition around the southern margin of the 'Harmon Sea'. Throughout the entire study area, siltstone and very fine-grained sandstone beds are molded into wave- or combined-flow ripples, showing that the entire region was influenced by storm waves. As a whole, the Harmon alloformation thins over 300 km, from > 145 m in the proximal foredeep in the west to 5 m in the NE. Internally, the Harmon is divided into five regionally-mappable allomembers HA through HE. In the far south and east, lenticular clean sandstone bodies up to 42 m thick 'hang' from several of the Harmon allomember bounding surfaces. These sandstone bodies are interpreted as paleo valley-fills.

The boundary between the Harmon and the overlying Cadotte alloformation is placed at 'surface' CE0. Although appearing as an abrupt contact in wireline logs, at outcrop in the east, surface CE0 is seen to be an interval, < 1 m thick, of rapid facies change from mudstone to sandstone. Towards the west, in the foredeep, the CE0 surface is expressed as a flooding surface overlain by a thin package of muddy strata, above which the succession becomes abruptly sandstone-rich. The facies most typical of the Cadotte alloformation is clean, hummocky, swaley, and trough cross-stratified sandstone or, locally, chert pebble conglomerate. These facies are interpreted to represent a wave-influenced shoreface environment. In the northern part of the study area, the clean shoreface sandstone of the Cadotte undergoes a lateral facies change into heterolithic strata comprising dm- to cm-scale interbeds of very fine sandstone and mudstone indicative of a shallow, storm-influenced shelf. In the south and east, log signatures and sparse outcrop control show that the shoreface sandstone of the Cadotte passes laterally into heterolithic facies interpreted to represent coeval coastal plain environments. In this marginal-marine area, lenticular bodies of sandstone up to 20 m thick hang from surface CE0; these sandbodies are interpreted as valley-fill deposits.

The Cadotte alloformation thins from 85 m in the west to 18 m in the east over ~300 km. Internally, the Cadotte is divided into three allomembers CA to CC, by two, regionally-traceable transgressive erosion surfaces. This shows that the Cadotte is a composite sandbody that records at least three regressive-transgressive events (Buckley & Plint, 2013; Henderson & Plint, in review), rather than a single regressive shoreface. The top of the Cadotte alloformation is defined by surface PE0 at the base of the overlying Paddy alloformation. Surface PE0 marks a major unconformity at which several faunal Zones are absent (Stelck et al. 1956; Koke & Stelck, 1984, 1985). Roca et al. (2008) showed that strata of the Paddy alloformation onlap progressively eastward onto PE0, emphasizing the unconformable nature of the contact.

Main Stratigraphic Results

1. The allostratigraphic correlations show that the five allomembers of the Harmon alloformation, and the three allomembers of the Cadotte alloformation, originally recognized by Buckley and Plint (2013), can be traced southward from Twp. 74 to Twp. 60, and from the edge of the deformed belt in the west to approximately Ranges 15-20 in the east. South of approximately Twp. 60, and east of approximately Ranges 21-23 W5, marine deposits of both the Harmon and Cadotte alloformations grade laterally into coeval coastal plain deposits. The Harmon alloformation shows no evidence of a 'shelf-slope-basin' physiography, a rollover point, or a distinct downlap surface. The depositional surface of the Harmon is therefore interpreted to have been a shallow (few tens of metres) and extremely low-gradient ramp-type shelf. Previous interpretations that suggested deposition in up to 100 m of water (e.g. Stelck & Leckie, 1988; Bloch, 1990), do not appear to be supported by either stratigraphic or sedimentological evidence.

2. The Harmon and Cadotte alloformations are consistently separated by surface CE0 that forms a horizontal boundary between the two units. In the more expanded western sections, surface CE0 is a flooding surface overlain by a metre-scale interval of mudstone overlain by clean sandstone, suggestive

of relative sea-level rise, followed by fall. Towards the east, where accommodation was less, CE0 is a sharp, or rapidly-gradational boundary between mudstone and sandstone, suggestive of relative sea-level fall. There is no evidence that sandstone of ‘Cadotte’ aspect interfingers downdip with mudstone of ‘Harmon’ aspect, showing that there is no genetic relationship between these two rock bodies; i.e. Cadotte sandstone is not the updip equivalent of Harmon mudstone.

3. Towards the south, both the Harmon and Cadotte alloformations can be traced laterally into heterolithic facies that, at outcrop, form a variety of coastal plain and marginal marine rocks mapped in the Foothills as Gates Formation. To the east, in subsurface, the nonmarine, updip facies of the Harmon and Cadotte alloformations are mapped as part of the Mannville Group. The southern boundary of both the Harmon and Cadotte alloformations has not been established, but must lie south of Twp. 56.

4. At maximum extent, the ‘Harmon Sea’ extended south to about Twp. 60, to the south of which marine ‘Harmon’ mudstone passes into coeval coastal plain deposits. An approximately coincident geographic boundary marks the southern limit of marine ‘Cadotte’ sandstone, to the south of which are equivalent coastal plain deposits.

5. In Harmon allomembers HB, HC, HD, HEa and HEb, the facies boundary between offshore muddy and nearshore sandy strata forms a lobate to cuspate pattern in plan view. This pattern is interpreted as evidence that rivers constructed elongate delta lobes at the southern margin of the Harmon Sea. The southern end of the Harmon Sea is interpreted to have been very shallow, with low wave energy, characterized by river-dominated, shoal-water deltas.

7. Sharp-based, lenticular sandstone bodies, 17-42 m thick, locally ‘hang’ from allomember-bounding surfaces in both the Harmon and Cadotte alloformations. These sandstone bodies are interpreted as the fills of paleovalleys. These sandbodies may represent the conduits that supplied sediment to the Harmon and Cadotte depositional systems. If they represent paleo-valleys, they provide additional evidence that Harmon and Cadotte allomember boundaries record both relative sea-level rise and fall and can therefore be interpreted as depositional sequence boundaries.

8. The five allomembers of the Harmon alloformation show the expected eastward-thinning wedge-shape, characteristic of a flexural foreland basin. Some allomembers pinch out about 100-150 km east of the present deformation front whereas distally, other allomembers become almost tabular and extend as a sheet, typically only a few metres thick, for 100-200 km towards the craton. In contrast, the Cadotte alloformation has a much more tabular geometry, with maximum subsidence located over the Peace River Arch; Cadotte deposition was more strongly controlled by subsidence of the arch, rather than regional flexure associated with Cordilleran loading. It is inferred that the rate of tectonic loading diminished from Harmon to Cadotte time.

Numerical modelling of Basin Subsidence

In order to investigate and isolate the factors responsible for the observed stratigraphic architecture of the Cadotte and Harmon members, the model *tAo,* developed by Garcia-Castellanos *et al.* 1997, was utilized to relate thrusting, flexure, sedimentary stratal geometry and lithosphere rheology. Preliminary model results reveal how accommodation within the basin changes as the width, height, and mass of an applied tectonic load are varied. The tectonic load represents the topographic accumulation that results as the thrust belt advances and material is pushed horizontally and stacked vertically. In particular, in order to produce the observed Harmon subsidence of ~150 m, the added tectonic load was reconstructed to have had a wedge shape about 125 km wide perpendicular to the orogen, with a maximim height of 300 m and a mass of the order of 10^{10} kg. The model indicated that the thrust front was located ~ 65 km west of the present deformation front.

It is important to appreciate that the response of the lithosphere to the imposed tectonic load is a direct result of the assumed mechanical properties of the lithosphere because that dictates how load is supported and dispersed through the plate. In this study, lithospheric strength was assumed to increase cratonward and, in addition, an elastic plate model was assumed. In past studies, an elastic model had proven to best model the stratigraphy in many foreland basins (eg. Jordan, 1981; Flemings and Jordan, 1990; Sinclair et al., 1991), and was expected to be the most appropriate plate flexure model in this setting as well. Long-term viscoelasticity occurring on long time scales (tens of millions of years) was not expected to affect the relatively short depositional time period of the Cadotte and Harmon members, interpreted to be deposited within less than ~ 4 myr. Although the results presented are preliminary, the over-arching goal of this modelling study was to test the conclusions, initially proposed by Buckley and Plint (2013), that the strongly wedge-shaped Harmon alloformation was deposited during a period of relatively rapid flexural subsidence, whereas the more tabular geometry of the Cadotte alloformation reflected a much lower rate of flexural subsidence.

Conclusions

The Harmon and Cadotte alloformations are divided, on the basis of marine transgressive surfaces, into five and three allomembers, respectively. The Harmon is a pronounced, westward-thickening wedge indicative of active orogenic growth and flexural subsidence. The Cadotte is much more tabular and suggests diminished tectonic activity and attendant subsidence. The Cadotte comprises three distinct stacked shoreface sandstones. Offshore Harmon marine mudstone does not intergrade updip with nearshore Cadotte sandstone; the units are not genetically related. In the south and east, a lateral transition from marine Harmon mudstone to sandstone takes place along an irregular boundary suggestive of river-domninated deltas. South of about Twp. 60, marine Harmon and Cadotte rocks both pass laterally into coastal plain facies. Isolated ?valley-filling sandstone bodies, 17-42 m thick hang from marine transgressive surfaces in both the Harmon and Cadotte and suggest important sea-level changes during deposition. Preliminary model results suggest that 150 m of Harmon subsidence was driven by an accreted load ~300 m tall and extending ~ 120 km normal to the deformation front.

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