[PS]Synsedimentary Deformation and Erosion of the Exshaw/Sappington Formation in West-Central Montana: Evidence for a Brief Basin Polarity Switch and Development of Paleohighs along the Western Bakken Fairway*

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Abstract

The Bakken-equivalent Sappington Formation in west-central Montana provides good evidence for tectonically driven instability and an explanation for why part of the Devonian-Mississippian rock record is locally absent. Similar to the Bakken, the Sappington Formation comprises organic-rich basal black shale, a shallowing-upward Siltstone Member, and younger upper black shale that correlates with the basal Lodgepole Formation. In south-central Montana, north of Yellowstone Park, all three members are well developed. The facies and stacking patterns record an east-to-west, down-to-basin polarity for the incipiently subsiding Central Montana Trough. To the northwest in the Three Forks area, the lower black shale is locally eroded below the basal part of the Siltstone Member (e.g. Logan Type Section) before thickening substantially to the west. The upper black shale displays a nearly opposite distribution. It is missing west of Three Forks and in other parts of northwestern Montana, like along the southern Sweetgrass Arch (Alberta Bakken Fairway), where the Siltstone Member is also missing.

West of Three Forks at Milligan Canyon, the Siltstone Member is deformed into meter-scale detached slump folds that moved down a southeast-oriented paleoslope. After slumping, the folds were sharply truncated by erosive currents and mid to distal ramp encrinite beds of the lower Lodgepole. A southeast paleoslope and widespread submarine erosion demonstrate that basin polarity switched to a west-to-east orientation during the Early Mississippian in western Montana. Paleohighs such as the Lemhi Arch (southwest Montana) and the paleo Sweetgrass Arch and 'Montania' (northwestern Montana) were active at this time and subjected to erosion or nondeposition. Basin polarity reverted back again to an east-to-west orientation after filling of accommodation space, continued Mississippian subsidence and westward progradation of the Madison Group.

We conclude that the polarity reversal and erosion of the western upper black shale provides evidence for basin inversion, indicative of a complexly loaded plate margin reactivated across shelf paleohighs and cratonic intrashelf basins (migration of an Antler forebulge?). Although strata often look more subtly disconformable, our observations explain why there is an erosive submarine hiatus in the earliest Mississippian and why key Bakken reservoir units were locally thinned or removed prior to Lodgepole deposition.

Synsedimentary deformation and erosion of the Exshaw/ Sappington Formation in west-central Montana: evidence for brief basin polarity switch and development of paleohighs along the western Bakken fairway

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SUMMARY

Recent outcrop study of the Bakken-equivalent Sappington Formation in the Three Forks area provides evidence for tectonically driven instability and explains the local absence of the upper black shale in the western Central Montana Trough. Thinning of the Sappington can also be seen regionally over the Scapegoat-Bannatyne Trend and over Montania to the northwest, as well as over the Lemhi Arch and Central Montana Uplift. Local development of synsedimentary folds at Milligan Canyon suggest seismic or gravity-generated resedimentation of Sappington silts and sands on a southeast-oriented paleoslope (which runs counter to east-west, shelf-to-basin Sappington stratigraphy and slope in the Central Montana Trough). Southeast-directed folding is also counter to long term Devonian and Mississippian paleoshelf orientation. Synsedimentary folds were sharply truncated by erosive currents and back filled by Lodgepole high-energy crinoidal grainstone before undergoing subsidence and burial below distal ramp facies.

INTRODUCTION

The presence or absence of black shales and a coarsening-upward Middle Member in the Sappington/Bakken is of interest in terms of similar regional stratigraphic variation and petroleum exploration. Also differentiation on logs between the Bakken and underlying Three Forks Formation can be unclear. Although these units have distinctive characteristics and are bound by sequence boundaries, stratigraphic variations are complicated especially in the west by nondeposition or erosion in an active continental borderland setting.

This work focuses on outcrop variations in the Sappington Formation at Milligan Canyon in the context of more regional correlations. The Sappington Formation was deposited in the Central Montana Trough and shows facies, thickness and sequence similarities to the three Bakken members of the intracontinental Williston Basin. At the edges of such basins these units were subject to facies changes as well as physical nondeposition/ erosion and temporal hiatuses suggestive of eustatic sea level changes and composite sequence boundaries. Like the northwestern Williston Basin of Saskatchewan, the Sappington Middle Member developed sandy, high-energy shoreface to intertidal facies in its upper part (Christopher, 1961, Angulo et al, 2009). We present a local example of more offshore correlatives of these facies (Sappington "western facies") that were folded and truncated below Lodgepole crinoidal grainstone, resulting in the nondeposition of an upper Bakken or basal Lodgepole black shale.

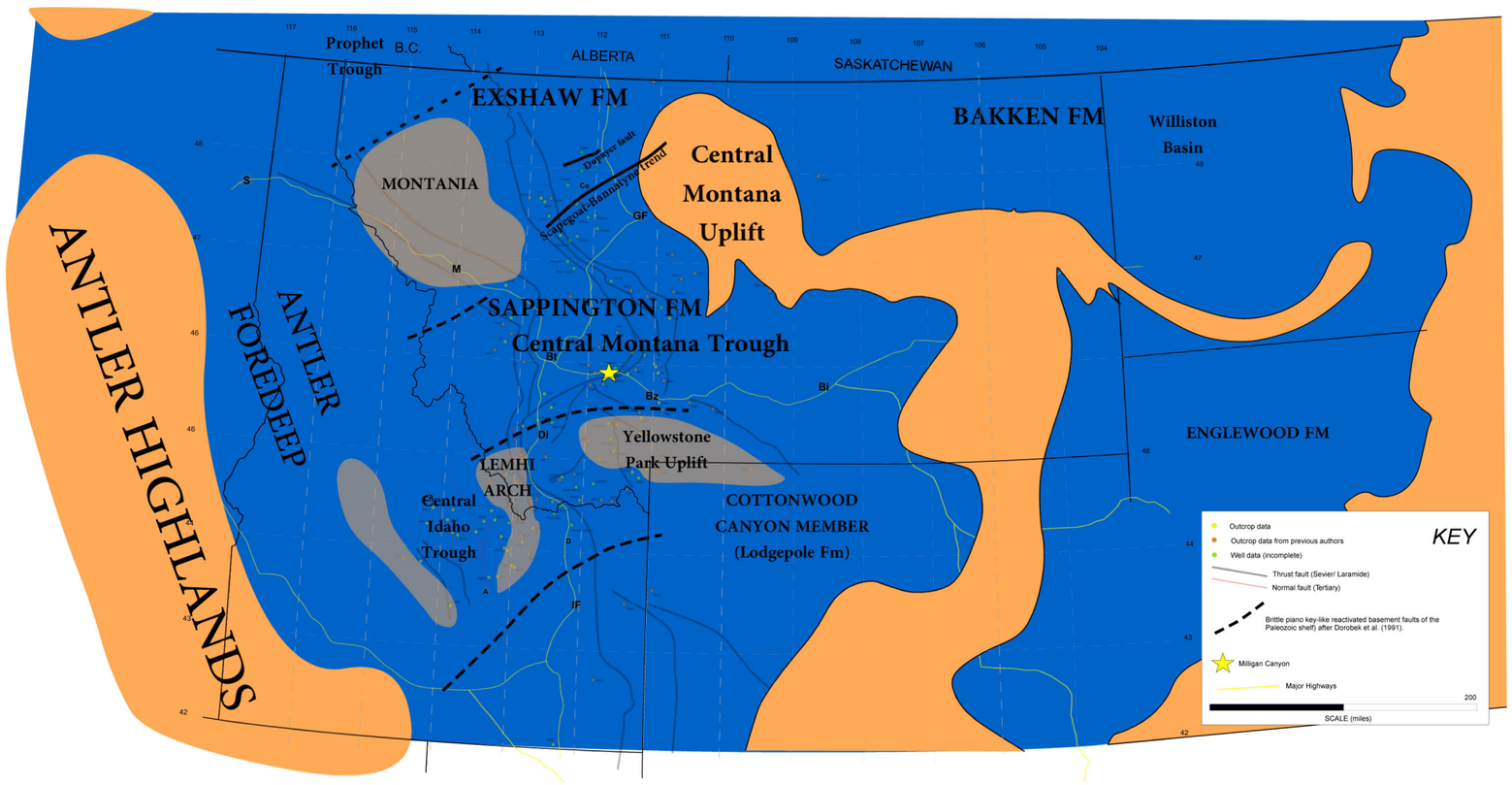
Stratigraphy

Similar to the Bakken and Exshaw formations, the Sappington Fm. comprises a Late Famennian organic-rich basal black shale (0 - 40 ft thick), a shallowing-upward siltstone member (reservoir: <60 to >100 ft), and an Early Tournaisian upper black shale (0 - 5 ft) that is sequentially correlative with the basal Lodgepole and Banff formations. A mid-siltstone Member shale unit (Unit 4) also occurs and can be regionally defined in the eastern Central Montana Trough.

Northwest of Yellowstone Park near Bozeman, all three Sappington members are well developed and individual units can be laterally correlated (after Gutschick et al., 1962; 1964, Hammond and Sandberg, 1958). The facies and stacking patterns suggest a generally east-to-west, down-to-basin polarity for the incipiently subsiding Central Montana Trough. Devonian and Mississippian units generally show significant thickness and facies changes away from the Montana-Wyoming stable craton/shelf and towards Idaho (i.e., over the subsident older, outer shelf, and in and around intrashelf basins and Antler borderlands).

Black Shale distribution

Near Three Forks, Montana the lower black shale is locally eroded below the basal transgressive limestone of the Siltstone Member and can thin from ~20+ ft at Beaver Creek, or 10 ft at Hardscrabble to less than 1 ft at the Logan Devonian Type Section. This thinning was most likely due to submarine erosion under a transgressive limestone (similar but different in scale to the Lodgepole disconformity above the upper black shale). The lower black shale thickens substantially to the southwest and, similar to the Exshaw Formation, may become a condensed deep sea interval below thick Mississippian turbidities. The upper black shale occurs east of western Montana where sandstone turbidites occur within it, suggesting that it may be genetically coeval with synsedimentary folds at Milligan Canyon as well as coarse, upper Sappington Unit 6 sandstones with black shale stringers observed at other locations. The upper black shale remains consistently thin below the Lodgepole Formation east of the Lombard thrust in the Helena Salient. Its distribution in the Central Montana Trough is nearly opposite to the lower black shale, with an area of overlap between the two units (see figure). The upper black shale is missing west of Three Forks, typically replaced by a thin transitional zone of sandy carbonates with scoured erosional surfaces (e.g. Lone Mountain).

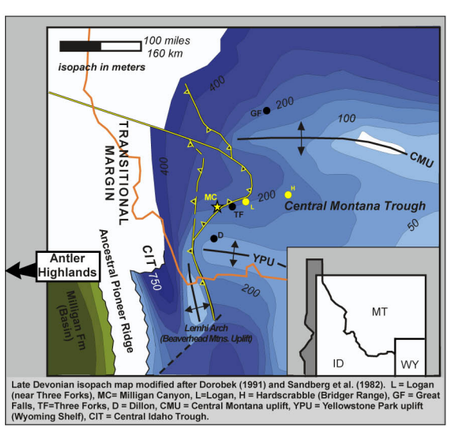


Latest Devonian paleogeographic sketch showing emergent/ submergent islands and subbasins along the shelf during Antler loading of the North American plate

(adapted after Baars, 1972)

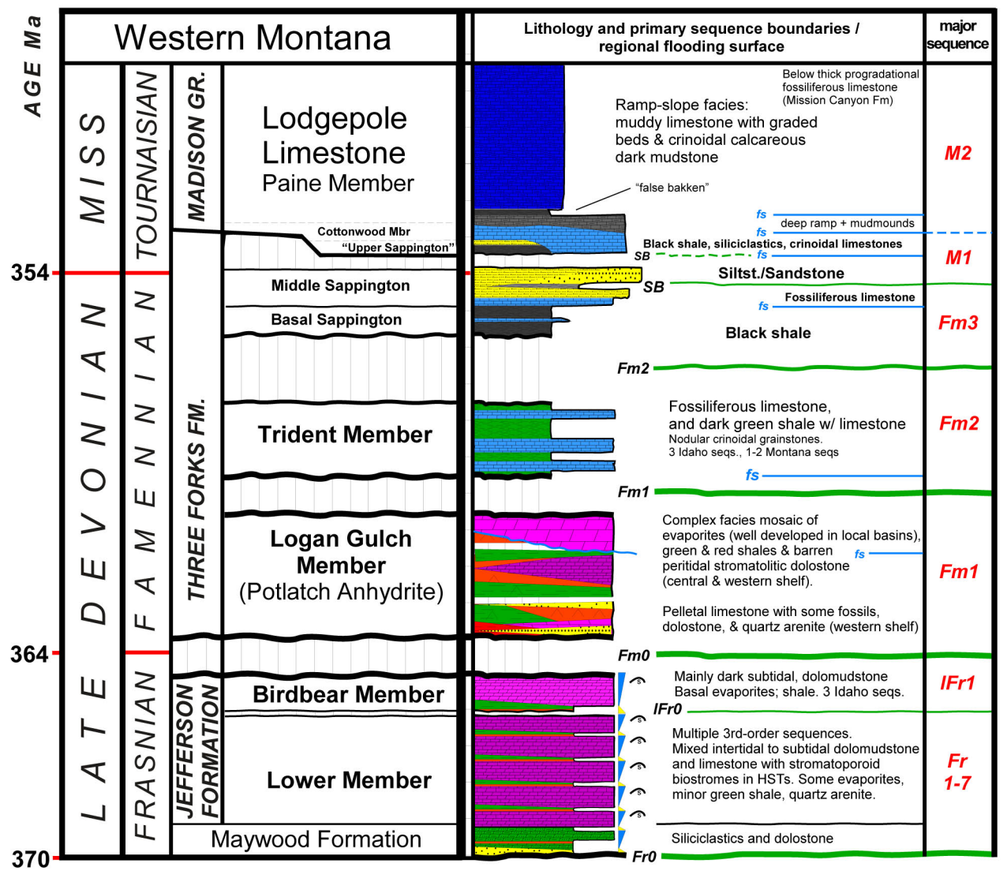
Truncated Synsedimentary Folds

A key outcrop occurs west of Three Forks on the same thrust panel with Lone Mountain at Milligan Canyon East where the upper siltstone unit is deformed into meter-scale detached synsedimentary folds that are consistent with slumping on a southeast oriented paleoslope. Following slumping, the Sappington was truncated by erosive currents and no upper black shale was deposited. Medium to thick bedded mid-ramp encrinite beds of the lower Lodgepole were deposited above the truncation surface. Nearby at Dry Hollow, upper Sappington high-energy, cross-bedded to massive medium sandstones occur undeformed below the lower Lodgepole. A southeast-oriented paleoslope and widespread submarine erosion suggest that the basin polarity switched to a west-to-east orientation during the Early Mississippian in western Montana. Ancient paleohighs such as the Lemhi Arch (Beaverheads Mountains uplift) in the south and the Scapegoat-Bannatyne Trend and 'Montania' in northwestern Montana were active at this time, associated with nondeposition and thinning of the Sappington and Three Forks. In some western locations the Lodgepole appears to overlie and thick black shale (lower + upper shale?) above the Late Devonian Jefferson or Birdbear/Nisku. Regional basin polarity reverted to an east-to-west orientation after filling of accommodation space, followed by continued intense Mississippian subsidence and large scale westward progradation of the Madison Group.



Late Devonian isopach map modified after Dorobek (1991) and Sandberg et al. (1982). L = Logan (near Three Forks), MC= Milligan Canyon, L=Logan, H = Hardscrabble (Bridger Range), GF = Great Falls, TF=Three Forks, D = Dillon, CMU = Central Montana uplift, YPU = Yellowstone Park uplift (Wyoming Shelf), CIT = Central Idaho Trough.

Approximate Late Devonian isopach



Late Devonian Stratigraphy of western Montana

Time-slice latest Devonain lithofacies & isopach maps (from Sandberg et al, 1982)

Three Forks Formation | **Sappington / Bakken Formation**

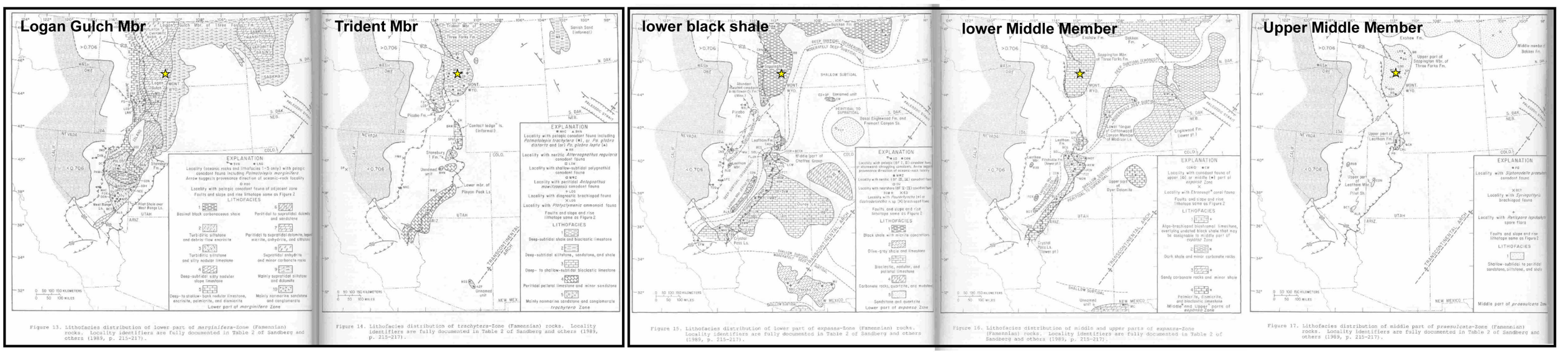


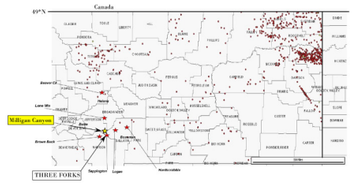
Figure 13. Lithofacies distribution of lower part of *marginifera*-Zone (Famennian) rocks. Locality identifiers are fully documented in Table 2 of Sandberg and others (1989, p. 215-217).

Figure 14. Lithofacies distribution of *trachytera*-Zone (Famennian) rocks. Locality identifiers are fully documented in Table 2 of Sandberg and others (1989, p. 215-217).

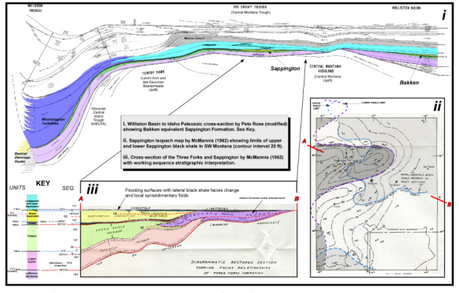
Figure 15. Lithofacies distribution of lower part of *expansa*-Zone (Famennian) rocks. Locality identifiers are fully documented in Table 2 of Sandberg and others (1989, p. 215-217).

Figure 16. Lithofacies distribution of middle and upper parts of *expansa*-Zone (Famennian) rocks. Locality identifiers are fully documented in Table 2 of Sandberg and others (1989, p. 215-217).

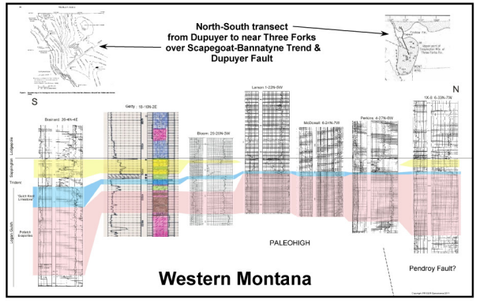
Figure 17. Lithofacies distribution of middle part of *praesulcata*-Zone (Famennian) rocks. Locality identifiers are fully documented in Table 2 of Sandberg and others (1989, p. 215-217).



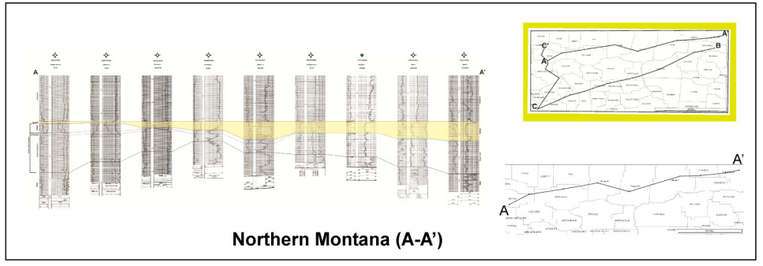
Montana Location Map - Wells and Outcrops



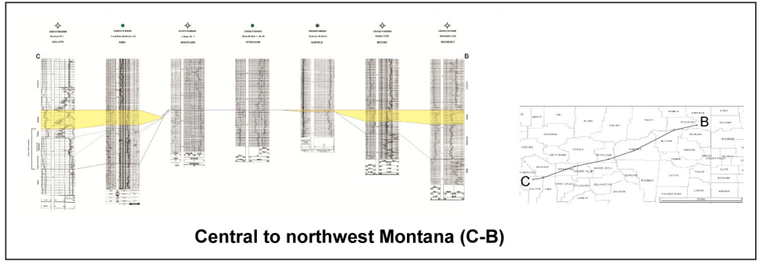
Late Devonian in the Central Montana Trough and Sappington black shale distribution



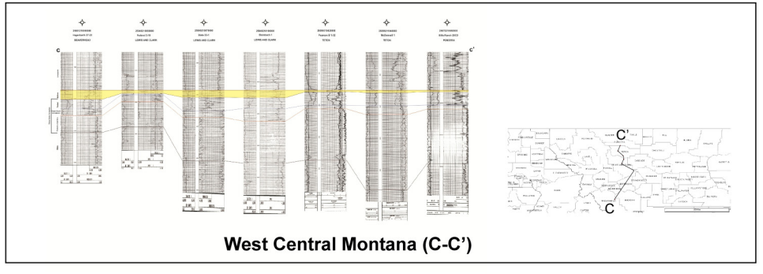
Western Montana



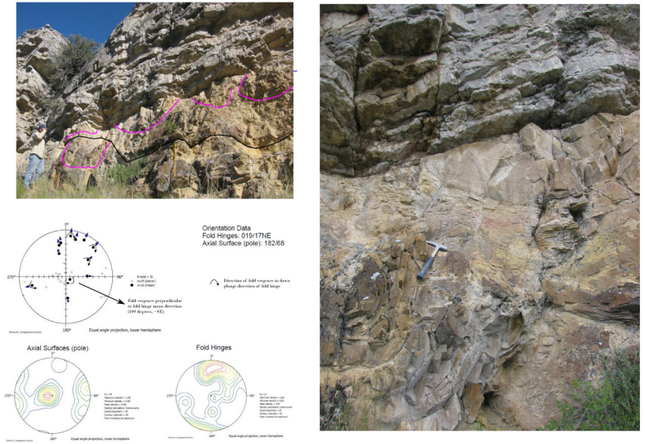
Northern Montana (A-A')



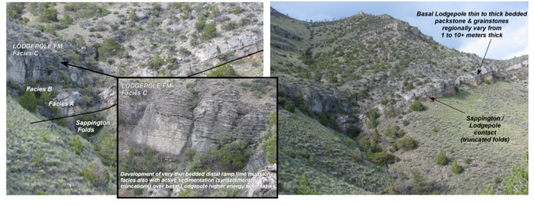
Central to northwest Montana (C-B)



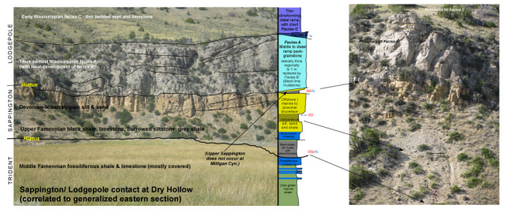
West Central Montana (C-C')



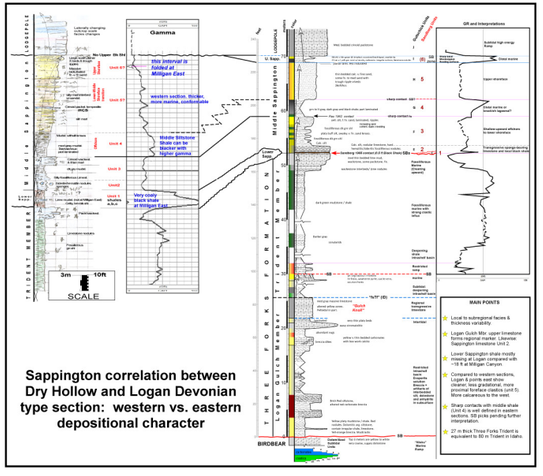
Synsedimentary folds in the upper Sappington at Milligan Canyon



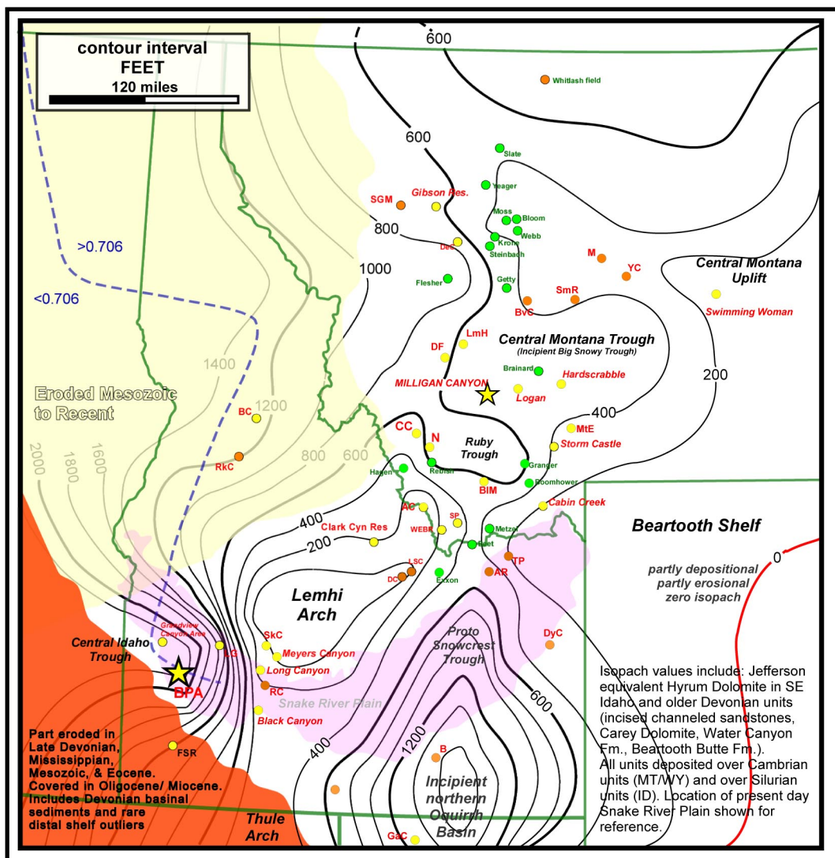
Synsedimentary folds at Milligan Canyon truncated by the Lodgepole Formation



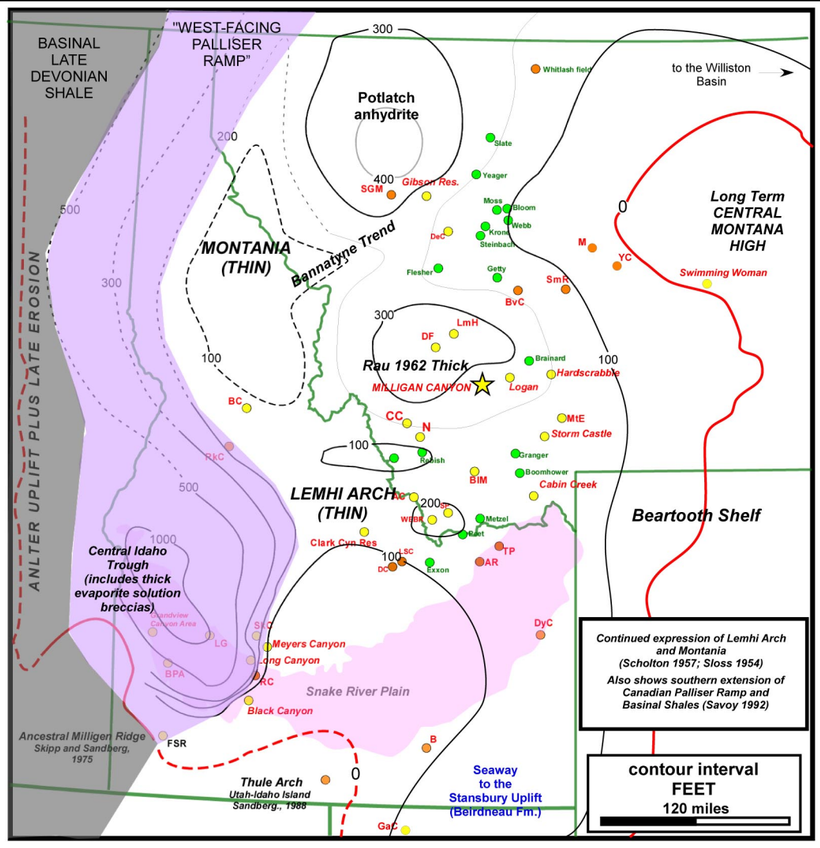
Sappington and basal, thickened Lodgepole at Dry Hollow, Milligan Canyon



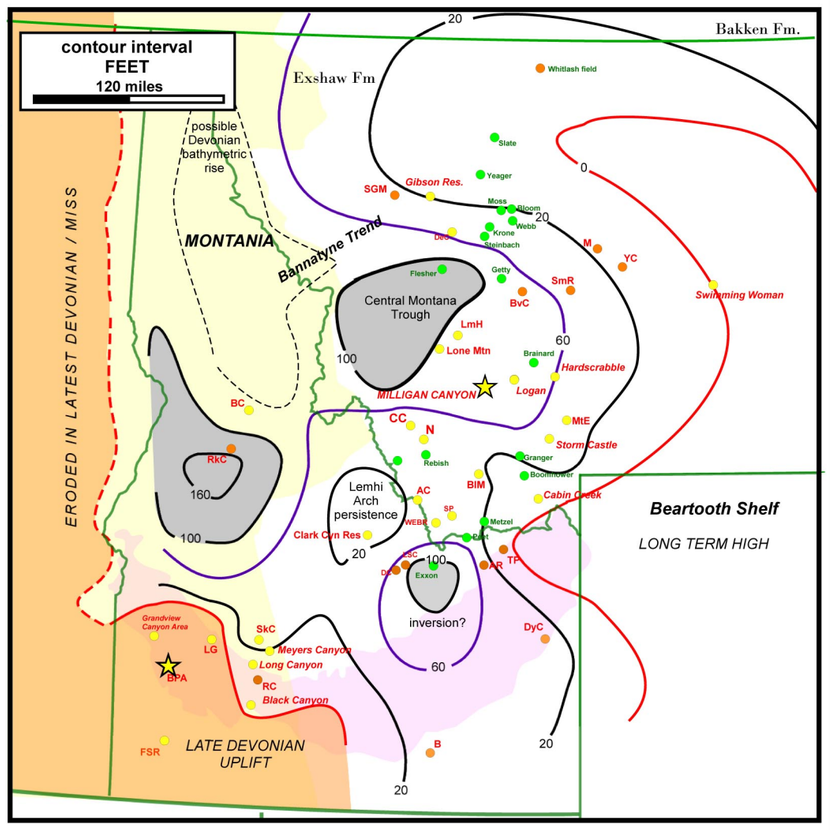
Sappington correlation between Dry Hollow and Logan Devonian type section: western vs. eastern depositional character



i. Isopach map of Frasnian and older strata (carbonates of the Jefferson Fm)



ii. Isopach of Famennian strata - Logan Gulch & Trident members of the Three Forks Formation (evaporite-carbonate-shale dominated)



iii. Isopach map of the Sappington Formation

Palinspastically restored isopach maps of the Devonian-Mississippian transition in western Montana

CONCLUSIONS

Using cross-sections and outcrop data we have shown some of the areas where the Sappington/Bakken thins or is eroded. Based on synsedimentary fold data at Milligan Canyon and other stratigraphic features of western Sappington and Lodgepole strata, we suggest brief polarity reversal and truncation of the upper black shale in a locally over-steepened slope setting. This deep water unit is otherwise of wide distribution to the east. Its absence in parts of the western shelf provide some evidence for tectonic basin inversion in the Central Montana Trough. This supports the idea of a loaded plate margin, reactivated Proterozoic basement faults, and outer shelf differential subsidence *and* uplift. Restored isopach maps of Late Devonian units show the evolution of intrashelf basins and paleohighs presenting formidable challenges to correlation. Such paleogeography suggests migration of a Late Devonian Antler forebulge, or a hybrid strike-slip setting. Our observations predict that there is an erosive submarine hiatus in the earliest Mississippian that locally thinned or removed the Sappington prior to Lodgepole deposition. Given that the Sappington, Exshaw and Bakken were mostly preserved in different paleogeographic settings they suggest a background of climatic-eustatic controls, before widespread intense subsidence below the Lodgepole system.

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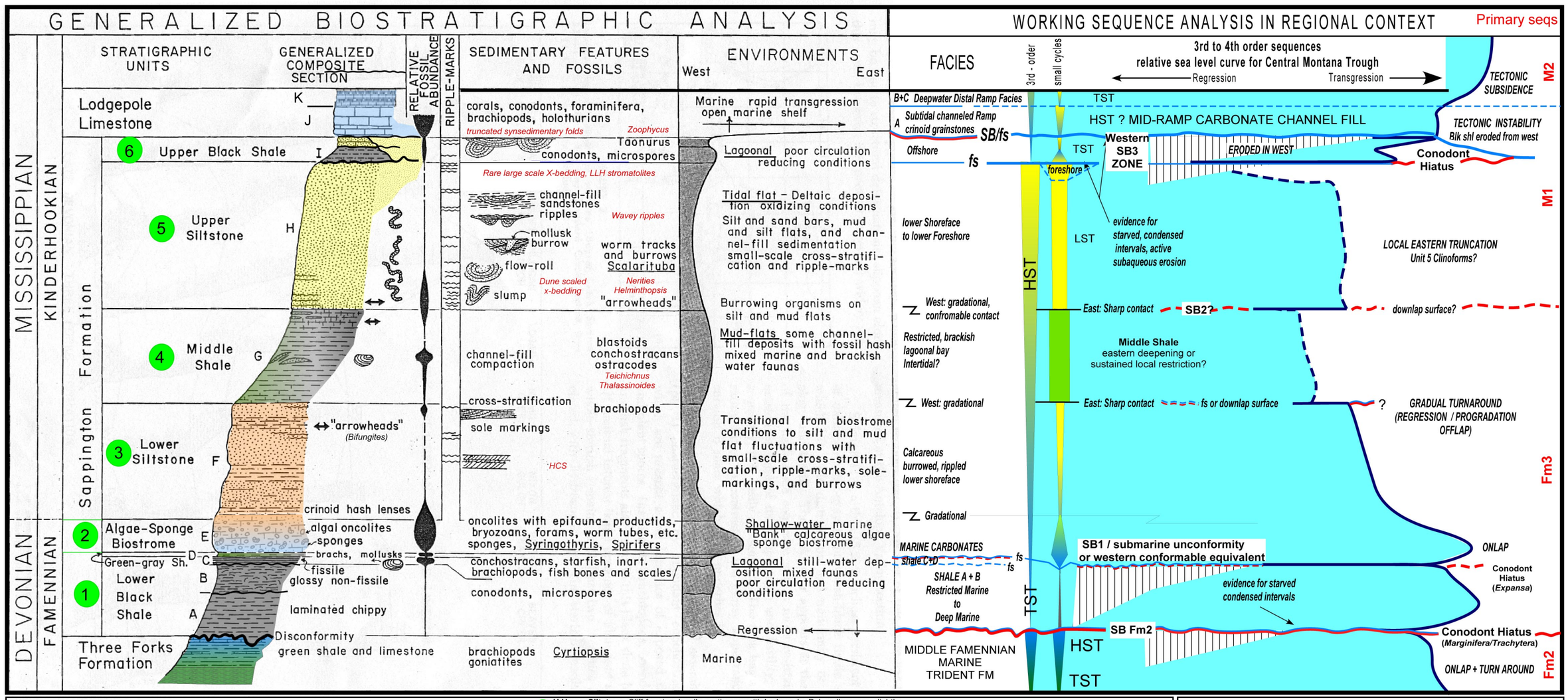
SAPPINGTON WORK IN PROGRESS

- More detailed section description and log analysis towards developing a Sappington sequence stratigraphy
- Palynology of the SW Montana Sappington and NW Montana Bakken (Mercedes Di Pasquo)
- Correlation of well logs with outcrop studies



LOWER BLACK SHALE 0-43 ft, ave. ~12 ft

C Persistent brown-black, dull luster to bright glossy. Thin, compact, minor resistant ledge < 1 ft. Unusual fossiliferous assemblage incl. : freshwater conchostracans, starfish, blastoids, *Lingula*, *Orbiculoidea*, fish parts, spores.

B Glossy contorted carbonaceous shale, concoidal fracture. No lamination. Plant spores only. Slickensided, Tuffaceous. 6 ft at Antelope Valley, nr. Sappington.

A Well laminated, fissile. Weathers to chippy. Depression fills on erosional surface. Few spores; conodonts. 7 ft in Bridger Mtns.

1

MIDDLE SAPPINGTON LIMESTONE ~3-8 ft

E Algae-Sponge Biostromal unit. Persistent widespread silty, argillaceous limestone w/ tendency to be shaley. Calcareous algal nodules w/ adnacsent organisms (Fe rich oncoids, some Si replacement) and sponges: Pebble to cobble sized. Production stifled by silt/clay influx. Sheet like in N-S direction from Beaver Ck. to Leatham Hollow, UT; Bridger Mtns. to Red Hill section. Forams, sponges, bryozoans, brachiopods, ostracodes.

D Green-Gray Shale. Sharply over lies black shale, with gradational to sharp upper contact. Granular, non calcareous, w/ white shelly material. Limes-upward. Brachiopods, clams, snails, crinoids. Leached internal and external molds (similar to Unit I above).

2

MIDDLE SAPPINGTON CLASTICS 50 - 100+ ft

H Upper Siltstone. Cliff-forming; locally continuous with Lodgepole. Pale yell orange, slightly calcareous, silt and v. fine sand. Fossils scarce except burrows. Ripple marks, flow rolls, x-beds (abundant trough ripples), sole marks, Segmented *Sclarituba* (*Nereites*). G to H is gradational in western sections w/ HCS. Eastern sections have more massive cliff forming siltstone; western sections have greater alternation of silty shale and channelled sandstone lenses.

5

G Middle shale. Dark green-gray, laminated, calc. shale with vertical silt tubes (*Teichichnus*?) irregular laminations. Forms slope between siltstone units. Characterised by burrows and arrow-head like *Bifungites fezzanensis*, abundant in upper part. Channel-fill silt at Antelope Valley contains blastoids, large and micro crinoids, conchostracans, orstrocodes, brachs, clams, conodonts, echinoid spines, bryzoans and worm trackways. Vertical tubes and lateral galleries

4

F Lower siltstone. Weathers orange, med. gray, clac. shaly siltstone and silty shale w/ impure limestone. Silt forms ledges; shales are recessive. Gradational with underlying Unit E. Local thin bioclastic lenses of hash; brachs common in upper most part. Fossils sparsely scattered throughout. Ripple marks, burrows. Unfavorable conditions for normal marine fauna. HCS.

3

UPPER BLACK SHALE 0- 5 ft AND BASAL LODGEPOLE

K - "Below wave base." Lime mudstone, wackestone and shaley argillaceous limestone. Chert at some locations.

J - "Above wave base". Crinoid pack/grainstone. Off lap and erosional beveling

I Black Shale. Black shale, silt, or yell. sandstone. Black shal e overlain by thin massive sandstones at many sections, with facies change to fossiliferous fine-med. sandstone, black shale streaked sandstone, and crinoidal sandstones. Western sections not deposited/ folded/truncated. Conodonts, spores, brachiopods (inarticulate) and fish parts. *Zoophycus* in upper siltstones (*Taonurus).*

6

UNIT LITHOLOGY

SB Fm2 = Stacked subearial (?) and subaqueous-cut sequence boundary ?

SB 1 = Equivalent to basal Williston Basin Bakken Sequence boundary below Middle Bakken "LST" (*sensu* Smith and Bustin 1996).

SB2 = equivalent to SB under Williston Basin Bay head deltas of Angulo et al (2009). Correlative to continuous sedimentation in western Central MT Trough

SB3 = East: multiple flooding surfaces. West: evidence for downslope synsedimentary folding and truncation with western uplift and erosion (forebuldge migration?) Further west near ID-MT border SB0, SB1, SB2 and upper flooding surfaces may be eroded or time-correlative with clastic turbidites forming a more significant disconformity (i.e. associated with arch uplift and downdrop)

Fm 3 = Late Famennian & Devonian-Mississippian,
M1,M2,M3 = Early Tournaisian (but not earliest Tournaisian)

SEQS.

Working Sappington description, seq. stratigraphy, sea level curves, comparison with early work (Gutschick, 1964)