Zeitschrift: Swiss bulletin für angewandte Geologie = Swiss bulletin pour la géologie appliquée = Swiss bulletin per la geologia applicata = Swiss bulletin for applied geology

Herausgeber: Schweizerische Vereinigung von Energie-Geowissenschaftern; Schweizerische Fachgruppe für Ingenieurgeologie

Band: 15 (2010)

Heft: 2

Artikel: Paleogeographic and stratigraphic responses to tectonic and eustatic forcing : the evolution of a Cenomanian delta complex in the Western Canada Foreland Basin

Autor: Plint, A. Guy

DOI: https://doi.org/10.5169/seals-227485

Swiss Bull. angew. Geol. Vol. 15/2, 2010 S. 23-33

Paleogeographic and stratigraphic responses to tectonic and eustatic forcing: The evolution of a Cenomanian delta complex in the Western Canada Foreland Basin

A. Guy Plint[1]

Extended abstract of a talk given at the University of Geneva (VSP/ASP Lecture Programme in cooperation with AAPG, 10 June 2010).

Regional Setting

Flexural subsidence adjacent to the rising Rocky Mountain Cordillera, regional dynamic tilting of North America, and eustatic rise combined to cause flooding of the interior of North America during the middle Cretaceous and the formation of a classic retro-arc foreland basin. The invading Boreal and Tethyan seas merged in the early Cenomanian, forming a shallow, elongate epeiric seaway (Fig. 1). The western margin of the seaway received abundant supplies of detrital clastic sediment eroded from the rising Cordillera. A large deltaic depositional system is represented in northern Alberta and adjacent British Columbia by the Dunvegan Formation. This formation, dominated by sandstone and mudstone, is up to about 300 m thick, and represents more than 400 km of SE-directed deltaic progradation along the axis of the foredeep. Progradation took place between the Early and Middle Cenomanian, and the delta complex was finally drowned by regional marine transgression in the early Late Cenomanian.

[1] Department of Earth Sciences, The University of Western Ontario, London, Ontario, N6A 5B7, Canada

Deltaic Environments

Three broad depositional environments are recognized. Prodelta laminated silty mudstones extend from 80 to > 150 km from the delta front, and downlap onto a regional condensed section termed the «Fish Scales Upper» (FSU) marker that comprises highly radioactive wave-rippled sandstones, < 1 m thick, rich in fish debris (Plint 2000; Fig. 2). Sandstones in the upper delta front show evidence of abundant wave action with hummocky and swaley cross-stratification, and wave ripples as the dominant sedimentary structures. Delta front sandstones commonly are sharp-based, suggestive of deposition during relative sea-level fall («forced regression»). Deltaic sandstones and mudstones pass updip into coastal plain deposits characterized by grey and green silty and carbonaceous mudstones with abundant roots and sphaerosiderite. Sandstones form lenticular bodies up to 10 m thick and < 100 m wide that generally lack lateral accretion surfaces. These units are interpreted to represent the fill of anastomosed rivers that typify modern alluvial systems that have extremely low gradients (1 : 3000 to < 1 : 5000). Thin crevasse splay sandstones are common, and many preserve dinosaur tracks on their lower surfaces (McCarthy et al. 1999; Lumsdon-West & Plint 2005).

Genetic Stratigraphic Packages

Successive progradational delta complexes are separated by regional transgressive marine mudstone packages that provide a means of dividing the succession into genetic allomembers, bounded by transgressive surfaces. Marine transgressive surfaces merge updip with major subaerial unconformities manifest as interfluve paleosols

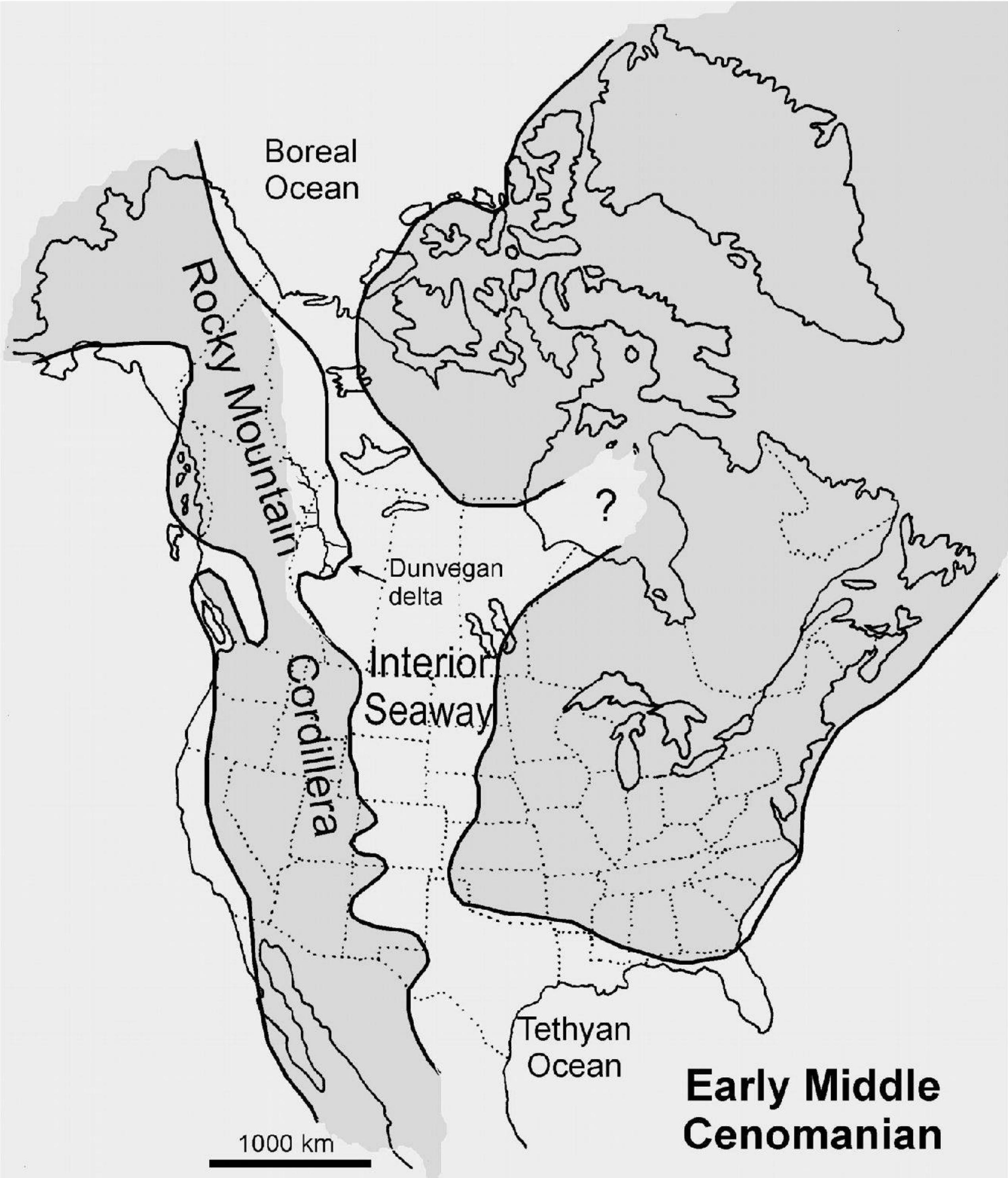

Fig. 1: Paleogeographic reconstruction of the Western Interior Seaway during the Middle Cenomanian. The northern Boreal Ocean probably merged with the southern Tethyan Ocean in the Early Cenomanian. The generalized distribution of the Dunvegan delta complex is shown (from Plint et al. 2009).

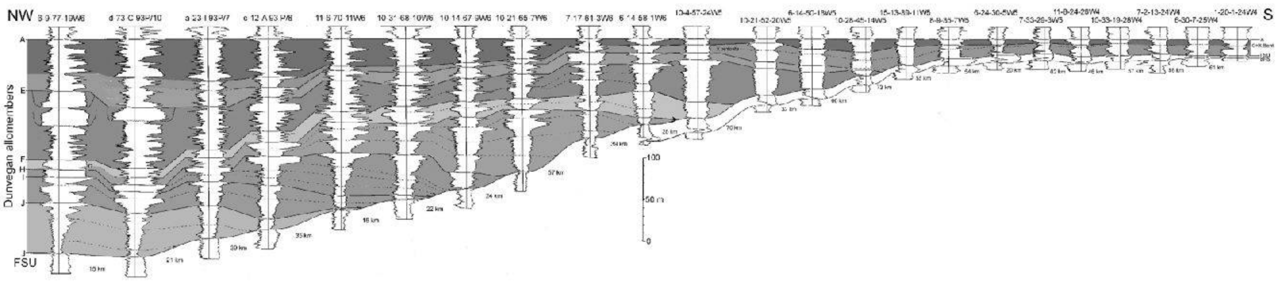

Fig. 2: Summary dip well-log (gamma ray and resistivity logs) cross-section extending 950 km from north-central Alberta to the Montana border. Deltaic strata of the Dunvegan Formation downlap south-eastward onto a prominent condensed section called the FSU marker. In the South, most lower and middle Cenomanian strata are either missing or extremely condensed into the FSU marker (from Plint et al. 2009).

(McCarthy & Plint 1998, 2003; Fig. 3). This allostratigraphic approach does not adhere exactly to the classical Exxon sequence model, but nevertheless is readily applied in practice. An attempt has been made to interpret allomembers in terms of sequences and systems tracts (Plint et al. 2001).

Paleovalley Systems

Paleovalley fills «hang» from interfluve surfaces (i.e. subaerial unconformities; Fig. 3). Paleovalley systems have been mapped on allomembers E, F, G and H, using 4800 well logs and more than 100 outcrop sections. Valleys are typically 1-2 km wide and average 21 m deep (Plint 2002, Fig. 4A). Valley-fills are dominated by trough cross-bedded fluvial sandstones showing well-developed lateral-accretion surfaces. In more downdip areas, valley-fills are more mud-rich and show good evidence for deposition under tidal influence (Plint & Wadsworth 2003, Fig 4B). Valleys appear to have been occupied by meandering rivers that gradually aggrad-

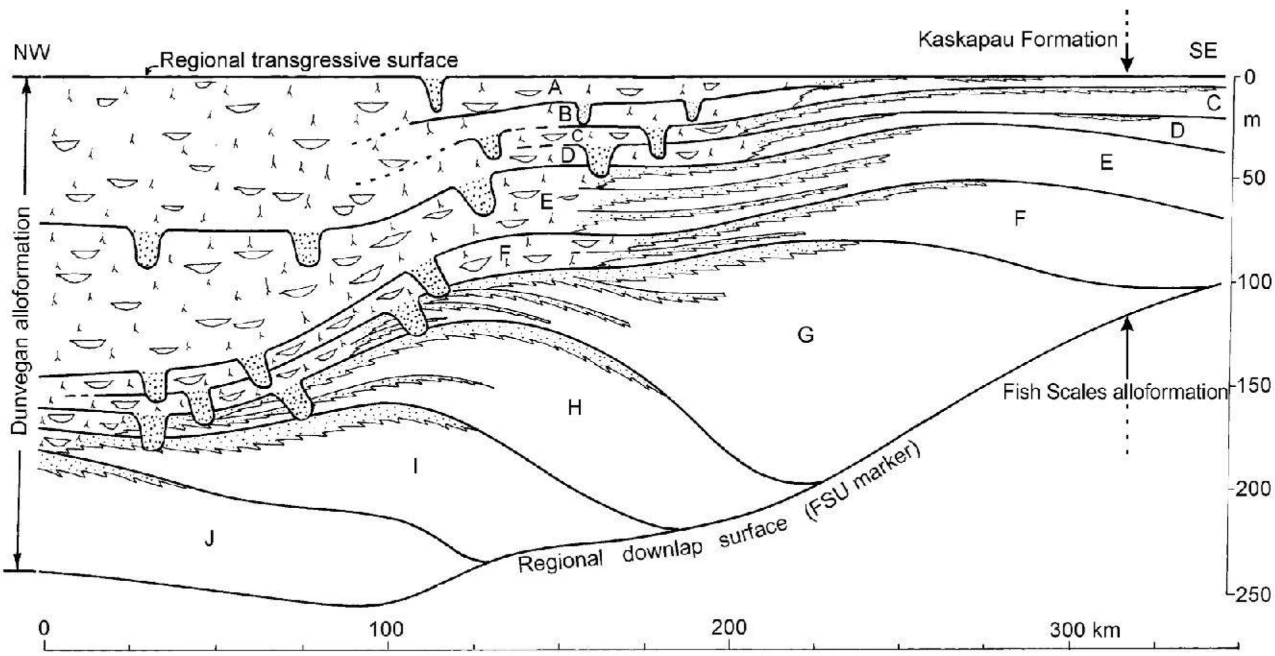

Fig. 3: Summary stratigraphic diagram, drawn to scale, showing the geometry and broad facies distribution of Dunvegan allomembers J-A in a NW-SE dip-oriented section (from Plint & Wadsworth 2003). Paleovalleys are incised into the top surfaces of most allomembers (which can also be interpreted as depositional sequences).

ed as base-level rose, filling the valley with a heterogeneous body of multi-storey point-bar sandstones, punctuated by locally-preserved interchannel mudstones. Bioturbated, sandier-upward successions, a few metres thick at the top of valley-fills may represent bay-head deltas (Fig. 4).

Systems Tracts and Migrating Shorelines

The stacking pattern of parasequences within allomembers shows an initially aggradational pattern, followed by pronounced offlap. Stacking patterns can be interpreted in terms of transgressive, highstand, falling stage and lowstand systems tracts, collectively forming a depositional sequence. Valley systems are interpreted to have been incised during the falling stage (Plint et al. 2001; Plint & Wadsworth 2003).

Successive transgressive and regressive shorelines were mapped for each Dunvegan sequence. Net deltaic progradation took place between Dunvegan allomembers J and C, although shorelines oscillated about 60–80 km between maximum transgressive and regressive positions (Fig. 5). In contrast, Dunvegan allomembers A and B show net

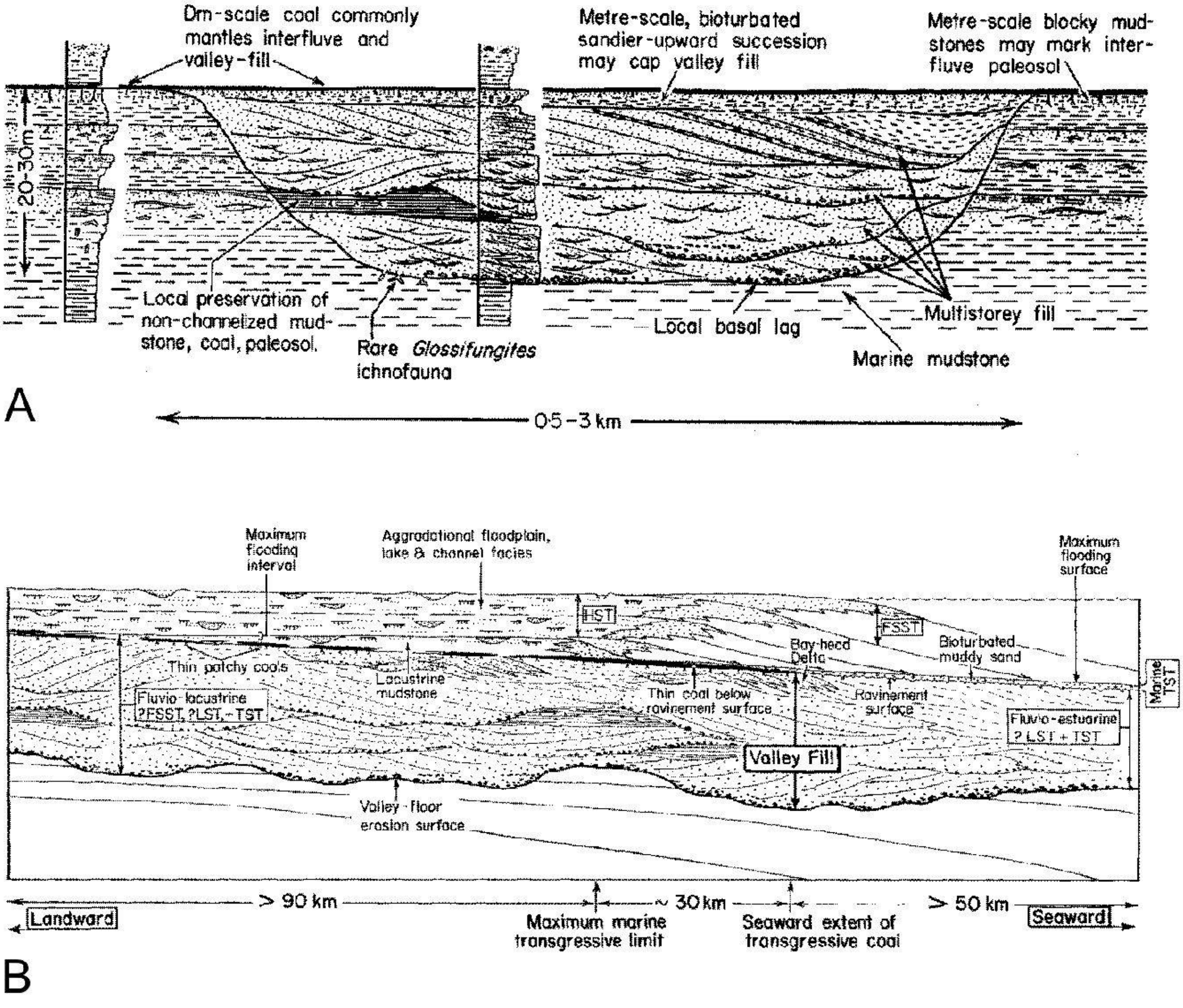

Fig. 4: A] Principal characteristics of Dunvegan paleovalley-fills seen in transverse view [from Plint & Wadsworth 2003]. B] Principal characteristics of Dunvegan paleovalley-fills seen in longitudinal view [from Plint & Wadsworth 2003]. The strata are divided into transgressive, highstand, falling stage and lowstand systems tracts.

backstep of about 250 km, although the regional transgression was punctuated by six high-frequency sequences. During net regression, progradational deltaic shorelines advanced about 50 km per sequence whereas during net transgression, transgresssive shorelines backstepped about 20 km per sequence (Hay & Plint 2009; Fig. 5). The low-frequency regressive-transgressive trend shown by Dunvegan shorelines is consistent with a global mid-Cenomanian eustatic lowstand that may be attributed to tectono-eustatic processes. The superimposed pattern of high-frequency sequences strongly suggests a eustatic control on a Milankovitch timescale.

Origin of Sequences

Depositional sequences are interpreted to be the result of eustatic changes on the order to 5-20 m on time-scales of < 200 000 years. Geometric considerations suggest that depositional sequences can not be attributed to changes in pattern or rate of tectonic subsidence. The only mechanism presently recognized to be capable of producing eustatic change of > 4 m on a timescale of the order of a few tens to a few hundred thousand years is glacio-eustasy (Miller et al. 2005). It therefore seems likely that the «greenhouse» world traditionally interpreted for the Cenomanian nevertheless included modest high-altitude ice caps on the Antarctic craton.

Controls on Valley Patterns

Paleovalleys on allomembers H, G and F have a preferred rectilinear pattern, and are inferred to have been influenced by very small syn-depositional offset on faults extending up from the Paleozoic basement (Fig. 6A). In contrast, valleys mapped on

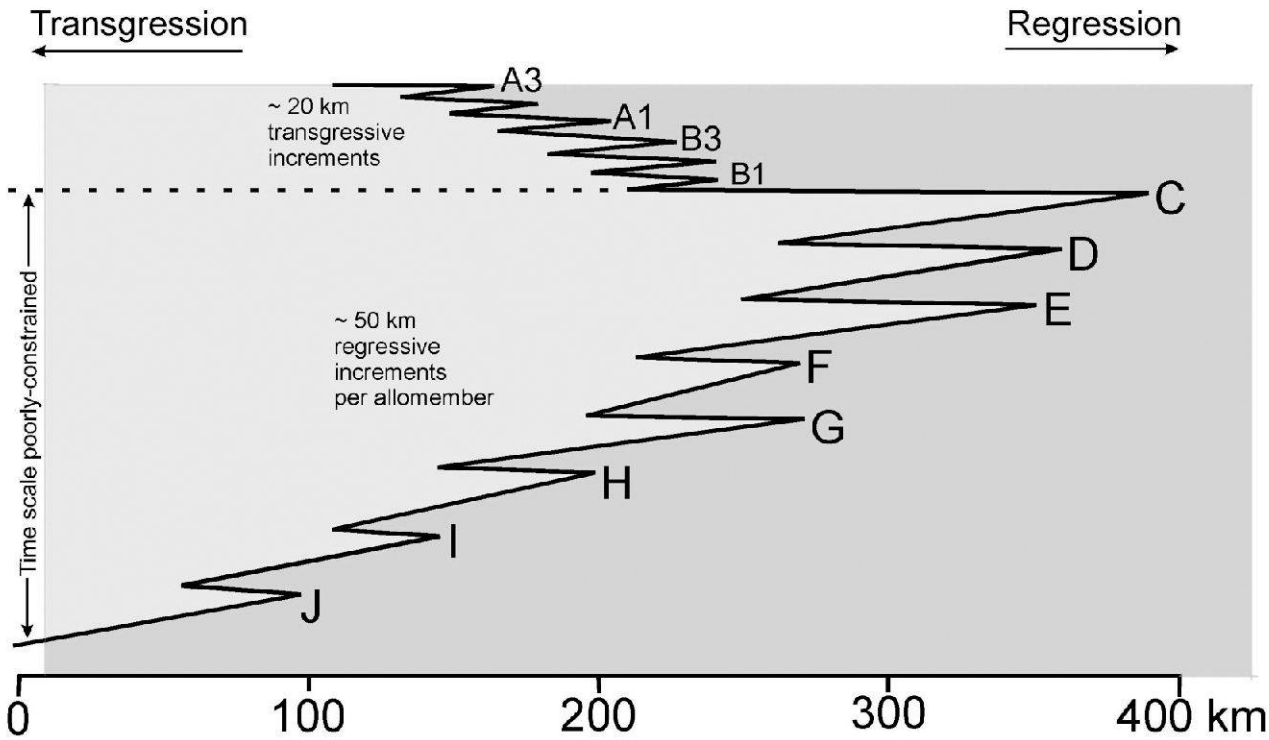

Fig. 5: Summary of generalized shoreline movements during deposition of the Dunvegan Formation, based on detailed paleogeographic maps in Plint 2000. Vertical time-scale is poorly-constrained; it seems likely that the entire formation was deposited in less than about two million years. Unpublished data suggest that the sequences in allomembers A and B may have been of shorter duration than those shown for allomembers J to C (based on Plint 2000 and Hay & Plint 2009).

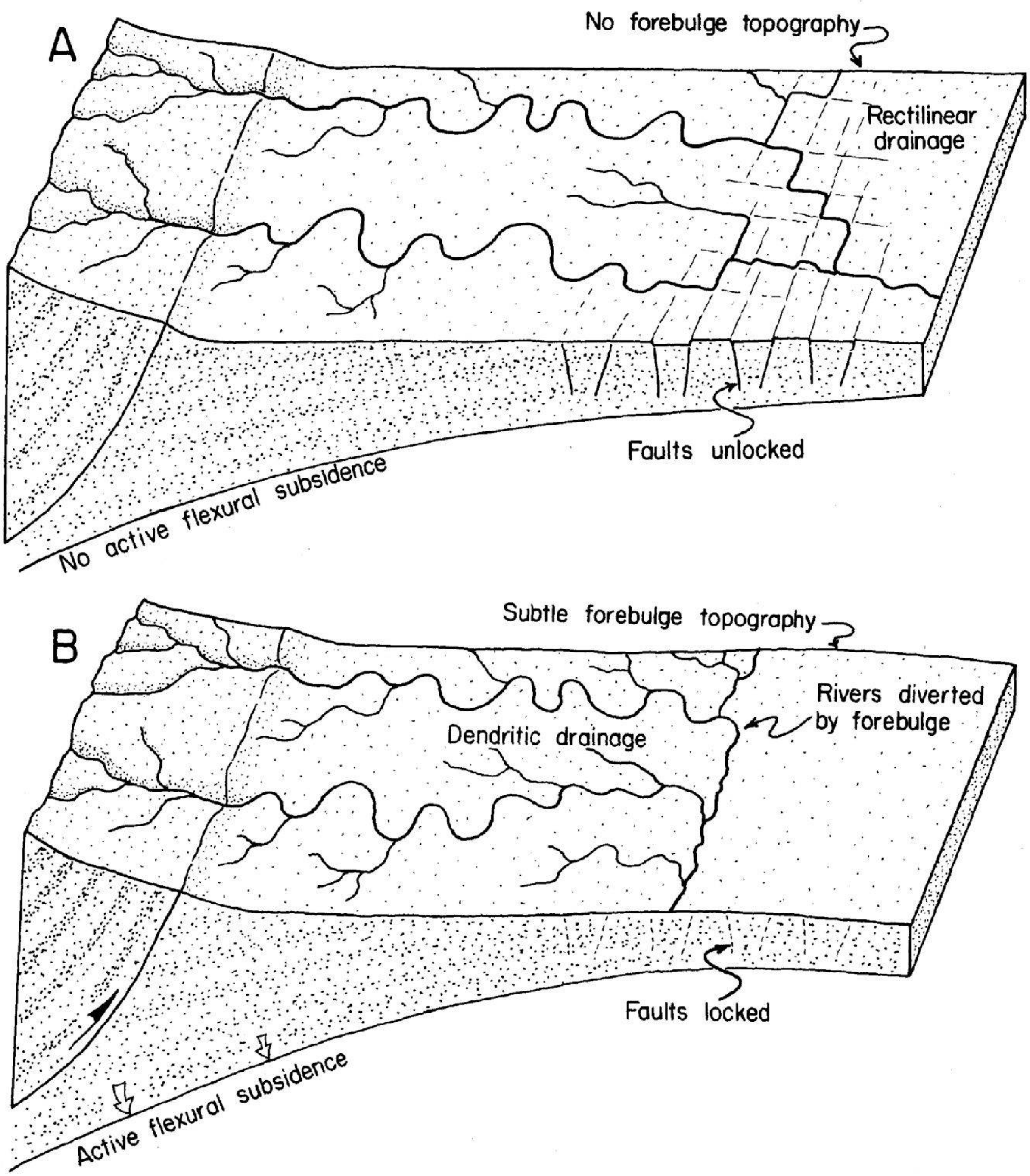

Fig. 6: A] Cartoon depicting the rectilinear pattern of paleovalleys formed in Dunvegan allomembers F, G and H. At this time, isopach maps show that there was negligible contemporaneous subsidence within the study area. It is interpreted that small (< 1 m?) vertical offset on isostatic (?) adjustment faults within the Paleozoic rocks of the underlying Peace River Arch controlled topography, and hence the pattern of rivers on the very low-gradient coastal plain. B] Cartoon depicting dendritic pattern of valleys in Dunvegan allomember E, and diversion of the trunk valley to the SE, parallel to the paleo-shoreline. This valley pattern is interpreted to be related to a new phase of contemporaneous subsidence in the western part of the study area (as indicated by isopach mapping). Faults in the Peace River Arch ceased to move, allowing rivers to migrate freely across the coastal plain, forming a dendritic pattern. It is possible that contemporaneous subsidence in the west caused uplift of a subtle forebulge in the east, that in turn lead to river diversion to the SE (from Plint & Wadsworth, 2006).

allomember E have a strongly dendritic pattern, seem to have been little influenced by faulting, and show diversion of the trunk valley system to the SE, parallel to paleoshoreline (Plint & Wadsworth 2006; Fig. 6B). Isopach maps show that allomembers H, G and F were deposited during a time of negligible updip subsidence (isopachs do not show thickening towards the west or NW). In contrast, allomember E shows pronounced updip thickening in the NW, suggestive of renewed, tectonically-driven subsidence in that area. The relationship of valley patterns to local subsidence regime suggests that basement faults were «unlocked» at times of no local subsidence but were «locked» when active tectonic loading was taking place, when subtle forebulge uplift may have diverted the trunk river to the SE (Plint & Wadsworth 2006; Fig. 6).

Subsidence Rate and Sediment Dispersal

Isopach maps show that, in the NW, Dunvegan deltas were initially deposited in an area of rapid subsidence, in water perhaps as much as 100 m deep in which tall, relatively steep muddy clinoforms were deposited. Clinoforms lap out ~ 80 km from the delta front, suggesting that offshore dispersal of mud was relatively inefficient. Within the clinoforms, wave ripples are absent below a paleo water-depth of about 40 m, suggesting that wave re-suspension of mud below this depth was rare (Fig. 7A). Towards the southeast, the deltas prograded into an area experiencing a lower subsidence rate. In this area of diminished subsidence, prodelta clinoforms gradually become longer and lower, finally becoming parallel for over 400 km. In the area of low subsidence rate, the sea floor is interpreted to have aggraded to < ~ 40 m water depth, above which storm-driven wave re-suspension resulted in efficient off- and along-shore dispersal of mud (Plint et al. 2009, Fig. 7B). The lateral change from steep, tall clinoforms, through less steep, less tall clinoforms, to no clinoforms over a 950 km dip transect suggests that offshore mud dispersal was strongly controlled by effective wave base, which appears to have lain at about 40 m. Clinoforms, which are rare in the Canadian portion of the foreland basin, seem to form only when accommodation is greater than supply, resulting in relatively deep water and consequent inefficient mud dispersal. The scarcity of clinoforms in most Cretaceous «shelf» mudstone units in Western Canada implies that for most of the time, supply was greater than accommodation, wave-driven dispersal was efficient, and water depth rarely exceeded ~ 40 m, even at distances of > 300 km from shore (e. g. Varban & Plint 2008, Hu & Plint 2009; Fig. 7).

Spatial and Temporal Changes in Subsidence Rate

Isopach maps of successive Dunvegan allomembers show the evolution of the flexural depocentre over about 2 million years (Plint 2003). Three maps (Figs. 8A-C) serve to illustrate the geometric evolution of the Dunvegan depocentre. Allomember J (Fig. 8A) comprises a deltaic succession up to 130 m thick. The sediment wedge thickens dramatically towards the NW and indicates the presence of a major flexural depocentre to the NW of the study area (Fig. 2). Allomembers I to F (exemplified by allomember G, Fig. 8B), show a sigmodial isopach pattern, thinning to the SE by downlap onto the condensed section (FSU surface; Figs. 2, 3), and also thinning updip to the NW. The consistent updip thinning of coastal plain sediments in allomembers I to F indicate that very little accommodation was being created on the coastal plain at this time. Isopach lines consistently trend perpendicular to the NW-SE trend of the present-day fold-and-thrust belt (Figs. 8A, B). This indicates that little or no contemporaneous subsidence was taking place in the immediately adjacent portion of the fold and thrust belt. Thus, the locus of subsidence prior to and including Dunvegan allomember J is interpreted to have lain far to the NW in northern British Columbia; subsidence has been related to the obduction of the Stikine Terrane onto the margin of North America (Plint et al. in press, 2011). The sigmoidal geometry of Dunvegan allomembers I through F (and allomembers C and D) suggest passive filling of a previously-created depocentre. Dunvegan allomember E, and allomembers A and B indicate a very different pattern of subsidence (Plint 2003, Hay & Plint 2009, Fig. 8C). A new semi-circular depocentre is evident in the west, suggesting contemporaneous flexural subsidence in response to renewed thrust activity in the adjacent fold and thrust belt. The western depocentre in Fig. 8C is filled entirely with coastal plain facies, implying that the sedimentation rate was adequate to fill the newly-created accommodation and hence prevented incursion of the sea. However, this new phase of local subsidence gradually shifted the accommodation : supply ratio in favour of accommodation, ultimately leading to the drowning of the entire delta complex at the top of allomember A (Hay & Plint 2009).

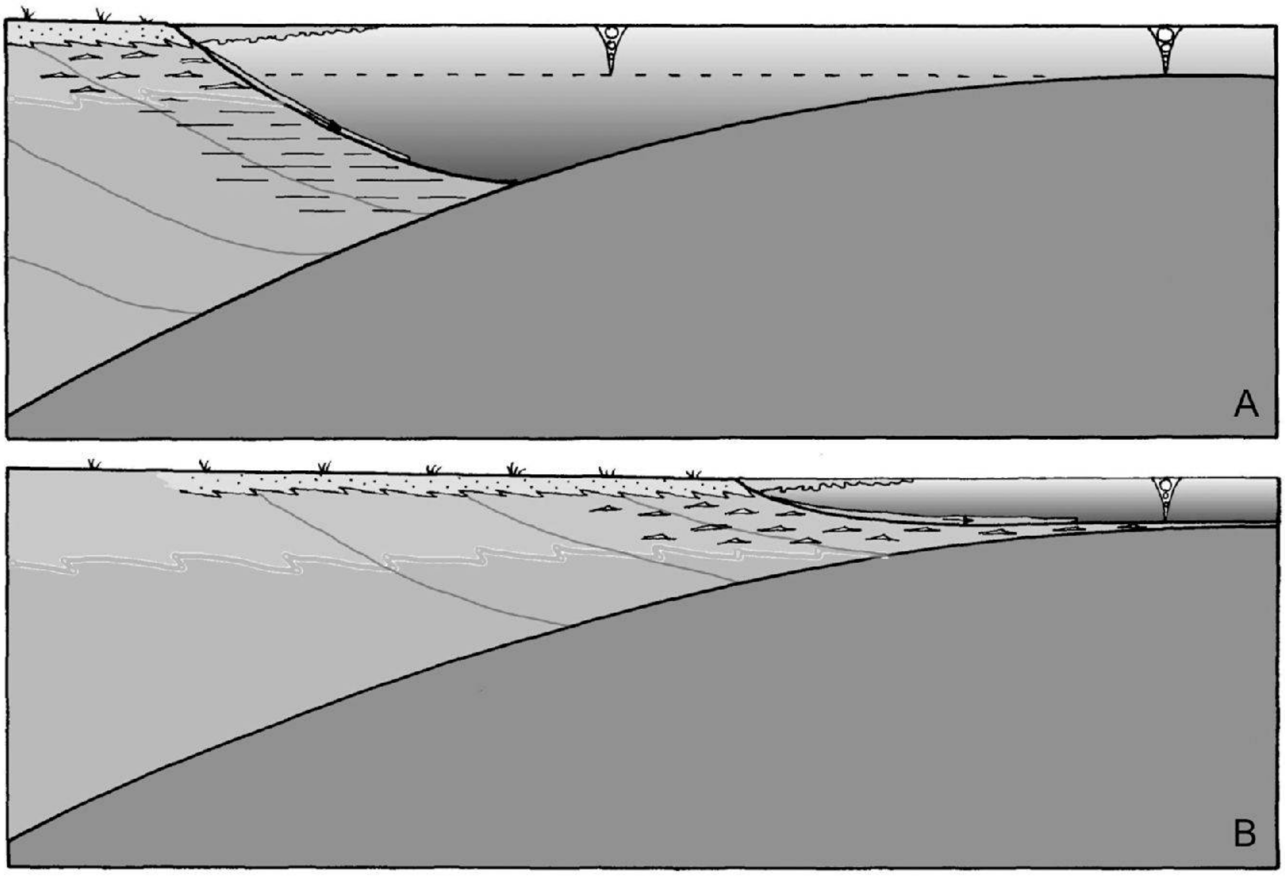

Fig. 7: A] Cartoon depicting interpreted mechanisms of dispersal of muddy sediment issuing from Dunvegan deltaic distributaries when the deltas were prograding into relatively deep water (~ 100 m) that resulted from a preceding phase of rapid flexural subsidence early in Dunvegan time (allomembers J-G). Mud in a hypopycnal plume rapidly flocculated and settled within < 50 km of shore. Storms are interpreted to have resuspended prodelta sediment to an effective wave base of about 40 m. Resuspended mud aggregates may have been moved downslope as wave-supported density flows, and/or along slope as geostrophic combined flows. The lap-out of prodelta mud about 80 km from the paleo-shore indicates the maximum distance to which mud could be remobilized and transported. B]. Cartoon depicting deposition of Dunvegan allomembers F to A, at a time when the deltas had prograded into an area of much lower subsidence. In this more southern region, the rate of sediment supply was adequate to maintain the sea floor at or above ~ 40 m depth and as a result, mud on the sea floor was resuspended by innumerable storms; the mud is interpreted to have been dispersed seaward and along-shelf by geostrophic flows (based on Plint et al. 2009).

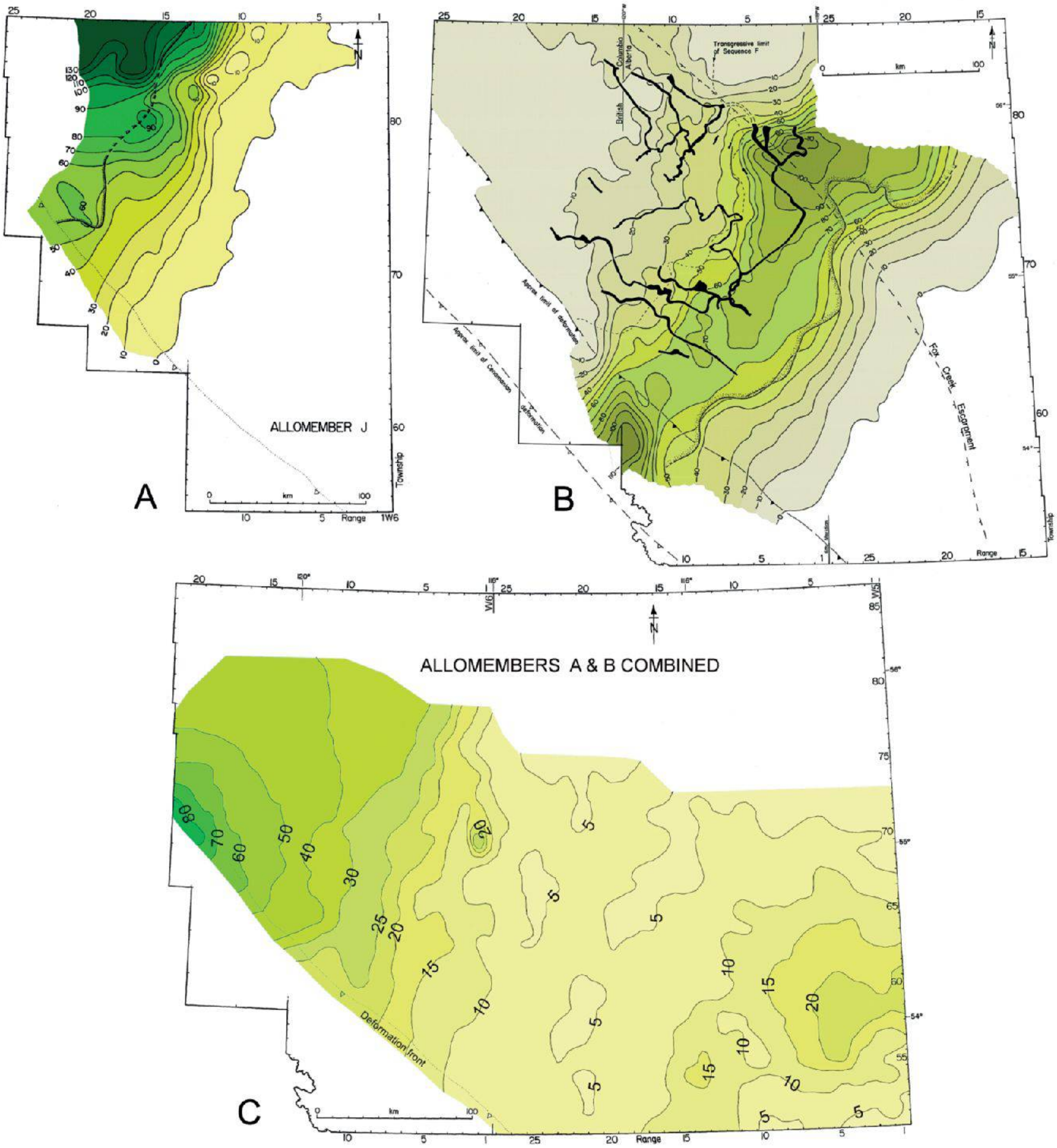

Fig. 8: A] Isopach map of Dunvegan allomember J, with superimposed progradational limit of the delta-front sandstone, shown by the stippled line. The strata thicken rapidly north-westward, and continue to do so to the NW of the study area. This is interpreted to record deposition during and following a phase of rapid tectonic subsidence due to accretion of the Stikine Terrane to the NW (from Plint 2003, Plint et al. in press). B] Isopach map of Dunvegan allomember G, showing progradational extent of the delta-front, and the distribution of paleo-valleys (from Plint & Wadsworth 2006). The updip thinning of coastal plain deposits shows that there was negligible contemporaneous subsidence in the NW. Similarly, the orientation of isopachs, perpendicular to the present margin of the fold and thrust belt show that there was no contemporaneous subsidence (and hence no contemporaneous thrusting), in the adjacent segment of the Cordillera to the West. C] Isopach map of Dunvegan allomembers A and B showing the appearance of a new depocentre in the NW corner of the study area; this is interpreted to record renewed crustal thickening immediately to the West. This depocentre is filled with coastal plain deposits, showing that the rate of sediment supply was adequate to prevent marine invasion of this area. Nevertheless, the regional marine transgression at the top of Dunvegan allomember A can probably be related largely to this new phase of tectonic subsidence (from Hay & Plint 2009).

Main Conclusions

1. Transgressive and regressive shoreline limits in the Dunvegan Formation migrated 60–80 km per sequence during overall regression of the delta complex. The time-scale (< 200 000 years) and inferred amplitude (< ~ 20 m) of sea-level change strongly suggests a glacio-eustatic control, modulated by Milankovitch-band climate cycles. The traditional view of the mid-Cretaceous as an ice-free «greenhouse world» may not be correct.
2. Flexural depocentres, with radius of 100 to > 300 km were created on timescales of 10 000's to a few 100 000 years. These arcuate depocentres accumulated strongly wedge-shaped packages of rock, and are inferred to record episodic thickening of the immediately adjacent orogenic wedge. Depocentres migrate hundreds of km along strike on a time-scale of 10 000's to 100 000's of years, reflecting short-term inhomogeneous strain in the fold and thrust belt.
3. A change in paleo-valley pattern, from rectilinear to dendritic, appears to coincide with a pulse of flexural subsidence. Rectilinear valleys may reflect control by subtle offset on faults extending up from the Paleozoic basement. Renewed flexure apparently locked faults and allowed rivers to adopt a «normal» dendritic pattern across a homogeneous substrate of unconsolidated coastal plain sediments.

References

Hay, M. J. & Plint, A. G. 2009: An allostratigraphic framework for a retrogradational delta complex: the uppermost Dunvegan Formation (Cenomanian) in subsurface and outcrop, Alberta and British Columbia. Bulletin of Canadian Petroleum Geology, 57, p. 323–349.

Hu, Y. G. & Plint, A. G. 2009: An allostratigraphic correlation of a mudstone-dominated syn-tectonic wedge: The Puskwaskau Formation (Santonian-Campanian) in outcrop and subsurface, Western Canada foreland basin. Bulletin of Canadian Petroleum Geology, 57, p. 1–33.

Lumsdon-West, M. P. & Plint, A. G. 2005: Changing Alluvial Style in Response to Changing Accommodation Rate in a Proximal Foreland Basin Setting: Upper Cretaceous Dunvegan Formation, NE British Columbia, Canada. In: Fluvial Sedimentology VII, ed. by M. D. Blum, S. B. Marriott & S. Leclair. International Association of Sedimentologists, Special Publication No. 35, p. 493–515.

McCarthy, P. J. & Plint, A. G. 1998: Recognition of interfluve sequence boundaries: Integrating paleopedology and sequence stratigraphy. Geology, v. 26, p. 387–390.

McCarthy, P. J., Faccini, U. F. & Plint, A. G. 1999: Evolution of an ancient floodplain: palaeosols and alluvial architecture in a sequence stratigraphic framework, Cenomanian Dunvegan Formation, NE British Columbia, Canada. Sedimentology, 46, 861–891.

McCarthy, P. J. & Plint, A. G. 2003: Spatial variability of palaeosols across Cretaceous interfluves in the Dunvegan Formation, NE British Columbia, Canada: palaeohydrologic, palaeogeomorphologic and stratigraphic implications. Sedimentology, 50, 187–220.

Miller, K. G., Wright, J. D. & Browning, J. V. 2005: Visions of ice sheets in a greenhouse world. Marine Geology, 217, 215–231.

Plint, A. G. 2000: Sequence stratigraphy and paleogeography of a Cenomanian deltaic complex: the Dunvegan and lower Kaskapau formations in subsurface and outcrop, Alberta and British Columbia, Canada. Bulletin of Canadian Petroleum Geology, 47, 43–79.

Plint, A. G. 2002: Paleo-valley systems in the Upper Cretaceous Dunvegan Formation, Alberta and British Columbia. Bulletin of Canadian Petroleum Geology, 50, 277–296.

Plint, A. G. 2003: Clastic sediment partitioning in a Cretaceous delta system, western Canada: Responses to tectonic and sea-level controls. Geologia Croatica, 56, 39–68.

Plint, A. G. & Wadsworth, J. A. 2003: Sedimentology and palaeogeomorphology of four large valley systems incising delta plains, Western Canada Foreland Basin: implications for mid-Cretaceous sea-level changes. Sedimentology, 50, 1147–1186.

Plint, A. G. & Wadsworth, J. A. 2006: Delta plain paleodrainage patterns reflect small-scale fault movement and subtle forebulge uplift: Upper Cretaceous Dunvegan Formation, Western Canada Foreland Basin. In: Incised Valley Systems in Time and Space, ed. by R. W. Dalrymple, D. A. Leckie & R. W. Tillman. Society of Economic Paleontologists and Mineralogists, Special Publication 85, 219–237.

Plint, A. G., McCarthy, P. J. & Faccini, U. F. 2001: Nonmarine sequence stratigraphy: Updip expression of sequence boundaries and systems tracts in a high-resolution framework, Cenomanian Dunvegan Formation, Alberta Foreland Basin, Canada. American Association of Petroleum Geologists, Bulletin, 85, 1967–2001.

Plint, A. G., Tyagi, A., Hay, M. J., Varban, B. L., Zhang, H. & Roca, X. 2009: Clinoforms, paleobathymetry, and mud dispersal across the Western Canada Cretaceous foreland basin: evidence from the Cenomanian Dunvegan Formation and contiguous strata. Journal of Sedimentary Research, 79, 144–161.

Plint, A. G., Tyagi, A., McCausland, P. J. A., Krawetz, J. R., Zhang, H., Roca, X., Hu, Y. G., Varban, B. L., Kreitner, M. A. & Hay, M. J. 2011: Dynamic relationship between subsidence, sedimentation, and unconformities in mid-Cretaceous, shallow marine strata of the Western Canada Foreland Basin: Links to Cordilleran Tectonics. In: Busby, C. & Azor, A. (eds.), Recent Advances in the Tectonics of Sedimentary Basins. Wiley Blackwell, in press.

Varban, B. L. & Plint, A.G. 2008: Palaeoenvironments, palaeogeography, and physiography of a large, shallow, muddy ramp: Late Cenomanian-Turonian Kaskapau Formation, Western Canada foreland basin. Sedimentology, 55, 201–233.