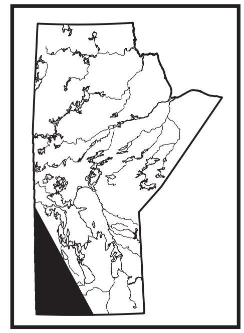
GS-13 Chemostratigraphy, paleontology and mineral potential of the Gammon Ferruginous Member of the Cretaceous Pierre Shale in southwestern Manitoba (parts of NTS 62F, G, H, J, K, N, O, 63C, F)

by J.D. Bamburak, J. Hatcher[1] and M.P.B. Nicolas



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Summary

The Cretaceous Gammon Ferruginous Member, with a maximum thickness of 56 m, is present in thousands of oil wells in southwestern Manitoba. The Member has also been sampled in outcrop along the Manitoba Escarpment and in the Pembina River valley, where in outcrop it is present between the overlying Pembina Member of the Pierre Shale and the underlying Boyne Member of the Carlile Formation. Relatively anomalous concentrations of rare earth elements and other metals, such as Pt, Pd, Cu, Ni, V and Zn, have been noted within the Gammon Ferruginous Member compared with other Cretaceous shale horizons. The increase in mineralization also corresponds to a noted increase in isolated occurrences of well-preserved vertebrate fossil skeletons in the earliest sedimentary rocks of the Pierre Shale. Additional geological and paleontological field investigations, combined with inorganic chemical and heavy mineral analyses of outcrop and drill core samples from the Gammon Ferruginous Member, and other Cretaceous formations, may lead to the discovery of a new type of mineable sedimentary deposit in Manitoba.

Introduction

The inorganic geochemical aspects of the Gammon Ferruginous Member of the Pierre Shale have been studied since 2008 as part of the Shallow Unconventional Shale Gas (SUSG) Project, which is reviewed by Nicolas and Bamburak (GS-12, this volume). The Gammon Ferruginous Member (Nicolas and Bamburak, Figure GS-12-1, this volume) has recently been recognized by the Manitoba Geological Survey (MGS) and the Canadian Fossil Discovery Centre (CFDC) to have a distinctive chemostratigraphic signature and accompanying fossil assemblage compared with that of overlying and underlying Upper Cretaceous units in southwestern Manitoba.

Previous work

Stratigraphy

The presence of up to 54.9 m of the Gammon Ferruginous Member in the subsurface in southwestern Manitoba was first documented in numerous oil wells by Bannatyne (1970, p. 26, 52, 53). The member is usually situated between calcareous speckled shale at the top of the Boyne Member of the Carlile Formation and the interbedded bentonite and black shale beds at the base of the Pembina Member of the Pierre Shale (Nicolas and Bamburak, Figure GS-12-1, this volume). In outcrop, the Gammon Ferruginous Member was first recognized at three localities, along the Vermilion River on the northern flank of Riding Mountain, 17.5 km southwest of the town of Dauphin, by McNeil and Caldwell (1981, p. 363–367, outcrop sections 76, 77, 78). These localities are shown in Figure GS-13-1 and are listed in Table GS-13-1 as localities 1b to 1d. The maximum thickness of the Gammon Ferruginous Member in the Riding Mountain area was reported by McNeil and Caldwell (1981) to be 4.39 m at locality 1c (described below).

The presence of additional outcrops containing thin (<1 m) Gammon Ferruginous Member beds along the Manitoba Escarpment in the Pembina Hills area was suggested by Bamburak (1996, p. 130) and this was confirmed at 11 localities by Bamburak and Nicolas (2010, a, b). The thickest interval of the Gammon Ferruginous Member in the Pembina Hills area was 3.2 m at the Spencer's Ditch locality 7 (Figure GS-13-2; described below).

The Gammon Ferruginous Member is equivalent to the Milk River Formation of Saskatchewan (Christopher and Yurkowski, 2007; Nicolas, 2009). Structure contour and isopach maps of the Milk River Formation (Gammon Ferruginous Member) were produced by the TGI Williston Basin Working Group (2008a, b). McNeil and Caldwell (1981, Figure 29) indicated that the Gammon Ferruginous Member can be subdivided in the subsurface into three units based upon spontaneous potential and resistivity curves from electrical logs from two petroleum exploration wells–CEGO Cayuga 13-31-3-29W1 in L.S. 13, Sec. 31, Twp. 3, Rge. 29, W 1st Mer. (abbreviated 13-31-3-29W1) and Widney Broomhill 3-3-5-28W1. They also showed that the units onlap each other moving from west to east across southern Manitoba and that only the uppermost Gammon Ferruginous Member unit may be

[1] Canadian Fossil Discovery Centre, 111-B Gilmour Street, Morden, Manitoba R6M 1N8

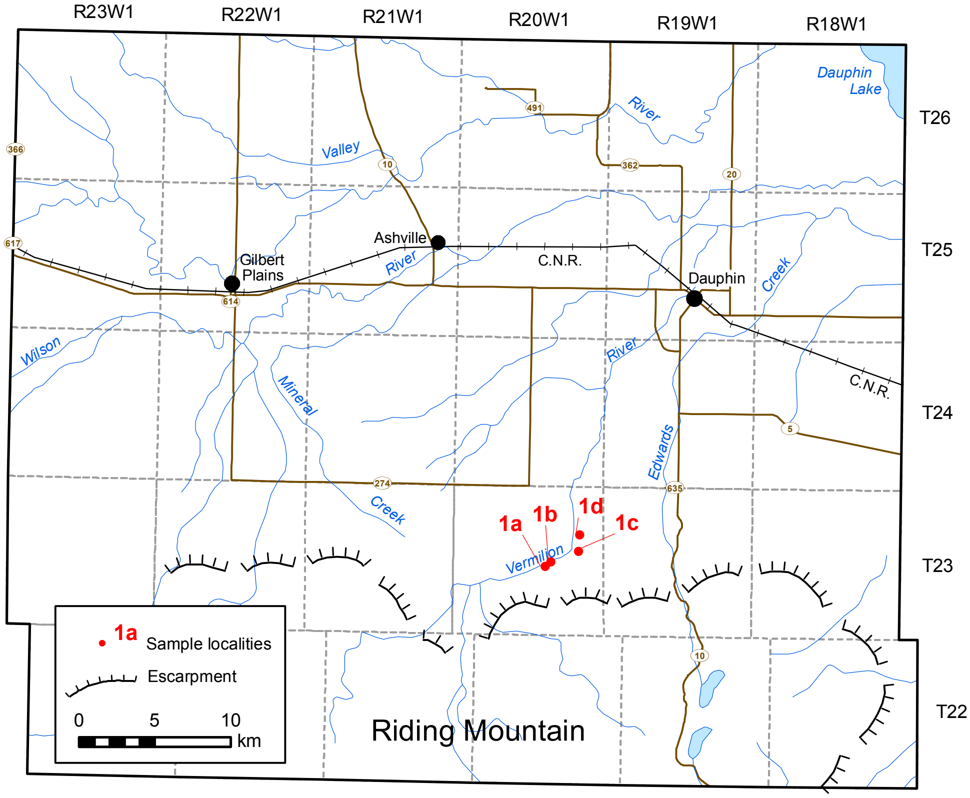

Figure GS-13-1: Gammon Ferruginous Member outcrop localities on the northern flank of Riding Mountain, southwestern Manitoba (modified from Bamburak and Nicolas, 2010a). Localities 1b, 1c and 1d correspond to outcrop sections 76, 77 and 78, respectively, of McNeil and Caldwell (1981).

present near the eastern edge of the outcrop belt along the Manitoba Escarpment. The distribution of the Gammon Ferruginous Member was also demonstrated in numerous cross-sections by McNeil and Caldwell (1981) to be extremely erratic in the subsurface because it is bound by upper and lower Cretaceous unconformities. As a result of nondeposition (or of subsequent erosion of previously deposited beds during the Cretaceous), the unit thickness of the member in southwestern Manitoba ranges from 0 (absent) to at least 4.39 m along the Manitoba Escarpment and to over 56 m in the subsurface west of the town of Melita (TGI Williston Basin Working Group, 2008a).

Geochemistry

Results of previous geochemical investigations, which have been carried out on the Gammon Ferruginous Member of the Pierre Shale in southwestern Manitoba, are described in Bamburak and Nicolas (2009, 2010a, b), Nicolas and Bamburak (2009, 2011a, b) and Nicolas et al. (2010). This work indicated that outcrop and drill-cutting samples of the Gammon Ferruginous Member appear to be relatively enriched in several rare earth elements (REEs) and in Th and U compared with most other Upper Cretaceous units in the southern part of the Manitoba Escarpment (Nicolas et al., 2010, Figure GS-14-2).

Outcrop exposures

In Manitoba, outcrops of the Gammon Ferruginous Member have only been found at the eastern edge of the Manitoba Escarpment in southwestern Manitoba–along the northern flank of Riding Mountain and the eastern flank of the Pembina Hills.

Riding Mountain–Vermilion River locality 1c

Outcrop section 77 of McNeil and Caldwell (1981, p. 364–366) was sampled by the MGS in 1999 (Bamburak, 1999). The location of the outcrop is shown in Figure GS-13-1, as locality 1c. Seven samples from the Gammon Ferruginous Member were collected and sent for geochemical analysis (Bamburak and Nicolas, 2010b). Selected results from this analysis showed a moderate increase in REE content of the Gammon Ferruginous Member compared with overlying and underlying Upper Cretaceous units.

Pembina Hills localities

According to Bamburak and Nicolas (2010a, Table GS-15-2), samples from Spencer's Ditch locality 7 have the highest values for most REEs, Th, U and P relative to all other Cretaceous shale analyses in the MGS chemostratigraphic database. Similarly, samples from

Table GS-13-1: Gammon Ferruginous Member outcrop localities in the Riding Mountain and Pembina Hills areas, southwestern Manitoba (modified from Bamburak and Nicolas, 2010a).

Locality no.	Name	Location	Easting[1]	Northing[1]	Station no.	Thickness (m)
Riding Mountain area						
1a	Vermilion River Gammon west	15-15-23-20W1	416427	5649592	99-12-VR-001	5.0
1b	Vermilion River outcrop section 76[2]	02-22-23-20W1	416682	5649782	not visited	5.1
1c	Vermilion River outcrop section 77[2]	03-14-23-20W1	417835	5649955	99-99-RM-002	4.39
1d	Vermilion River outcrop section 78[2]	07-23-23-20W1	418125	5650125	badly slumped	3.08
Pembina Hills area						
2	Roseisle Bridge	W13-11-06-08W1	539650	5480027	99-96-BR-20-1	0.4
					99-10-MI-009	
3	Arnold North	10-16-05-07W1	547233	5471635	99-96-BR-3-7	unknown
					99-10-MI-007	
4	South Tobacco Creek Tributary	NW13-34-04-07W1	547905	5466863	99-96-BR-28-1	0.24
					99-1--MI-016	
5	West Cox	14-26-04-07W1	550246	5465266	99-10-MI-012	0.3
6	Mount Nebo	04-19-04-06W1	553031	5460947	99-10-MI-008	0.18
7	Spencer's Ditch	15-31-03-06W1	553843	5457258	99-96-BR-23-3	3.0
					106-08-62G8-3	
					99-10-MI-001	
					99-12-SD-001	
8	Spencer Pit - Shannon Creek	09-31-03-06W1	554183	5456744	99-10-MI-011	0.1
9	Stanley Park West	N13-21-02-06W1	556900	5443850	99-06-BR-31-3	0.5
10	Friesen Roadcut	04-07-02-05W1	563579	5439347	99-95-MI-5-8	0.2
					106-08-62G1-25	
					99-10-MI-002	
11	Mile Four North	SE1-29-01-05W1	566632	5434174	99-95-MI-5-4R	unknown
12	Holo Crossing	01-13-01-07W1	553407	5431337	106-08-62G1-11	0.2
					99-10-MI-004	
13	Pembina River Valley, North Dakota, U.S., outcrop section 107[2,3]	SW30-163N-57W	567566	5418014	not visited	0.43
14	Little North Pembina River Valley, North Dakota, U.S.	NE13-163N-58W	567221	5421884	99-10-WA-001	0.27
15	Stonehenge	12-21-01-05W1	566979	5433657	99-11-MI-007	0.14

[1] NAD83, Zone 14U
[2] McNeil and Caldwell, 1981
[3] Gill and Cobban, 1965

the Holo Crossing locality 12 (Figure GS-13-2) have the highest values for Yb, Lu, Ni and Zn, while samples from the Mount Nebo locality 6 (Figure GS-13-2) have the highest Cu and V values (Bamburak and Nicolas, 2010a, Table GS-15-2).

The highest Pt and Pd contents are documented from two outcrop samples representing the Cretaceous Gammon Ferruginous and Pembina members of the Pierre Shale. The sample from South Tobacco Creek Tributary locality 4 (Figure GS-13-2) contained 11.6 ppb Pt and 13.3 ppb Pd (Peck et al., 2000, p. 8) and the sample from Arnold North locality 3 (Figure GS-13-2) contained 14.8 ppb Pt and 12.5 ppb Pd (Bamburak and Nicolas, 2010b). It should be noted that the Pembina Member sample was collected near the base of the outcrop section and may actually be part of the underlying Gammon Ferruginous Member.

Drill-cutting samples

Relative Daly Sinclair HZNTL 8-31-7-29W1 well

A series of drill-cutting samples were collected over 5 m intervals from 330 to 455 m (true vertical depth)

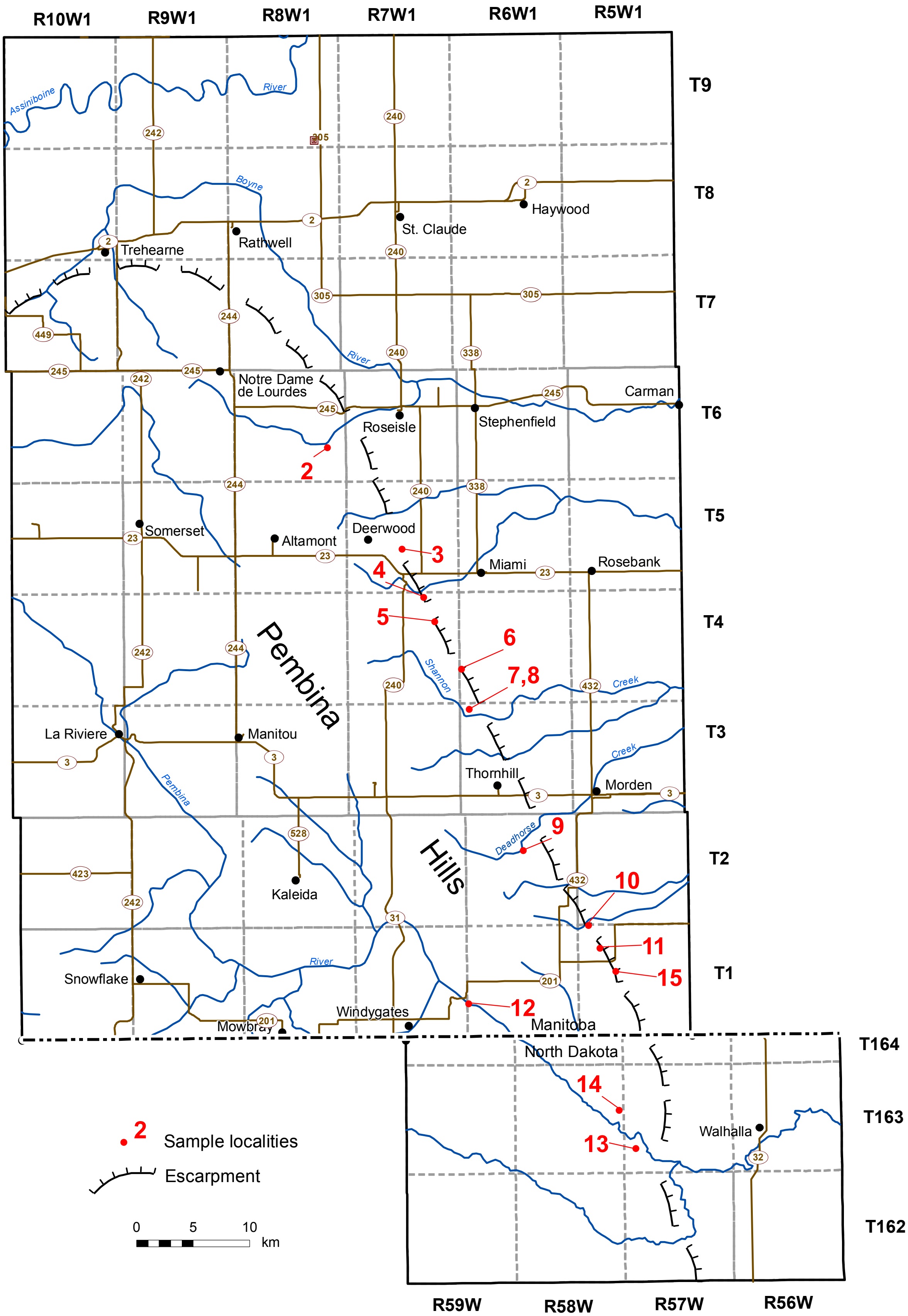

Figure GS-13-2: Gammon Ferruginous Member outcrop localities in the Pembina Hills area of southwestern Manitoba and northeastern North Dakota (modified from Bamburak and Nicolas, 2010a).

from the Relative Daly Sinclair HZNTL 8-31-7-29W1 petroleum well (surface hole location of 16-30-7-29W1). The stratigraphic units covered by these samples include the Millwood Member, Pembina Member, Gammon Ferruginous Member, Boyne Member and Morden Member. Testing of the Th, U and REE mineral potential of the Gammon Ferruginous Member samples from the unwashed drill-cutting samples was described by Bamburak and Nicolas (2010a) and Nicolas and Bamburak (2011a, b). It should be noted that Nicolas and Bamburak (GS-12, this volume) present organic geochemistry and bulk mineralogy results conducted on equivalent but washed drill-cutting samples from the same well. These results revised the allocation of formations and members, based on well log calibrations, from that shown in Table 3 of Nicolas and Bamburak (2011b).

As a first approach, MGS sent unwashed drill-cutting samples for chemical analysis, to avoid risking the loss of any mineralized fine fraction. The results of this preliminary test indicated that the drill-cutting samples collected from the Gammon Ferruginous Member were only slightly elevated in Th, U and REEs relative to background values (Bamburak and Nicolas, 2010a, b). To test whether or not the results relative to background values could be improved, the drill-cutting samples were subsequently washed and the cleaned samples were resubmitted by MGS for inorganic geochemical analysis (Nicolas and Bamburak, 2011a, b), as described below.

Paleontology

McNeil and Caldwell (1981) postulated that subsidence of the uplift that occurred after deposition of the Boyne Member allowed for the Gammon Ferruginous Member sediments of the earliest Pierre Sea to make incisions into the bevelled Boyne Member surfaces, and then subsequently, the Pierre Sea spread out farther across Manitoba and lead to the deposition of the Pembina Member sediments.

Although the Gammon Ferruginous Member is rarely exposed in outcrop throughout the Manitoba Escarpment, the CFDC field crew has spent portions of the past three field seasons (2010–2012) in the Pembina Hills area excavating extensively in this unique rock unit. The Gammon Ferruginous Member was reported by McNeil and Caldwell (1981) to consist of three units as identified in electric logs, but lithological descriptions were not provided. Excavation by the CFDC over three summers at Spencer's Ditch locality 7 confirms the presence of three distinctive units which, in keeping with the informal terms used by McNeil and Caldwell in 1981, are referred to as the lower Gammon Ferruginous Member, middle Gammon Ferruginous Member and upper Gammon Ferruginous Member.

***Xiphactinus* Kill Zone quarry (Spencer's Ditch locality 7)**

Vertebrate fossil skeletons have been recovered by the CFDC from all three units of the 3.2 m thick Gammon Ferruginous Member in a large fossil excavation, informally called the *Xiphactinus* Kill Zone quarry (Figure GS-13-3), at Spencer's Ditch locality 7. The lower Gammon Ferruginous Member (38 cm thick) is a grey organic-rich, noncalcareous shale with at least four bentonite layers, sometimes turbulently mixed into one thicker band, and has produced CFDC specimens M.09.01.13 (*Clidastes*) and F.09.03.13 *(Xiphactinus)*.

The middle Gammon Ferruginous Member (115 cm thick) is composed of black, waxy, noncalcareous, organic-rich shale with abundant red-weathering siderite concretions and has produced a large mosasaur (CFDC specimen M.2011.01.13), directly associated with numerous fish taxa, and an abnormal abundance

Figure GS-13-3: *Canadian Fossil Discovery Centre (CFDC) fossil crew in the Xiphactinus Kill Zone quarry in the immediate vicinity of the 2009 discovery of the large fish, Xhiphactinus (CFDC specimen F.09.03.13), from the lower unit of the Gammon Ferruginous Member of the Pierre Shale at the Spencer's Ditch locality 7 (L.S. 15, Sec. 31, Twp. 3, Rge. 6, W 1st Mer.), southwestern Manitoba. Plaster cast, shown in lower left side of photo, encloses delicate fossil remains that will be transported for processing at the CFDC.*

of fossil birds along with a whole microvertebrate fossil assemblage composed primarily of small (1–4 mm) fish teeth, scales and vertebrae (Figure GS-13-4). The upper Gammon Ferruginous Member (167 cm thick) is composed of fissile, grey, clay-rich, swelling, noncalcareous to calcareous shale with two 3 cm thick bentonite beds and has produced a 4 cm thick layer of ichnofossil burrows and one fossil bird, CFDC specimen B.2010.02.13 (*Hesperornis*) which was collected in 2010.

The lower, middle and upper units of the Gammon Ferruginous Member at this locality also appear to be sedimentary precursors to the Pembina-Millwood member transition later in the Pierre Shale sequence. The above described lithology of the lower unit of the Gammon Ferruginous is similar to the lithology of the organic-rich shale and Ardmore bentonite succession of the lower Pembina Member. The lithology of the middle unit of the Gammon Ferruginous Member is similar to the reddish-brown organic-rich lithology of the upper Pembina Member; and the upper unit of the Gammon Ferruginous Member is similar to the Millwood Member. Such lithological precursors are common within the Cretaceous sequence of the Manitoba Escarpment (i.e., the Ashville Formation, Morden Shale and Pembina Member of the Pierre Shale are all black, organic-rich, noncalcareous shale similar to each other in their structural lithology).

Environment of deposition

The Spencer's Ditch locality 7 outcrop of the Gammon Ferruginous Member in Manitoba is the second thickest outcrop of this member in the Manitoba Escarpment (Bamburak and Nicolas, 2010) and continues to produce vertebrate fossils of tremendous paleontological significance. The sand grains within the lower and middle units of the Gammon Ferruginous Member tend to be angular, indicating that they have not traveled far from their erosional source. Furthermore, the abnormal concentration of flightless bird fossils preserved in the *Xiphactinus* Kill Zone quarry could also allude to a reasonably nearshore environment of deposition. Nicholls (1988) first noted the concentration of fossil birds at this locality in 1988, along with a comparatively lower number of larger marine reptile skeletons. Nicholls (1988) hypothesized that Spencer's Ditch locality 7 may have represented a sheltered area particularly abundant in birds, where mosasaurs and plesiosaurs did not frequently congregate.

Recent palynology analysis of the bentonite layers sampled by the CFDC from the lower unit of the Gammon Ferruginous Member at this locality has identified terrestrially derived conifer pollens *Bisaccate* and *Classopollis classoides.* Of these two conifer pollens, *C. classoides* is known to have occupied well-drained soils of upland slopes and lowlands near coastal areas, preferring the warm climate of transgressive seas (Srivastava, 1976). The presence of *C. classoides* in the lower unit of the Gammon Ferruginous Member is consistent with McNeil and Caldwell's (1981) interpretation that the earliest sediments of the transgressive Pierre Sea developed incisions into the lower surfaces of the Boyne Sea, and successively overstepped the previously deposited chalky unit of the Boyne Member (McNeil and Caldwell, 1981). Conifer pollens have been well documented in nearshore terrestrial ecosystems of North America in Cretaceous time, including fluvial deposition along lowland coastal plains directly into the Western Interior Seaway (Hatcher, 2006).

As indicated earlier, MGS has found occurrences of anomalous REE, Pt and Pd values (Peck et al., 2000) within the Gammon Ferruginous Member. This has led the authors to hypothesize that shallow pools where Gammon Ferruginous Member deposition occurred, trapped Cretaceous animals and the mineral richness of the depositional environment carried a high degree of

Figure GS-13-4: *View of a bone bed in the Xiphactinus Kill Zone quarry within the middle Gammon Ferruginous Member at Spencer's Ditch locality 7 (L.S. 15, Sec. 31, Twp. 3, Rge. 6, W 1st Mer.). The member hosts a whole microvertebrate fossil assemblage, in addition to mosasaur, fish and bird remains. Several vertebrae can been seen just above the base of the flag, located on the right side of the photo. For scale, the two rib bones, shown in centre of photo, are approximately 4 cm thick.*

toxicity, which could partially explain why so many taxa have been found by the CFDC within a localized outcrop.

Current investigations

Spencer's Ditch locality 7

On the basis of the results of the previous inorganic geochemical analyses of the Gammon Ferruginous Member of the Pierre Shale, it was decided to bulk sample the 3.2 m thick member at the Spencer's Ditch locality 7, which has the highest values for most REEs, Th, U and P relative to all other Cretaceous shale analyses in the chemostratigraphic database. Three duplicate samples (of about 12 kg each) were collected by the CFDC within three contiguous beds at the site. Single samples from the lower (38 cm thick), middle (115 cm thick) and upper (167 cm thick) beds at the Spencer's Ditch locality 7 will be forwarded to Activation Laboratories (Ancaster, Ontario) for heavy mineral concentration, followed by instrumental neutron activation analysis (INAA), electron probe micro-analyses (EMPA) for monazite and xenotime, and by fire assay with an inductively coupled plasma–mass spectrometry (ICP-MS) finish for Pt and Pd.

During the summer, an attempt was made, without success, to find additional outcrops of Gammon Ferruginous Member upstream, to the west of the Spencer's Ditch locality 7, on Shannon Creek (Figure GS-13-2). Only badly disturbed sections (due to ice thrusting and slumping) and very thin intervals of the beds could be found, which made sampling impractical.

Vermilion River locality 1a

An additional 5 m thick outcrop of Gammon Ferruginous Member (beneath the overlying Pembina Member) was identified at locality 1a in Figure GS-13-1. It is located in 15-15-23-20W1, immediately to the west of outcrop section 76 of McNeil and Caldwell (1981). The bedrock exposure, with approximate dimensions of 30–35 m high and 150 m long (Figure GS-13-5), was briefly examined and sampled by MGS during in 2012. Six contiguous Gammon Ferruginous samples were collected from 0.25 m intervals near the oxidized base of the member; these will be sent out for geochemical analysis.

Relative Daly Sinclair HZNTL 8-31-7-29W1 well

As noted above, washed samples from the Relative Daly Sinclair HZNTL 8-31-7-29W1 well were submitted for organic geochemistry and bulk mineralogy. The results of these studies are described by Nicolas and Bamburak (GS-12, this volume). And, as stated above, split washed samples were resubmitted by MGS for inorganic geochemical analysis to try to improve upon test results obtained from the unwashed samples, reported in 2011 (Nicolas and Bamburak, 2011a, b). The results of the current analysis are contained in MGS Data Repository Item DRI2012003[2]. Comparison of the results that were obtained, using different analytical techniques, are inconclusive with some values being lower and others higher than the 2011 results. However, there was a general improvement in the reported values after washing.

Figure GS-13-5: *Gammon Ferruginous Member outcrop in L.S. 15, Sec. 15, Twp. 23, Rge. 20, W 1st Mer. M. Nicolas (shown within circle) is positioned approximately halfway up the steeply sloping outcrop, above the Pembina Member-Gammon Ferruginous Member contact. Oxidized Gammon Ferruginous Member was sampled from a freshened surface near the base of the outcrop over a 1.25 m interval (shown within square).*

[2] MGS Data Repository Item DRI2012003, containing the data or other information sources used to compile this report, is available online to download free of charge at http://www2.gov.mb.ca/itm-cat/web/freedownloads.html, or on request from minesinfo@gov.mb.ca or Mineral Resources Library, Manitoba Innovation, Energy and Mines, 360–1395 Ellice Avenue, Winnipeg, Manitoba R3G 3P2, Canada.

Figure GS-13-6 shows a chondrite-normalized REE diagram for the washed drill-cutting samples from the Relative Daly Sinclair HZNTL 8-31-7-29W1 well, which was prepared by E. Yang of MGS. According to E. Yang (pers. comm., 2012), the samples from the four different members (from two different formations) resemble one another in terms of REE patterns. Although the REE abundances display some differences, all are similar to the North American Shale in Rollinson (1993).

It should also be noted that since the each sample was collected over a 5 m interval, the actual contacts between the various formations and members likely fell within the intervals. This would explain the highest values within the basal bed of the Pembina Member, as shown in Figure GS-13-6, which probably includes a zone of lateritic enrichment of the Gammon Ferruginous Member at the unconformable contact between the Pembina and Gammon Ferruginous members. Likewise, the contact between the Gammon Ferruginous Member and the Boyne Member of the Carlile Formation is likely within the 5 m interval and this would explain the small difference in values between the basal Gammon Ferruginous Member beds and the uppermost beds of the Boyne Member. The Morden Member sample was collected 35 m farther down the drillhole and has a much lower relative REE signature.

The lack of definitive stratigraphic breaks within the 5 m sampling intervals in petroleum wells of southwestern Manitoba and the mixing that occurs during the drilling has proven to be a major detriment to obtaining a good estimate of the economic potential of the Gammon Ferruginous Member for REEs and other elements in the subsurface. Further work should concentrate on obtaining continuous core for geochemical sampling before the mineral potential of any Cretaceous sedimentary strata can be adequately determined.

Economic considerations

Along the Manitoba Escarpment, the Gammon Ferruginous Member of the Pierre Shale appears to be enriched in REEs and other elements. However, its thickness is quite variable making it difficult to evaluate its mineral resource potential. Recent activities may help with this evaluation. Additional fieldwork by MGS in the immediate vicinity of known exposures has resulted in locating new sampling sites. Also, an increase in paleontological field investigations by the CFDC in the upland region of Pembina Hills and throughout the Manitoba Escarpment may lead to the discovery of new outcrops of the Gammon Ferruginous Member of the Pierre Shale so that fossiliferous content and corresponding mineral and REEs concentrations can be determined.

In the subsurface, the known thickness of the Gammon Ferruginous Member dramatically increases towards the southwest. However, coring of the Cretaceous section in southwestern Manitoba (possibly done in conjunction with petroleum exploration and development) will be required to determine whether there is a potential for the discovery of mineable sedimentary deposits containing REEs and/or other elements, such as Pt, Pd, Cu, Ni, V and Zn.

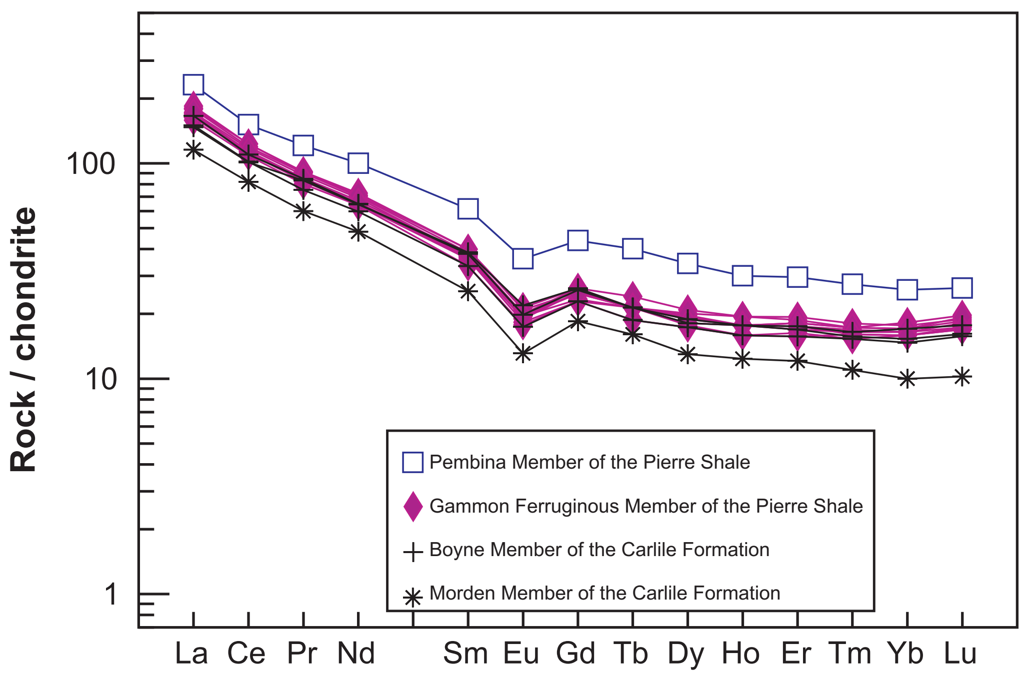

Figure GS-13-6: *Chondrite-normalized rare earth element (REE) diagram for washed drill-cutting samples from Relative Daly Sinclair HZNTL 8-31-7-29W1 well (L.S. 8, Sec. 31, Twp. 7, Rge. 29, W 1st Mer.). Normalized values are from Sun and McDonough (1989).*

Acknowledgments

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References

Bamburak, J.D. 1996: Bentonite investigations and industrial mineral mapping of the Brandon map area (NTS 62G); *in* Report of Activities 1996, Manitoba Energy and Mines, Geological Services, p. 127–133.

Bamburak, J.D. 1999: Cretaceous black shale investigations in the northern part of the Manitoba Escarpment (parts of NTS 62J/W, 62K/N, 62N/E and 63C/W); *in* Report of Activities 1999, Manitoba Industry, Trade and Mines, Geological Services, p. 120–122.

Bamburak, J.D. and Nicolas, M.P.B. 2009: Mineral potential of Mesozoic rocks in southwest Manitoba; Manitoba Mining and Minerals Convention 2009, Winnipeg, Geoscientific Presentation PRES2009-25 (poster presentation).

Bamburak, J.D. and Nicolas, M.P.B. 2010a: Gammon Ferruginous Member of the Cretaceous Pierre Shale in southwestern Manitoba: distribution and mineral potential (parts of NTS 62F, G, J, K, N, O, 63C); *in* Report of Activities 2010, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 170–177.

Bamburak, J.D. and Nicolas, M.P.B. 2010b: Selected analyses of the Gammon Ferruginous Member of the Cretaceous Pierre Shale, southwestern Manitoba (parts of NTS 62F, G, J, K, N, O, 63C); Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Data Repository Item DRI2010001, Microsoft Excel® file.

Bannatyne, B.B. 1970: The clays and shales of Manitoba; Manitoba Mines and Natural Resources, Mines Branch, Publication 67-1, 107 p.

Christopher, J.E. and Yurkowski, M. 2007: An Upper Cretaceous (Milk River Formation) analogue of the Swift Current Platform and its relationship to elements of the Precambrian basement, southern Saskatchewan; *in* Summary of Investigations 2007, Volume 1, Saskatchewan Geological Survey, Saskatchewan Industry and Resources, Miscellaneous Report 2007-4.1, CD-ROM, Paper A-9, 18 p.

Gill, J.R. and Cobban, W.A. 1965: Stratigraphy of the Pierre Shale, Valley City and Pembina Mountain areas, North Dakota; United States Geological Survey, Professional Paper 392-A, 20 p.

Hatcher, J. 2006: Maastrichtian vertebrata: On the palaeoecology of Hell Hollow; *in* Ninth International Symposium on Mesozoic Terrestrial Ecosystems and Biota, P.M. Barrett and S.E. Evans (ed.), Natural History Museum, London, United Kingdom, p. 52–54.

McNeil, D.H. and Caldwell, W.G.E. 1981: Cretaceous rocks and their Foraminifera in Manitoba Escarpment; The Geological Association of Canada, Special Paper no. 21, 439 p.

Nicholls, E.L. 1988: Marine vertebrates of the Pembina Member of the Pierre Shale (Campanian, Upper Cretaceous) of Manitoba and their significance to the biogeography of the Western Interior Seaway; Ph.D. thesis, University of Calgary, Calgary, Alberta, 317 p.

Nicolas, M.P.B. 2009: Williston Basin Project (Targeted Geoscience Initiative II): summary report on Mesozoic stratigraphy, mapping and hydrocarbon assessment, southwestern Manitoba; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Geoscientific Paper GP2009-1, 19 p.

Nicolas, M.P.B. and Bamburak, J.D. 2009: Geochemistry and mineralogy of Cretaceous shale, Manitoba (parts of NTS 62C, F, G, H, J, K, N): preliminary results; *in* Report of Activities 2009, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 165–174.

Nicolas, M.P.B. and Bamburak, J.D. 2011a: Geochemistry and mineralogy of Cretaceous shale, southwestern Manitoba (parts of NTS 62F, G, J, K, N, 63C): phase 2 results; *in* Report of Activities 2011, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 143–149.

Nicolas, M.P.B. and Bamburak, J.D. 2011b: Inorganic chemistry results from Cretaceous shale outcrop and chip samples from phase 2, Shallow Unconventional Shale Gas Project, southwestern Manitoba; Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Data Repository Item DRI2011005, Microsoft Excel® file.

Nicolas, M.P.B., Edmonds, S.T., Chow, N. and Bamburak, J.D. 2010: Shallow unconventional Cretaceous shale gas in southwestern Manitoba: an update (parts of NTS 62C, F, G, H, J, K, N); *in* Report of Activities 2010, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 159–169.

Peck, D.C., Theyer, P., Hulbert, L., Xiong, J., Fedikow, M.A.F. and Cameron, H.D.M. 2000: Preliminary exploration database for platinum-group elements in Manitoba; Manitoba Industry, Trade and Mines, Manitoba Geological Survey, Open File Report OF2000-5, 1 CD-ROM.

Rollinson, H.R. 1993: Using Geochemical Data: Evaluation, Presentation, Interpretation; Longman Scientific & Technical, London, United Kingdom, 352 p.

Srivastava, S.K. 1976: The fossil pollen Genus Classopollis; Lethaia, v. 9, no. 4, p.437–457.

Sun, S.-s. and McDonough, W.F. 1989: Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes; *in* Magmatism in the Ocean Basins, A.D. Saunders and M.J. Norry (ed.), Geological Society, Special Publication 42, p. 313–345.

TGI Williston Basin Working Group 2008a: Cretaceous Milk River Formation (Gammon Ferruginous): isopach; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-KMR-I, scale 1:1 000 000, URL <http://www.gov.mb.ca/stem/mrd/geo/willistontgi/mapfiles/pdfs/004_cret_milk_river_fm_iso.pdf> [September 17, 2012].

TGI Williston Basin Working Group 2008b: Cretaceous Milk River Formation (Gammon Ferruginous): structure contour; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2008-KMR-S, scale 1:1 000 000, URL <http://www.gov.mb.ca/stem/mrd/geo/willistontgi/mapfiles/pdfs/004_cret_milk_river_fm_str.pdf> [September 17, 2012].