Stratigraphy, Sedimentology, Structural History and Exploration History of the Mississippian at Moose Mountain Southwestern Alberta Foothills

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OBJECTIVE

The aim of the excursion is to present an integrated study of the Mississippian rocks of Moose Mountain, with emphasis on stratigraphy, sedimentology, structural geology and hydrocarbon exploration.

NOTE

This itinerary follows bank and cliff exposures adjacent to Canyon Creek. The participants are reminded that care should be taken on these exposures, and safety procedures respected. Attention is also drawn to Provincial Laws which prohibit the excavation of rock and fossil samples without a specific permit.

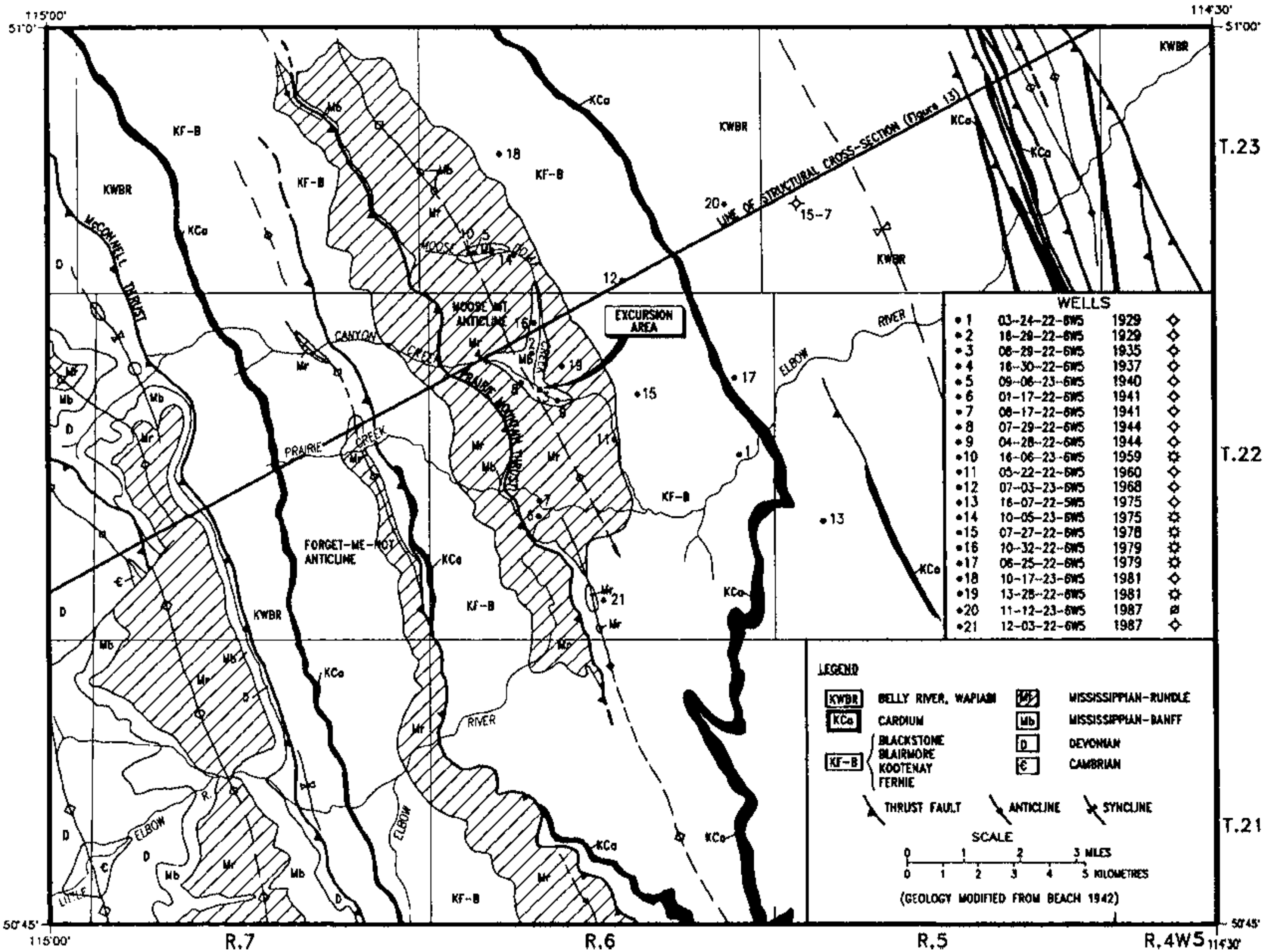
INTRODUCTION

The Carboniferous inlier of Moose Mountain (Figure 1), situated 55 km W.S.W. of Calgary, is one of a number of structural culminations which bring Palaeozoic strata to surface in the Foothills tract east of the McConnell Thrust (Front Ranges). This culmination (a surface pericline) owes its origin to the localized elevation and folding of a major thrust sheet by deformation of the underlying strata.

A Mississippian succession ranging in age from early Kinderhookian to late Meramecian is exposed, equating to the Lower Carboniferous, early Tournaisian to late Visean (the standard European nomenclature is favoured by the Canadian "establishment", see Figure 2). This inlier is important in that it provides excellent surface exposures of a stratigraphic succession analogous to the hydrocarbon producing subsurface of the southwestern plains and foothills, where several of the economically important stratigraphic units are defined only by subsurface stratotypes.

Moose Mountain is a producing gas field with modest well control (well-logs and cores). These subsurface data provide an opportunity to present an integrated and coherent interpretation of this type of Foothills structural play system, while the long history of exploration (since 1929) clearly documents the philosophical changes which have led to the exploration success. The extensive core control further enables refinement of stratigraphic calibration and allows comparison of the Mississippian stratigraphy and sedimentology over the 22 km or so of structural shortening between the surface and subsurface thrust sheets.

FIGURE 1: SIMPLIFIED GEOLOGICAL MAP OF THE MOOSE MOUNTAIN AREA ALBERTA



The excursion traverses 540 m of Mississippian stratigraphy in the eastern limb of the Moose Mountain Anticline. The base of the exposed section is within 27 m of the Devonian (Famennian) Palliser Formation and the ascending succession includes representatives of the Exshaw, Banff, Pekisko, Shunda, Turner Valley and Mount Head formations.

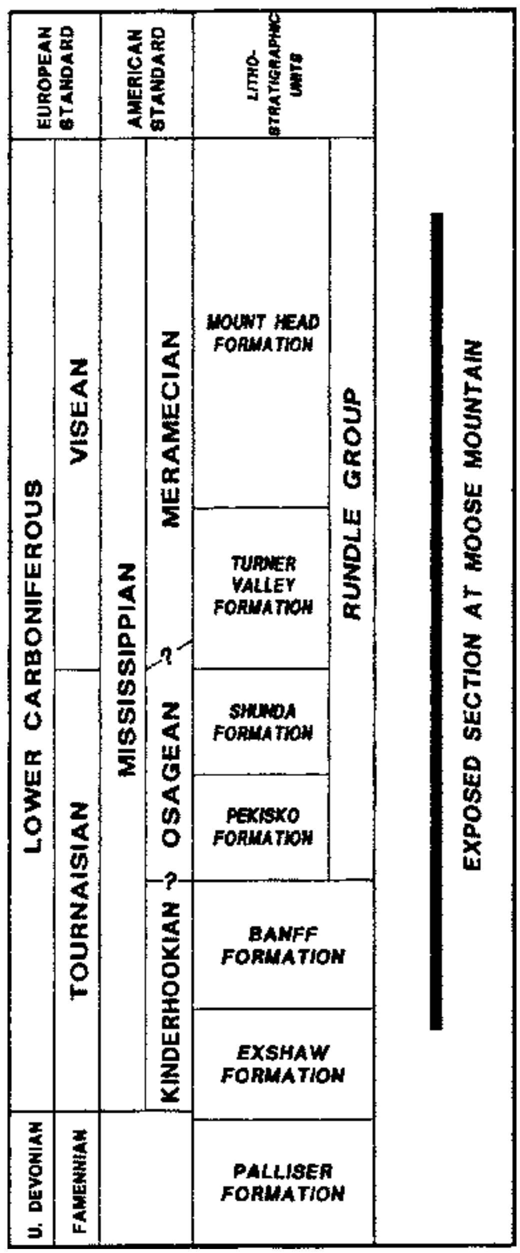


FIGURE 2 Chronostratigraphic calibration of the lithostratigraphic succession at Moose Mountain relative to European and American standards.

Moose Mountain was first mapped for the Geological Survey by Cairnes in 1905 (memoir published in 1908, reprinted 1914) in a study primarily concerned with Mesozoic coal reserves. Later publications on the area include the contributions on structure and stratigraphy by MacNeil (1943) and Beach (1942, 1943, map and memoir, resurvey by the Geological Survey), structural studies by Dahlstrom & Henderson (1959) and Ower (1975), facies interpretations by Illings (1959a,b—based on studies for Shell Canada), Middleton (1963) and Speranza (1984, M.Sc. thesis), relation of facies to dolomitization by Murray & Lucia (1967). Field excursion guides for the Moose Mountain area include Brook & Sturrock (1978), Macqueen & Dolph (1978) and Bamber *et al.* (1981).

DEPOSITIONAL AND STRATIGRAPHIC FRAMEWORK

The preserved record of Mississippian strata in western Canada (Alberta and British Columbia) indicate two principal facies belts: a thick eastern tract of ramp and platform carbonates and a western coeval thin basinal shale facies (Bamber *et al.* 1984), with the latter only fully preserved in N.E. British Columbia (Prophet and Besa River formations).

One of the main controlling tectonophysical elements was the narrow pericratonic Prophet Trough (Richards, 1989), formed by the downwarping/faulting of the western margin of the cratonic platform of the ancestral North American Plate (Figure 3). This extensional basin was originally interpreted by Tempelman-Kluit (1979) as a successful rift which graduated into a fully fledged ocean. However, detailed synthesis by Richards (*op. cit.*) has shown that the basin was more likely formed from plate convergence, with extension and subsidence occurring in back-arc and foreland basin settings, initiated during the broadly synchronous Antler, Cariboo and Ellesmerian orogenies (late Devonian - early Carboniferous). The Prophet Trough was probably a foreland basin with foredeep in the south and a back-arc setting to the north (Richards *op. cit.).* Continued intra-Carboniferous subsidence of the Prophet Trough was interpreted as post orogenic relaxation. The Peace River Embayment, originating from the collapse of the Peace River Arch, formed an eastern expansion of the trough, while various intracratonic basins, troughs and arches controlled the local palaeogeography and bathymetry of the cratonic platform.

Sediments of the “eastern carbonate belt” prograded westward into the Prophet Trough forming a regressive wedge punctuated by several significant transgressive events. In west-central Alberta the depositional framework evolved from ramp to platform geometry, with the latter forming the dominant depositional control from middle Tournaisian to late Visean (Osagean to Meramecian).

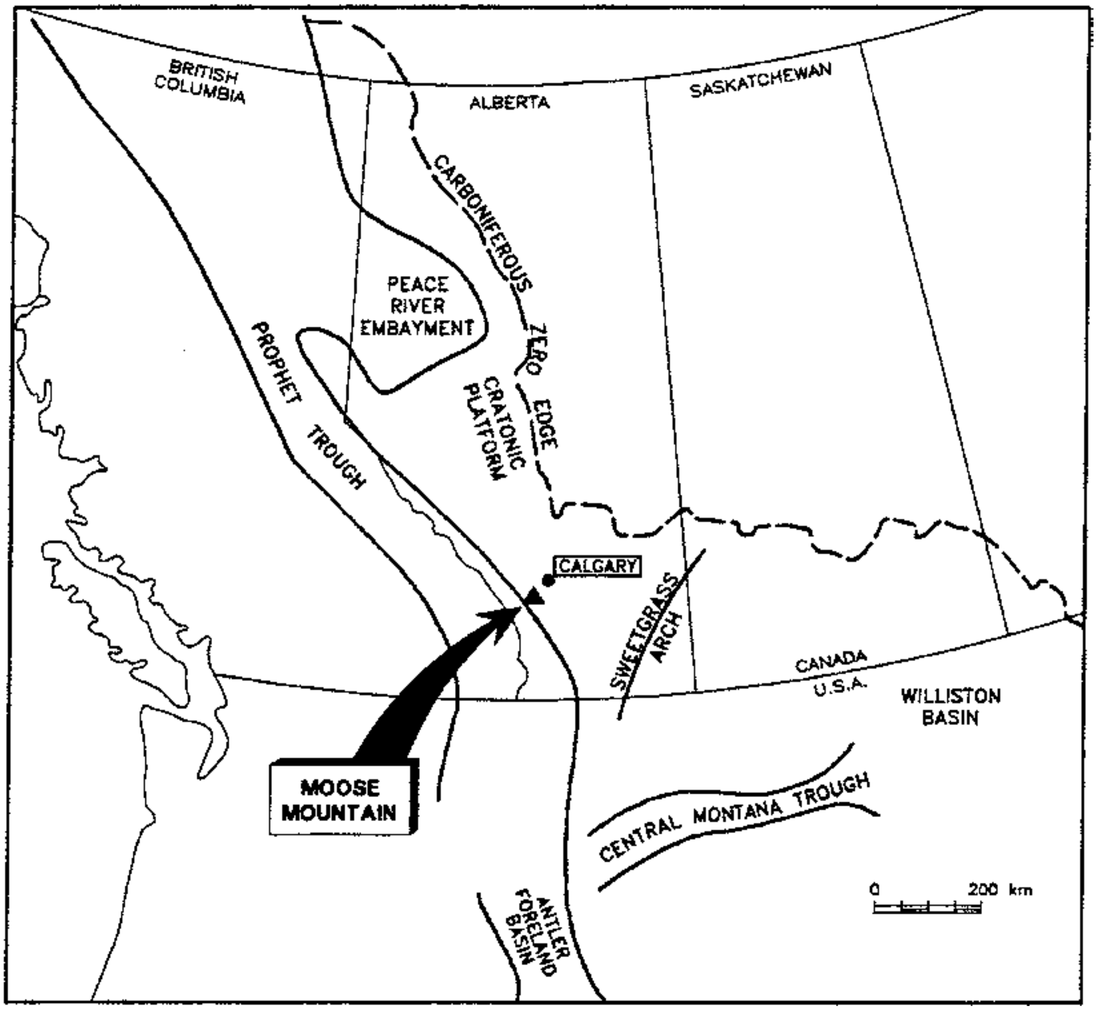


FIGURE 3 Sketch map showing the location of Moose Mountain relative to the principal Carboniferous palaeogeographic elements of westem Canada and contiguous U.S.A. (data from Richards, 1989; Richards *et al.* 1991).

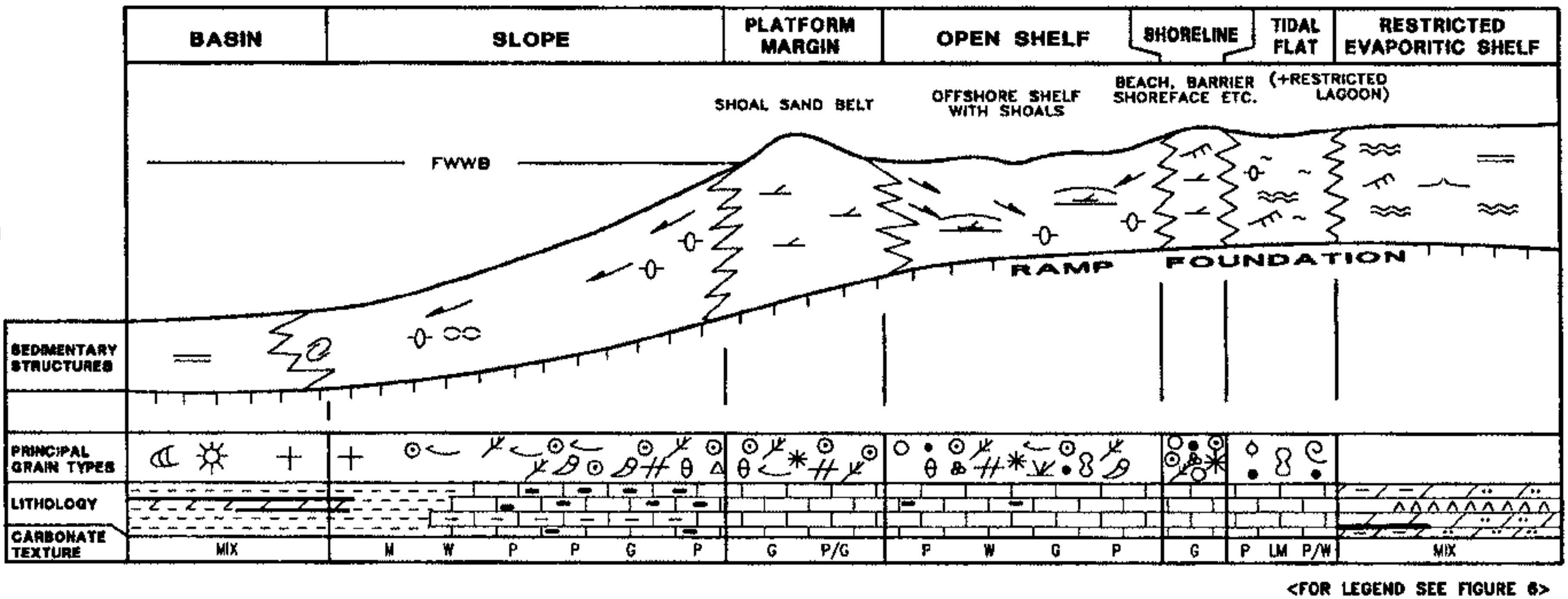
Definition and models of the Mississippian facies belts encountered in western Canada have been presented by Macqueen & Bamber (1968), Mamet (1976) and more recently Richards (1989). In the latter publication generalized models for early Carboniferous ramp and a platform are illustrated. Both models show a progression of facies from restricted supratidal shelf to deep water slope and basin, with the main differentiating character being the extent and duration of a shoal facies (crinoidal and/ or oolitic grainstone) in the shallow water shelf settings. Platform geometries evolved where extensive shoal facies were established and maintained, eventually defining a marginal tract and a shelf break. The distinction between ramp and platform is somewhat subtle.

Figure 4 illustrates a simplified platform model. The subdued nature of the platform is partly an ecological control, related to the rarity of the reef ecosystem (probably due to competition stress rather than lack of frame-building metazoans). The subtidal carbonate factory (ramp and platform) was supplied by a prolific biota dominated by echinoderms, bryozoans, brachiopods, corals with locally significant algal and foraminiferal microbiota. The biota of the peritidal and restricted shelf was dominated by cyanobacteria (stromatolites), skeletal algae, calcispheres and gastropods.

The stratigraphic units exposed at Moose Mountain (Canyon Creek) and their chronostratigraphic calibration are shown in Figure 2. As a consequence of the westward progradation of the Mississippian succession into the Prophet Trough, there is a marked east to west change in lithofacies. This has prompted the lithostratigraphic differentiation of lateral (coeval) formations and members (see Figure 5), many of which have marked diachronous boundaries. The changes in lithostratigraphic content and nomenclature is particularly marked between the Foothills and Front Ranges.

For definition of the Mississippian lithostratigraphic units in and around Moose Mountain the reader is referred to the papers of Macqueen & Bamber (1967,1968), Macqueen & Sandberg (1970), Macqueen *et al.* (1972), Richards & Higgins (1988), Richards *et al.* (1991), Glass (1990, western Canadian lexicon) and the regional reviews of Bamber *et al.* (1984) and Richards (1989). A broad sequence stratigraphic approach was utilized in the latter publication.

FIGURE 4: CONCEPTUAL DISTRIBUTION OF MISSISSIPPIAN FACIES BELTS OVER A SUBDUED PLATFORM GEOMETRY, MODIFIED FROM RICHARDS 1989, MACQUEEN & BAMBER 1968



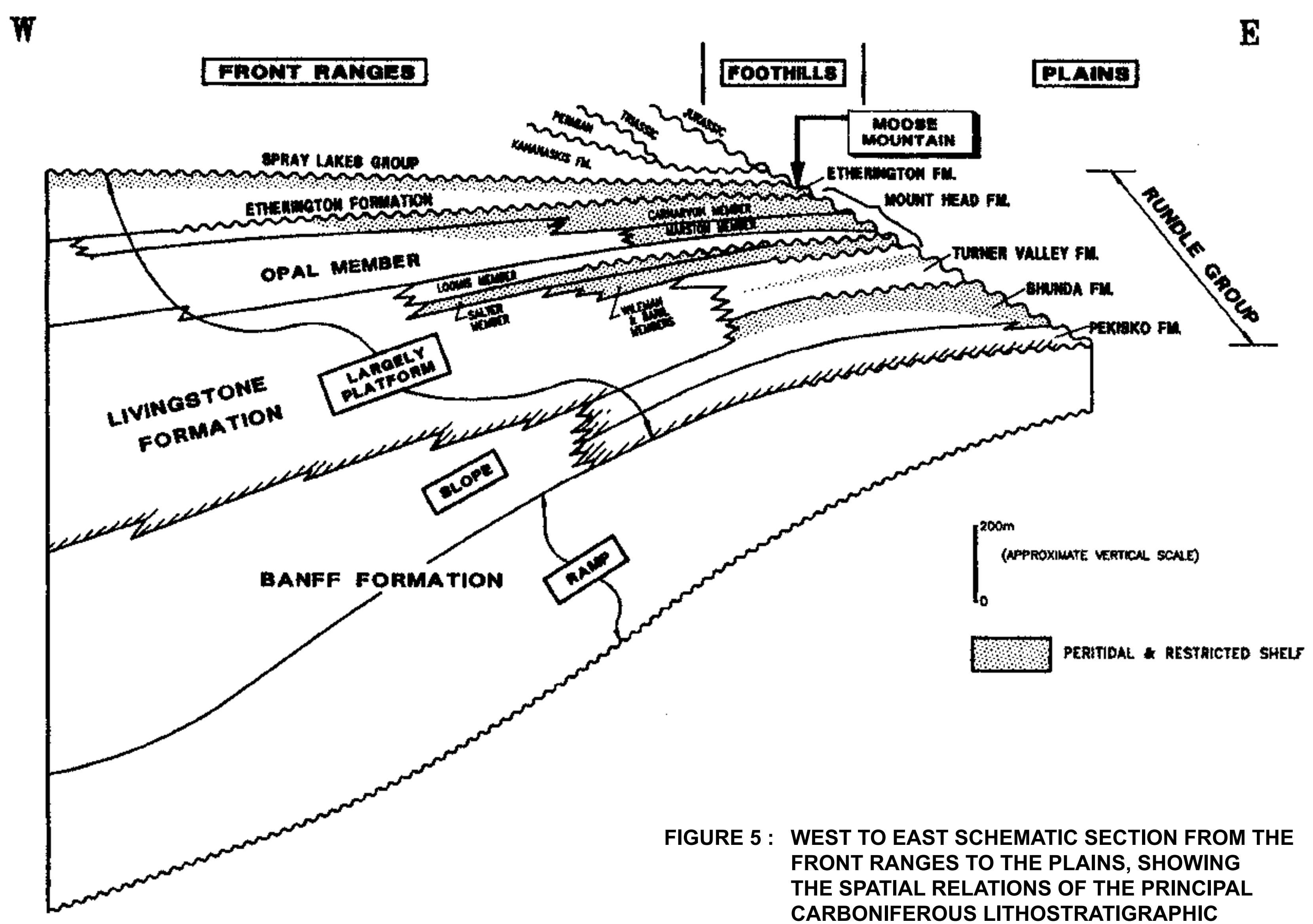


FIGURE 5 : WEST TO EAST SCHEMATIC SECTION FROM THE FRONT RANGES TO THE PLAINS, SHOWING THE SPATIAL RELATIONS OF THE PRINCIPAL CARBONIFEROUS LITHOSTRATIGRAPHIC SUBDIVISIONS. A SIMPLIFIED SEDIMENTOLOGICAL FRAMEWORK IS SHOWN.

MODIFIED FROM RICHARDS 1989

CANYON CREEK SECTION

The full Mississippian succession (including the complete Exshaw Formation) is represented in the Canyon Creek area by approximately 570 m of strata with all but the basal 27 m exposed. This succession includes representatives of the upper member of the Exshaw Formation (“Siltstone Member”), the Banff Formation and a full Rundle Group (Pekisko, Shunda, Turner Valley) up to the middle (or upper part) of the Mount Head. Higher Mississippian strata together with any representative of the Pennsylvanian to Triassic, have been removed below the sub-Jurassic and earlier unconformities (Figure 5). The Mount Head Formation (in the Moose Mountain area) is unconformably overlain by Jurassic Fernie Formation; the latter is well exposed in Canyon Creek east of the gas plant, where a shallowing-upward sequence from offshore mudstone to shoreface sandstone (with hummocky cross-stratification in transitional units) is exposed.

Two major shallowing-upward sequences are represented in the Mississippian, the Exshaw and the Banff through Rundle. The latter regressive trend is interrupted by numerous transgressive pulses. Formation contacts typically are disconformities, represented by both submarine and subaerial erosion surfaces.

Details of the Mississippian section in Canyon Creek are shown in the synoptic columnar section (Figure 6). This calibrates observations of the exposed section against the gamma-ray log from the same surface sheet in the 7-3-23-6W5 well. The latter well-log is also correlated with the subsurface Mississippian (Lower Thrust Sheet) from the 16-6-23-6W5 well, which has a near continuous cored section from the middle of the Turner Valley Formation to the top of the Banff Formation.

Exshaw Formation

The initial deposits of the Exshaw Formation indicate a significant transgression over a mid ramp setting of the underlying Famennian Palliser Formation; subsequent strata, in the Moose Mountain area, document a regressive trend to shallow subtidal conditions. Deposition of this formation is continuous across the Devonian - Carboniferous system boundary.

In the stratotype at Jura Creek, some 35 km N.W. of the Canyon Creek section, Macqueen & Sandberg (1970) recognized two members, a “Black Shale Unit” overlain by a “Siltstone Unit”. This section was recently redescribed in detail by Richards & Higgins (1988) and Richards *et al.* (1991) who have provided further conodont biostratigraphic refinement.

FIGURE 6 : COMPOSITE COLUMNAR SECTION OF THE EXPOSED MISSISSIPPIAN AT CANYON CREEK

LOG SHOWS LITHOSTRATIGRAPHIC SUBDIVISION, LITHOLOGICAL CHARACTER AND INFERRED DEPOSITIONAL FRAMEWORK. THE SECTION IS CALIBRATED AGAINST THE GAMMA-RAY LOG OF THE MISSISSIPPIAN (SURFACE SHEET) IN THE 7-3-23-6W5 WELL, WHICH IN TURN IS CORRELATED WITH THE GR LOG FROM THE LOWER THRUST SHEET. CHOICE OF THE 16-6-23-6W5 WELL WAS INFLUENCED BY THE NEAR CONTINUOUS CORED SECTION (MIDDLE TURNER VALLEY TO TOP BANFF) WHICH PROVIDES INVALUABLE INFORMATION ON STRATIGRAPHIC SUBDIVISION AND SEDIMENTOLOGY. THE PALINSPASTIC SEPARATION BETWEEN THE SURFACE EXPOSURES AND THE 16-6 WELL IS APPROXIMATELY 22KM.

GENERAL LEGEND (FOR ALL COLUMNAR LOGS)

LIMESTONE
DOLOSTONE
CHERT (BANDS & NODULES)
SANDSTONE
SILTSTONE
MUDSTONE
ANHYDRITE
COLLAPSE BRECCIA & SOLUTIONAL RESIDUUM (AFTER ANHYDRITE LOSS)

(NB. SUPERIMPOSED ORNAMENT DESCRIBES LITHOLOGICAL HETEROGENEITES)

F1-5 FEATURE FORMING UNITS
① FIELD TRIP STOPS

SKELETAL ALGAE
CALCISPHERE
SPONGE SPICULE
RADIOLARIAN
FORAMINIFERA
SOLITARY RUGOSE CORAL
COLONIAL RUGOSE CORAL (LITHOSTROTIONID)
-C- CORAL BED
SYRINGOPORA
BRYOZOAN
BRACHIOPOD
GASTROPOD
BIVALVE
CEPHALOPOD
CRINOID

BLASTOID
ECHINOID SPINE
PELLET/PELOID
COATED GRAIN (OOID, VADOID ETC)
LITHOCLAST
ONCOLITE
STROMATOLITE
CRUST (LAMINATED CALCITE OR DOLOSTONE)
CAVITY WITH GEOPETAL SEDIMENT
TEPEE
FENESTRAE
BURROW
RHIZOLITH
]R RUBBLY BEDDING (RHIZOBRECCIATION ETC.)
VUG AFTER DISSOLUTION OF ANHYDRITE NODULE

CONCRETIONARY LENTICULAR BEDDING
LAMINATED
CROSS-BEDDING
RIPPLE CROSS LAMINATION
SLUMP FOLD
GRADED (FINING UP) UNIT
DISCONFORMITY
ALLOCHTHONOUS EVENT BED (TEMPESTITE, CALCITURBIDITE ETC.)
LM LIME MUDSTONE
W WACKESTONE
P PACKSTONE
G GRAINSTONE
R RUDSTONE
F FLOATSTONE
D DEDOLOMITE
SI SILT, CALCISILTITE ETC.
MIX MICROCRYSTALLINE
M MICROSPAR

M MUDSTONE
LM LIME MUDSTONE
SI SILTSTONE (& MICROCRYSTALLINE)
FC FINE CALCARENITE
CC COARSE CALCARENITE

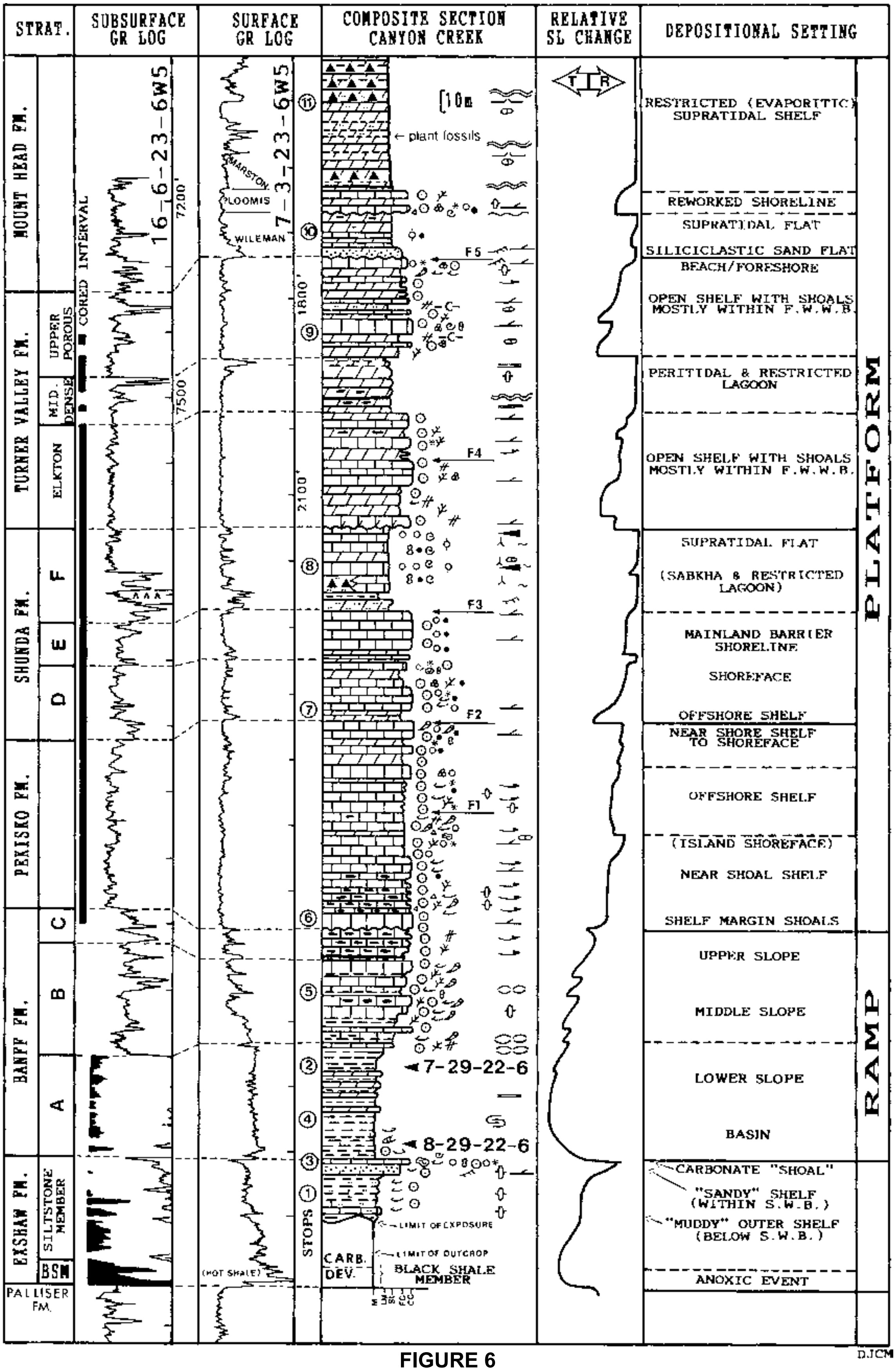

STRAT.
SUBSURFACE GR LOG
SURFACE GR LOG
COMPOSITE SECTION CANYON CREEK
RELATIVE SL CHANGE
DEPOSITIONAL SETTING
MOUNT HEAD FM.
TURNER VALLEY FM.
UPPER POROUS
MID. DENSE
ELKTON
SHUNDA FM.
F
E
D
PEKISKO FM.
C
BANFF FM.
B
A
EXSHAW FM.
SILTSTONE MEMBER
BSM
PALLISER FM.
CORED INTERVAL
16-6-23-6W5
7200'
7500'
7-3-23-6W5
MARSTON
LOOMIS
WILEMAN
1800'
2100'
(HOT SHALE)
STOPS
10m
plant fossils
F5
F4
F3
F2
F1
7-29-22-6
8-29-22-6
LIMIT OF EXPOSURE
LIMIT OF OUTCROP
CARB.
DEV.
BLACK SHALE MEMBER
T
R
RESTRICTED (EVAPORITIC) SUPRATIDAL SHELF
REWORKED SHORELINE
SUPRATIDAL FLAT
SILICICLASTIC SAND FLAT
BEACH/FORESHORE
OPEN SHELF WITH SHOALS MOSTLY WITHIN F.W.W.B.
PERITIDAL & RESTRICTED LAGOON
OPEN SHELF WITH SHOALS MOSTLY WITHIN F.W.W.B.
SUPRATIDAL FLAT
(SABKHA & RESTRICTED LAGOON)
MAINLAND BARRIER SHORELINE
SHOREFACE
OFFSHORE SHELF
NEAR SHORE SHELF TO SHOREFACE
OFFSHORE SHELF
(ISLAND SHOREFACE)
NEAR SHOAL SHELF
SHELF MARGIN SHOALS
UPPER SLOPE
MIDDLE SLOPE
LOWER SLOPE
BASIN
CARBONATE "SHOAL"
"SANDY" SHELF (WITHIN S.W.B.)
"MUDDY" OUTER SHELF (BELOW S.W.B.)
ANOXIC EVENT
PLATFORM
RAMP
D.JCM

FIGURE 6

(Figure 6 was originally a foldout: This page intentionally blank.)

The Black Shale Member is 9.3 m in the type section (*fide* Richards & Higgins, 1988) and maintains this thickness over a large area. The initial regional transgression resulted in a bathymetry estimated at between 150 and 300 m by de Wit (1987) and below storm wave base and less than 300 m by Richards & Higgins (1988). This transgression was accompanied by anoxic bottom water conditions and production of mudrocks high in organic matter (T.O.C. values typically 3 to 10%). These mudrocks subsequently became a significant hydrocarbon source horizon (the radioactive "hot shale" *auct*.). The boundary between the Devonian and Carboniferous systems in the type-section has been confined (on conodont evidence) to a section of strata in the upper part of the member, with the best estimate some 2.3 m from the top. The overlying Siltstone Member consists of argillaceous siltstone and limestone (37.4 m *fide* Richards & Higgins, 1988), which contains a conspicuous ichnofauna ("*Scalarituba*" dominated) and, although still suggestive of a moderate water-depth below storm wave base, marked a shallowing and an end of the anoxic event (Richards & Higgins, 1988); the contact with the overlying Banff Formation is here a disconformity attributed to submarine erosion.

At Canyon Creek a 28-m exposure of the Siltstone Member shows three discrete stratigraphic units, *viz:* a lower unit ("A", 21.8 m) of burrowed argillaceous sediments (calcareous, dolomitic and silty) with a characteristic brachiopod dominated faunule (Table 1), overlain by a very fine grained sandstone with conspicuous "*Scalarituba"* and *Helminthopsis* traces and localized medium scale cross-bedding ("Unit B", 4.8 m), capped by a 1.6-m oolitic and oncolitic grainstone (rudstone and floatstone, "Unit C") (see under **Stops 1 & 3**). Clearly the succession at Canyon Creek is considerably more proximal than at the type section, with the shallowing-upward sequence documenting a bathymetric range from below storm wave base to water depths of ooid formation and cyanophyte proliferation. This shallowing-upward trend is well illustrated by the cleaning-up of the gamma-ray log (Figure 6).

Banff and Pekisko formations

Deposition of the Banff Formation commenced with a major transgression, regarded as a widespread eustatic (early Middle Tournaisian) sea-level rise (see Richards & Higgins *op. cit.* p 410). In the Canyon Creek section the limestone unit of the Exshaw is directly overlain by dark grey calcareous mudstone of the Banff Member A (informal nomenclature, see Richards 1989, fig. 9.42), with no apparent erosive contact. The mudstone contains crinoids, benthonic bivalves and cephalopods in the lower few metres, but becomes devoid of biota, less calcareous and more fissile up-section. Slump folds have been recognized at one horizon (see under **Stops 3 & 4**). This transgression appears to have been progressive and resulted in water depths of several hundred metres (basinal setting).

Laminated microcrystalline dolostone and concretionary microspar characterize the upper part of the unit. Member A attains a thickness of 55 m and forms a characteristic high gamma motif (Figure 6).

Members B and C of the Banff (collectively 53 m) reflect a shallowing upward into ramp slope and eventually upper slope (proximal outer ramp) setting, with the shallowing accompanied by an increase in benthonic biota and consequent change to limestone dominated facies. Minor depositional cycles are conspicuous in Member B, with transgressive mudstone or muddy carbonate shallowing upward to bioclastic packstone and rudstone. The latter typically contain a diverse fauna of brachiopods, bryozoans, crinoids and blastoids. This fauna is judged to be largely autochthonous, and the beds are locally biostromal. Small scar features, below the main Banff-Pekisko cliff, are formed by the limestones at the top of these cycles (see under **Stop 5**), and the minor cyclical pattern is clearly differentiated on the gamma-ray log (see Figure 6).

A conspicuous incoming of chert bands and nodules marks the onset of Member C, while discrete beds and lenses of coarse crinoidal grainstone and rudstone, interbedded with dark grey argillaceous packstone, characterize the upper part of the member. The crinoidal units are allochthonous and are interpreted as event beds of tempestite origin. These units increase in number toward the Pekisko Formation contact (**Stop 6**) and often occur as lenticular (cut and fill) beds which have a channel form. Middleton (1963) showed that these channels had a N.E. to S.W. orientation, that is, across the depositional trend thus "running down the submarine slope". The Banff-Pekisko contact occurs at a recessive notch, below the prominent cliff-forming basal Pekisko limestone. This contact shows a few metres of relief and is interpreted as an erosional disconformity.

Light grey crinoidal grainstone and rudstone (cross-bedded in some sections) form the base of the Pekisko and these are overlain by cherty packstone and crinoidal tempestite beds similar to the uppermost Banff. These tempestite units show an upward change from beds with sharp top and base and crude grading to well graded beds with sharp base and transitional tops. This upper Banff to basal Pekisko section reflects the western progradation of a crinoidal shoal environment; the tempestite units in the Banff Member C derived from the front of the shoal and those in the Pekisko (above the thick crinoidal shoal beds) presumably derived from a back near-shoal environment. The formational contact discontinuity must mark only a minor disruption in the shoal passage, and the latter marks the local establishment of a platform geometry, a setting which dominates the deposition of the succeeding Rundle Group.

[ASIDE: The crinoidal shoal facies is an important component of many of the Mississippian formations in the Foothills and Front Ranges, and is probably the most significant control of platform geometries (i.e. there is no development of shelf margin buildups [Cracoean rather than Waulsortian] analogous to those of the late Visean of N.W. Europe). These shoals, well developed in the Pekisko and Turner Valley formations of Canyon Creek, and forming a dominant facies of the Livingstone Formation of the Front Ranges (see below), are generally recognized as cross-bedded, variably sorted, light grey, coarse crinoidal grainstone and rudstone, with fenestrate bryozoans and blastoids forming significant biotic contributions. They were formed at variable depths and appear to represent a spectrum of depositional settings from *in situ* crinoid bank/thickets shedding wave modified sands to wave and tide controlled “dead” sands (showing well developed medium scale cross sets often with sand wave morphology), with near shoal environments containing a significant component of shed crinoidal tempestite beds**]**.

Higher beds in the Pekisko include shallow subtidal shoal grainstone (crinoidal but often significantly oolitic and peloidal), packstone with tempestite units and subordinate peritidal dolostone; these represent a range of depositional settings from open shelf to near-shore and island. Total thickness of Pekisko Formation in Canyon Creek is 96 m (see **Stops 6 & 7**).

The Pekisko Formation and much of the overlying Shunda change facies westward, in and toward the Front Ranges (Figure 5), where they pass into Banff Formation slope facies (see Moore, 1958; Middleton, 1963; Richards, 1989).

Shunda Formation

A 90-m section of the Shunda Formation is present in the Canyon Creek exposures (Figure 6) and is referable to the informal members D, E, and F of Richards *et al*. (1994), these were initially designated as A,B,C in Richards *et al*. (1991, fig. 28). Previously the base of the Shunda (in the vicinity of Moose Mountain), had been chosen at an horizon correlative to the base of Member E (Middleton, 1963) and even the base of Member F (Rupp, 1969).

A significant transgressive event marks the onset of the Shunda Formation with the resultant deposition of low energy offshore wackestone over grainstone of the uppermost Pekisko. There is, however, a rapid shallowing back to nearshore grainstone (bioclastic, oolitic and peloidal) within Member D, while the succeeding members represent shoreline barrier island and tidal flat deposition. Conspicuous facies variations occur, particularly in Member F, despite the maintenance of a fairly constant thickness (see Middleton, 1963, p. 1818). Peritidal deposits include fenestral limestone, rooted in parts (with pedogenic and hypersaline vadose products, **Stop 8**), rippled dolomitic siltstone and solution residuums and breccia after the dissolution of sabkha-type anhydrite beds.

Turner Valley Formation

In the Canyon Creek exposures (eastern limb of Moose Dome) there is 127 m of Turner Valley Formation represented (Figure 6), some 16 m thicker than that in the Lower Thrust Sheet. This formation requires stratigraphic revision at the member level, with the three informal (industry influenced) named members “Lower Porous” (= Elkton), “Middle Dense” and “Upper Porous” still in current use (Penner, 1957; 1958; 1959). Rupp (1969) recognized five subdivisions of the Turner Valley in the subsurface of the Jumping Pound Field, but these are somewhat parochial and not widely used. The Turner Valley overlies the Shunda disconformably, the contact marking a significant transgression to an open shelf environment.

The Elkton (“Lower Porous”) is some 55 m thick and consists of an alternation of cross-bedded crinoidal shoal grainstone and inter shoal packstone and wackestone (often containing significant crinoidal grainstone tempestite beds). This interval was studied in detail by Murray and Lucia (1967), who documented the rapid facies change from higher energy grainstone to lower energy packstone and wackestone. A N.E. and S.W. trend to the foresets of the grainstone beds was deduced (*op. cit.*) and the facies interpreted as channel-like bodies controlled by tidal currents. A wave modified shoal facies is, however, favoured here.

Peritidal lithologies of the overlying Middle Dense (an abrupt regressive interlude) consist of laminated (early diagenetic) dolostone, which are conspicuously cherty and silty in parts, while local development of burrowed lagoonal sediments also occur. The top of the member is marked by an argillaceous, silty and pyritic dolostone, which forms a prominent high gamma-ray spike on the well log (Figure 6), and is correlatable over large areas. There is considerable variation in thickness of this regressive unit in the Moose Mountain exposures (see Middleton, 1963 p.1818).

The base of the Upper Porous marks a transgression back to an open shelf setting comparable to that of the Elkton, with subsequent sedimentation showing the same range of facies. One additional component is the occurrence of coral beds (“biostromes”) consisting of colonies of *Syringopora* and lithostrotionids (often large in size), which can be traced for significant distances (see under **Stop 9**). The youngest Upper Porous beds exposed in Canyon Creek are mixed bioclastic and oolitic grainstone of shoreface and foreshore affinities (see under **Stop 10**). The base of the overlying Mount Head Formation is disconformable and may represent a fairly significant erosion surface with loss of section toward the N.E. (see Middleton, 1963 p.1817).

Much of the Upper and Lower Porous have been replaced to a fine and medium crystalline subhedral dolomite during shallow burial diagenesis; the leached secondary pore system of this dolostone provides the principal hydrocarbon reservoir.

Westward the upper part of the Shunda, the Turner Valley and the lower four members of the succeeding Mount Head Formation (see below) change facies and formational identity and pass into the Livingstone Formation of the Front Ranges (Macqueen & Bamber 1967; 1968; Bamber *et al*. 1981; see Figure 5). The latter formation consists largely of thick bedded, often cross-bedded, crinoidal-bryozoan grainstone and rudstone, a facies which characterizes the platform margin shoal "sand" belt.

Mount Head Formation

A thickness of between 105 and 140 m of the Mount Head Formation is preserved in the Moose Mountain surface exposures. No attempt has been made in the past to correlate this succession with the six members recognized in the Front Ranges of the Highwood area. These members (Wileman, Baril, Salter, Loomis, Marston and Carnarvon) represent an alternation of peritidal (or restricted shelf) dolostone and subtidal limestone. One obstacle in differentiating the members at Canyon Creek is the apparent facies change to an amalgamation of the restricted dolostone facies and associated evaporites. However, recent work on the section has shown that a thin grainstone unit (?transgressive shoreline) overlying a marked erosion surface is present 18 m above the base of the formation and is tentatively identified as the Loomis Member. The underlying strata appear to be all Wileman, thus the Baril and Salter members have been cut out (Figures 5, 6).

A conspicuous orange weathering, ripple cross-laminated and cross-bedded, very fine grained sandstone forms the basal unit of the Wileman (see under **Stop 10**), and is overlain by silty dolostone and dark grey limestone (including dedolomite). This succession is referable to intertidal, restricted lagoon and supratidal flat conditions.The succession above the ?Loomis consists of brown weathering dolostone, silty in parts, with stromatolitic lamination commonly developed. Up to five zones of residuum and breccia after anhydrite dissolution are present, with the intervening beds often showing collapse or foundering structures (see under **Stop 11**). Depositional setting for this dolostone (and former anhydrite) was an extensive "supratidal" evaporitic shelf. These units are tentatively assigned to the Marston and probably Carnarvon members, while the correlatives of the uppermost part of the section are unknown; there is a possibility (solely on thickness considerations) that the Etherington Formation might be represented.

DIAGENESIS OF MISSISSIPPIAN SEDIMENTS

Diagenetic phases and processes affecting the Mississippian carbonates of Moose Mountain (both surface and subsurface repeats) are documented in Figure 7. The interpretation of processes and timing is deductive and not supported by analytical data (isotopes or fluid inclusions etc.). Nevertheless the arrangement does fit the observed petrographic data and serves to illustrate the complexity of the diagenetic history. Because the Mississippian is here considered as a single unit (a succession of more than 570 m) there is an obvious overlap and synchroneity between surface and shallow burial diagenetic events. Also because of subsequent thrust stacking, there is a depth related variation in the intensity of late diagenetic processes.

Early and near surface diagenesis

Early diagenetic surface and near surface processes include marine cementation (isopachous cements well developed in Shunda grainstone, Figure 8), vadose products (hypersaline and meteoric, in Shunda fenestral wackestone), evaporitic (sabkha-type) anhydrite emplacement (Mount Head and Shunda) and related evaporitic tidal flat dolomitization. The latter is the least ambiguous of the various dolomite types encountered in this Mississippian succession (see below), with dolostone lithoclasts in undolomitized ?Loomis grainstone (interbedded with the dolostone) testifying to the early origin.

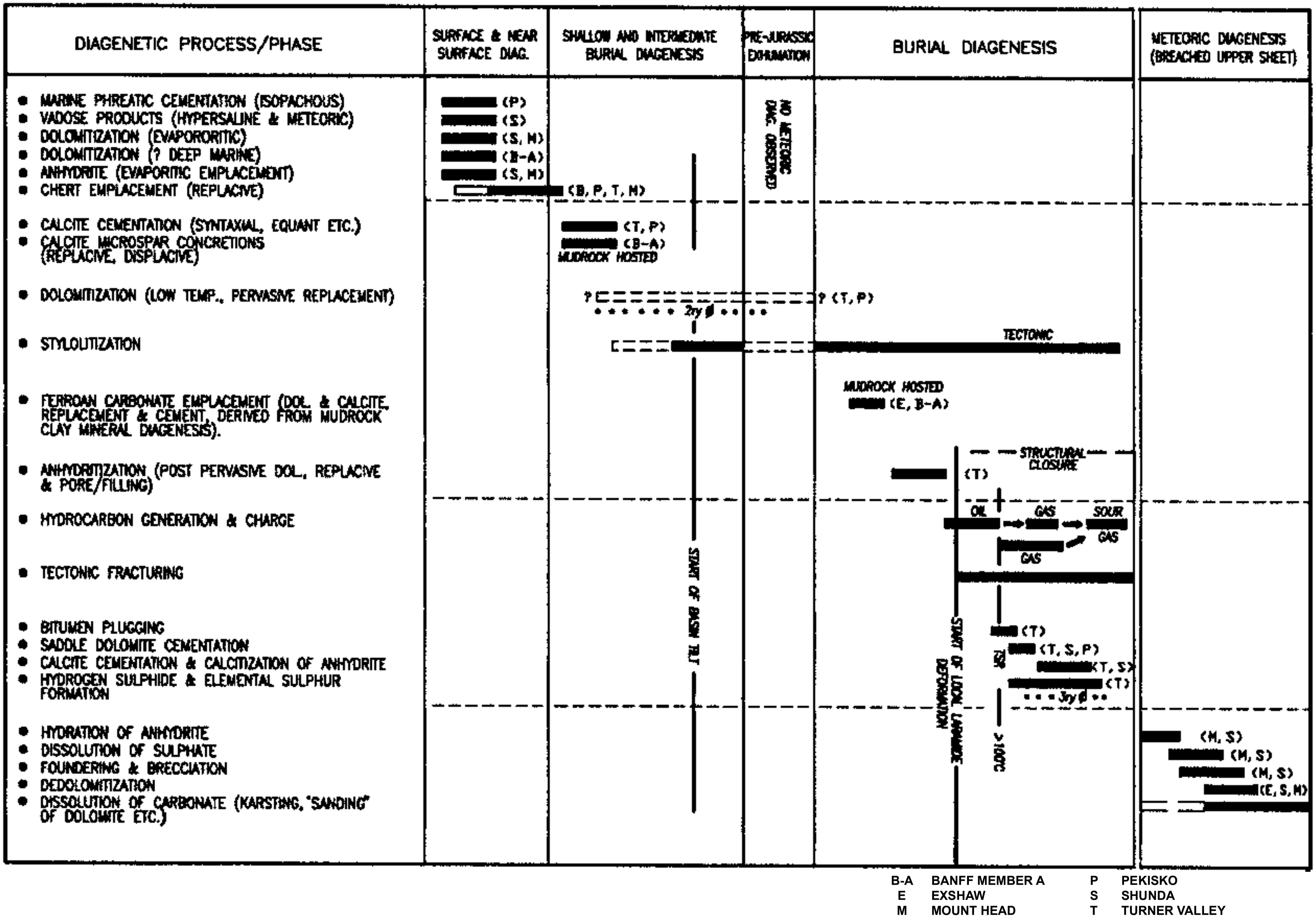
Finely crystalline dolostone occurring in mudstone of the Banff Member A is another candidate for early dolomitization, and is interpreted as the product of deep water (sea-water) dolomitization induced by organic matter diagenesis. Chert emplacement, particularly evident in the uppermost Banff and Lower Pekisko formations, is an early precompactional diagenetic phase.

Burial diagenesis

Diagenesis in the burial regime accounts for many of the significant modifications to the Mississippian rocks, with processes referable to shallow (intra-Carboniferous), and deeper (post Jurassic) burial settings.

Calcite cementation *via* syntaxial overgrowths particularly on echinoderm grains (e.g. Turner Valley and Pekisko grainstone), and some equant spars are referable to a shallow burial selting (meteoric or connate “marine” phreatic), with the syntaxial cements definitely predating the pervasive dolomitization.

FIGURE 7 : DIAGENETIC PHASES, PROCESSES & INFERRED PARAGENESIS OF THE MISSISSIPPIAN AT MOOSE MOUNTAIN



Concretionary limestone (non-ferroan calcite microspar) occurring in mudstone at the top of the Banff Member A, were emplaced during shallow burial and before significant compaction. This microspar is likely related to organic matter diagenesis.

Origin of the pervasive dolomitization that affects the Turner Valley (forming the principal Mississippian reservoir) is speculative and has not been fully addressed in the literature. This dolomitization can, however, be reasonably assigned to shallow or intermediate burial diagenesis. The replacive dolostone is typically fine to medium crystalline and hypidiotopic, with the secondary pore-system (biomoldic, intercrystalline etc.) after dissolution of residual calcite, appearing to be synchronous or closely associated with the replacement. There is a tendency for the replacement to be focused where the initial lithologies contained lime-mudstone, i.e. matrix selective in wackestone and packstone (see Murray & Lucia, 1967), a phenomenon explained by the larger surface area offered by the finer grain size. Thus in partly dolomitized successions it is these lithologies that are replaced; where dolomitization is more intense, grainstone is also altered. Replacement is both fabric retentive (with delicate components replaced or ghosted) and fabric destructive. The dolomite is considered to be a low temperature phase (finely crystalline, subhedral and not of saddle form).

There is an increase in the proportion of this replacive dolostone between the surface exposures of Moose Mountain and the subsurface. In the Elbow River road cut (Prairie Mountain Thrust, west side of the Moose Mountain structure) for example, approximately 72% of the formation is dolostone, compared to 87% in the cored subsurface (these figures include dolostone in the “Middle Dense” Member, approximately 15%, which is early diagenetic in origin). This west to east increase in replacement is continued in the subsurface as noted by Stein (1977), who attributed it to processes at the sub-Jurassic unconformity. A dolomitized “cap” has been reported by Lake (1989) at the Mississippian subcrop in south-east Saskatchewan, but this is a very confined zone of replacement (in terms of thickness). Dewatering of the overlying clay rich strata was suggested for the source of magnesium for the replacement (*ibid*). It is doubtful whether this or any other process at the unconformity could produce the widespread replacement encountered in the Turner Valley Formation.

The eastward increase in dolomitization may have been a pre-unconformity trend. Murray & Lucia (1967), for example, suggested an early diagenetic reflux of dolomitizing brines from the Mount Head to account for the replacement. Given the high proportion of evaporitic units in the Mount Head and the eastward palaeogeographic trend to increased evaporitic facies, the application of this model is worthy of further consideration.

Low temperature replacive dolostone in Devonian subsurface formations (e.g. Keg River and Swan Hills formations) have been attributed to updip flow of basinal brines during basin tilting in late Palaeozoic to Jurassic (Qing & Mountjoy, 1988; Kaufman *et al.* 1991). This model may have utility for the Mississippian occurrences, although if brines were derived from deeper levels in the western subsurface, it is difficult to visualize why the replacement should be so largely confined to the Turner Valley. Illing (1959) invoked a magnesium source (for the Turner Valley dolomitization) from deep connate waters released during compaction, and suggested that pre-dolomitization permeability trends were the main controlling factor for the localization of the replacement.

The origin of the pervasive dolomitization is thus a problem, a shallow to intermediate (pre-Laramide) burial diagenetic origin is the most reasonable possibility, but choice of a model requires significant investigation.

Ferroan overgrowths occur on dolomites from the Banff Member A and ferroan dolomite (including some saddle dolomite) and ferroan calcite cements and replacive microspar are common in the Exshaw Formation Siltstone Member (units A & B). The source of these ferroan carbonates is postulated to be the burial diagenesis of the closely associated shales (Banff and Exshaw), with the necessary ions (Fe, Mg, Ca etc.) derived from clay minerals either through structural transformations (e.g. smectite - illite, *sensu* McHargue & Price, 1982) or from the release of absorbed ions on the clays and associated organic matter.

A phase of anhydritization followed the pervasive dolomitization, this locally replaced the dolostone and occluded some secondary pores. The origin of this anhydrite is obscure, but it occurred between the main phase of dolomitization and bitumen emplacement.

Later burial diagenesis is related to intra-Laramide structuring and the development of closure. There is evidence of some initial oil charge (presumably Exshaw sourced) and cracking (or consumption) with resultant emplacement of bitumen, while concomitant and subsequent thermochemical sulphate reduction (TSR) produced H_2S, saddle dolomite, native sulphur, calcitized anhydrite and calcite cementation (products detectable in both the surface and subsurface sheets). Saddle dolomite, often a product of TSR (see Machel, 1987b), occurs in small quantities in matrix pores and fractures throughout the Mississippian carbonates. It is, however, particularly abundant in the pore system (fenestrae and root molds) of the Shunda Member F (Figure 9) (**Stop 8**), which were formerly infilled by anhydrite (remnants are still present in some pores encased in replacive calcite, Figure 10). Calcitized anhydrite at this locality and calcite (with minor native sulphur and bitumen) infilling vugs after replacive anhydrite nodules in the Turner Valley Formation (**Stop 9**) are further support for this process in the surface sheet.

Temperatures for the TSR reaction to initiate are considered to be in the 100-134° C range (Machel 1987a; 1989). Clearly the reaction was more intense in the lower (deeper) Mississippian thrust repeats and proportionally greater in the underlying Palliser. Site of the reaction was controlled to some degree by the ability of the hydrocarbon to interface with the sulphate, and thus would be more intensive where better permeabilities allowed access. Oil reactions with sulphate would have characterized the early redox reactions with associated bitumen formation, while later TSR reactions probably involved only methane and hydrogen sulphide (see Machel *op.cit.*; Krouse *et al.* 1988). Gas in the subsurface Mississippian contains approximately 11% H_2S while in the Palliser it ranges from 25% to more than 45%. Sour gas is seeping from the Upper Thrust Sheet adjacent to Canyon Creek near **Stop 1**.

Late meteoric diagenesis

The Cenozoic surface breaching of the Mississippian initiated late meteoric diagenesis including dedolomitization (e.g. Exshaw, Shunda, Turner Valley and Mount Head), dissolution of anhydrite and associated foundering and brecciation (Figure 11), while localized dissolution of calcite and dolomite produced disaggregation ("sanding") of some beds (Turner Valley replacive dolostones are particularly prone to this weathering phenomenon).

There is good evidence that the dissolution of anhydrite occurred at this time rather than during the pre-Jurassic erosional episodes. Collapse breccia and solutional residuums are all that remains of the Shunda and Mount Head anhydrite beds in exposed sections, while in the subsurface these anhydrites are largely intact. In the 13-28-22-6W5 well, for instance, the anhydrite occurs (2310 to 2330 m) within 12 m of the unconformable Jurassic Fernie contact. It is likely that hydration of the anhydrite to gypsum preceded the actual dissolution; this is supported in well data from the Moose #2 (8-29-22-6W5) where gypsum and anhydrite are recorded from the Devonian of the surface sheet, and from the McColl-Frontenac Moose Mountain #1 well (9-6-23-6W5), where gypsum was also noted (MacNeil, 1943 p. 46).

Microbial or abiological initiated redox reactions at the natural sour gas seeps (**Stop 1**) have resulted in the present day precipitation of elemental sulphur and calcite (see Figure 12).

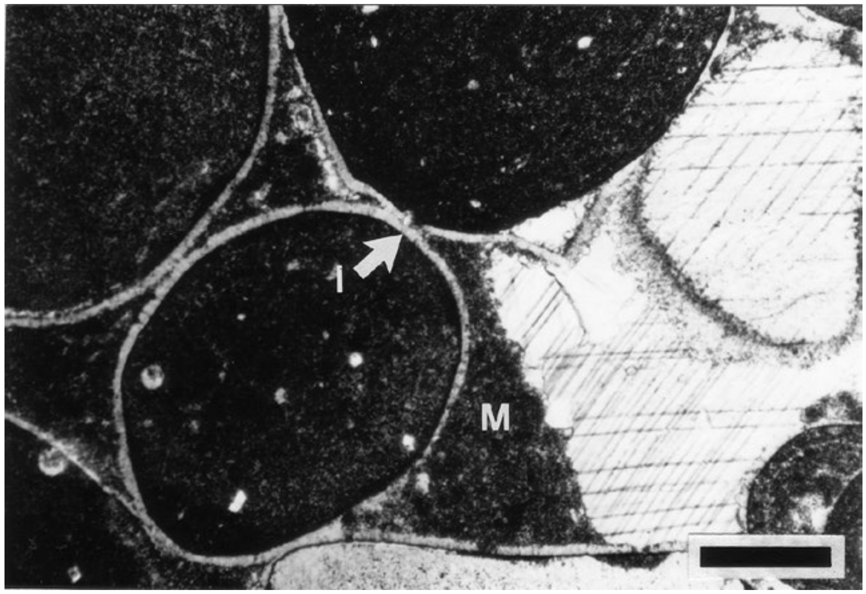


FIGURE 8 Shunda Formation (Member D): thin-section photomicrograph (plane polarized light, scale bar 0.25 mm) showing an isopachous marine cement (I) coating rounded lime-mudstone intraclasts. The original lithology was a coarse grainstone, which was subsequently infiltrated by carbonate mud (M). Calstan Shell Moose 16-6-23-6W5, 7928′ (2417 m).

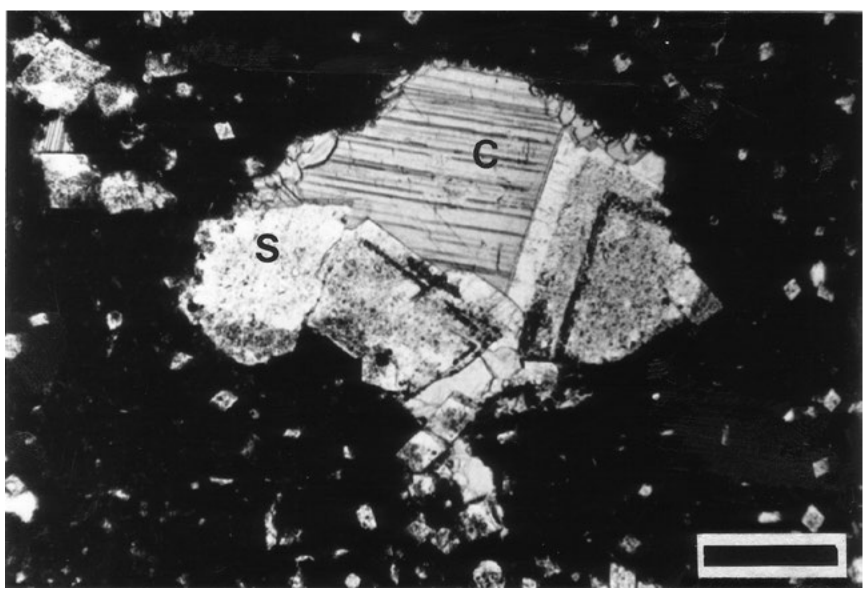


FIGURE 9 Shunda Formation (Member F) Stop 8: thin-section photomicrograph (plane polarized light, scale bar 0.25 mm) of saddle dolomite (S) and calcite (C) occluding a fenestral pore in a wackestone.

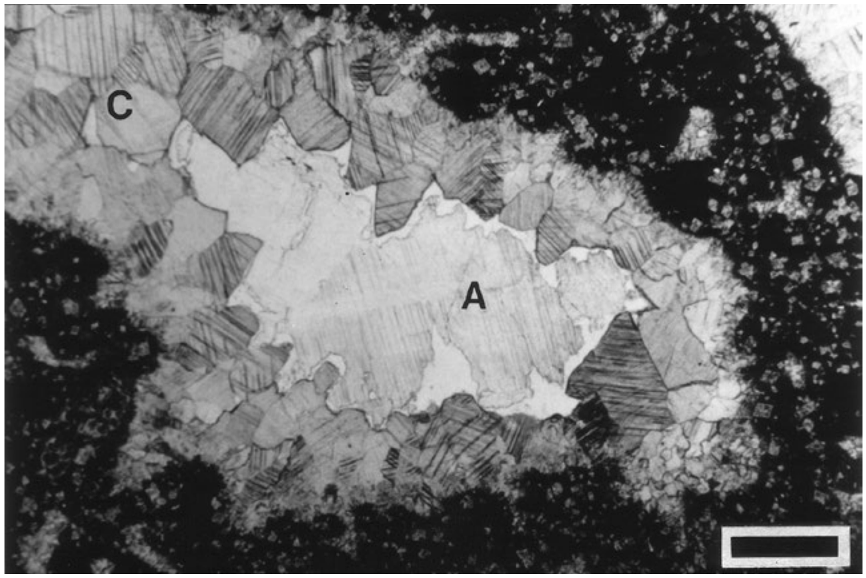


FIGURE 10 Shunda Formation (Member F) Stop 8: thin-section photomicrograph (plane polarized light, scale bar 0.5 mm) showing a fenestral pore occluded by calcite (C) and anhydrite (A). The calcite probably resulted from calcitization of the anhydrite.

FIGURE 11 Collapse structure in Mount Head dolostone. This resulted from anhydrite dissolution in the underlying section. Exposure in bank of dry stream bed (immediately east of Canyon Creek) 120 m E.S.E. of the ?Loomis exposure of Stop 10.

FIGURE 12 Natural sour gas seep showing sulphur (S) coated cobbles. A film of precipitated calcite (C) has formed on the standing water (see under Stop 1).

STRUCTURAL GEOLOGY

Setting

The Rocky Mountains of Alberta comprise a series of thrust-sheets which bring rocks as old as Precambrian to surface outcrop. These thrust-sheets and their bounding sole-thrusts dip almost exclusively towards the S.W. indicating that movement was from S.W. to N.E. Age of thrusting was Late Cretaceous to early Tertiary (Laramide) with a possible precursor pulse of Jurassic age (Columbian).

Many of the thrusts are major translation surfaces, some with over 20 km of shortening across the fault, and cumulative shortening through the entire belt is estimated as greater than 150 km. (Bally *et al.* 1966). Style of deformation is almost entirely “thin skinned” with little evidence of basement involvement. At surface the thrusts have long continuous (sinuous) outcrop patterns. The most easterly of these is the McConnell Thrust which brings Cambrian and younger rocks to surface.

At outcrop, east of the McConnell Thrust, a zone of highly imbricated and deformed Mesozoic to Tertiary rocks some 50 km wide, forms the Foothills.

Within the Foothills, the Moose Mountain and several other Palaeozoic inliers are developed. These are characterized by rocks as old as Mississippian coming to surface outcrop in broad anticlinal structures but with no significant outcropping thrust. For a general account of the Rocky Mountain thrust belt the reader is referred to the publications of McMechan & Thompson (1989), Dahlstrom (1970), and Bally *et al.* (1966).

Moose Mountain Anticline surface structure

Moose Mountain Anticline is a N.W. to S.E. trending structure, some 26 km long and 11 km wide (Ower, 1975 p.22), lying 10 km east of the McConnell Thrust (Figure 1). The anticline is centred on Townships 22 and 23, Range 6 West 5 and was first mapped in 1905 for the Geological Survey (see Cairnes, 1914), and resurveyed in 1942 (see Beach, 1943).

Surface expression of the fold, which exposes Mississippian Exshaw Formation in the core, is an asymmetric anticline with south-westerly limb dips of 30-35° and north-easterly limb dips of up to 60°. In reality, the fold is not a simple anticline but more of an anticlinorium with several minor folds superimposed on the major anticline, especially toward the north. The axial plane of the fold dips towards the S.W. at about 30° near surface, increasing to 45° at depth. The fold axis plunges gently towards the N.W. at about 10° at surface, decreasing to less than 2° in the subsurface. The fold also plunges gently to the S.E. to produce a doubly plunging closed anticline or pericline, known for many years as “Moose Dome” (see structure contour maps of MacNeil, 1943 figure 5; Dalhstrom & Henderson, 1959 figure 5; Ower, 1975 figure 1). Structural closure on the top of the Mississippian has been estimated in excess of 610 m (Beach,1943; Ower,1975).

Palaeozoic rocks of Moose Dome are flanked by Mesozoic strata which have been locally deformed into tight isoclinal folds cut by numerous small thrust-faults.

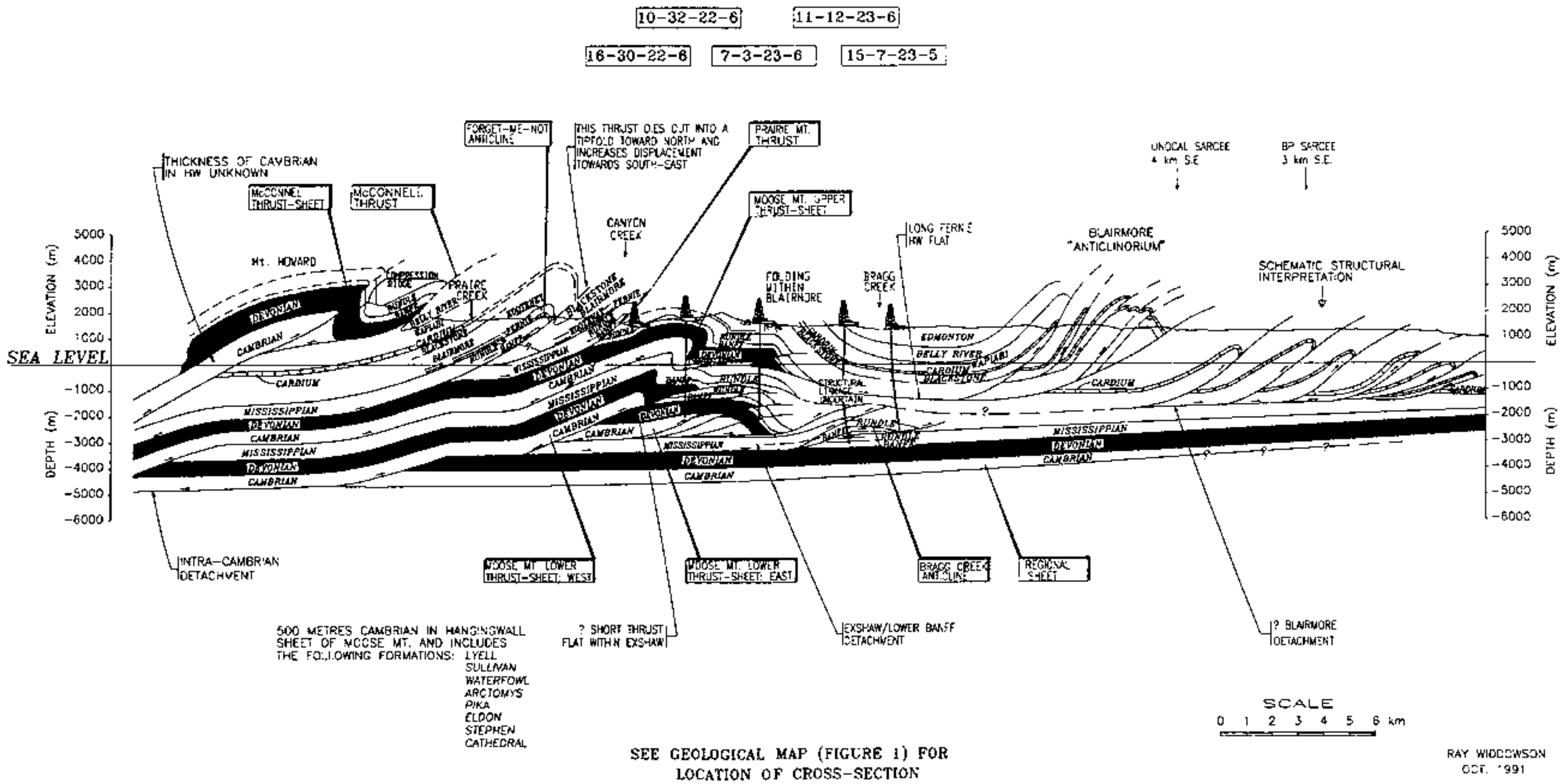
The S.W. flank of Moose Dome is complicated by two thrust slices of Mississippian and younger rocks which create the Prairie Mountain Fault and the Forget-me-not Anticline. The structure of these features together with a full description of the subsurface geometry of “Moose Dome” follows.

Moose Mountain subsurface structure

The subsurface structure of the Moose Mountain Anticline is illustrated by means of a single structural cross-section (Figure 13). This section incorporates available well data and surface outcrop information, but has not been constrained by any seismic data.

FIGURE 13 : STRUCTURAL CROSS-SECTION THROUGH MOOSE MOUNTAIN

SOUTH-WEST NORTH-EAST



(Figure 13 was originally a foldout: This page intentionally blank.)

The section was constructed on a bearing of 241° (approximately S.W.) perpendicular to the tectonic strike, and close to the central culmination of the structure where there are several deep well penetrations.

Ower (1975) documented the historical evolution of structural interpretations of Moose Mountain, from “thrust-faulted anticline” to “folded fault” (see Scott, 1951) and to Ower’s (*op. cit.*) own interpretation of a complex “series of stacked fault plates overridden by [a] much larger surface plate, which is folded into an anticlinal structure” (“death of a folded fault”).

The cross-section presented here incorporates data from the more recent well penetrations particularly the 10-32-22-6W5 well, and proposes a different structural model from that of Ower (*op. cit.*). In our interpretation the Upper Thrust Sheet is deformed and folded by emplacement of a complex lower thrust system.

The main structural elements on the line of section are as follows:

McConnell Thrust Sheet

Two features of this structure are pertinent to the present interpretation of Moose Mountain; firstly, that the sole thrust is developed within the Cambrian, and secondly, that displacement at the Palaeozoic level is at least 15 km.

Forget-me-not Anticline

This is a distinct, narrow topographic ridge of Mississippian rocks which consists of a tight anticline with a steep to vertical N.E. limb. On the N.E. side the fold is bounded by a thrust-fault which, in the north, dips at about 45° S.W. and places Mississippian rocks on the Fernie. Further south the thrust is less steep (15 to 30° and places Mississippian on strata as young as Wapiabi (*fide* Beach, 1943). This difference suggests displacement on the thrust is increasing southwards, an interpretation supported by the increasing outcrop width of the Mississippian in that direction.

Towards the N.W. this Mississippian anticline narrows and plunges beneath the Mesozoic cover rocks until eventually the only surface manifestation is a tight anticline of Kootenay sediments.

In the subsurface the structure is interpreted as a Mississippian ramp anticline with a floor thrust in the Exshaw or Banff (both common detachment horizons in the Alberta Foothills).

Prairie Mountain Thrust

This is a very similar feature to the Forget-me-not Anticline and is interpreted to be a thrust-sheet of Mississippian and younger rocks which has branched upwards towards the N.E. from the Moose Mountain Upper Thrust Sheet (described below).

The oldest rocks outcropping in the hangingwall of this thrust are Mississippian Banff and so the detachment horizon is interpreted to be within the Banff or underlying Exshaw. The Mississippian in the hangingwall dips 20-35° S.W. with no sign of anticlinal folding except in the N.W. This suggests at least 1 km of shortening where the cross-section has been drawn (Figure 13). Towards the S.E. the outcropping thrust dies into an anticlinal fold involving Fernie before merging into the general Moose Dome structure, while in the N.E. the surface thrust veers due north and displacement gradually diminishes.

Moose Mountain Upper thrust Sheet

This is the next thrust-sheet carrying Palaeozoic rocks to the N.E. of the McConnell Thrust, but unlike the latter the sole thrust does not come to surface outcrop as a single major thrust.

The oldest rocks in the hanging wall of the sheet are Cambrian Cathedral Formation as found in the 10-32-22-6W5 and 12-3-22-6W5 wells, suggesting a detachment horizon within the Middle Cambrian Mount Whyte Formation. Minor internal deformation within the sheet includes the Forget-me-not Anticline and Prairie Mountain Fault described above, plus some thrust repetition within the Devonian as indicated by the 12-3 well. The most spectacular deformation is the recumbent anticlinal fold encountered within the Cambrian in the 10-32 well. This fold is the product of ramp anticline development within the underlying thrust-sheet. The Cambrian, Devonian and Mississippian strata thin and cut out in turn towards the N.E. as the hangingwall cut-off for each unit is encountered. For example, the Cambrian is very thin in the 7-3-22-6W5 well, the Devonian is cut out in 6-25-22-6W5 and the leading edge of the Mississippian must be just N.E. of 6-25-22-6W5.

The intra-Cambrian sole thrust emplaces Cambrian Cathedral Formation directly upon Mississippian Mount Head Formation (with perhaps a thin sliver of Fernie) across the western part of the structure, but towards the N.E. between the 10-32-22-6W5 and 7-3-22-6W5 wells, the detachment climbs up section from the top Mississippian into the Nikanassin and, ultimately, *via* a series of ramps and flats, comes to surface as the “Blairmore Anticlinorium” some 20 km N.E. of Moose Dome (Figures 1 & 13). Total shortening over this thrust fault is estimated at some 25 km.

Footwall cut-offs within the Palaeozoic section that match those of the hangingwall cut-offs described above, are developed beneath the McConnell thrust-sheet (see Figure 13).

Moose Mountain Lower Thrust Sheet

This thrust sheet comprises rocks of Cambrian, Devonian and Mississippian age and is developed underneath the Moose Mountain Upper Thrust Sheet. Like the Upper Thrust Sheet the sole thrust is developed within the Middle Cambrian and the upper thrust detachment is within basal Fernie. Between these two thrust-flats a major thrust ramp in the Devonian/Mississippian section is interrupted by a thrust flat within the Exshaw. To the N.E. of the 7-3-22-6W5 well the thrust fault cuts up-section from the basal Fernie, through the Mesozoic. Total shortening on this thrust is estimated at 10 km. Within the Lower Thrust Sheet a considerable degree of deformation is apparent. An important thrust, which branches from the top of the Mississippian footwall ramp, divides the Lower Thrust Sheet into an eastern and western portion.

The **eastern** part of the Lower Thrust Sheet dips gently S.W. with conspicuous internal imbrication splaying towards the N.E. (from the sole thrust) and dissecting the whole Devonian and Mississippian succession. The leading edge of the sheet dips steeply N.E. (40-60°) in the 7-3-23-6W5, 6-25-22-6W5 and 10-17-23-6W5 wells, which indicates that the hanging wall cut-offs of the various Palaeozoic units are almost perpendicular to the gently S.W. dipping floor thrust. This combination of steep leading edge and internal imbrication suggests that the advancing thrust sheet may have encountered an obstacle preventing further thrust-displacement to the N.E. Just such an obstacle is present in the form of a Mississippian ramp anticline, named the Bragg Creek Anticline in this guide (Figure 13). However, for this anticline to have acted as a barrier, it must have developed before final emplacement of the Lower Thrust Sheet, that is, out-of-sequence.

The **western** portion of the Lower Thrust Sheet together with the whole of the Upper Thrust Sheet is deformed into a spectacular recumbent fold. This fold is essentially a ramp anticline developed above the branching thrust. In detail, the emplacement of a near-vertical hangingwall Cambrian ramp on to a top Devonian (Exshaw) footwall flat has created the oversteepened fold. The 12-3-22-6W5 well drilled in the south, found a thick folded sequence of hangingwall Devonian thrust over footwall Mississippian Rundle, just to the N.E. of (interpreted) near-vertical Cambrian thrust over flat Devonian. Towards the N.E. the branching thrust emplaces Mississippian on to Mississippian until just S.W. of the 7-3-23-6W5 well where the thrust cuts up section and hangingwall Mississippian strata are progressively cut out against footwall Mesozoic clastics.

Bragg Creek Anticline

This is a ramp anticline, involving Mississippian, developed immediately to the N.E. of the Moose Mountain complex. The structure, which has been drilled by two wells, is quite separate from Moose Mountain.

Foreland basin cover sequence deformation

The Mesozoic to Tertiary rocks to the N.E. of Moose Mountain are deformed into a series of folds and thrusted structures. The shortening represented by these structures is a product of contraction within the Palaeozoic further to the S.W. It is our interpretation that the Mesozoic shortening, represented by the “Blairmore Anticlinorium” some 15 km N.E. of Moose Mountain, balances the Palaeozoic contraction occurring in the Moose Mountain Upper Thrust Sheet (i.e. some 25 km). Similarly the shortening within the Mesozoic to the N.E. of the “Blairmore Anticlinorium” is interpreted to balance the Palaeozoic contraction within the Moose Mountain Lower Thrust Sheet. Shortening within the Bragg Creek Anticline is also considered to feed into this latter system.

STRUCTURAL EVOLUTION

The interpreted evolution of the Moose Mountain structure is depicted in Figure 14. Here the formation and emplacement of the structure is considered in terms of four discrete stages, although in reality the actual processes were probably more of a dynamic continuum. The structural history is basically one of in-sequence thrust development, that is, new thrusts developed beneath and to the N.E. of existing thrust-sheets; there are, however, some important exceptions (see below). For simplicity only the deformation of the Palaeozoic strata has been illustrated in Figure 14.

Stage 1

The McConnell Thrust cuts up-section towards the N.E. through the Cambrian, Devonian and Mississippian from a major sole thrust within the Cambrian Mount Whyte Formation. The hangingwall Cambrian and younger sequence is emplaced directly on to flat-lying Mississippian rocks for an unknown distance before the thrust cuts further upsection through the Mesozoic. At some stage during this process bulk slippage of the footwall along the base Mississippian (Exshaw) detachment led to the development of two Mississippian ramp anticlines about 10 km to the N.E.

Stage 2

The mid-Cambrian sole thrust beneath the McConnell Thrust propagated further to the N.E. until it once again cut up-section through the Palaeozoic (perhaps prompted by a change in slope above an old down-to-the-west extensional fault—a common phenomenon in the Alberta thrust belt). Cambrian rocks of the Moose Mountain Upper Thrust Sheet were emplaced directly onto Mississippian strata at “regional” for a distance of some 8 km before the thrust cut up-section through the Mesozoic.

The McConnell Thrust Sheet plus the two small Mississippian ramp anticlines (and all the existing thrust-sheets further S.W.) were passively carried forward to the N.E. above the mid-Cambrian detachment.

Stage 3

Further propagation of the mid-Cambrian sole-thrust continued to the N.E. and once again cut up-section through the Palaeozoic, emplacing Cambrian rocks of the Moose Mountain Lower Thrust Sheet on to Mississippian strata at “regional”.

Because the footwall ramp of the Lower Thrust Sheet is geographically so close to the footwall ramp of the previously developed Upper Thrust Sheet, the latter was passively carried above the growing Lower Thrust Sheet producing a double Palaeozoic thrust-sheet above “regional”.

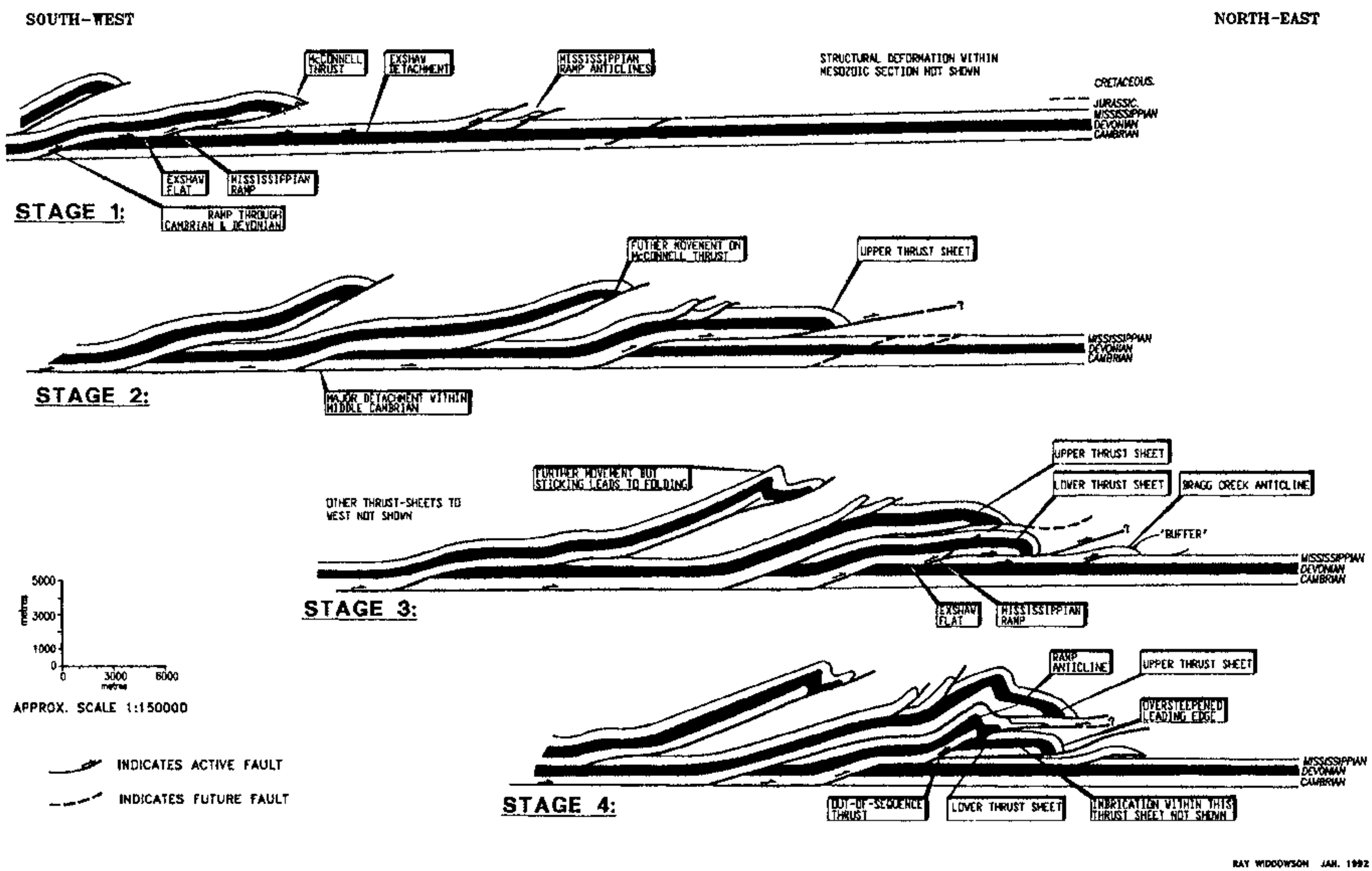
The oversteepened nature of the hangingwall rocks within the Lower Thrust Sheet together with internal imbrication of the sheet suggests that the Bragg Creek Anticline developed early in Stage 3 and created a buffer to further thrust emplacement from the S.W.

Stage 4

Further compression from the S.W. transported the existing structural complex along the mid-Cambrian sole thrust, but the sole thrust itself did not propagate further to the N.E. as on previous occasions. Instead the shortening “fed” upwards into the existing thrust system. However, this system was already locked up due to the Bragg Creek Anticline “buffer” to the N.E. and so internal deformation of the existing thrust-sheets was the only alternative.

As a result of this sequence of development, the outcropping Mississippian of Moose Mountain is now elevated some 5 km above regional and palinspastically restores some 25 km to the S.W.

FIGURE 14 : STRUCTURAL EVOLUTION OF THE MOOSE MOUNTAIN THRUST COMPLEX



STAGE 1:

McCONNELL THRUST-SHEET CONTAINING CAMBRIAN AND YOUNGER ROCKS PARTIALLY EMPLACED. SHORTENING OF MISSISSIPPIAN ABOVE EXSHAW DETACHMENT PRODUCED TWO MISSISSIPPIAN RAMP ANTICLINES SOME 10 km OUT IN THE FORELAND.

STAGE 2:

MOOSE MOUNTAIN UPPER-THRUST SHEET (CONTAINING CAMBRIAN AND YOUNGER ROCKS) EMPLACED DIRECTLY ONTO MISSISSIPPIAN AT REGIONAL (? BASAL NORDEGG DETACHMENT). McCONNELL THRUST SHEET (AND OTHER THRUST SHEETS TO THE WEST) PASSIVELY CARRIED TOWARDS N.E. WITH FURTHER MINOR DEFORMATION.

STAGE 3:

MOOSE MOUNTAIN LOWER-THRUST SHEET DETACHED IN THE CAMBRIAN, EMPLACED UPON MISSISSIPPIAN AT REGIONAL. MOOSE MOUNTAIN UPPER THRUST SHEET PASSIVELY ELEVATED AND CARRIED FORWARD TOGETHER WITH OTHER SHEETS TO WEST. DURING EARLY EMPLACEMENT MISSISSIPPIAN RAMP ANTICLINE DEVELOPS 10 KM TO N.E. AND ACTS AS A BUFFER TO FURTHER LATERAL THRUST- EMPLACEMENT.

STAGE 4:

FURTHER MOVEMENT OF LOWER THRUST SHEET TOWARDS N.E. IMPEDED BY FRONTAL RAMP-ANTICLINE CAUSING OVERSTEEPENING OF LEADING EDGE. STRAIN RELIEVED BY DEVELOPMENT OF AN OUT-OF-SEQUENCE THRUST WHICH CUTS LOWER THRUST SHEET IN TWO. EMPLACEMENT OF WESTERN PORTION UP STEEP RAMP CREATES RAMP-ANTICLINE WITHIN OVERLYING DOUBLE THRUST-SHEET COMPLEX.

EXPLORATION HISTORY

With the 1924 discovery of the Turner Valley (Mississippian) Field (see Gallup, 1975), the Foothills became an active area for hydrocarbon exploration. Early drilling at Moose Mountain concentrated on the surface anticlinal structure at sub-Mississippian levels, with natural gas seeps probably providing some impetus for the tests (Tippett, 1987 p.77). Nine wells were spudded into the Upper Thrust Sheet between 1929 and 1944; of these one produced small quantities of gas (locally used on adjacent wellsites) and another was completed as a minor oil producer (see MacNeil, 1943). According to Ower (1975) the opinion after this early drilling phase was that the structure had been fully tested and that lack of viable reservoirs with matrix porosity, resulted in the failure to find commercial quantities of hydrocarbons.

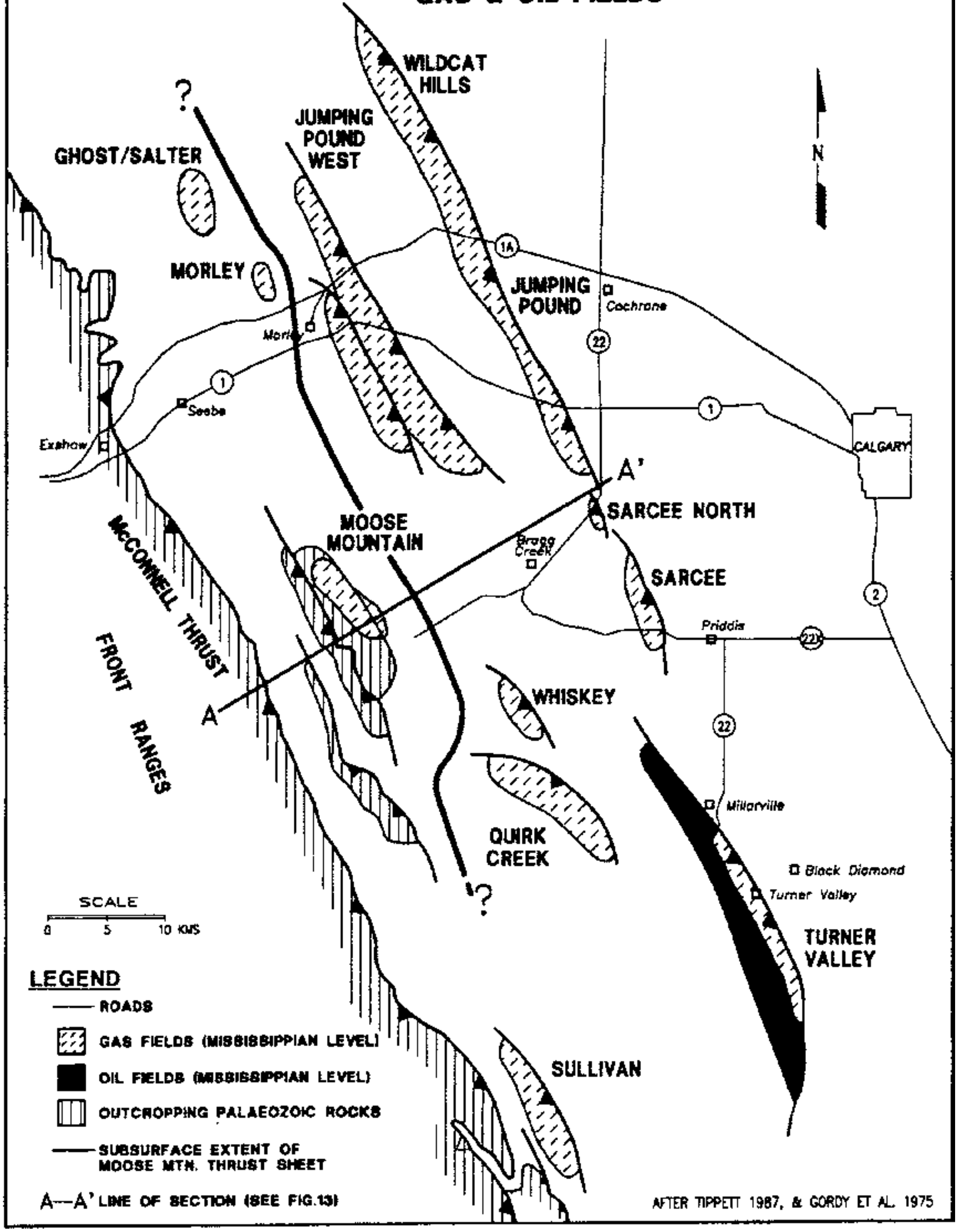
A renewed exploration effort was made in the Moose Mountain area after the postulation that the surface structure was underlain by a major thrust, and possibly a folded thrust (Scott, 1951) analogous to the Savannah Creek gas field discovered in 1952 (see Hennessey, 1975). This resulted in the gas discovery of Calstan Shell Moose 16-6-23-6W5 in 1959. Subsequently a further 10 wells were drilled between 1960 and 1987 resulting in four additional discoveries, and the delineation of three pools. For a general background to the Foothills gas and oil fields see Tippett (1987). The adjacent fields of the Foothills tract (west of Calgary) are shown in Figure 15.

Historical listing of the wells drilled in the Moose Mountain area is given below (see Figure 1 for locations). The exploration results, interpreted geology and structural position of the tests are given, related where possible, to the structural cross-section (Figure 13).

1. **Heron Bragg Creek 3-24-22-6W5 1929, (D & A).** Drilled on the S.E. plunge of the structure this well presumably encountered a sequence analogous to the upper section of 7-3-23-6W5 well (see 12) and terminated at 1094 m in the ?Devonian of the Upper Thrust Sheet. Gas and oil shows were recorded from the ?Mississippian.

2. **Moose Oils #1 16-29-22-6W5 1929, (D & A).** This well, drilled in Moose Dome Creek, was spudded in the Exshaw and terminated at 864 m in the upper Cambrian of the Upper Thrust Sheet. Structurally the well was drilled just S.W. of the subsequent 10-32-22-6W5 well (see 16) and recorded “good shows” including a blow of gas and distillate from Cambrian fractures at 852 m (Ower, 1975). The well intersected the structural crest of an overturned Cambrian fold (Figure 13) where abundant fracturing would be expected. According to MacNeil (1943, p. 50) the well was initially completed in 1933 for gas, with small quantities used at the Moose Oil No. 2 wellsite to heat the buildings and operate a pump and dynamo. Further gas from the well was utilized during the drilling operations at McColl-Frontenac’s Moose Mountain No. 1 (see 5).

FIGURE 15 : LOCATION OF MOOSE MOUNTAIN RELATIVE TO ADJACENT FOOTHILLS (MISSISSIPPIAN) GAS & OIL FIELDS



3. **Moose Oils #2 8-29-22-6W5 1935, (Abandoned Oilwell).** Spudded in the base of the Banff Formation 1 km south of the above 16-29 location, this well found gas at 465 m (flowed 1.5 mmcfd *fide* MacNeil, 1943) and oil between 465 m and 467 m in the Devonian Fairholme of the Upper Thrust Sheet. The well was completed and produced 8944 barrels of 47° API oil over a 7 year period before being abandoned. MacNeil (1943) reports that the initial potential was 8 barrels a day, which was not improved by acidization or deepening of the well.

4. **Model Canyon Bragg Creek 16-30-22-6W5 1937, (D & A).** No shows were recorded from this well which was drilled 1.5 km west of the Moose Oils #1 well. It spudded in the Shunda and terminated at 57 m in the Pekisko.

5. **McColl-Frontenac Moose Mountain #1 9-6-23-6W5 1940, (D & A).** This well was drilled 3.5 km along strike to the N.E. of Moose Oils #1. It was spudded in the Banff Formation and reached "total depth" at 1585 m in Cambrian rocks of the Upper Thrust Sheet, having encountered minor oil and gas shows in the overlying Devonian section. This was the deepest of the tests into the Upper Thrust Sheet and penetrated 792 m of Cambrian. This data provided some constraints in the prediction of the position of the main underlying thrust fault (Ower, 1975), which was subsequently penetrated in the 16-6 discovery well (see 10).

6. **Dome 1-17-22-6W5 1941, (D & A).** Located 4.5 km due south of Moose Oils #1 (see 2) on the south-easterly plunge of the fold, this well spudded in the ?Pekisko of the Upper Thrust Sheet (here in the footwall of the Prairie Mountain Thrust) and terminated at only 21.6 m.

7. **Dome 8-17-22-6W5 1941, (D & A).** Drilled 0.5 km north of the 1-17 location, this test reached a "total depth" of 891.5 m. Little data is available for the well but presumably it was spudded in the footwall of the Prairie Mountain Thrust (like the previous well) and may just have reached Cambrian of the Upper Thrust Sheet some 2 km down flank from the crest of the Moose Mountain Anticline.

8. **Canadian Royalties 7-29-22-6W5 1944, (D & A).** This well was drilled just 0.5 km W.N.W. of Moose Oils #2. It spudded in Banff (Member A) reaching a "total depth" of 652 m possibly just into uppermost Cambrian of the Upper Thrust Sheet. No shows were reported.

9. **Elbow Falls #2 4-28-22-6W5 1944, (D & A).** Spudded 1 km S.E. of the previous location, this well eventually (after a second attempt) reached a "total depth" of 963 m. It drilled through the Banff, Exshaw, Devonian and presumably stopped just into the Cambrian of the Upper Thrust Sheet. The well was drilled close to the crest of the structure but only gas and oil shows were recorded.

10. **Calstan Shell Moose 16-6-23-6W5 1959, (Gaswell).** Drilled on the crest of the surface fold at the N.W. part of the structure (100 m west of the 9-6-23-6 location, see 5), this was the first deep well ("total depth" of 4270 m), and the first significant gas discovery in the Moose Field. The well was spudded in the Banff and penetrated the Exshaw Formation, the Devonian and Cambrian of the Upper Thrust Sheet and then drilled into a gas bearing thrust repeat of the Rundle in the western part of the Lower Thrust Sheet. In the deeper section the well proved Devonian thrust over Mississippian rocks of the eastern part of the Lower Thrust Sheet. After extensive production testing of the Turner Valley the well was completed and flowed 7.2 mmcfd (14.6% H_2S) with 7.7 bbls condensate/mmcfd A.O.F) from a 24 m zone of low permeability dolostone (Ower, 1975).

11. **Calstan Shell Moose 5-22-22-6W5 1960, (D & A).** This test was drilled some 7.5 km to the S.E. of the previous well, and higher up on the eastern flank of the surface structure (Figure 13). The prospective Turner Valley of the Lower Thrust Sheet was found to be deeper than in 16-6 and was wet (Ower, 1975). Otherwise, the stratigraphy penetrated to "total depth" at 3442 m was similar.

12. **Shell Moose 7-3-23-6W5 1968, (D & A).** Located as a step-out to test the N.E. flank of the structure, the well penetrated a wet Turner Valley section (deeper than expected) close to the leading edge of the Lower Thrust Sheet. The well section has been used to constrain the structural cross-section (see Figure 13 for the structure and stratigraphy penetrated). A complex imbricated steep N.E. limb of the structure was proved in the deeper well section.

13. **Husky *et al* Whiskey 16-7-22-5W5 1975, (D & A).** This well was drilled 9 km along strike to the S.E. of the previous well (and 3 km S.E. of the Heron Bragg Creek 3-24 well, see 1). It found a similar sequence to 7-3-23-6W5 and was also dry.

14. **Shell Home Moose 10-5-23-6W5 1975, (Gaswell).** Drilled to test the N.W. part of the structure 1 km east of the 16-6 location (see 10). The well proved thick, steeply dipping Devonian above a thin Cambrian section in the Upper Thrust Sheet and then penetrated gas-bearing Mississippian of the Lower Thrust Sheet (west).

15. **Shell Home Moose 7-27-22-6W5 1978, (Gaswell).** Situated 5 km along strike and S.E. from the previous well, this test encountered a similar gas-bearing Mississippian of the Lower Thrust Sheet (west), but closer to the N.E. leading edge. The stratigraphy of the well is comparable to that in the 10-5 well.

16. **Shell Home Getty Moose 10-32-22-6W5 1979, (Gaswell).** Located between the gas discoveries in the N.W. (16-6 and 10-5) and the 7-27-22-6W5 discovery in the S.E., this well (stratigraphy shown on the cross-section, Figure 13) proved a steeply overturned anticlinal fold within the Cambrian of the Upper Thrust Sheet above gas-bearing Mississippian of the Lower Thrust Sheet (west).

17. **Chevron Shell Moose 6-25-22-6W5 1979, (S. I. Gaswell).** This well was a step-out on the N.E. flank of the structure, some 3 km due east of the 7-27-22-6W5 location. The well penetrated the Upper Thrust Sheet closer to its N.E. leading edge than the 7-3-23-6W5 well (along strike to the N.W., see 12) with the hangingwall Mississippian thrust directly on to Mesozoics with no Devonian or Cambrian present. Gas-bearing Mississippian was located in the Lower Thrust Sheet (west) presumably at a higher structural elevation than in the (dry) 7-3 well.

18. **Shell Home Moose 10-17-23-6W5 1981, (D & A).** Situated as a 4.5 km step-out to the N.W. of 7-3-23-6W5 (see 12), the well proved a full Mississippian, Devonian and Cambrian hangingwall sequence of the Upper Thrust Sheet, but the Mississippian of the Lower Thrust Sheet was dry, presumably outside closure.

19. **Shell Home Moose 13-28-22-6W5 1981, (Gaswell).** Drilled between the 10-32-22-6W5 and 7-27-22-6W5 gas discoveries, the well proved a major overturned fold pair involving the Devonian and Cambrian in the hangingwall of the Upper Thrust Sheet. As expected the well encountered gas-bearing Mississippian in the Lower Thrust Sheet (west).

20. **Shell Chevron Moose 11-12-23-6W5 1987, (D&A).** This well, illustrated on the cross-section (Figure 13), tested the Mississippian ramp anticline (the “Bragg Creek Anticline” first tested by the 15-7-23-5W5 well in 1969, not listed) to the N.E. of the Moose Mountain structure “proper”. It found the hangingwall Mississippian some 200 m shallower than the original well and following production testing was suspended as a (?non-commercial) gas discovery.

21. **Shell Moose 12-3-22-6W5 1987, (D & A).** An ambitious step-out, drilled on the S.W. flank of the structure, this well located a full Mississippian, Devonian and Cambrian sequence in the hangingwall of the Upper Thrust Sheet, emplaced directly onto Mississippian of the Lower Thrust Sheet (west)—as would be predicted. However, the reservoir was deeper than further north and was wet. Subsequently the well was deepened to over 4500 m and eventually terminated in Cambrian rock of the Lower Thrust Sheet (east). This well data provided invaluable structural and stratigraphic calibration.

RESERVOIR AND PRODUCTION

Three pools are presently assigned to the Moose Mountain Field with Mississippian Turner Valley and the Devonian Wabamun (= Palliser) forming the principal reservoirs. The pools are designated (ERCB) Rundle A (mean formation depth 2194 m), Rundle B (2567 m) and Wabamun (2555 m) with initial marketable gas reserves (ERCB Dec. 1990) of 73 BCF, 36 BCF and 16 BCF respectively. Production from the two Rundle pools began in 1985-86. The gas is sour with the Turner Valley averaging 11.1% H_2S and the Wabamun 44.8% (ranging between 31 and 65%).

The **Rundle A Pool** is in a hanging wall position in the lower thrust complex. Here a pay thickness (Turner Valley) of 25 m averaging 6% porosity is assigned. Four wells are producing from this pool *viz*: 13-28-22-6W5, 10-32-22-6W5, 10-5-23-6W5, 16-6-23-6W5 with a cumulative production to date (fourth quarter 1991) of 24 BCF.

The **Rundle B Pool** is in a footwall position in the lower thrust complex. The pay thickness is given as 60 m (Turner Valley) with average porosities of 6.5%. The pool is drained from a single well 7-27-22-6W5, which has produced 18 BCF up to December 1991 (see below).

Production data for these wells are as follows:-

WELL	INITIAL (mmcfd)	MAX (mmcfd)	END '91 (mmcfd)	CUM. GAS (BCF)	CUM. WATER (bbls)
13-28	2	7	6.6	3	1150
10-32	5.5	12.25	11.2	7.14	2700
10-5	5.25	9.5	7.6	12.1	3805
16-6	2	2.2	2.2	1.54	417
7-27	10	14	11.3	17.9	4132

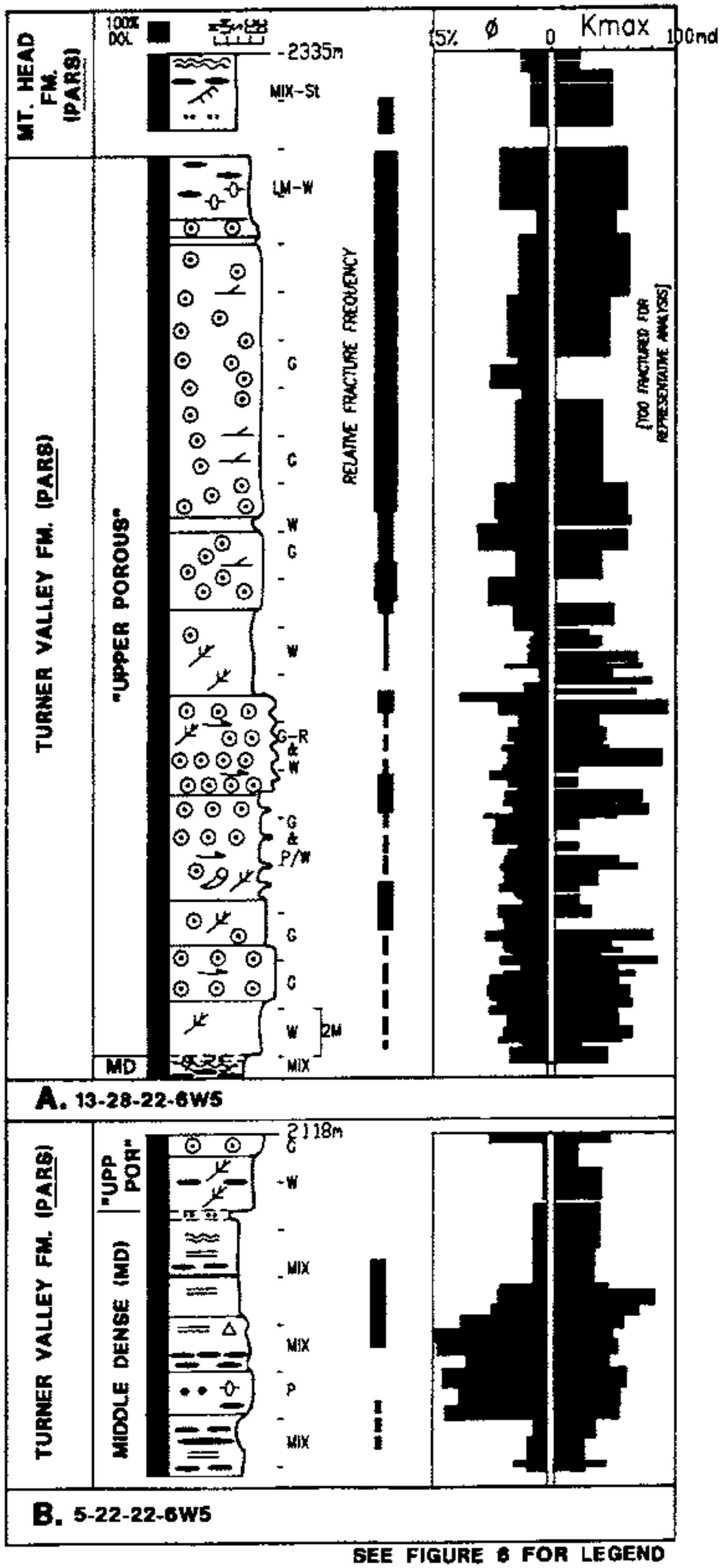
INITIAL = initial flow rate; MAX = maximum flow rate; END '91 = flow rate at end of 1991; CUM. GAS = cumulative gas production; CUM. WATER = cumulative water production.

The Turner Valley Formation reservoir is developed wholly in replacive dolostone, with "pay" contributions made by all three component members (Lower Porous, Middle Dense and Upper Porous). Most of the productive dolostone is the result of shallow burial replacement of subtidal limestones, although that in the Middle Dense is almost certainly of an early diagenetic origin. Typical "poroperms" for the Upper Porous and Middle Dense are shown in Figure 16.

FIGURE 16: EXAMPLES OF TURNER VALLEY POROPERMS.

A. UPPER POROUS (13-28-22-6W5, CORES 3-11)

B. MIDDLE DENSE, (5-22-22-6W5, CORE 5)



The pore system of the Lower and Upper Porous members consists of secondary porosity after dissolution of residual calcite/limestone which formed biomoldic (often micro-biomoldic, Figure 17) and intercrystalline porosity, while local contributions from a tertiary dissolutional pore system (related to thermochemical sulphate reduction) is often present. The matrix porosity is generally poor to fair (3-7%) with low permeabilities; natural fracture sets, however, locally and significantly enhance the permeabilities. The Middle Dense is somewhat enigmatic in this area as it locally has good to very good porosity (up to 14%). This is visually cryptic, and consists of a fine micro-intercrystalline pore-system developed in a microcrystalline idiotopic dolostone.

Because of the poor matrix permeabilities the reservoir generally requires a careful and tenacious completion involving acid squeeze and “frac”.

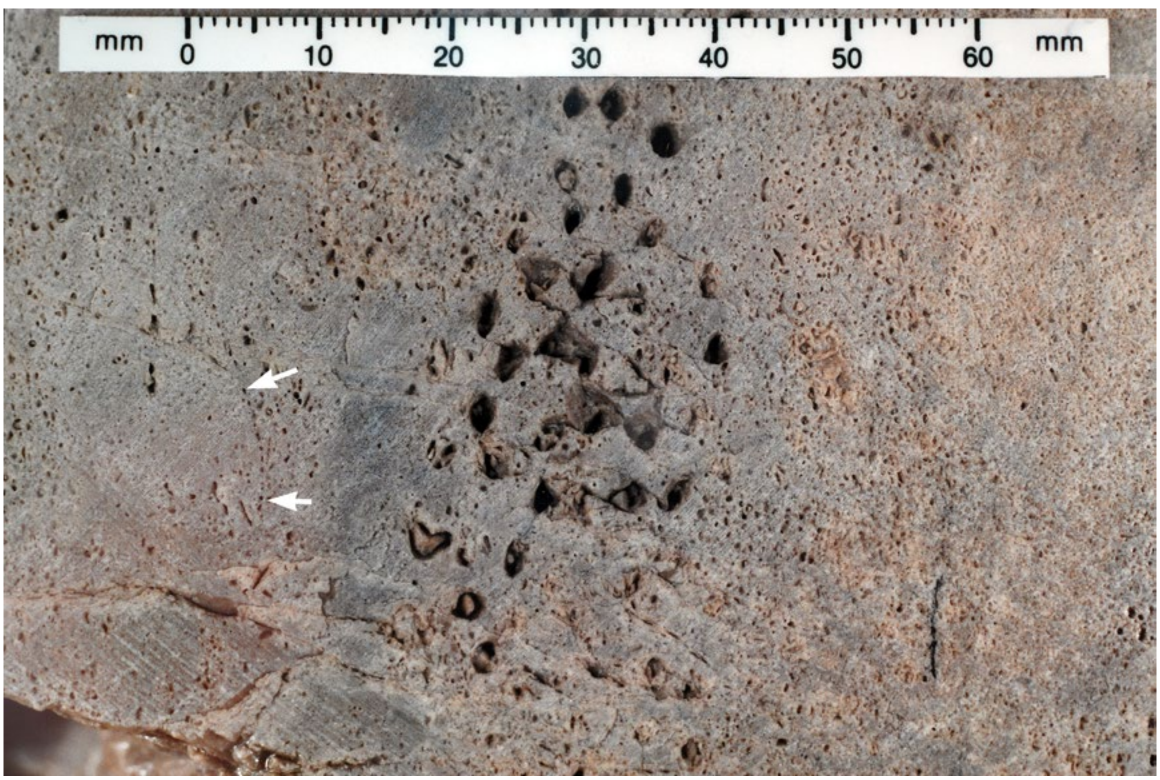


FIGURE 17 Turner Valley (“Upper Porous”) dolostone reservoir: the pore system is largely composed of biomolds and micro-biomolds. A leached *Syringopora* colony forms the large pores, and many of the smaller are bryozoan molds (e.g. a leached fenestrate bryozoan frond is arrowed). Shell Home Moose 10-5-23-6W5, 6941′ (2116 m).

NOTES ON EXCURSION STOPS

Locations of the field trip stops are shown on the geological map (Figure 18). Detailed columnar logs for most of the exposures to be visited are included, and are indicated in the headings.

STOP 1: EXSHAW FORMATION [FIGURE 19]

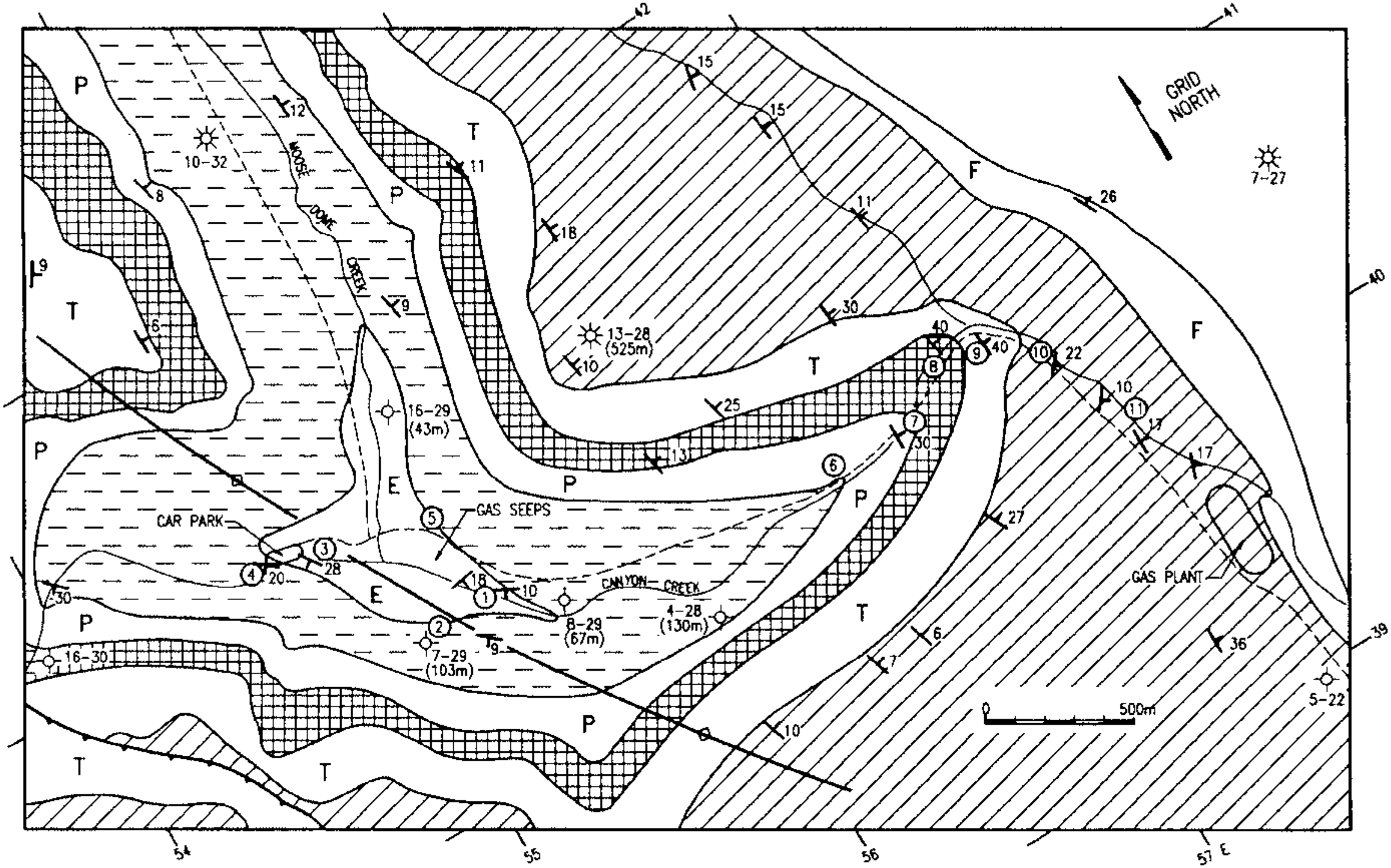
Part of the "Siltstone Member" of the Exshaw Formation outcrops in a small inlier centred on the confluence of Canyon Creek and Moose Dome Creek. Stream bank and low cliffs at this stop expose 28 m of the formation (Figure 20), while the total outcrop thickness is in the order of 44 m. The complete Exshaw Formation of the Upper Thrust Sheet is 59 m, thus in the vicinity of the gas seeps adjacent to the beaver ponds, the top of the Palliser Formation (Devonian, Famennian) is 15 m beneath ground-level. Previously the stratigraphic significance of these exposures was overlooked, and they were regarded as part of the Banff Formation.

Three discrete lithologic units are represented in the section (in ascending order), a brown weathering calcareous silty mudstone, grading to argillaceous limestone (21.8 m), overlain by a calcareous very fine grained sandstone (4.8 m) also brown weathering, capped by a pale weathering limestone (1.6 m, see details under Stop 3).

The calcareous silty-dolomitic mudstone (A, Figure 19) contains a conspicuous brachiopod biota. This faunule (Table 1) is dominated by the small sessile unattached chonetacean *Plicochonetes* which occurs in significant numbers. Although the brachiopod is preserved mostly as articulated valves, with little evidence of significant drifting, there is only a low percentage in life position, i.e. ventral (convex) valve down (18% from bedding plane counts). The mudstone is, however, intensely burrowed by *Helminthopsis* (fine form 0.5 mm to 1 mm in width) and *Palaeophycus* (Figure 21), and it is suggested that the *Plicochonetes* community was under constant disturbance from the soft-bodied burrowers. Once the chonetacean was rotated to the ventral (convex) up position the brachiopod would be unable to feed and would perish.

The depositional environment for this mudstone is considered to be moderate depth offshore shelf, well below storm wave base. Calcareous content of the mudstone includes that from skeletal debris, but also a significant contribution from replacive ferroan microspar. The more resistive beds toward the base of the exposure consist of argillaceous dolomitic limestone. Here, however, textural evidence indicates they are largely dedolomite (Figure 22), with the precursor dolomite including some ferroan content.

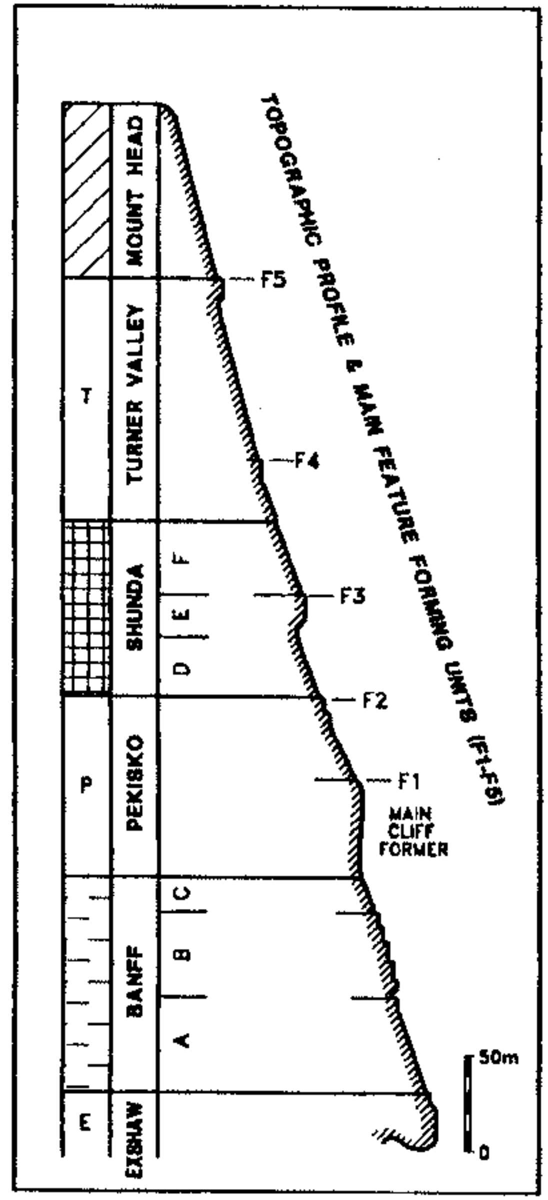
FIGURE 18 : GEOLOGICAL MAP OF PART OF CANYON CREEK



LEGEND

- F — MESOZOICS (F=FERNIE)
- MOUNT HEAD FORMATION
- T — TURNER VALLEY FORMATION
- SHUNDA FORMATION
- P — PEKISKO FORMATION
- BANFF FORMATION
- E — EXSHAW FORMATION

- THRUST FAULT
- ANTICLINE
- INCLINED STRATA, DIP IN DEGREES
- ABANDONED WELL
- GAS WELL
- (43m) WELL DEPTH TO TOP PALLISER FORMATION
- ① EXCURSION STOP



GEOLOGY MODIFIED FROM OLLERENSHAW & BAMBER IN BAMBER ET AL. 1981, & INCORPORATES SOME DIP DATA FROM BEACH 1942.

NOTE: The kilometre grid is that of the Universal Transverse Mercator Grid, N.T.S. sheet 82 J/15 (Bragg Creek).

Present day weathering of these lithologies has corroded the ferroan carbonates on the exposed rock surface, liberating iron oxides and imparting the superficial brown colouration.

The overlying very fine grained quartz sandstone unit (B, Figure 19) exhibits medium scale cross-bedding (possibly hummocky cross-bedding in part) and minor ripple cross-lamination. A sparse macro-fauna of brachiopods and crinoids is present, and the sandstone is intensely burrowed by the meandering traces of "*Scalarituba*" (Figure 23) and *Helminthopsis*. The sandstone is dolomitic and highly calcareous, with the calcite aggressive to the dolomite crystals and the detrital quartz (resulting in a diagenetic diminution of siliciclastic grain size, Figure 24). Ferroan dolomite and ferroan calcite are again conspicuous and have oxidized to give the brown colouration analogous to the underlying mudstone. This sandstone represents a shallowing from the underlying mudstone facies, into shelf conditions between storm and fair weather wave base, or probably shallower.

The above ichnofauna is an assemblage commonly documented from the early Mississippian. Bjerstedt (1987; 1988) for example, has recorded *Scalarituba* - *Helminthopsis* associations in several facies from the deltaic Price Formation of West Virginia, including outer shelf fair-weather silty mudstone (and capping sandstone tempestites), lower shoreface and interdistributary bays.

[ASIDE: The septate ("meniscate") back-filled burrows referred to above as "*Scalarituba*" are analogous to those occurring elsewhere in the Exshaw and Banff formations and commonly cited as *Scalarituba* (e.g. Macqueen & Sandberg, 1970). Recently these Exshaw traces have been referred to the ichnogenus *Taenidium* (Richards & Higgins, 1988; Richards et al. 1991).

Scalarituba is now confidently synonymized under *Nereites* (see D'Alessandro & Bromley, 1987; Seilacher, 1983). The distinction of the *Scalarituba*-form of *Nereites* from the superficially similar septate genus *Taenidium* is the presence, in the former, of bioturbated lateral lobes producing halos around the central axes of the traces (see Chamberlain, 1971, plate 31, fig. 1). Due to taphonomic factors, however, these halos are commonly not visible (Chamberlain & Clark 1973, p. 678).

No lateral lobes have positively been identified on the Canyon Creek "*Scalarituba*" in sandstone preservation, and the criterion of their recognition where the burrows cross (Frey *et al*. 1984) has not yet proved diagnostic. However, in rarer examples where the sandstone is argillaceous, the halos can sometimes be discerned. The "*Scalarituba*" of the Canyon Creek Exshaw is therefore likely to be *Nereites*.]

TABLE 1
FAUNULE OF THE EXSHAW FORMATION
SILTSTONE MEMBER (UNIT A), CANYON CREEK

NUMBER		TAXONOMIC GROUP	LIFE HABIT
	BRYOZOA		
r	rhabdomesinid		
	BRACHIOPODA		
1	? *Beecheria* sp.	T	P
14	? *Hemiplethorhynchus* sp.	R	P
1	*Lingula* sp.	I	P/B
352	*Plicochonetes* sp.	St	P-S
21	*Rhipidomella* cf. *rockportensis* Carter	O	P
5	*R*. cf. *tenuicostata* Weller	O	P
4	*Schizophoria* sp.	O	P
44	*Schuchertella* sp.	St	P-S
39	*Verkhotomia* cf. *jucunda* Carter	S	P-S
	GASTROPODA		
1	*Platyceras* (*Platyceras*) sp.		A
	BIVALVIA		
1	*Sanguinolites* sp.		B
	CRINOIDEA		
c	undet. columnals		

Taxonomic group (brachiopods): I = Inarticulata; O = Orthida; R = Rhynchonellida; S = Spiriferida; St = Strophomenida; T = Terebratulida.

Life habit: P = pediculate (epifaunal filter feeder); P/B = pediculate burrower (infaunal filter feeder); P-S = initial pediculate attachment followed by free living stage, shell supported (epifaunal filter feeder); A =”attached” (epifaunal on crinoid calices, commensal and coprophagous or antagonistic); B = burrower (infaunal filter feeder). Note: the *Schuchertella* species is apically thickened and lacks a posterior ventral cicatrix or clustered perforations of an internally divided pedicle (Schumann, 1969).

Number: individuals in a collection of 483 shells; for non-shelly taxa r = rare, c = common.

STOPS 1,3&4

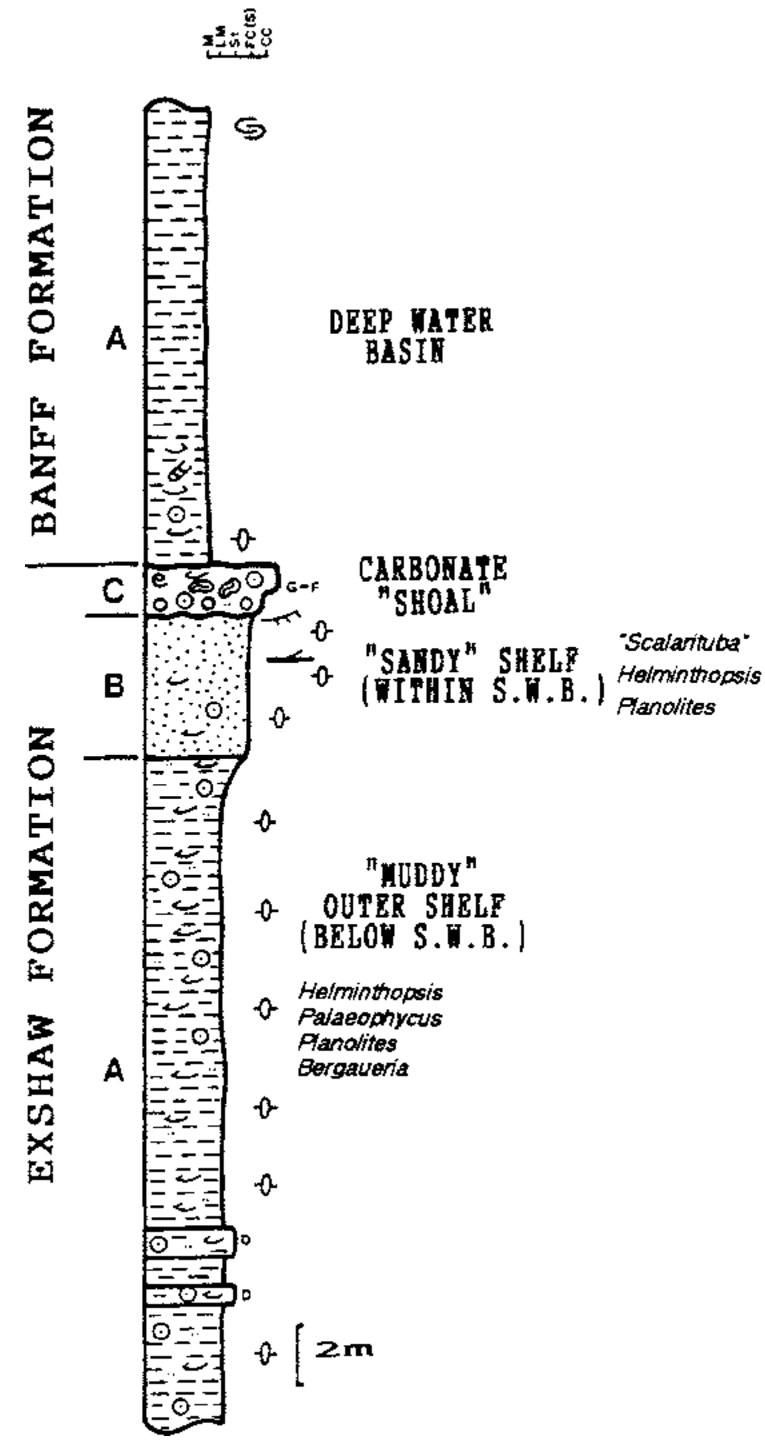


FIGURE 19 Columnar section through the exposed Exshaw and lower Banff (Member A) formations. See under Stops 1, 3 & 4. For legend see Figure 6.

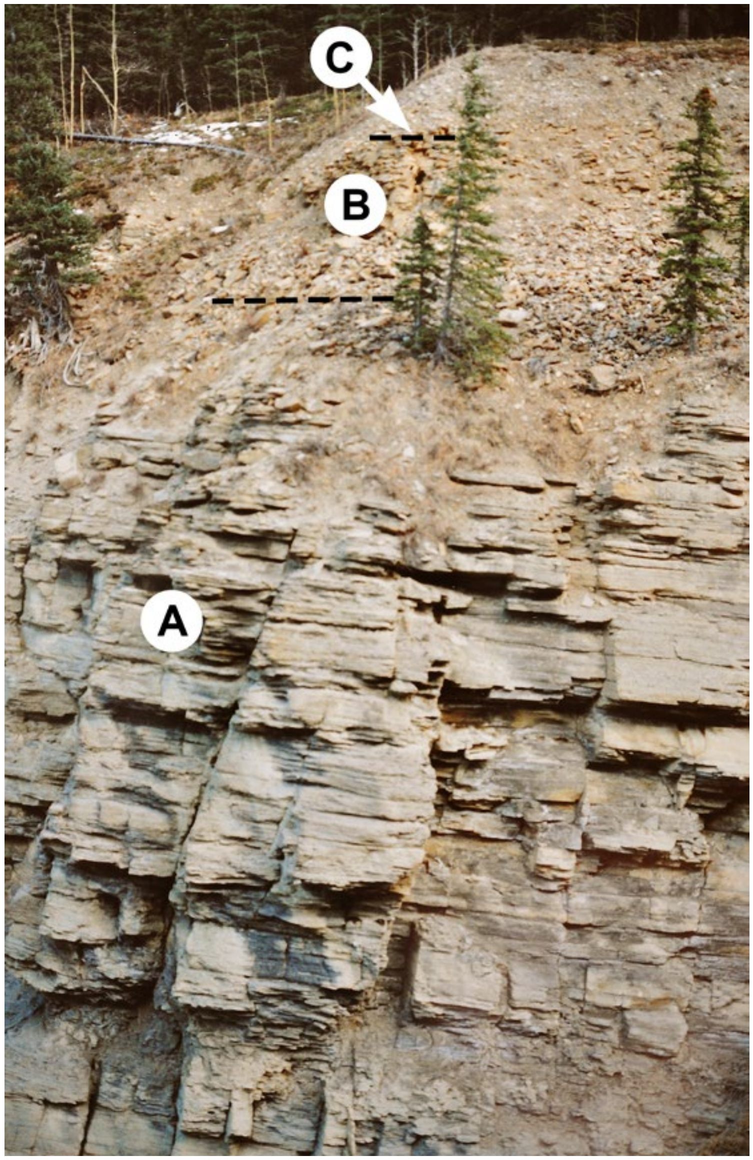


FIGURE 20 Stop 1: Exshaw Formation exposure showing component lithologic units. A is shelly, burrowed, calcareous mudstone; B, burrowed, calcareous, very fine grained sandstone and C, ooid and oncolite bearing grainstone (rudstone and floatstone).

FIGURE 21 Stop 1, Exshaw Formation, (Unit A): *Palaeophycus* traces in calcareous silty mudstone. This ichnotaxa was interpreted by Pemberton & Frey (1982) as the passive filled dwelling burrow of a predaceous or filter-feeding animal.

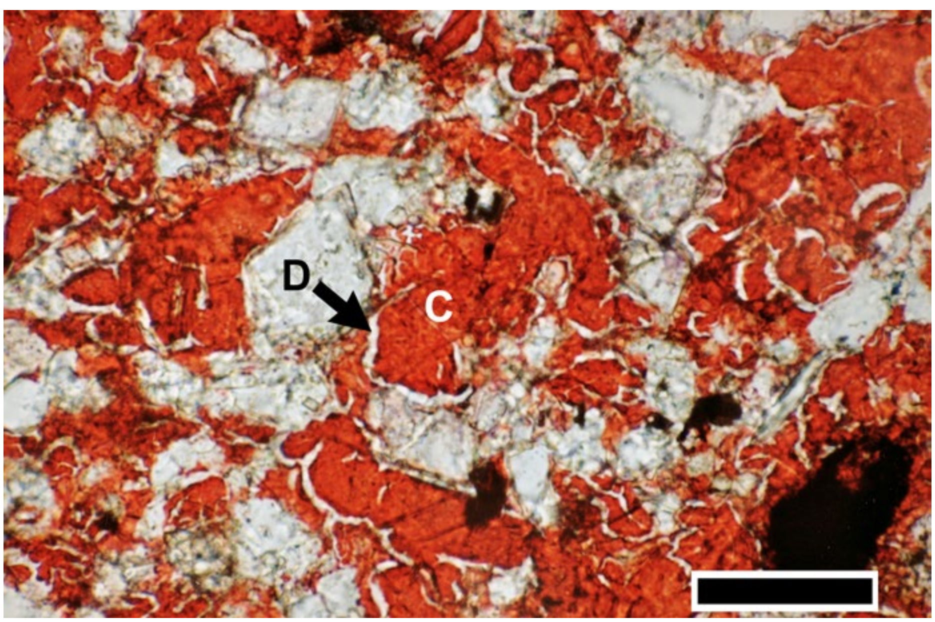


FIGURE 22 Stop 1, Exshaw Formation (Unit A): thin-section photomicrograph (plane polarized light, scale bar 0.05 mm) of a partially dedolomitized argillaceous dolomite. The calcite (C), stained with A.R.S., has replaced the cores of the precursor dolomite leaving unaltered rims (D). The dedolomite beds form the more resistive units at the base of the section.

FIGURE 23 Stop 1, Exshaw Formation (Unit B): "*Scalarituba*" traces in very fine grained calcareous sandstone. These burrows consist of an alternation of faecal and sediment endocones (Chamberlain & Clark, 1973) and represent the back-filled burrows of a deposit feeding vermiform animal (Chamberlain, 1971).

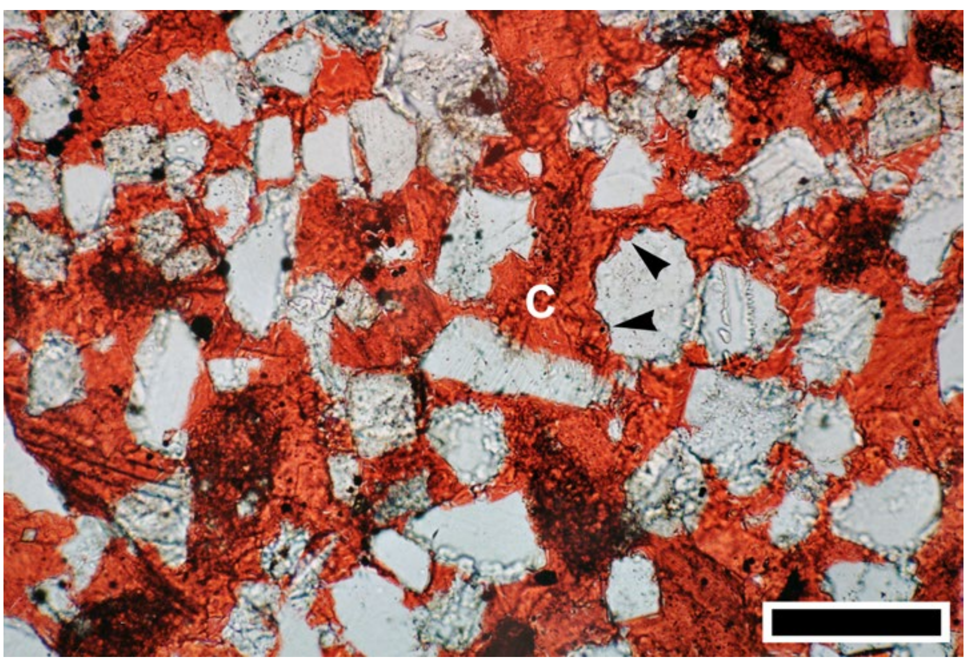


FIGURE 24 Stop 1, Exshaw Formation (Unit B): thin-section photomicrograph (plane polarized light, scale bar 0.1 mm) showing calcareous, very fine grained sandstone. The calcite (C) stained with A.R.S., is aggressive to the detrital quartz, and produces the floating texture and the embayed grain surfaces (example arrowed).

STOP 2: WELLSITE OF CANADIAN ROYALTIES #1 (7-29-22-6W5)

The wellsite is situated on the wooded slope 300 m south of the confluence of Moose Dome Creek and Canyon Creek (Figure 18). It was spudded in March 1944 and was suspended in August 1946 at a depth of 610 m (Devonian, Fairholme). The well was re-entered in December 1948 and deepened a further 42 m (to 652 m) before being finally abandoned (January 1949). There were no recorded hydrocarbon shows. The site is of interest for the "archaeological" remains including the wooden derrick (compare Figure 25) and a large pile of core; according to the scout ticket only sidewall cores were taken! **(please do not disturb this site or remove the core).** The well, spudded in the Banff Member A, is useful in calibrating the position of the Exshaw, the base of which is given as 339′ (103 m).

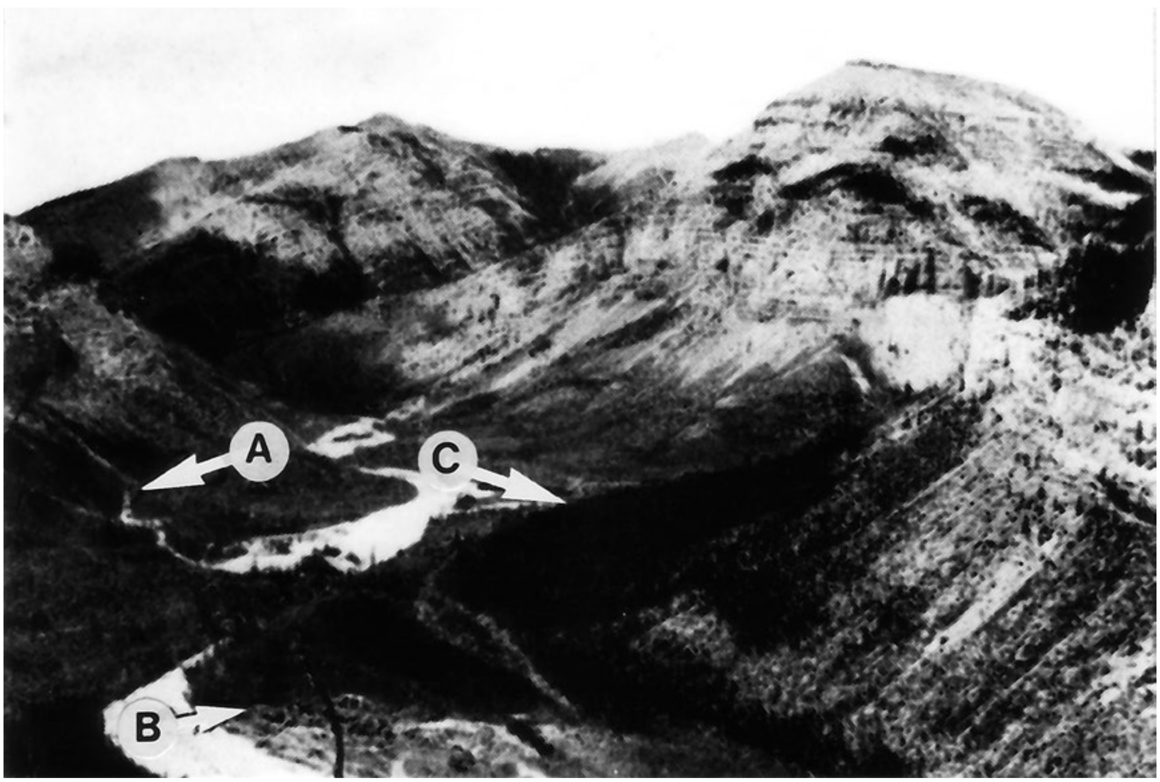


FIGURE 25 Stop 2: view west along Canyon Creek (c. 1942) showing the derrick (A) of Canadian Royalties 7-29-22-6W5, which spudded on March 14th 1944 (obviously the lease was prepared sometime in advance!). Also indicated is the wellsite (B) of the oil-producing Moose Oils #2 8-29-22-6W5. The earlier test, Moose Oils #1 16-29-22-6W5, was located in Moose Dome Creek (C), formerly known as Sulphur Creek, some 450 m upstream of the confluence with Canyon Creek. Modified from MacNeil (1943).

The Moose Oils #2 well (8-29-22-6W5) located adjacent to Canyon Creek (Figures 18 & 25), 450 m E.S.E. of the 7-29 location, was spudded in the base of the Banff

Formation, not far above the mappable Exshaw contact. The top Palliser in this well was recorded at 220′ (67 m) thus providing further useful confirmation of the stratigraphic position of the exposed Exshaw (see Figure 6). The latter well (spudded in July 1935) is of interest in that it encountered oil in fractured Devonian Fairholme Group at 1532′ and was completed as an oilwell; it produced 8944 bbls of a 47° API oil over a 7 year period (Ower, 1975). Average daily production was about 8 bbls (MacNeil,1943).

STOP 3: EXSHAW - BANFF CONTACT [FIGURE 19]

A small exposure at the confluence of Canyon Creek and a narrow dry gully (opposite the car park) clearly shows the contact between the Exshaw and Banff formations. Here the fine grained burrowed sandstone unit of the Exshaw (Unit B, see under Stop 1) is overlain by 1.6 m of limestone (Exshaw Unit C), which in turn is overlain by mudstone of the Banff Formation (Member A). The limestone is an oolitic-bioclastic grainstone (Figure 26) at the base and grades-up into oncolitic-bioclastic rudstone/floatstone (Figure 27). Bioclastic grains are diverse and include crinoids, echinoid spines, gastropods, brachiopods (orthoids and chonetoids), bryozoans and skeletal algae. Micrite envelopes (Figure 26) are conspicuous on crinoidal and molluscan debris, and detrital quartz grains are disseminated throughout. A slight scoured base to the unit was observed in the exposures at Stop 1, and a thin bed with scoured base (tempestite) is exposed toward the top of the unit at this locality. Clearly the limestone represents (or is derived from) a very shallow subtidal shoal environment (only a few metres depth at most) and may be considered as the regressive maximum of the Exshaw sequence.

The Banff Formation immediately overlying the limestone consists of dark grey calcareous mudstone with a benthonic fauna of crinoids, brachiopods and small infaunal bivalves. Three metres above the base there is a marked depletion in this biota, where only sparsely scattered bivalves and rare goniatites occur. Higher beds are less calcareous and apparently devoid of macrofossils. Depositionally the basal Banff mudstone represents a rapid and progressive deepening to water depths far below storm wave base into a basinal bathymetric regime.

FIGURE 26 Stop 3, Exshaw Formation (Unit C): thin-section photomicrograph (plane polarized light, scale bar 0.2 mm) of an oolitic-bioclastic grainstone. Note the micrite envelope (arrowed) on the crinoid fragment.

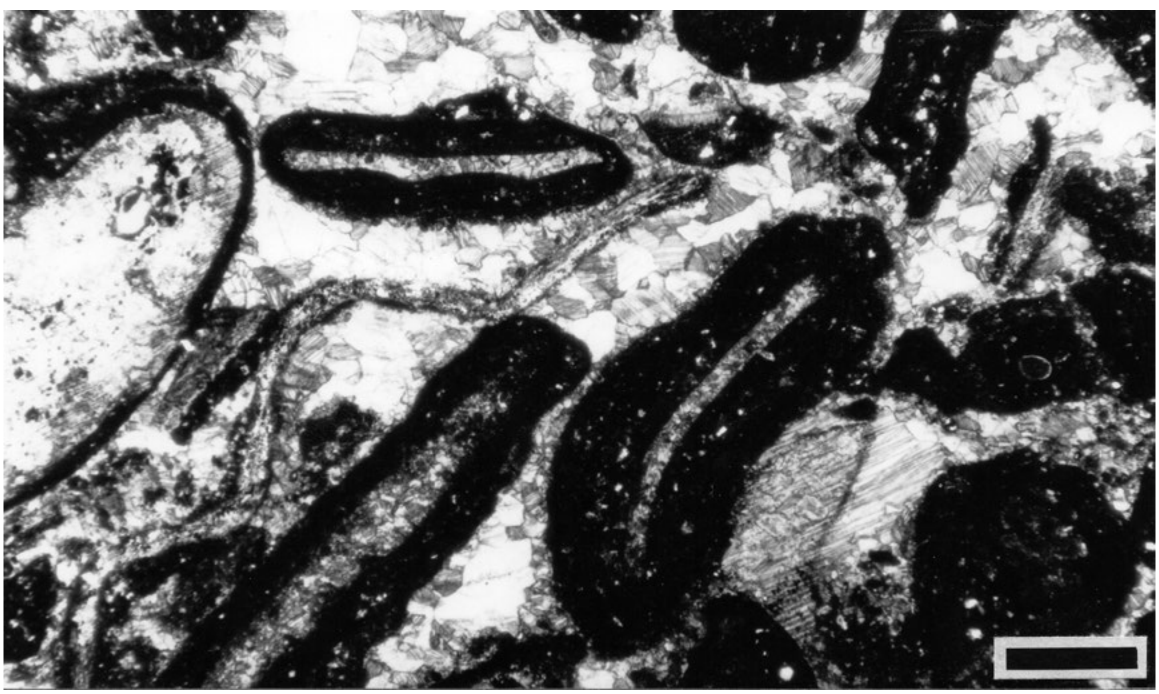


FIGURE 27 Stop 3. Exshaw Formation (Unit C): thin-section photomicrograph (plane polarized light, scale bar 0.5 mm) of an oncolite dominated bioclastic grainstone (rudstone/floatstone). The oncolitic encrustations are mostly nucleated around molluscan fragments.

STOP 4: BANFF FORMATION MEMBER A [FIGURE 19]

A section of stream bank, opposite the car park, exposes fissile, dark grey, slightly calcareous mudstone. This "shale" forms a monotonous succession devoid of macrobiota with sedimentary structures (apart from the shaley lamination) confined to small scale slumps (Figure 28) in a bed 15 m above the base of the formation. This succession of mudrock represents the deepest water deposits exposed in the Moose Mountain area, with the depositional setting interpreted as deep water basin.

Upstream more resistive carbonate beds, belonging to younger parts of the Banff Member A, are exposed. These include argillaceous laminated dolostone (microcrystalline and hypidiotopic, with later stage ferroan overgrowths) interpreted as the products of deep water dolomitization. These beds are involved in asymmetric folds facing N.E. This facing direction is compatible with the expected shear sense during Laramide thrusting; the folds resulting from either deformation over a fault tip or disturbance above a detachment.

FIGURE 28 Stop 4, Banff Formation (Member A): slump fold in fissile slightly calcareous mudstone.

STOP 5: BANFF FORMATION MEMBERS A & B

Roadside view-point (adjacent to poorly exposed Exshaw - Banff contact in road cutting). View N.W. toward the core of "Moose Dome" shows a continuous exposed section from Banff Formation Member B to the top of the Turner Valley Formation (Figures 29 & 30). The axial plane of the surface anticline runs through the western part of the section adjacent to the Ice Caves; here the fold has a steep 30° western limb and shallow 9° eastern limb.

The top of the Banff Member A is not visible but forms a small feature in the exposures immediately west of the 10-32-22-6W5 wellsite, where it consists of concretionary lenticular bedded limestone in mudstone, and contains a fauna of crinoids, brachiopods and bryozoans. Petrographically this limestone is a calcite microspar, a texture typical of concretionary growth. The Banff Member A thus shallows up from barren basinal mudstone devoid of biota, to lower ramp slope fossiliferous calcareous mudstone. Growth of concretionary microspar may represent the by-product of microbial oxidation of organic matter in the host sediment (Coleman, 1985).

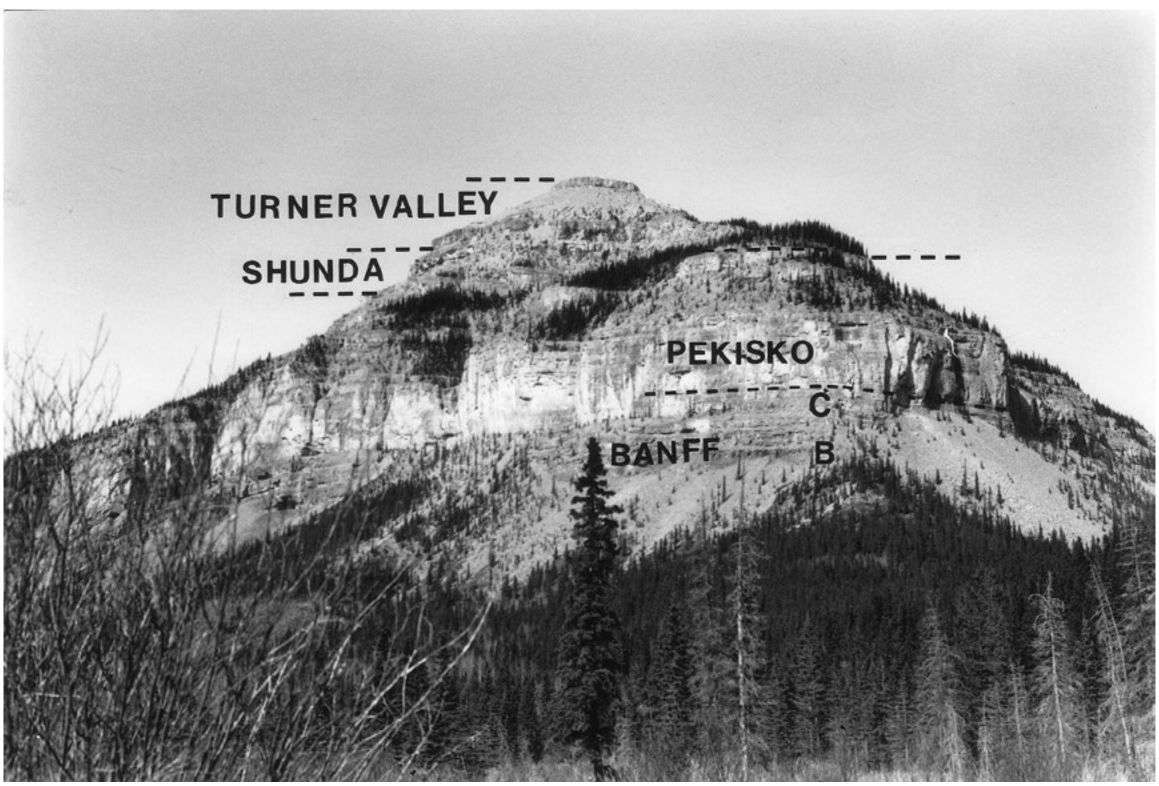


FIGURE 29 Stop 5: cliff exposures in the centre of the Moose Mountain Anticline (north of Canyon Creek, west of Moose Dome Creek) showing an exposed section from the Banff Formation (Member B) to the top of the Turner Valley.

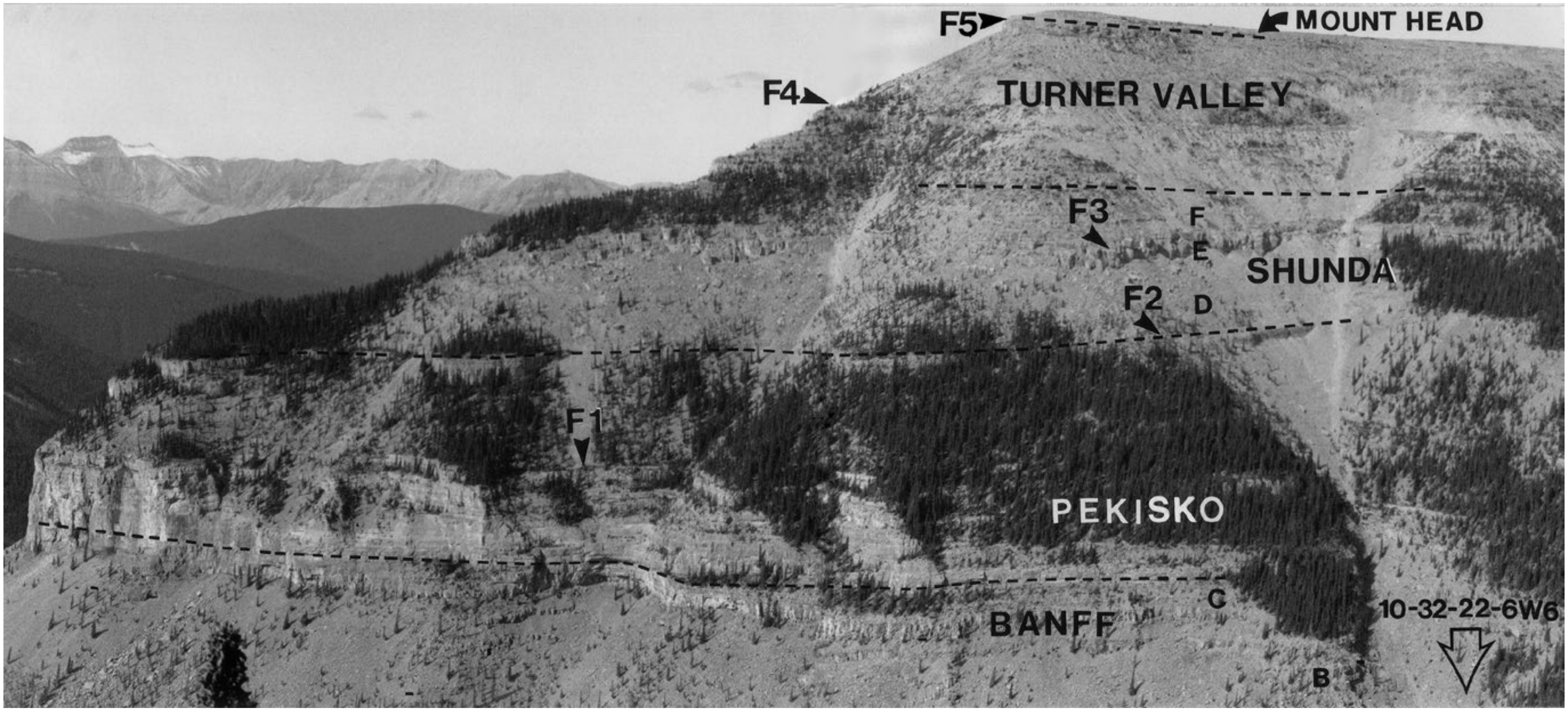


FIGURE 30 Cliffs west of Moose Dome Creek, above the 10-32-22-6W5 wellsite, showing an exposed section from the Banff Formation (Member B) to the base of the Wileman Member (Mount Head). The formational contacts are shown in relation to the main feature-forming units (F1-5, see also Figures 6 & 18).

Banff Formation Member B consists of four shallowing-upward minor cycles. These form small scar features below the prominent cliff-former of the Pekisko limestone (Figure 29) and have clearly discernible log signatures (Figure 6). The cycles grade upward from mudstone and concretionary limestone to bioclastic slightly cherty packstone (floatstone and rudstone). The latter contain a prolific fauna of echinoderms (largely crinoids and blastoids) and "lophophorates" including a modest diversity of brachiopods (Carter, 1987) together with ramose and fenestrate bryozoans. This fauna appears to be largely autochthonous and the beds are locally almost "biostromal". *Zoophycos* burrows are commonly present in the muddier lithologies. Depositional environment for this member ranges cyclically through lower and middle ramp slope, with stratigraphically higher units reaching upper slope.

The lithological and biotic associations of the Banff Member B, and the inferred middle ramp slope setting, are analogous to the "foundation" facies (pre-buildup surfaces) of "Waulsortian" mounds. This mudmound facies apparently failed to develop, with no documented occurrences reported from the central and southwestern Alberta Foothills or Front Ranges. Pekisko examples are, however, known from ramp settings on the southern margin of the Peace River Embayment (see Davies *et al*. 1988).

STOP 6: BANFF - PEKISKO CONTACT [FIGURE 31]

Cliff sections (Figure 32) expose the Banff-Pekisko contact, this according to lithostratigraphic semantics is also the contact between the Banff Formation and Rundle Group. The exposed Banff Formation is assigned to Member C, and consists of cherty crinoidal-bryozoan packstone, argillaceous in part, with scattered brachiopods and corals. Interbedded with the packstone are beds and lenses of allochthonous crinoidal grainstone/packstone to rudstone, which are interpreted as storm induced event beds (tempestites) derived from up-ramp crinoidal shoal facies. These have "channel"-like form near the Pekisko contact (Figure 33). The formational contact is marked by a recessive notch created by a thin, more argillaceous bed (Banff) with the basal Pekisko (9 m of crinoidal grainstone to rudstone) forming the resistive cliff. The Banff-Pekisko contact hereabouts represents a diastem considered by Richards (1989) to be a transgressive erosion (ravinement) surface. Within the limits of the exposure there is 2 m of relief on this contact (Figure 32).

The basal Pekisko crinoidal rudstone is a series of stacked beds which show little internal organization although there are some scoured surfaces. In nearby sections (e.g. the crags above and west of the 10-32-22-6W5 wellsite, Moose Dome Creek) medium scale cross-bedding is conspicuous at this horizon. The unit is considered to represent the passage of a crinoidal offshore shoal facies.

Lack of cross-sets in these particular exposures might indicate a very proximal position to the shoal with deposition still under the influence of storm “events”. In terms of depositional sequence the Banff is shallowing up into a near shoal environment. The disconformity at the formational contact is probably a trivial event.

Above the thick crinoidal rudstone there is a return to a cherty crinoidal-bryozoan packstone (2 m) analogous to the Banff, while the overlying beds show further tempestite deposition. The latter beds (Figure 34) are discrete crinoidal grainstone-rudstone units (Figure 35) with scour bases, sharp tops, rip-up clasts and crudely graded profiles (Figure 34). The intervening beds are cherty bioclastic packstone (Figure 36) often showing endichnial crinoid filled burrows (Figure 34). There is a change in the character of the tempestite units in higher parts of the section (16 m above the formation base), where the beds are finer grained and better graded. The package of tempestite units within the Pekisko apparently documents the progressive westerly migration of the shoal facies, with proximal back shoal tempestites passing into more distal (shelf) tempestites. This passage of the shoal facies also represents a change from ramp to platform depositional geometry, the latter persisting throughout much of the Rundle Group.

There is a return to cross-bedded shoal facies some 27 m above the base of the formation, with associated tempestite units, while 36 m above the base there is an incoming of a substantial oolitic component (see Figure 6). A marked increase in the diversity of grain-types is apparent in these higher beds with foraminifera, skeletal algae, gastropods, ostracods and peloids commonly present. Micrite envelopes are typically developed on the crinoid fragments. The middle Pekisko represents shallow water shelf (well within fair weather wave base), and possibly island shoreline. Thin silty dolostone of tidal flat affinities (e.g. 44 m above the base of the formation) represent the regressive maxima of some minor cycles.

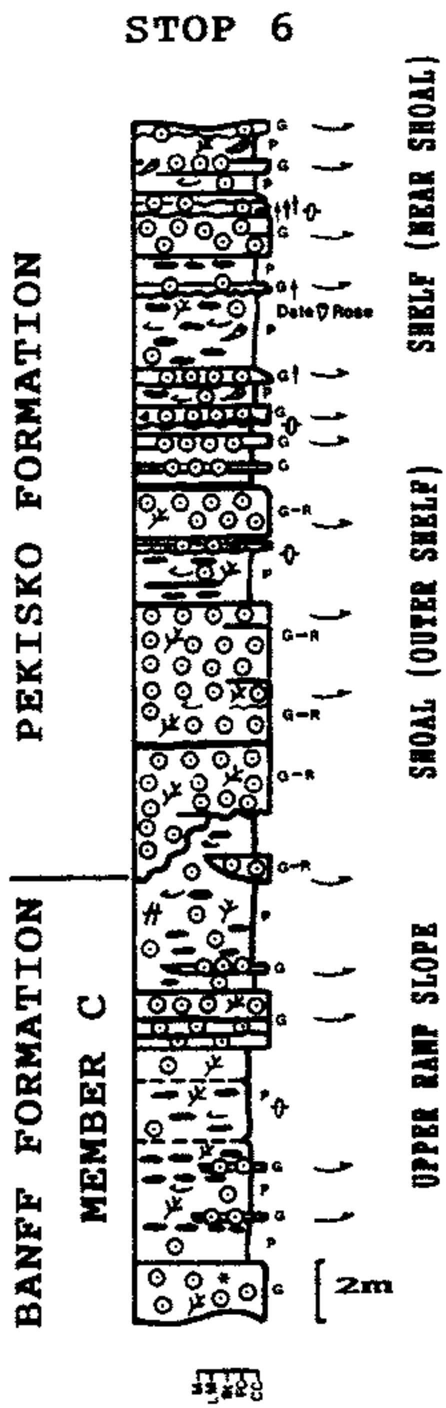


FIGURE 31 Columnar section through the exposed Banff-Pekisko formational contact at Stop 6. For legend see Figure 6.

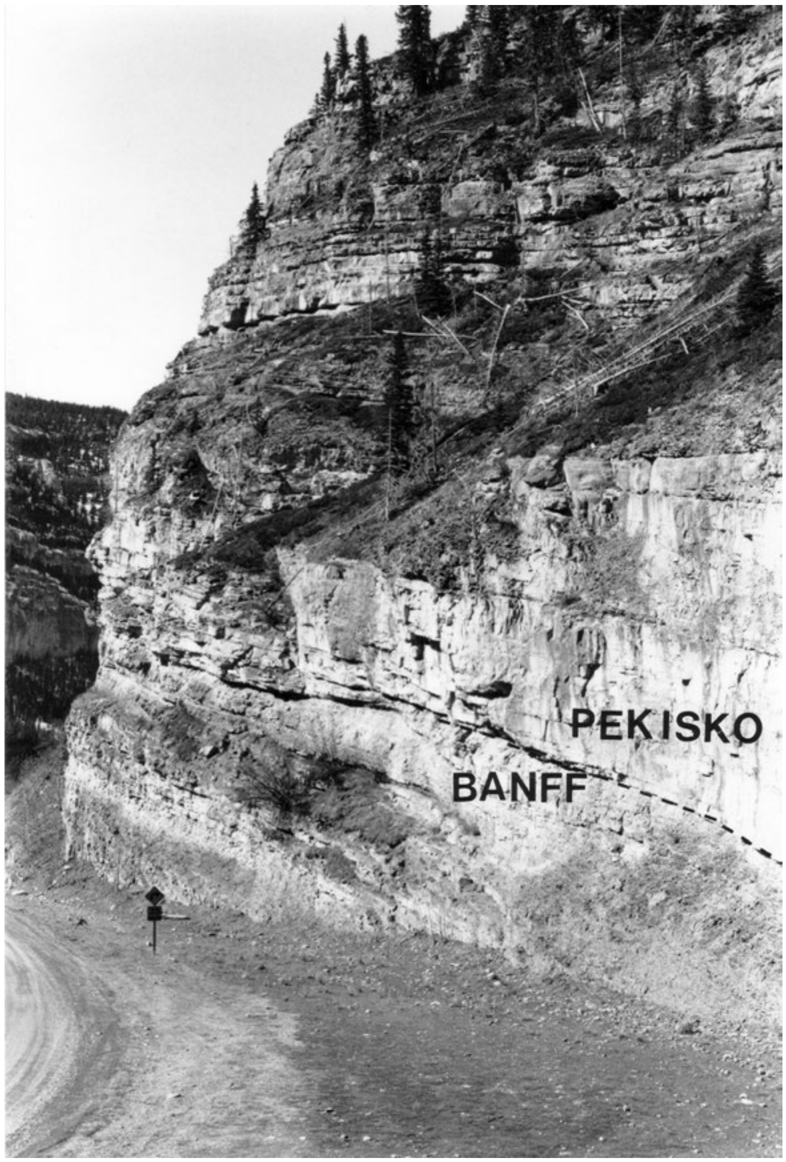


FIGURE 32 Stop 6: contact of the Banff and Pekisko formations. The Pekisko is marked by the incoming of cliff-forming crinoidal grainstone.

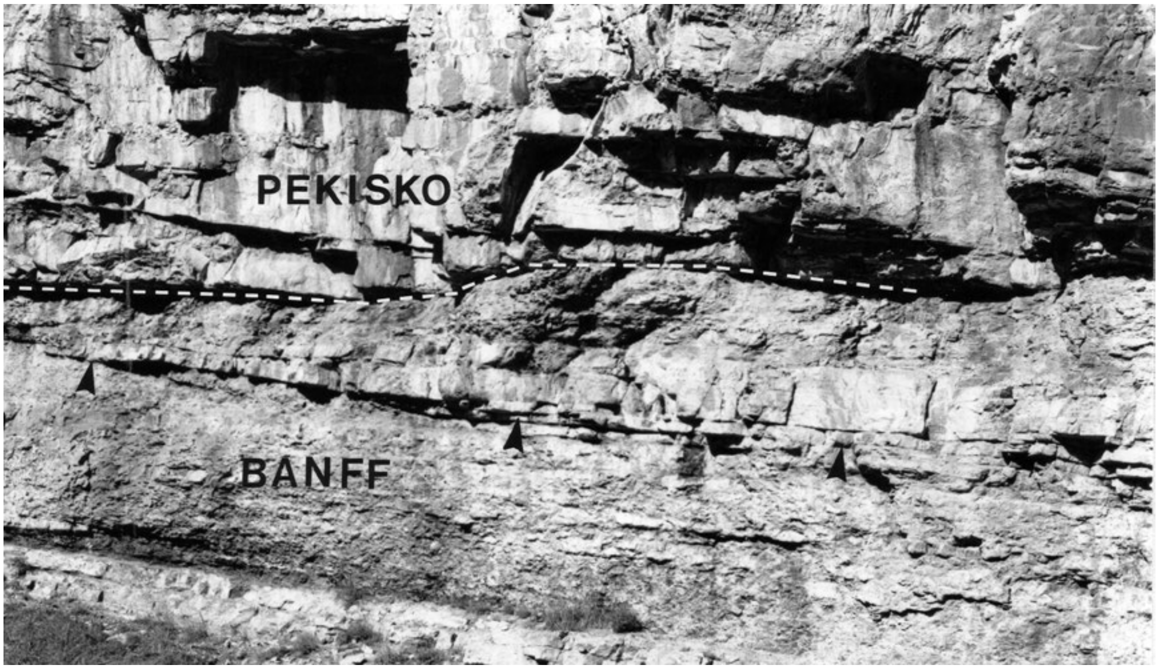


FIGURE 33 Stop 6: detail of the Banff-Pekisko contact showing the relief on the disconformity surface (dashed) and the lenticular and channel like (cut and fill) nature (arrowed) of a crinoidal tempestite bed at the top of the Banff Member C.

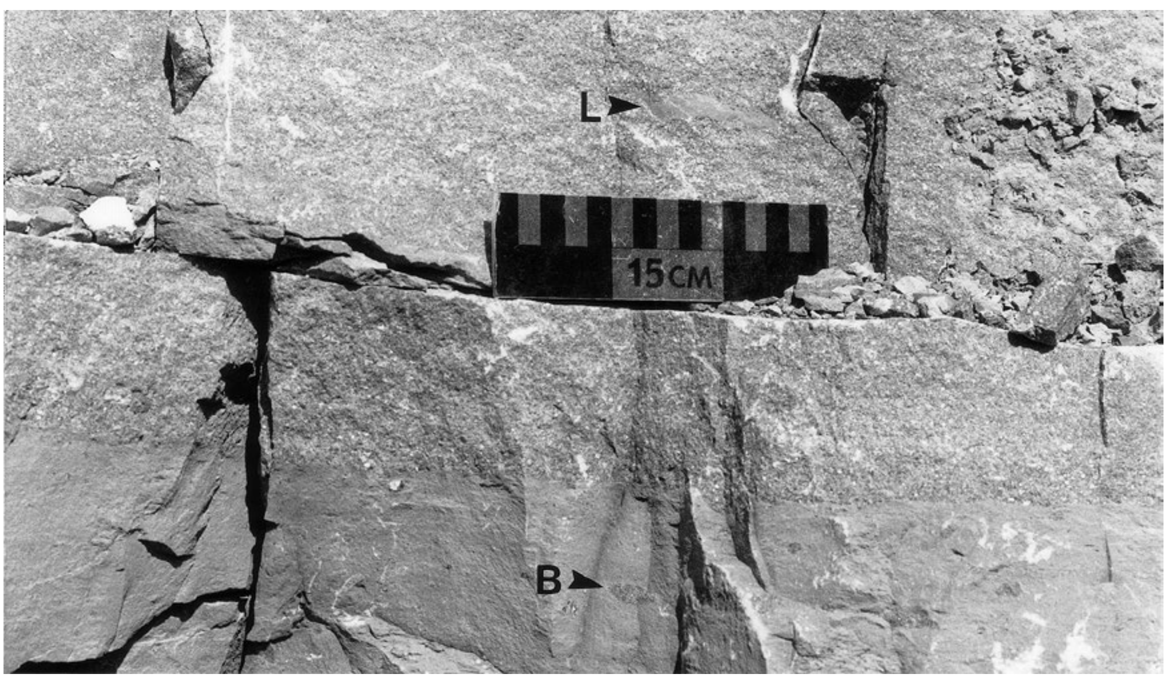


FIGURE 34 Stop 6, Pekisko Formation: tempestite unit (upper bed) consisting of a crinoidal grainstone to rudstone (see Figure 35). Note the sharp bed base (these are typically scoured), the lithological contrast from the background packstone (see Figure 36), the “rip-up” lithoclast (L) in the grainstone and the infilled burrows (B) in the underlying bed.

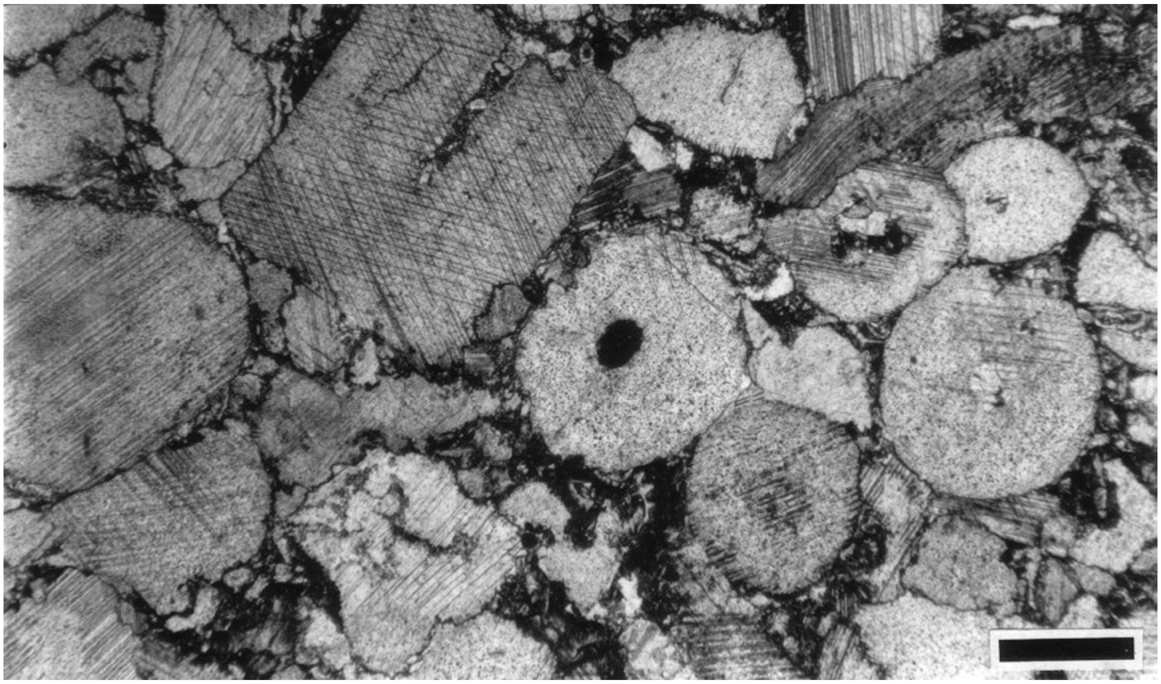


FIGURE 35 Stop 6, Pekisko Formation: thin-section photomicrograph (plane polarized light, scale bar 0.5 mm) of a crinoidal grainstone/rudstone from the tempestite bed shown in Figure 34.

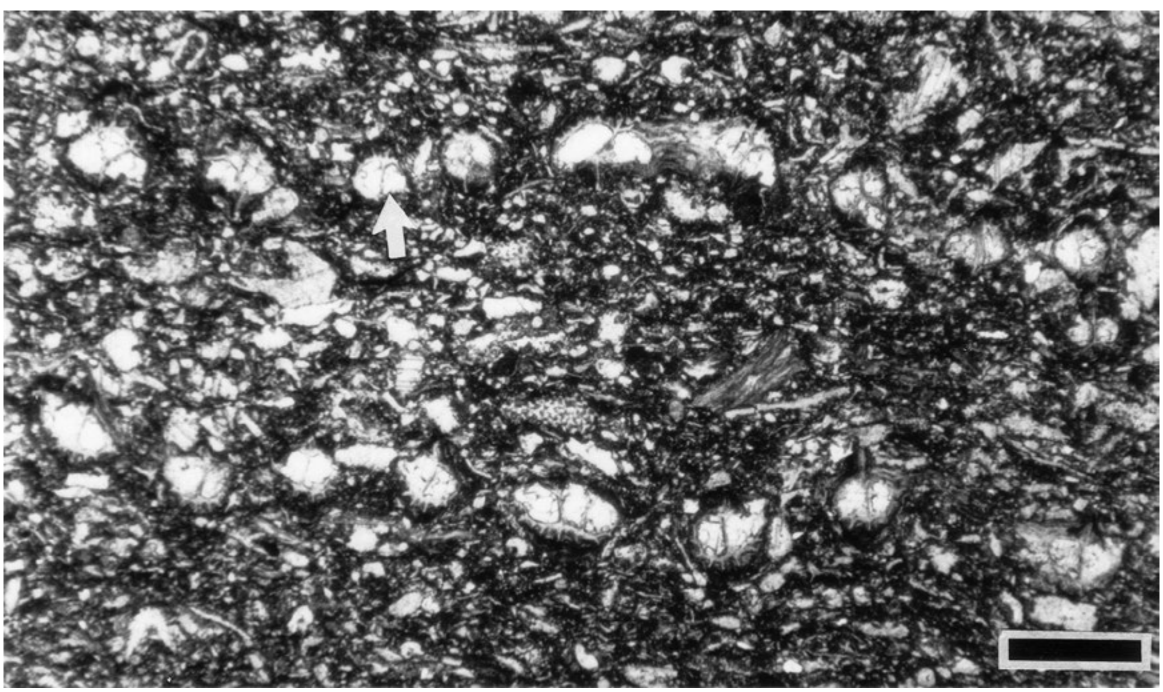


FIGURE 36 Stop 6, Pekisko Formation: thin-section photomicrograph (plane polarized light, scale bar 0.5 mm) of an unevenly grained bioclastic packstone. This lithology forms the “background” sediment between the tempestite beds (see Figure 34). Bioclasts include crinoid, bryozoan and brachiopod “hash” together with entire fronds of fenestrate bryozoans (arrowed).

STOP 7: PEKISKO-SHUNDA CONTACT

The top of a 9-m cliff forming unit at the western end of the exposed section is the Pekisko-Shunda contact. This unit forms the prominent feature (F2, see Figure 30) on adjacent mountain sides. Choice of this horizon as the formation boundary follows the regional correlations of Richards *et al*. (1994.).

The uppermost Pekisko consists of dark grey coarse grainstone, typically skeletal and peloidal (Figure 37), but with a significant content of ooids. Bioclastic grains include crinoids, echinoid spines, foraminifera, thin-shelled brachiopods and skeletal algae, while solitary rugose corals form a conspicuous macrofaunal component. The grainstone is lenticular bedded in part, which probably reflects original medium to large scale cross-sets, and is interpreted as a nearshore inner shelf to shoreface sand.

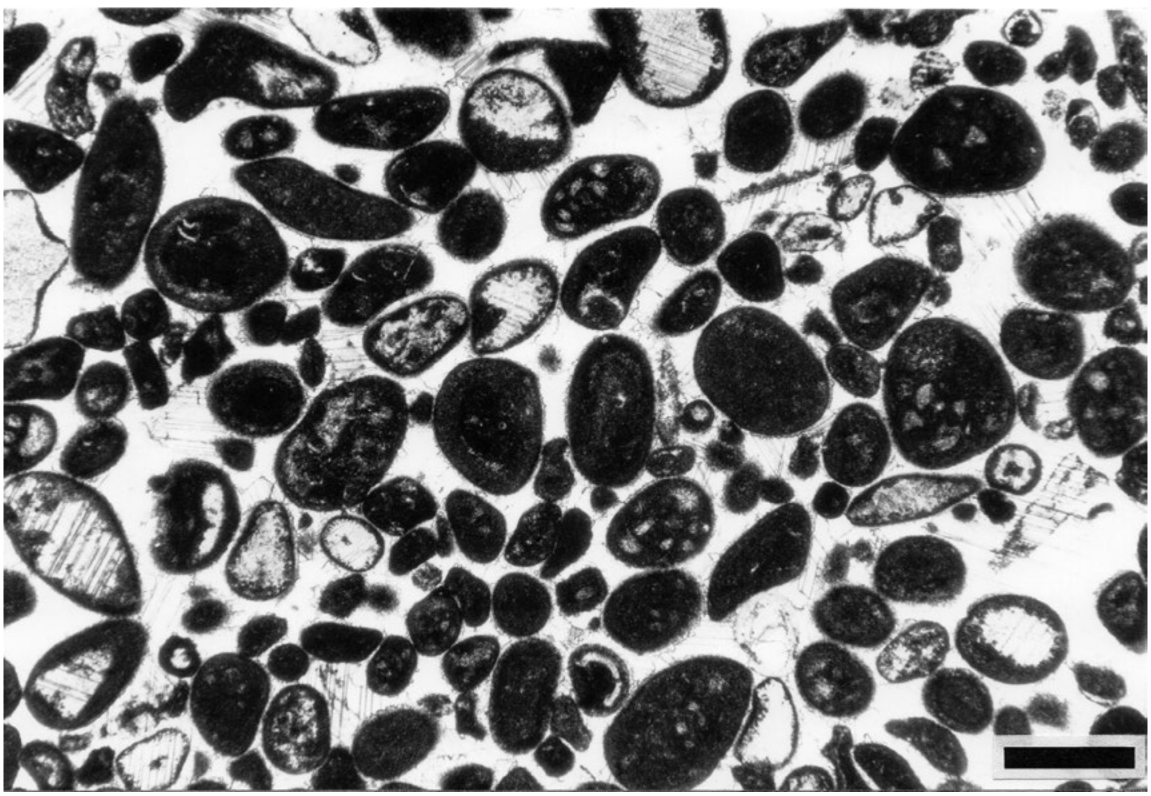


FIGURE 37 Stop 7, Pekisko Formation: thin-section photomicrograph (plane polarized light, scale bar 0.5 mm) of a fairly well sorted bioclastic grainstone from the top of the formation. Grains include foraminifera, crinoids, skeletal algae, echinoid spines together with peloids and scattered ooids (not all visible in this field). Grain micritization was rampant, and formed micrite envelopes and peloids (where the endobiont infestation was more intense).

Three informal Shunda members have been recognized in this vicinity by Richards *et al*. (1994), and designated D, E and F. The base of the “Member D” is represented in the section by a recessive 5-m gap. In core from the Lower Thrust Sheet (16-6-23-6W5, see Figure 6) this interval correlates with a burrowed crinoidal-bryozoan wackestone (7961 to 8018′), which appears to be transgressive in origin, while regional studies by Richards (*pers. comm*. Feb. 1992) confirm an important flooding event at this level.

The overlying limestone consists of dark and medium dark peloidal-bioclastic grainstone with sparsely scattered ooids. This grainstone shows a diverse assemblage of bioclasts including crinoids, bryozoans, foraminifera, echinoid spines, thin-shelled brachiopods, gastropods and skeletal algae. Corals are less significant than in the uppermost Pekisko. The brachiopods are concentrated in certain beds as coquinas (often fragmental) and locally impart a lamination to the rock. Some beds show medium scale cross-bedding. This grainstone is referred to a shoreface and foreshore setting. The youngest exposed beds assigned to this member consist of dolostone with bioclastic layers, and appear to indicate tidal flat deposits with storm laminae. In the cored section from the Lower Thrust Sheet (16-6-23-6W5, Figure 6), the upper part of Member D is represented by a coarse “peloidal”-bioclastic grainstone, with many of the “peloids” consisting of rounded lime-mudstone intraclasts of peritidal origin (some containing calcispheres), which had subsequently been “coated”. This grainstone shows well developed isopachous marine cements (Figure 8).

Shunda “Member E” and the lowest beds of “Member F” weather recessively, and are represented by a 34-m gap in the section below the quarry exposure. Elsewhere in the vicinity, however, the upper part of “Member E” produces a strong feature-forming limestone unit (F3, see Figures 18 & 30) some 17 m thick, consisting of medium to large scale cross-bedded peloidal-oolitic-bioclastic grainstone, interpreted as part of a mainland barrier shoreline complex. In the Lower Thrust Sheet the base of Member E is marked by the first incoming of laminated tidal flat dolostone. The latter lithology dominates this stratigraphic interval with only minor interbeds of grainstone and brachiopod (rhynchonelloid) coquina. The base of “Member F” in the cored section is represented by laminated dolomitic silt containing nodular anhydrite.

STOP 8: SHUNDA FORMATION (MEMBER F) AND TURNER VALLEY FORMATION (ELKTON MEMBER) [FIGURE 38]

The quarry section exposes 32 m of Shunda and 5 m of the overlying Turner Valley, the formational contact occurring 1.2 m below a vegetated ledge (Figure 39). The Shunda section belongs wholly to "Member F" with only 6 m or so of the base of the stratigraphic unit unexposed. The majority of the section consists of limestone, with subordinate dolostone and thin argillaceous partings. A 1-m greenish mudstone is exposed at the base of the section; this can be accurately calibrated with a high "gamma-ray kick" on the 7-3-23-6W5 well log (surface sheet, Figure 6).

The limestone is a medium dark grey, fine grained peloidal-bioclastic wackestone and packstone, typically fenestral, with gastropod shell hash, calcispheres and skeletal algae (particularly *Proninella*, Figure 40), forming the majority of the bioclasts. Gastropods (low spired and trochiform) are the only conspicuous macrofossils and are locally present in great numbers, but always as external molds. Rhizoliths (root molds, Figure 41) are common throughout and are often associated with rubbly (?rhizobrecciated) zones. In the upper part of the section they occur at the tops of successive 30 cm thick beds.

Microid and pisoid coated grains are conspicuous at many horizons where they contribute to beds with complex fabrics involving rhizoliths, laminated crusts (micritic and dolomitic) and fibrous "cement" crusts (interpreted as hybrid calcrete horizons).

In a prominent bed in the middle of the quarry section coated grain accumulations overlie and intercalate with the laminated micritic and dolostone crusts. Here the pisoids show variable cortex structure from distinctly radial and isopachous to fine and coarse (regular and irregular) micritic laminae, or intra-pisoid combinations of micritic and radial cortex. The larger radial pisoids frequently exhibit early internal fractures and recoated external breakage surfaces (Figure 42). Some pisoids consist of composite cemented "agglutinated" microids, while radial isopachous crusts locally coat pisoids forming "fitted" laminae. A later stage micritic coating commonly envelopes and "cements" the pisoids *via* meniscus or bridge-like connections (Figure 42, see Tucker & Wright, 1990 figure 1.30). Coated grains with largely micritic laminae show some similarities to soil glaebules, while those with the radial cortex (originally aragonite) are more analogous to supratidal (phreatic-vadose) pisoids (formed in hypersaline pools sourced, for example, by groundwater brine resurgence; see Handford *et al*. 1984; Ferguson *et al*. 1982; Loreau & Purser, 1973). The textural relations of these coated grains to the micritic and dolomitic crusts is somewhat reminiscent of the Permian Capitan Reef (backreef) pisoid beds of New Mexico and Texas (Dunham, 1969; Estaban & Pray, 1983). However, the later phase micritic bridging "cement" of the Shunda bed is more pedogenic in character and compares favourably with the microbial micrite precipitates described by Wright (1986). The bed thus appears to reflect a combination of the two diagenetic regimes (hypersaline and meteoric pedogenic).

The multiple rooted zones (many without associated pedogenic profiles) must reflect frequent floral colonization under a meteoric (fresh-water) influence, or alternatively colonization or an endemic tidal flat halophytic vegetation.

Toward the top of the section, small solutional cavities occur beneath an undulate bedding plane. These cavities have geopetal sediment infills, and are interpreted as products of meteoric solution.

Many of the pores (fenestrae, root molds etc.) are infilled with saddle dolomite (Figure 9) and calcite, while anhydrite remnants are sometimes present “encased” in the calcite (Figure 10). It seems reasonable that both the saddle dolomite and much of the calcite (together with calcitization of anhydrite) are the products of thermochemical sulphate reduction, and that many of the pores were originally filled with anhydrite. Ovoid open cavities of various dimensions (present in several beds), also testify to the former presence of anhydrite (anhydrite not consumed in the TSR reactions would have been leached during the surface breaching of the Mississippian).

Areally this member of the Shunda shows much facies variation; stream bank sections in the western limb of the Moose Mountain anticline, for instance, expose ripple cross-laminated siltstone, collapse breccia (and residuum) after anhydrite dissolution (Figure 43) and stromatolitic units, as well as the rooted wackestone. A 6-m sabkha style displacive anhydrite unit occurs in the cored section of the lower sheet (16-6-23-6W5, see Figure 44) interbedded with dolomite and silty dolomite with abundant anhydrite nodules (the nodular and “massive” anhydrite units occurring over some 18 m of section). Beneath the massive anhydrite in this core is a greenish mudstone which resembles that at the base of the quarry section.

The Shunda Member F thus represents an areally complex spectrum of peritidal environments with the supratidal setting dominating. Combinations of meteoric and possible hypersaline diagenesis imply that restricted embayments and local shoreline barriers must have characterized the palaeogeography.

The contact of the Shunda with the Turner Valley Formation (Elkton Member) is sharp and disconformable. The exposed Turner Valley here consists of partly to wholly dolomitized, cross-bedded, medium and light grey crinoidal-bryozoan grainstone (open shelf shoal), and indicates a significant flooding event.

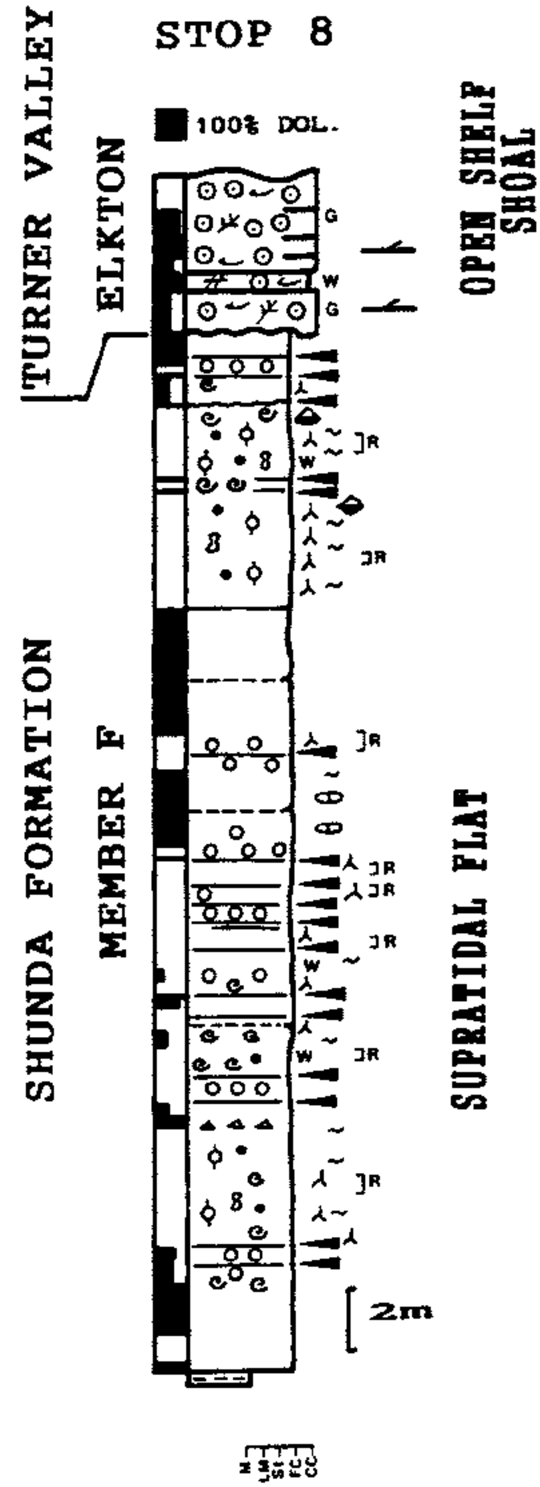


FIGURE 38 Columnar log of the exposed Shunda Formation (Member F) and overlying basal Turner Valley in the quarry section at Stop 8. For legend see Figure 6.

FIGURE 39 Stop 8: quarry exposures in the Shunda Formation (Member F) see columnar log Figure 38. The contact with the overlying Turner Valley (TV) Elkton Member is exposed at the top of the section. A greenish mudstone bed occurs at the base of the quarry (arrowed).

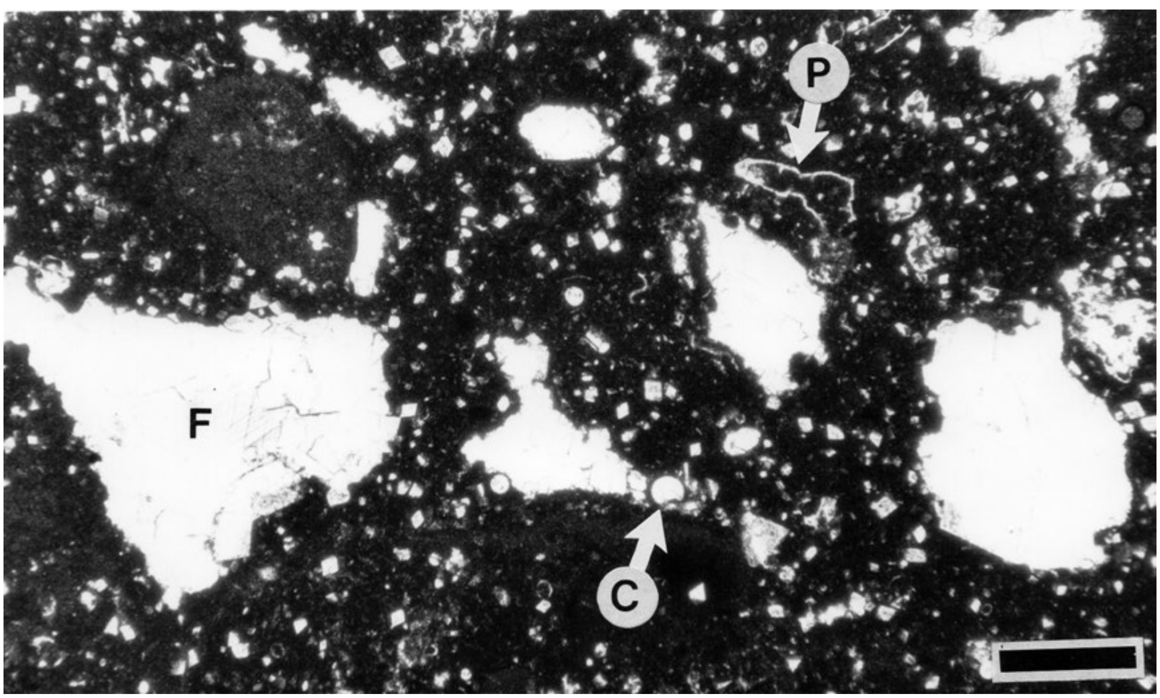


FIGURE 40 Stop 8, Shunda Formation (Member F): thin-section photomicrograph (plane polarized light, scale bar 0.5 mm) of a lime-mudstone to wackestone with well developed fenestrae (F). Grains include peloids, skeletal algae (particularly *Proninella*, P) and calcispheres (C). Note the disseminated replacive dolomite rhombs.

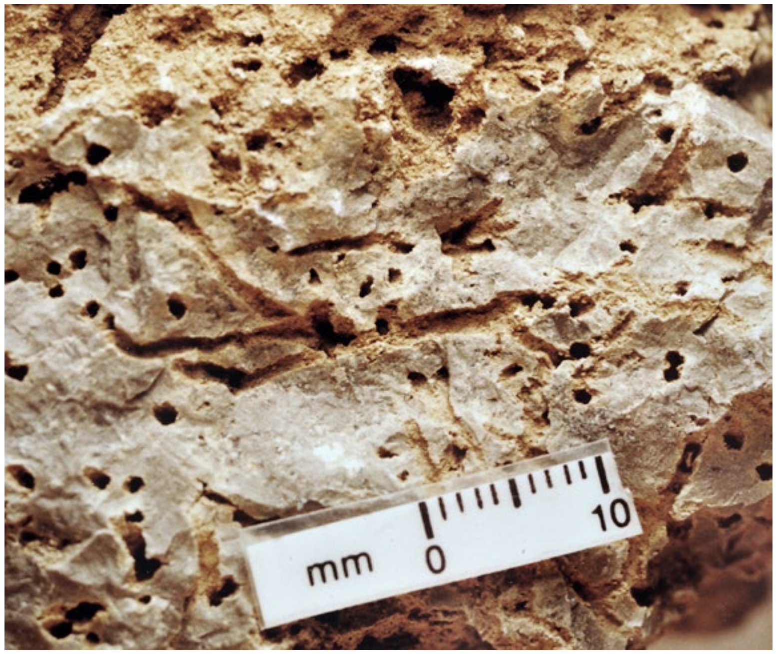


FIGURE 41 Stop 8, Shunda Formation (Member F): rhizoliths (root molds) in a fenestral wackestone.

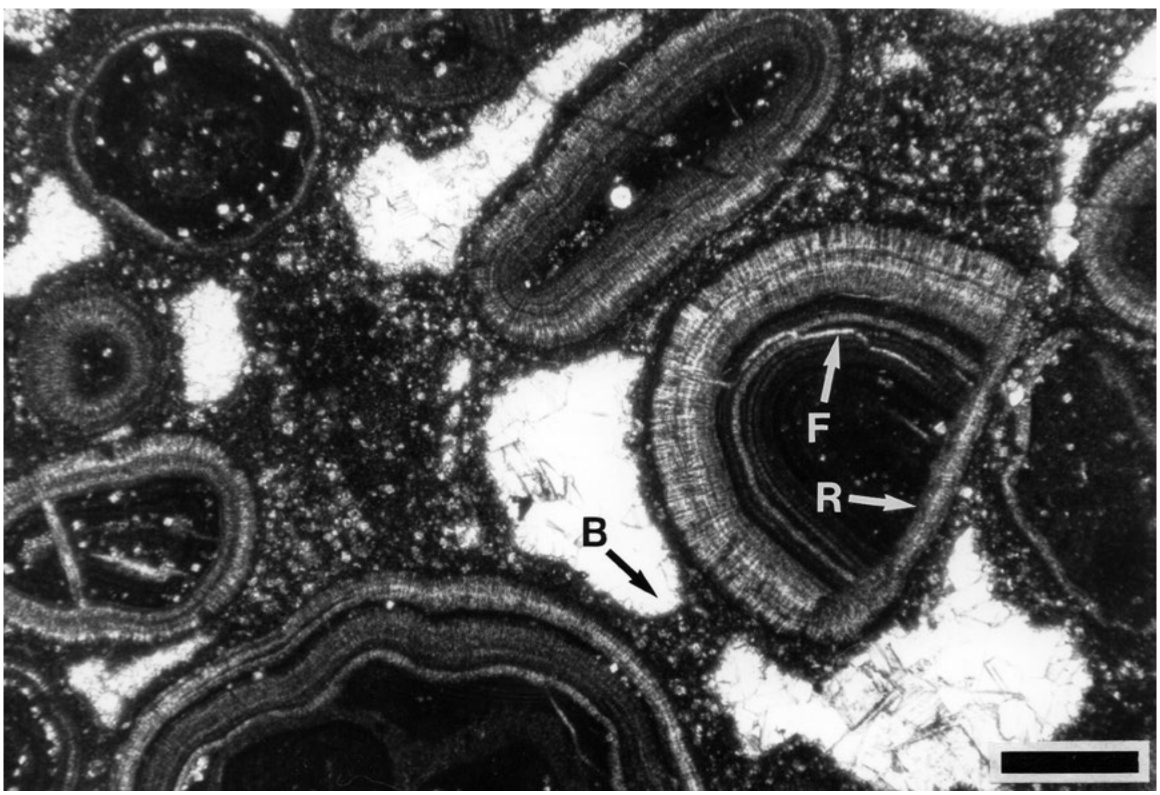


FIGURE 42 Stop 8, Shunda Formation (Member F): thin-section photomicrograph (plane polarized light, scale bar 0.5 mm) of a pisoid unit (associated with laminar calcite crusts). The pisoids show both micritic and radial cortex and have micrite coats which bridge (B) and cement the grains. The pisoids show healed internal fractures (F) and recoated (R) external fracture surfaces. The textural relations appears to indicate both hypersaline phreatic/vadose and meteoric pedogenic influences.

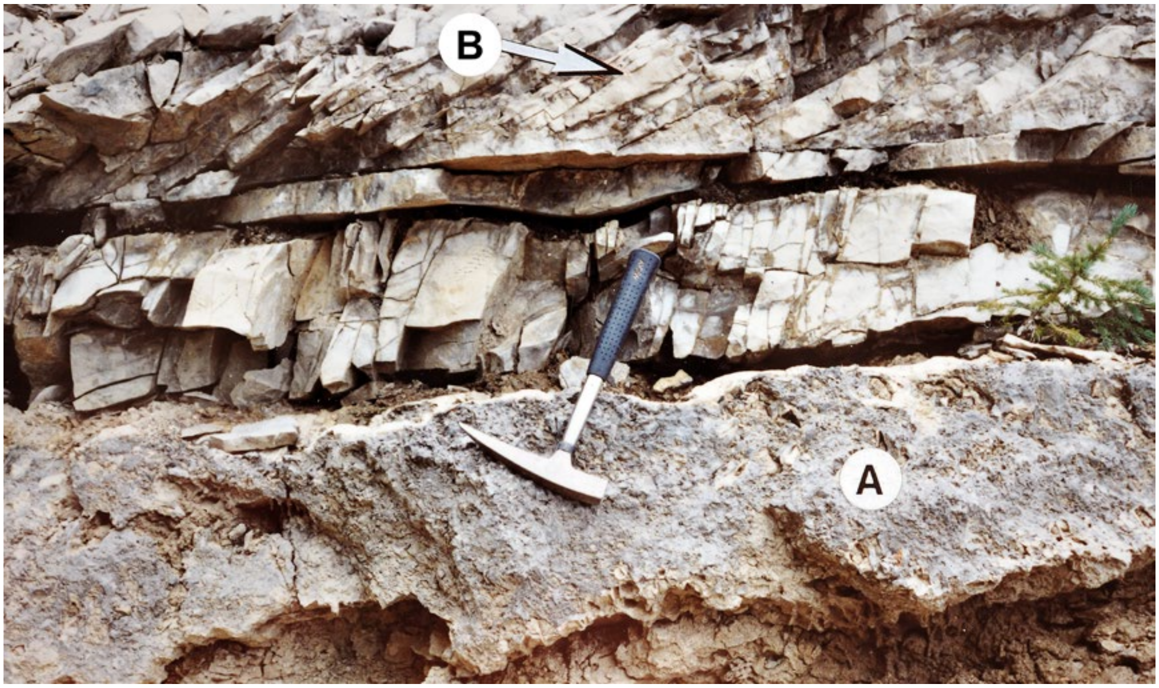


FIGURE 43 Shunda Formation (Member F): stream bank exposures in Canyon Creek (western limb of the Moose Mountain Anticline), showing collapse breccia and residuum (A) after anhydrite dissolution. The overlying dolostone beds (B) show fracture cleavage (in planar and sigmoidal sets) which had resulted from flexural shear.

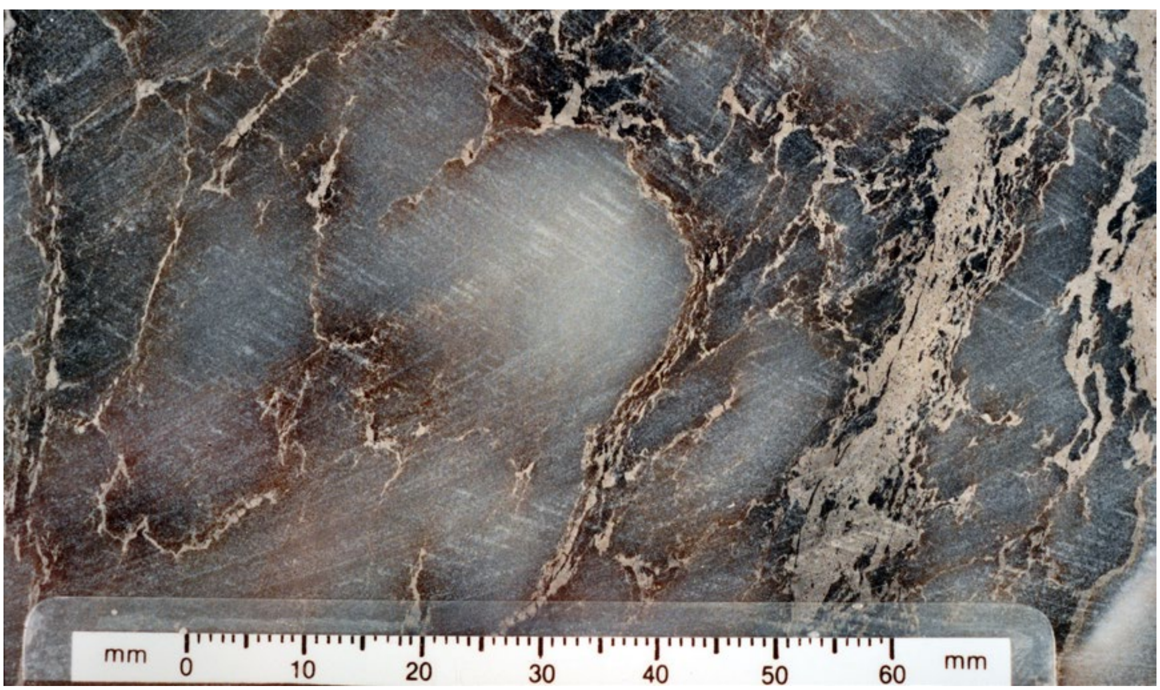


FIGURE 44 Shunda Formation: core photograph of nodular almost "chicken wire" anhydrite preserved in the Lower Thrust Sheet. Calstan Shell Moose 16-6-23-6W5, 7794′ (2376 m).

BETWEEN STOPS 8 AND 9: (TURNER VALLEY FORMATION)

The Turner Valley Formation in Canyon Creek is 127 m thick. Much of this is replacive dolostone, which has a tendency to weather recessively (due to solutional disaggregation —"sanding"), and is generally not visible. Those exposed portions of the formation are typically the undolomitized or poorly dolomitized sections. Exposures of the lower member (Elkton = "Lower Porous", maximum thickness 55 m) occur at the top of the quarry section (Figure 38) and in roadside exposures 4 m and 10 m thick, 18 m and 37 m respectively above the base of the formation. Mixed bioclastic (crinoid - bryozoan - foraminifera - brachiopod) grainstone, cross-bedded in part, form the lower of the exposures and the base of the higher, and at the latter locality (west of bend in the road) the grainstone is overlain by partly dolomitized cherty crinoidal-bryozoan pack/wackestone. Depositional setting for the Elkton is interpreted as open shelf with crinoidal shoals and lower energy intershoal facies, the latter typically containing allochthonous storm event beds. These tempestite units are present in both the surface exposures and the subsurface cores (see Figure 45).

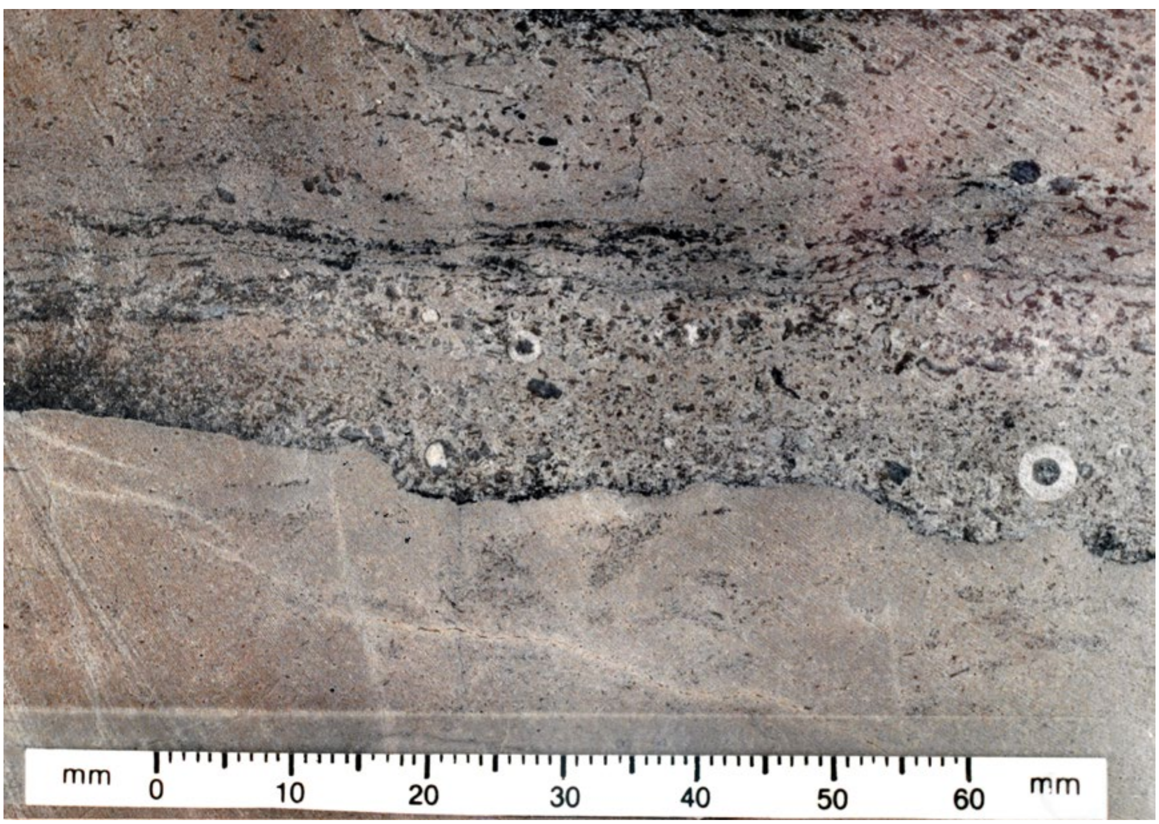


FIGURE 45 Elkton ("Lower Porous") dolostone: core photograph of a thin bioclastic (crinoidal-bryozoan) tempestite unit overlying scoured surface of wackestone. Shell Home Moose 10-5-23-6W5, 7031′ (2143 m).

The middle member of the Turner Valley ("Middle Dense") is 27 m thick, but is not exposed in this section; it consists of peritidal dolostone, which is silty and cherty in part. At the top of this regressive unit is a 3-m silty dolostone capped with a pyritic and argillaceous bed. This produces a prominent spike on the gamma-ray log (see Figure 6), which is areally correlatable over large distances. Despite the oil industry term "Middle Dense", alluding to the typically poor reservoir quality, localized very good micro-intercrystalline porosities can occur in this stratigraphic unit. The base of this member is calculated to be just east of the bend in the road, and the top approximately at the roadside "pipeline" crossing sign.

STOP 9: TURNER VALLEY ("UPPER POROUS") [FIGURE 46]

A 16-m section of the middle part of the "Upper Porous" Member is exposed along an overgrown track on the south side of the road, and is approached by traversing the bank adjacent to a small roadside exposure. The base of the section (6 m) consists of dolomitized packstone and wackestone, with a 1-m interbedded crinoidal grainstone-rudstone. Prominent leached colonies of *Syringopora* (Figure 47) occur in a replacive dolostone. This bed is one of two (in this member) that is laterally persistent and can be correlated to the roadcut near Elbow Falls (Prairie Mountain Thrust). The underlying bed (originally a crinoidal-bryozoan wackestone) contains calcite lined vugs after replacive anhydrite, some of which contain traces of elemental sulphur, again evidence of thermochemical sulphate reduction in the Upper Thrust Sheet.

The overlying beds (10 m) are slightly dolomitized bioclastic grainstone-rudstone which exhibit low angle medium scale cross-bedding. Bioclasts are dominated by crinoids, but fenestrate bryozoans, foraminifera, blastoids, brachiopods, gastropods and corals are represented. The basal section of this grainstone unit forms the small roadside exposure.

The cross-bedded grainstone and underlying beds represent open shelf shoal and intershoal environments, with the coral bed in the latter forming a "biostromal" interlude. The lowest energy deposits occurring in the "Upper Porous" are wackestone and packstone with a fauna confined to delicate fenestrate bryozoans (see Figure 48), these represent the deeper water components of minor transgressive-regressive cycles.

The dolomitization pattern shown at this exposure exemplifies the primary lithological control of the replacive dolostone, with lime-mud or mud supported lithologies being more prone to replacement than sparry limestone such as the crinoidal grainstone with syntaxial overgrowths (see Murray & Lucia, 1967). Petrographic evidence from this locality shows that the dolomitization (shallow burial) post-dated the cements. The replacive dolostone with biomoldic and intercrystalline porosity is the principal producing reservoir of Moose Mountain and adjacent Foothills fields.

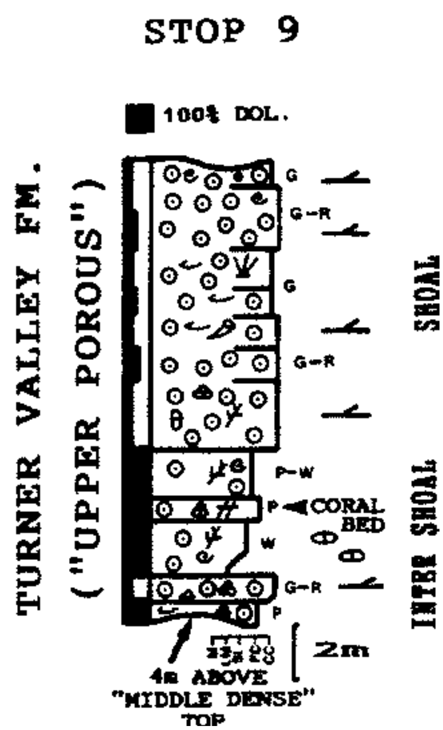


FIGURE 46 Columnar log of the Turner Valley ''Upper Porous" Member exposed at Stop 9. For legend see Figure 6.

FIGURE 47 Stop 9, Turner Valley Formation "Upper Porous": leached *Syringopora* colony in replacive dolostone (matrix originally wackestone). This coral bed is one of two which are locally persistent, and can be correlated to sections in the Prairie Mountain Thrust (road cut near Elbow Falls).

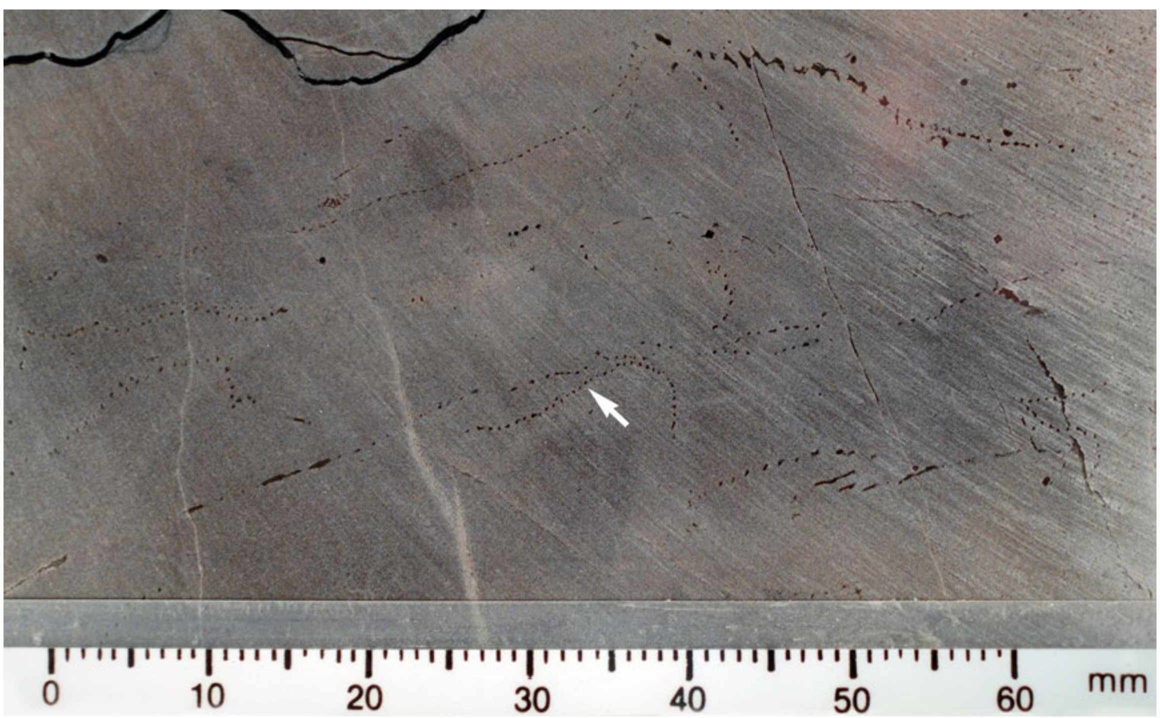


FIGURE 48 Turner Valley Formation "Upper Porous" dolostone: core photograph of lime-mudstone to wackestone with entire fenestrate bryozoan fronds (example arrowed). This facies represents a low energy environment, probably developed at a depth greater than the typical bathymetric range for the shelf (and possibly represents a minor transgressive interlude). Shell Home Moose 13-28-22-6W5, 2361.4 m.

VIEWPOINT: TURNER VALLEY - MOUNT HEAD FORMATION CONTACT (BETWEEN STOPS 9 AND 10) [FIGURE 49]

The cliff and bank north of the stream expose the contact between the Turner Valley and Mount Head formations (Figure 50). This was previously chosen (Bamber *et al*. 1981) at a recessive notch toward the base of the cliff. The latter is a shear plane and the overlying limestone is better placed in the Turner Valley. A sharp contact between this limestone and brown weathering sandstone, occurs at the top of the cliff, and this is a more appropriate formational contact.

The Turner Valley ("Upper Porous") beneath the recessive notch consists of packstone, wackestone and subordinate grainstone, which represent offshore mostly low energy deposition. The wackestone units are significantly dolomitized and contain a conspicuous bed with disarticulated brachiopod valves and solitary rugose corals. This bed also contains *Zoophycos* burrows, with the traces often replaced by chert. The cliff forming uppermost Turner Valley is a cross-bedded and ripple cross-laminated mixed bioclastic-peloidal grainstone with scattered ooids, which is only slightly dolomitized, and is interpreted as a shoreface to foreshore sand. This limestone produces the feature-forming unit (F5, see Figures 18 & 30) on the nearby mountain sides. The contact with the Mount Head is disconformable, and possibly represents a significant erosion surface with loss of section in the subsurface to the east.

Calibration of the Canyon Creek Mount Head Formation with the recognized component members has not previously been attempted, although realistic lithological comparisons can be made.

The basal beds of the Mount Head Formation are typical of the Wileman Member and consist of brown weathering, dolomitic, very fine grained sandstone (5 m), ripple-laminated and cross-bedded, which are overlain by 14 m of silty dolostone and dark limestone (and dedolomite, see under **Stop 10**). This succession represents a siliciclastic dominated ?intertidal sand flat, while the succeeding carbonates indicate restricted lagoon and supratidal flat deposits. Overlying the latter, with a conspicuous erosive contact, is a transgressive cross-bedded grainstone which compares to the Loomis Member. If this correlation is correct, it would necessitate the removal of the Baril and Salter correlatives at the erosion surface. The ?Loomis (9 m) here includes two grainstone units with an intervening silty dolostone.

Approximately 3 m of cherty stromatolitic laminated dolostone overlies the ?Loomis, with a 2-m collapse breccia (solutional residuum after anhydrite dissolution) capping the dolostone (exposed in the valley bottom just west of the cutline): these supratidal deposits are referred to the Marston Member.

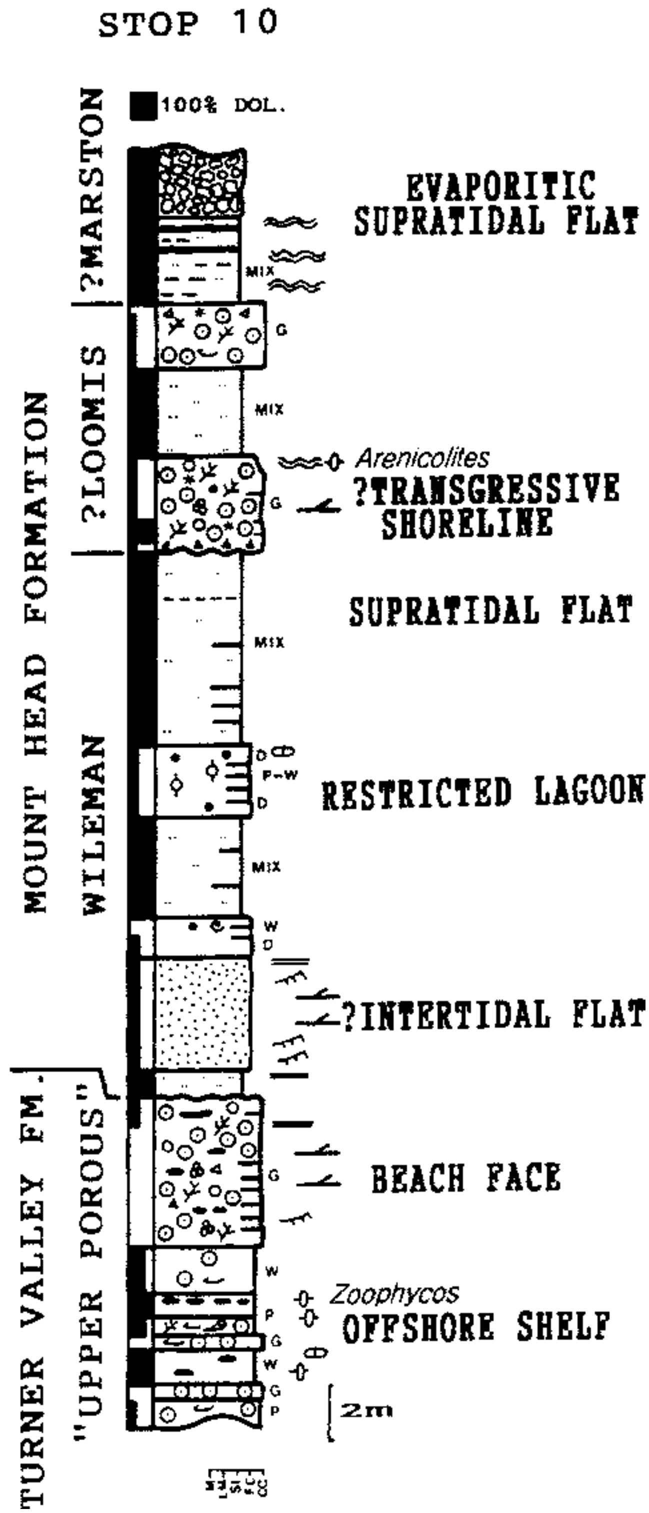


FIGURE 49 Columnar log of the exposed Turner Valley - Mount Head formational contact near Stop 10. For legend see Figure 6.

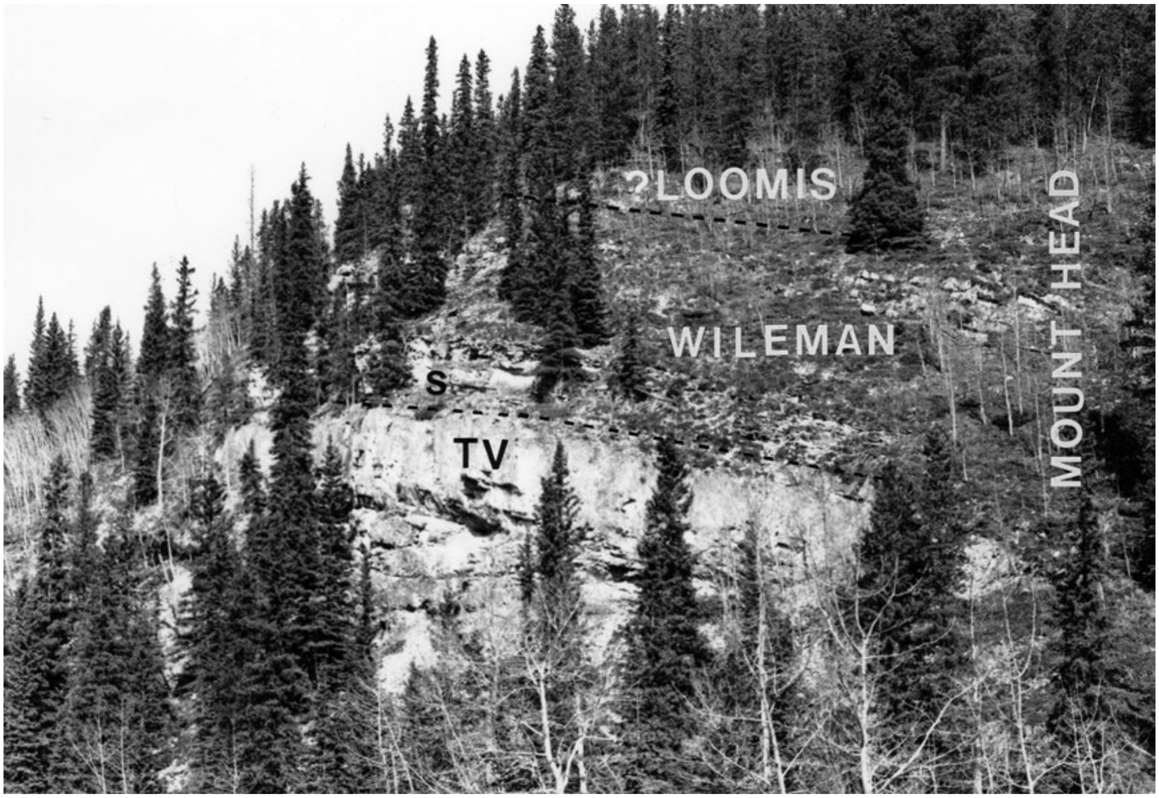


FIGURE 50 Between Stops 9 & 10: Turner Valley (TV) - Mount Head formational contact exposed in the cliffs N.W. of Stop 10. The exposures of the Wileman and ?Loomis members are indicated. Note the Baril and Salter members appear to be cut out at an erosion surface below the ?Loomis. A 5-m section of very fine grained sandstone (S) forms the basal beds of Wileman.

STOP 10: MOUNT HEAD FORMATION (WILEMAN & ?LOOMIS MEMBERS) [FIGURE 49]

An 18-m section of the Mount Head is exposed in the road-cut. The base of the section correlates to the beds immediately above the Wileman sandstone. Two horizons of dark limestone, separated by silty dolostone, form the lower part of the exposure. These limestones show complex textural relations. They were originally peloidal-bioclastic (calcispheres and gastropod shell hash) pack/wackestone, which were partly dolomitized and then subsequently dedolomitized back to limestone.

The upper part of the section consists of further silty dolostone (Wileman), with the lower “leaf” of the ?Loomis grainstone forming the top of the exposure. The undulate disconformable base of the grainstone is clearly discernible and the lower 0.4 m of the bed contains a concentration of lithoclasts. The limestone is a mixed bioclastic grainstone, with scattered peloids, ooids and dolostone intraclasts; bioclastic components include crinoids, bryozoans, echinoid spines, foraminifera, ostracodes and brachiopods (Figure 51). At the top of the unit “ribbon-like” dolomite laminae cap the grainstone; these are penetrated by vertical burrows. Wileman lithofacies in this section represent restricted lagoon and supratidal settings, while the transgressive ?Loomis grainstone suggests a sheet sand formed by the reworking of a shoreline facies. The burrowed laminae at the top of the grainstone bed probably formed in an intertidal setting.

FIGURE 51 Stop 10, Mount Head ?Loomis Member: thin-section photomicrograph (plane polarized light, scale bar 0.5 mm) of a bioclastic-peloidal grainstone, interpreted as a reworked shoreline “sand”. Grains include echinoderm fragments (crinoids and echinoid spines), bryozoans, foraminifera and ooids. Dolostone lithoclasts (not shown in this field) are quite numerous.

STOP 11: MOUNT HEAD FORMATION (?MARSTON - ?CARNARVON)

Cliff sections (Figure 52) expose microcrystalline dolostone, silty and laminated (stromatolitic) in part (Figure 53), with small tepee structures commonly developed. Three discrete horizons of solutional residuum, after anhydrite loss, are exposed (in ascending order 0.9 m, 1.5 m and 1.7 m in thickness). These consist of breccia in an argillaceous and silty matrix and are often associated with collapse and foundering structures in the overlying strata. Depositional setting for this section of the Mount Head is an extensive restricted evaporitic supratidal flat. The dissolution of anhydrite is probably related to late Laramide surface (Cenozoic) breaching of the upper thrust sheet.

The dolostone is locally well fractured (almost a fracture cleavage) with the sets varying from bed to bed. These are attributed to extensional stress induced by flexural shear.

This higher section of the Mount Head is tentatively referred to the Marston and or Carnarvon members on spatial considerations. Downstream from the upper collapse zone there is a further 65 m of Mississippian section (poorly exposed dolostone and siltstone) below the base of the Fernie Formation (Jurassic). This may include correlatives of the Etherington Formation (Chesterian, late Visean-Serpukhovian).

FIGURE 52 Stop 11, Mount Head Formation (?Marston or ?Carnarvon): cliff exposures showing well bedded, silty, microcrystalline dolostone. A collapse breccia zone after anhydrite dissolution is indicated (C). This is the youngest of three evaporite beds exposed at this locality.

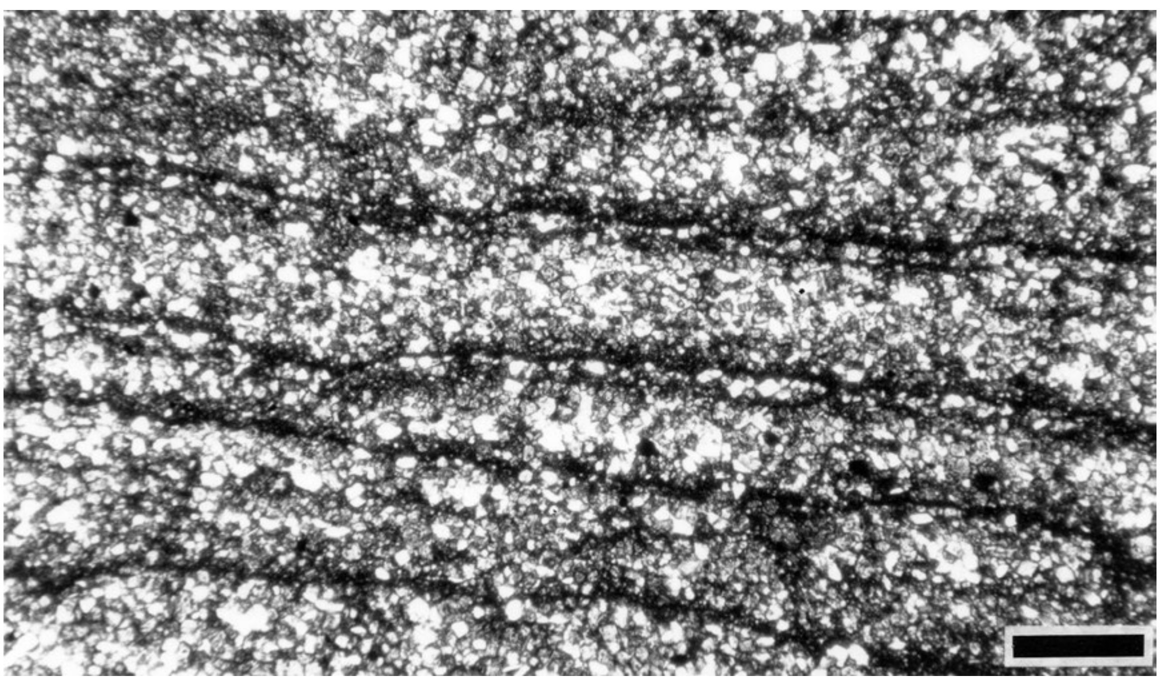


FIGURE 53 Stop 11, Mount Head Formation: thin-section photomicrograph (plane polarized light, scale bar 0.5 mm) of a silty (terrigenous quartz) microcrystalline dolostone, with cryptocrystalline stromatolitic laminae.

APPENDIX: UPDATE OF DRILLING ACTIVITY

Subsequent to the original publication of this field guide there has been considerable industry activity in the Moose Mountain area, particularly in the north where Husky and their partner Rigel made an oil discovery in early 1993. In view of the local interest shown in this potentially exciting find an attempt has been made to update this guide book by means of a further structural cross-section in the northern part of the field (Figure 54). This interpretation is based solely on publicly available data and does not integrate any seismic derived information.

The Husky Discovery

The objective of the Husky Rigel Moose 2-23-23-7W5 well (subsequently identified as 16-14-23-7W5, based upon its sub-surface T.D. location) was undoubtedly to test the concept that an undrilled structural high at the prospective Mississippian level is developed within the Lower Thrust sheet to the west of the main Moose Mountain gas pool (as proposed in Figure 13).

The well, drilled in late 1992/early 1993 directionally towards the S.E., spudded into Mississippian carbonates, and after a slightly thicker than expected Mississippian section (due to probable minor thrust repetition of the section) encountered a normal thickness of Devonian. A slightly thickened Cambrian section (due to the combined effects of a 30° dip and slightly deviated borehole) was then found to be thrust over itself giving in total, a much over thickened Cambrian interval. The well then passed through a major floor thrust carrying Cambrian Cathedral Formation on Mississippian Mt. Head.

Initially listed as a gas well, there were reports of oil (38° API) to surface and the recovery of 500 bbls in 15 hours (800 bopd) from 71 metres of pay within the Mt. Head - Turner Valley interval. The well was terminated at a depth of 3000 m within the Mississippian Pekisko Formation.

Discussion

The 1-28-23-7W5 well drilled in 1990 by Shell (see below) found a thick, thrust-repeated Cambrian section within the Upper Thrust Sheet (Figure 54). None of these thrusts appear to have cut the outcropping Mississippian and so a Cambrian duplex is proposed with a floor thrust at the base of the Cambrian section and a roof thrust near the top or within the basal Devonian.

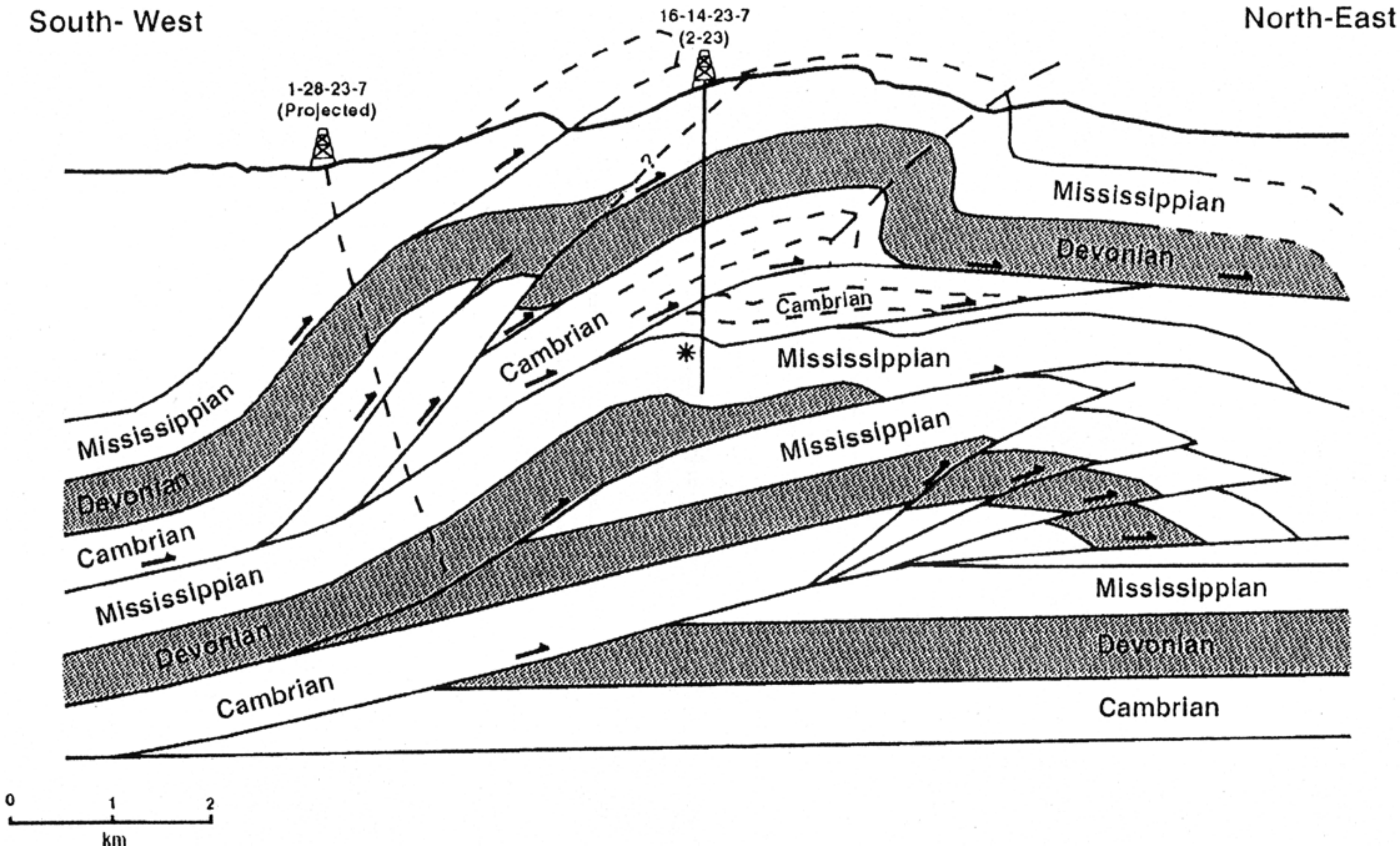


FIGURE 54: MOOSE MOUNTAIN (NORTH); STRUCTURAL SKETCH THROUGH HUSKY ET AL'S RECENT DISCOVERY (16-14-23-7W5).

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Given this amount of thrust repetition of the Cambrian only 3 km to the north-west it was not surprising that the 16-14 well found a similar tectonic thickening within the Cambrian of the Upper Thrust Sheet. Figure 54 shows the intra-Cambrian thrust at 16-14 linking south-westwards into the main 'base' Cambrian floor thrust. Towards the N.E. this thrust is believed to cut up section through the Cambrian and then run bedding-parallel along the base Devonian. The fault-bend fold created in the hanging wall of this ramp/flat thrust configuration involves the whole overlying stratigraphic sequence and controls the geometry of the Moose Mountain surface anticlinal fold. The Cambrian section encountered in the footwall of this thrust is also the basal section in the hanging wall of the highly deformed Upper Thrust Sheet.

The underlying hydrocarbon-bearing Mississippian culmination is interpreted to be a detachment fold/ramp anticline developed in the hanging wall of the "out-of-sequence" thrust which cuts the Lower Thrust Sheet.

Listing of Moose Mountain Wells (continued from p. 39)

22. Shell Moose 1-28-23-7W5 1989/90, (D & A). Drilled 9 km N.W. of 16-6-23-6 the objective of this well was to test a sub-thrust Devonian duplex, developed on the N.W. flank of the Moose Mountain structure. The well found a slightly over-thickened Mississippian/Devonian section in the hangingwall of the Upper Thrust-Sheet and then a much over thickened Cambrian section (at 1310 m). This section is believed to be thrust-repeated and has been interpreted as a duplex (see Figure 54). Underneath the floor thrust to the Upper Thrust-Sheet the well found a thin Fernie section and then Mississippian and Devonian rocks of the Lower Thrust-Sheet. The Mississippian reservoir was outside closure at this locality.

23. Husky et al Moose 16-14-23-7W5 1992/93, (Gas well). This well drilled from a surface pad at 2-23-23-7, was the first to test the concept of a separate Mississippian culmination within the Lower Thrust Sheet, to the west of the existing Moose Mountain gas pool. The well was drilled on the northern part of the structure approximately in between Shell's 1-28 well to the N.W. and the Calstan Shell 16-6 well to the S.E. Within the Upper Thrust Sheet the well found a slightly overthickened Mississippian section (probably thrust-repeated), a normal Devonian section and then a tectonically thickened Cambrian sequence—quite similar in many ways to the 1-28 well to the north-west. Beneath the floor-thrust to the Upper Thrust Sheet the well encountered hydrocarbon-bearing Mississippian rocks with reports of oil (38° API) to surface and the recovery of 500 bbls in 15 hours (800 bopd) from 71 m of pay in the Mount Head/Turner Valley. The well was terminated at a depth of 3000 m in the Pekisko Formation. This discovery generated enormous interest in this part of the foothills and Husky and their partners began an intensive appraisal programme of their find.

24. Shell Moose 6-23-22-6W5 1993, (D & A). Located 2 km S.E. of 7-27-22-6 (which found Mississippian gas in the eastern part of the Lower Thrust Sheet) this well drilled a similar Palaeozoic sequence in the hangingwall of the Upper Thrust Sheet. Beneath the floor thrust the Mount Head/Turner Valley was encountered (underneath Fernie) slightly deeper than in 7-27-22-6 and then below the interpreted out-of-sequence thrust, the Mount Head of the Lower Thrust Sheet was penetrated outside of closure beneath a relatively thick Blairmore-Fernie section.

25. **Husky Rigel Moose 10-14-23-7W5 1994.** This well was drilled from the same surface pad (at 2-23-23-7) as the 16-14-23-7 discovery well of the previous year. Total depth is recorded as 3094 m and the status is described as “standing”. No other data are available at this stage.

26. **Husky Rigel Moose 12-12-23-7W5 1994.** Drilled directly after the 10-14 well some 2 km to the S.S.E. of the 16-14 discovery, from a surface pad at 13-12-23-7. Total depth is recorded as 2931 m and the status of the well is described as “standing”. No other data are available at this time.

27. **Husky Rigel Moose 10-22-23-7W5 1994.** Spudded in June 1994 (from a surface pad at 16-22-23-7) some 2 km to the N.W. of the 16-14 discovery, this well reached a total depth of 2762 m in the Mississippian Shunda. Apparently the well has been production cased, but no other data are available at this time.

28. **Husky Rigel Moose 10-12-23-7W5 (Licensed).** The well will be spudded from the same surface location as 12-12-23-7 (at 13-12-23-7).

29. **Husky Rigel Moose 2-27-23-7W5 (Licensed).** This well will be drilled from the same surface location as 10-22-23-7 (at 16-22-23-7).

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