AER/AGS Special Report 100

Petrographic Analysis of 21 Shale and Siltstone Outcrop Samples from Alberta

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Abstract

This report includes sampling location information of shale and siltstone samples collected by the AGS from various outcrops in Alberta and analytical results from a summary report from CBM Solutions Ltd. (now Trican Geological Solutions) who conducted a petrographic analysis on these samples. Samples analyzed were collected from the following geological units under investigation for their tight- and shale-gas potential: Palliser, Exshaw, lower Banff, Blackstone, and Second White Specks formations. The report includes thin-section descriptions and micrographs taken at appropriate magnifications to illustrate structure, porosity, organic matter content, and the composition and nature of optically resolvable grains and matrix.

1 Introduction

In 2007, the Alberta Geological Survey (AGS) initiated a project to determine the quantity and spatial extent of shale gas resources in Alberta. Since then, this project has expanded to include shale- and siltstone-hosted hydrocarbons (oil, gas, and natural gas liquids) in the province (Rokosh et al., 2012). The AGS is releasing reports and digital data to disseminate knowledge from the project. These data and reports can be accessed from the AGS website (http://ags.aer.ca).

This report disseminates results from a petrographic analysis conducted for AGS by CBM Solutions Ltd. (now Trican Geological Solutions) of 21 samples from outcrops in Alberta of various geological strata under investigation for their tight- and shale-gas potential (Appendix 1).

2 Sample Locations and Descriptions

Table 1 lists the samples and sites examined in the study. Figure 1 displays the locations of the sample sites associated with the report. Photographs of the outcrop sections where the samples were collected are presented in Figures 2 to 5.

3 Summary

The AGS submitted to CBM Solutions Ltd. (now Trican Geological Solutions) for petrographic analysis 21 thin sections of outcrop samples from geological strata under investigation for their tight- and shale-gas potential in Alberta. Sampled strata include those of the Palliser, Exshaw, lower Banff, Blackstone and Second White Specks formations. The results of the petrographic analysis include thin-section descriptions and photomicrographs that illustrate the structure, porosity, organic matter content, and composition and nature of optically resolvable grains and matrix of each sample.

Table 1. Samples collected for petrographic analysis. All samples were extracted over an interval of about 20 centimetres.

Sample No.	Site	Outcrop	UTM Zone	UTM Datum	UTM Easting	UTM Northing	Elevation (metres)	Strata	Sample position
6531	JC2	Jura Creek, Exshaw Type Section	11	NAD83	628902	5661581	1509.1	Palliser/Exshaw contact	0.0 to 0.005 m above Palliser contact
6507	JC1	Jura Creek, Exshaw Type Section	11	NAD83	628902	5661581	1509	Exshaw	0.0 to 0.04 m above Palliser contact
6509	JC1	Jura Creek, Exshaw Type Section	11	NAD83	628902	5661581	1509.4	Exshaw	0.09 to 0.36 m above Palliser contact
6514	JC1	Jura Creek, Exshaw Type Section	11	NAD83	628902	5661581	1510.6	Exshaw	1.29 to 1.57 m above Palliser contact
6541	NO1	Nordegg Railroad	11	NAD83	567642	5816426	1327	Exshaw	3.7 m above Palliser contact
6548	NO2	Nordegg Railroad	11	NAD83	567642	5816426	1307	Lower Banff	21.4 m above Palliser contact
6549	NO3	Nordegg Railroad	11	NAD83	567642	5816426	1307	Lower Banff	29.4 m above Palliser contact
6550	NO4	Nordegg Railroad	11	NAD83	567642	5816426	1307	Lower Banff	37.4 m above Palliser contact
7301	NO5	Nordegg Railroad	11	NAD83	567642	5816426	1307	Lower Banff	45.4 m above Palliser contact
7303	NO3	Nordegg Railroad	11	NAD83	567642	5816426	1315	Lower Banff	53.5 m above Palliser contact
7304	NO3	Nordegg Railroad	11	NAD83	567642	5816426	1315	Lower Banff	61.4 m above Palliser contact
7305	NO3	Nordegg Railroad	11	NAD83	567642	5816426	1315	Lower Banff	61.5 m above Palliser contact
7307	NO3	Nordegg Railroad	11	NAD83	567642	5816426	1315	Lower Banff	71.4 m above Palliser contact
7308	NO3	Nordegg Railroad	11	NAD83	567642	5816426	1315	Lower Banff	71.5 m above Palliser contact

Sample No.	Site	Outcrop	UTM Zone	UTM Datum	UTM Easting	UTM Northing	Elevation (metres)	Strata	Sample position
7309	NO3	Nordegg Railroad	11	NAD83	567642	5816426	1315	Lower Banff	83.4 m above Palliser contact
7310	NO3	Nordegg Railroad	11	NAD83	567642	5816426	1315	Lower Banff	83.5 m above Palliser contact
7311	NO3	Nordegg Railroad	11	NAD83	567642	5816426	1315	Lower Banff	103.4 m above Palliser contact
7312	NO3	Nordegg Railroad	11	NAD83	567642	5816426	1315	Lower Banff	103.5 m above Palliser contact
7313	NO4	Nordegg Railroad	11	NAD83	567642	5816426	1316	Lower Banff	120.0 m above Palliser contact
7329	BR01	Birch Mountains, Asphalt Creek	12	NAD83	443512	6387776	652.2	Colorado, Second White Specks	1.2 m above creek
7254	BS02	Cadomin Railroad	11	NAD83	478167	5875014	1522.2	Colorado, Blackstone	

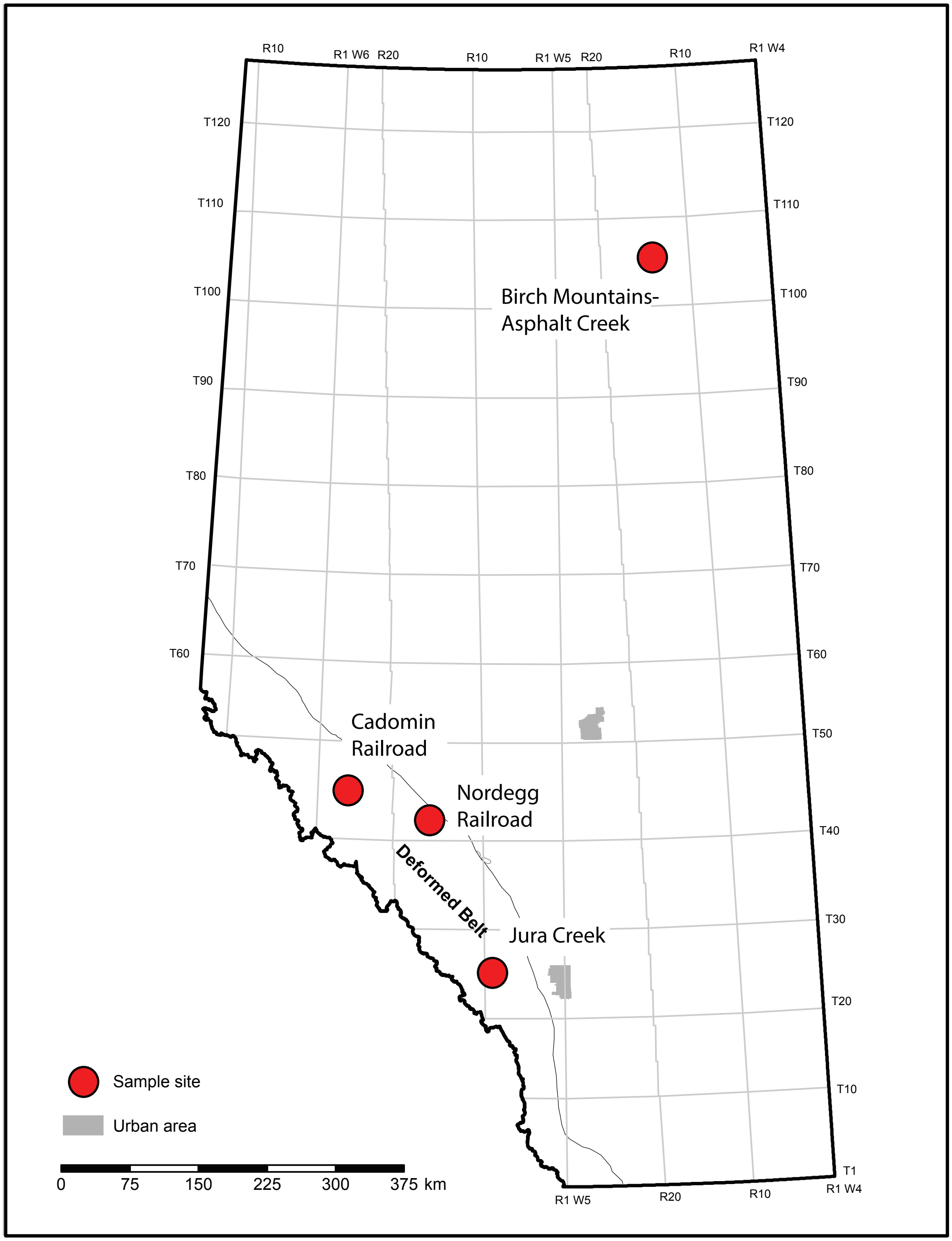

Figure 1. Location of sample sites for this report.

Figure 2. Exshaw Formation section overlying the Costigan Member of the Palliser Formation at Jura Creek, near Canmore. The Exshaw black shale (arrow) is about 9 m thick. See Figure 1 for outcrop location and Appendix 1 for petrographic analysis.

Figure 3. Slightly overturned outcrop of the Exshaw and Banff formations at a railroad cut near Nordegg. Up section is to the left. See Figure 1 for outcrop location and Appendix 1 for petrographic analysis.

Figure 4. Colorado Group (Blackstone Formation) section near Cadomin. See Figure 1 for outcrop location and Appendix 1 for petrographic analysis.

Figure 5. Colorado Group section at Asphalt Creek, Birch Mountains. See Figure 1 for outcrop location and Appendix 1 for petrographic analysis.

4 References

Rokosh, C.D., Lyster, S., Anderson, S.D.A., Beaton, A.P., Berhane, H., Brazzoni, T., Chen, D., Cheng, Y., Mack, T., Pana, C. and Pawlowicz, J.G. (2012): Summary of Alberta's shale- and siltstone-hosted hydrocarbon resource potential; Energy Resources Conservation Board, ERCB/AGS Open File Report 2012-06, 327 p., URL <http://ags.aer.ca/publications/OFR_2012_06.html> [May 2016].

Appendix 1 – CBM Solutions Report

A Petrographic Study of 21 Samples for CBM Solutions

Project: BEAT 3458

Overview:

Thin sections of 21 samples of unknown provenance were analysed petrographically in transmitted light. Orientation of samples and hand specimens were not provided.

Methods and Terminology:

The thin sections were examined under low magnification to determine general lithological character. Specifically, the presence of bedding or lamination, veins and fractures, fissility of the rock (shaliness), and any macroscopic signs of porosity, or strain indicators were noted for each sample. Four of the samples are clastic rocks, most with a carbonate component. The remaining 17 samples are limestones with varying degrees of authigenic alteration. Some of the samples are partially silicified (growth of forms of authigenic quartz as replacement of detrital components, cements, as well as vein fill). One-half of each sample was stained with Alizarin Red A for identification of calcite.

Thin sections were examined in transmitted light, and photomicrographs taken at appropriate magnifications to illustrate structure, porosity, organic matter content and the composition and nature of optically resolvable grains and matrix. The matrix of these rocks is predominantly micritic calcite cement. Most of the samples contain some dark organic matter (OM) within the matrix, which is opaque in transmitted light. In the case of high OM content, the proportion of other opaque components, such as iron sulphides, becomes difficult to determine. Where this is the case it is noted in the reports. Photomicrographs are generally at 20X, 80X and 320X magnification, although in some cases pertinent details are more visible at low or intermediate magnifications, and such are noted in the petrographic reports. Imaging organic-rich shales or calcareous mudstones in transmitted light can be problematic because of the high contrast between transparent detrital or crystalline grains and opaque matrix, thus very fine detail cannot always be reproduced in photomicrographs of very fine grained rocks. Formation names were not specified, and samples were not marked for orientation. Generally it is possible to determine way-up, however, and photos are presented in what is judged to be the correct way-up orientation.

Terminology for very fine grained clastic rocks is somewhat variable, but generally incorporates claystones, mudstones and siltstones into the grab-bag term 'shale'. For petrographic purposes, the following general rules are applied. The term *mudrock* encompasses rocks composed of clay- and silt-sized detritus. The terms *clayshale* and *claystone* are used to describe rocks containing less than 33% silt-sized particles, and displaying a laminated (fissile) or non-laminated fabric, respectively. Rocks composed of between 33% and 66% silt-sized particles displaying a laminated fabric are *mudshales*, and with a massive fabric, *mudstones*. In these reports the fine grained samples are massive claystones. The term 'silty' is appended to the general terms if it appears there is close to 33% silt embedded in the matrix.

Terminology for carbonates uses the Folk (1962) system for textural classification based on the presence of framework grains (*allochems*) and matrix (*micritic calcite* cement or 'micrite', and *sparry calcite* cement or 'spar'). In general, limestones are made up of varying proportions of framework, matrix and cement. Framework allochems consists of entire or fragmental skeletal grains (bioclasts), and other, nonskeletal grains - ooids, peloids, intraclasts. These tend to be silt-size or larger. Matrix is likely to originate as carbonate mud - micro-crystals of calcite or aragonite precipitated by numerous benthic organisms. Micritic calcite tends to alter rapidly in texture (*neomorphism*) into interlocking calcite crystals which may increase in size as the neomorphism progresses. Sparry calcite consists of large (0.02 - 0.1mm) clear precipitated crystals which fill interstitial pore spaces and solution cavities, as a cement. Unfortunately, diagenesis is pervasive and successive in limestones and may remove virtually all vestiges of original depositional fabric and chemistry. Dolomite is present in almost all of the samples studied, generally as authigenic rhombic crystals within the matrix, as a replacement mineral in cement, vein and cavity fill, or as detrital grains.

An attempt has been made to keep the rock names as simple as possible, as each thin section can be highly variable in terms of the proportions of matrix to allochems, the size of these allochems, and the degree of alteration of both. Thus a micritic rock in which there is generally an abundance of framework grains, to the point of being grain-supported, is termed a *packed biomicrite* (see table below), even if lesser parts of the sample are matrix-supported. Where possible from optical observations alone, the sequence of alteration has been summarized. Porosity of the rock is not quantified, but the nature of observable porosity is described, photographed, and estimated as extensive, significant, minor, absent, etc.

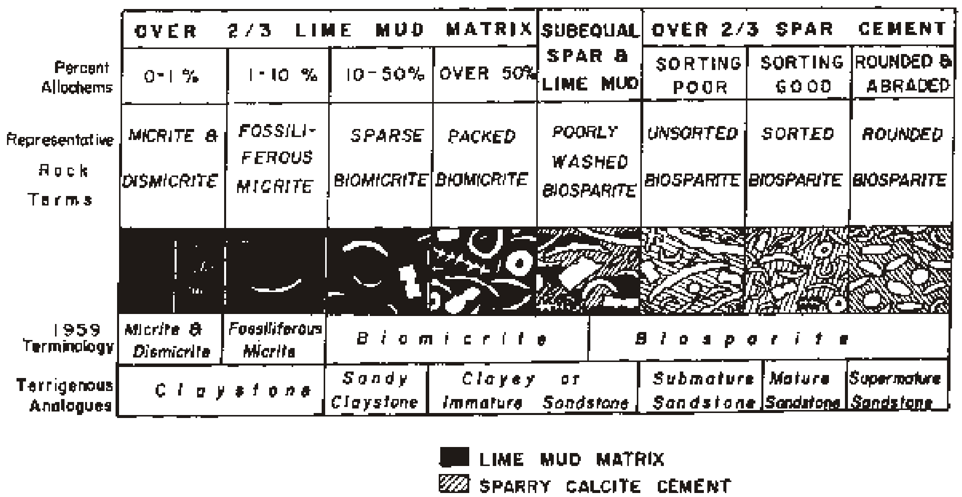

FIGURE 5.2 Spectral subdivision of limestone types. From Folk (1962). Reprinted by permission of the American Association of Petroleum Geologists.

General Observations and Conclusions:

Site JC1:

Three clastic rock samples, a sandstone (quartz wacke) and 2 organic rich claystones. 6507-1 is an immature coarse sandstone with extensive calcite veining, and a contact with an organic-rich packed biomicrite (clast?). 6509-2 and 6514-3 are faintly laminated organic rich silty claystones.

Sites JC2, N01, N02, BS02, N03, N04:

The 17 samples from these sites are all detrital limestones, principally calcisiltites and calcarenites with varying degrees of dolomitization and silicification. The framework component of these rocks includes a wide assortment of skeletal fragments, tests and shells of pelecypods, gastropods, bryozoans, a variety of algal components and rare bone fragments. No attempt was made in this analysis, which focuses on sedimentary structures, porosity, diagenetic effects and strain indicators, to catalogue or analyse the paleontology of the limestones. The matrix of all samples was originally lime mud (micrite), which is altered in varying degrees to calcite and dolomite cements, and in some cases replaced by silica, usually chert. In many of the samples the lime mud appears to have been bioturbated. Few have undisturbed sedimentary structures. The sequence and degree of diagenesis, and the degree of fracturing, vein filling, and vein alteration, are described where possible for each sample. Likewise the presence and degree of porosity, as cavities, vugs and channels is described, usually photographed, measured, and an estimate made of it's significance. As a general observation, primary porosity is absent from this suite, having been completely occluded by diagenesis and authigenesis, and secondary porosity, either by dissolution or strain, is very low.

Site BR01:

The single sample from this "bone bed" site, 7329-21, is a fine sandstone, a quartz wacke. About 15% of the grains, averaging fine- to medium-sand size, are collophane bone fragments. Another 15% are chert clasts. The bulk of the particles are subrounded to subangular slightly pitted quartz. The clasts are supported in a cement of sparry calcite. There is a minor amount of organic matter (OM) concentrated as wavy laminae and within pores in the bone fragments.

Analyses performed by Steve Phillips, PhD, for CBM Solutions, Calgary.
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Formation: Exshaw
Outcrop: Jura Creek
Sample Number: 6507, elevation 1509.0 metres
Summary: Thin section with cover slip. Stained for calcite. Sandstone: organic rich medium-grained quartz wacke.

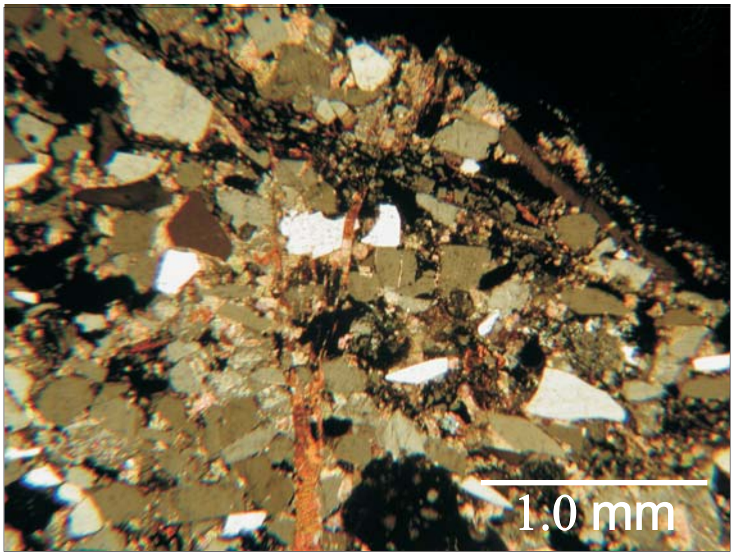

Plate 1 X 2 0 Cross Nicols: Overview of poorly sorted immature medium grained sandstone. Sand grains are predominantly quartz, but with complex intergrain boundaries, overgrowths, dissolution and replacement textures and mineralogy. Matrix and cement includes both detrital and authigenic clays, chert, authigenic quartz cement and some calcite cement. Dark grain upper right is apparently part of a pebble-sized organic-rich biomicrite (limestone) clast. Bedding is chaotic to absent. There is no visible primary porosity. Organic matter is disseminated throughout the matrix.

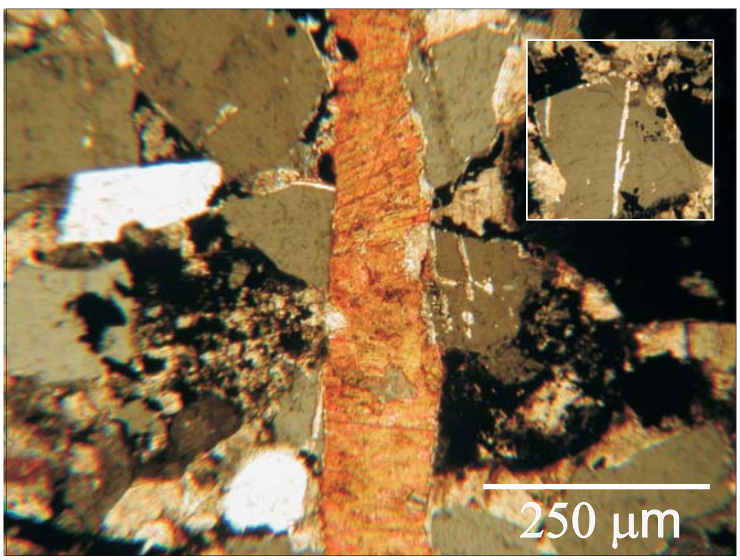

Plate 2 X 8 0X N : Abundant branching veins cut sub-vertically through the sample. Veins penetrate grain boundaries. Calcite vein-fill (red stain) is intensely twinned, reflecting post-emplacement strain. Many of the quartz sand grains contain a network of older fine quartz veins (inset).

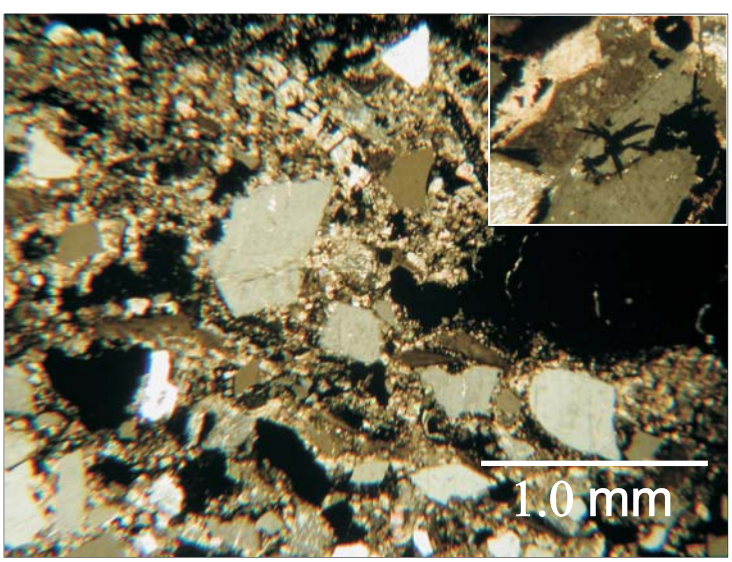

Plate 3 X 2 0 X N : There is an abundance of opaque minerals in the sample, both detrital heavy minerals (dark grains) and authigenic minerals. Inset X 80 XN - radiating bladed crystals of an authigenic opaque mineral.

Formation: Exshaw
Outcrop: Jura Creek
Sample Number: 6509, elevation 1509.4 metres
Summary: Thin section with cover slip. Stained for calcite. Section through an organic-rich laminated silty claystone.

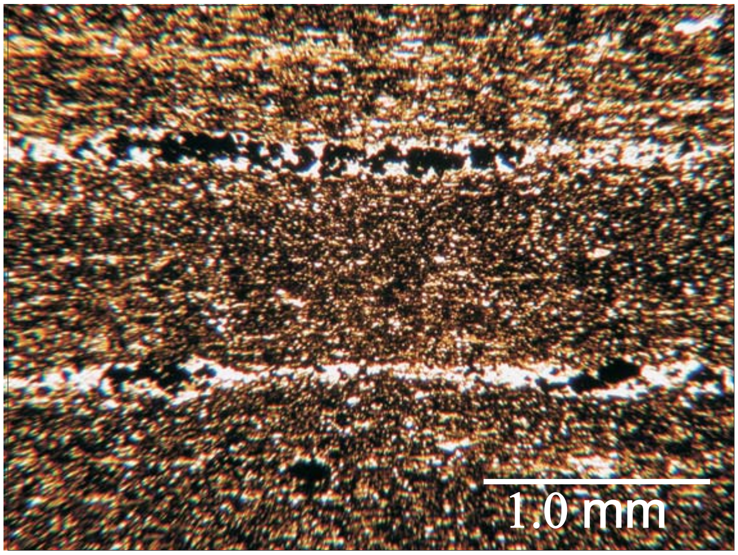

Plate 1 X 2 0 Plane Polarized light: Overview of laminated silty claystone. Laminae are irregular beds of concentrated medium silt-size (.018 - .03mm), detrital quartz and opaque mineral grains, variously cemented (see below). Bulk of rock fabric is massive silty claystone with abundant organic matter disseminated and concentrated along bedding planes. There is no detectable alignment of phyllosilicates within the claystone, indicating a lack of fissility. This is also suggested by the sinuous and 'hackly' nature of fractures in the sample (see below).

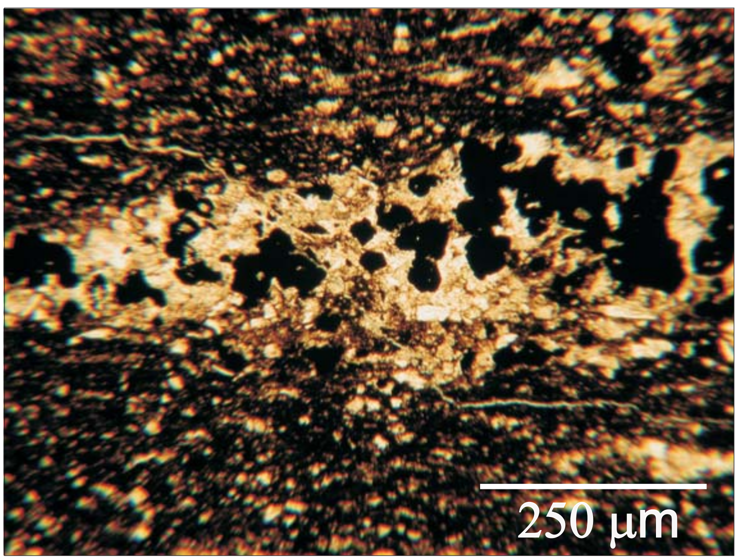

Plate 2 X 80 PP: Close-up view of part of silt lamina within claystone. Note the sinuous fracture (channel porosity?) passing diagonally across bedding. Fracture aperture is <.002mm. Microfractures are common throughout the sample, and in some cases are partly filled with calcite cement, suggesting that at least some may not be an artifact of coring and sample preparation. Where visible, fracturing generally bypasses larger grains.

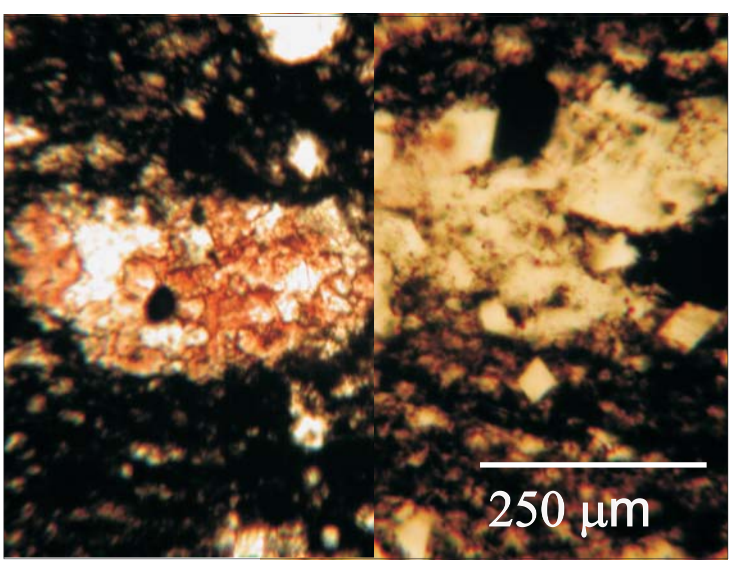

Plate 3 X 8 0 plane polarized light: Calcite cement (left side of plate, red stain) and cryptocrystalline quartz cement (right) in silt laminae.
Note the presence of corroded quartz grains within the calcite cemented lens, and dolomite rhombs in the right hand image.
The high organic matter content of the claystone obscures much of the fabric and prevents estimation of opaque heavy mineral content and cement constituents.

Formation: Exshaw
Outcrop: Jura Creek
Sample Number: 6514, elevation 1510.6 metres
Summary: Thin section with cover slip. Stained for calcite. Section through an organic-rich faintly laminated claystone.

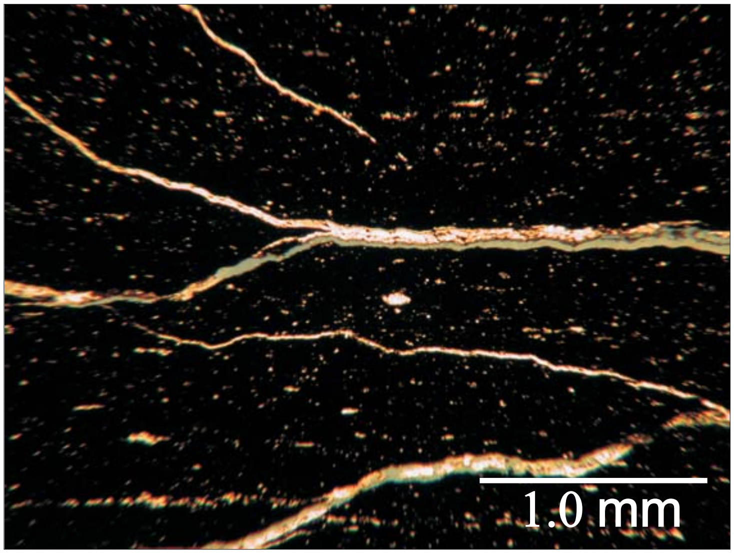

Plate 1 X 20 Plane Polarized light: Overview of a faintly laminated fractured claystone. Fine-silt sized grains of quartz and some larger carbonate grains are scattered throughout a matrix mostly obscured by organic matter . Faint laminae are concentrations of silt on bedding planes. There is no visible indication of fissility (i.e. alignment of clay minerals). The many veins (fractures) tend to follow bedding to some extent, but also cut diagonally across bedding. There is no visible porosity in the matrix, but many of the fractures (channel porosity) are open to varying degrees.

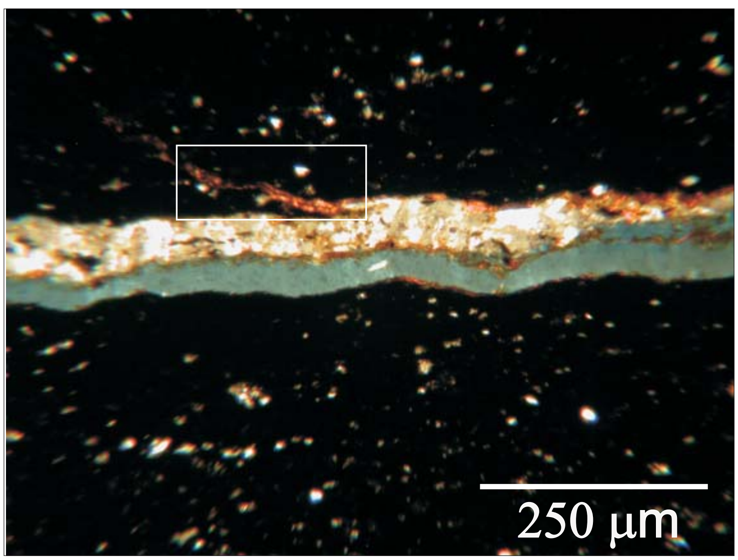

Plate 2 X 8 0Cross Polarized light: Vein fillings are both calcite (red stain) and quartz, and reveal at least two phases of emplacement. Calcite initially filled fine fractures within the rock. The rectangle at centre shows a microfracture with an aperture <0.002mm filled with finely crystalline calcite. The large open fracture is lined with similar calcite, but the bulk of the fill is quartz.
Fractures have re-opened, possibly as a result of coring and sample preparation. Apertures of open fractures range from <0.002mm to 0.05mm.

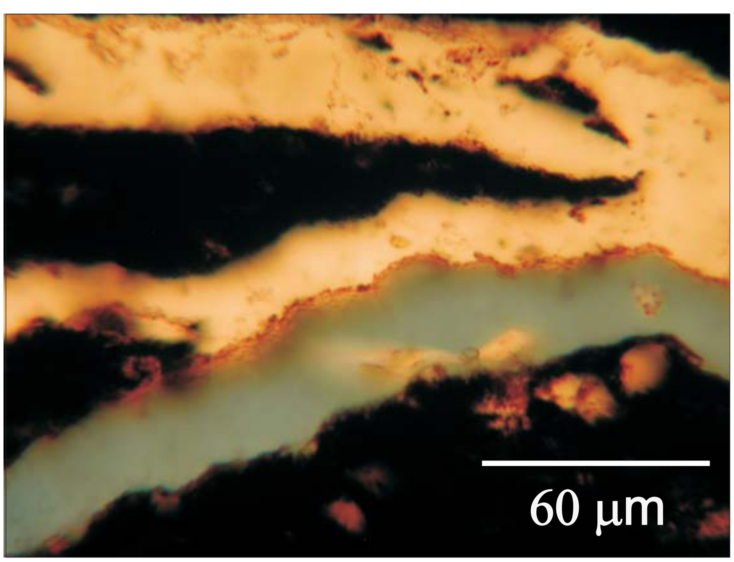

Plate 3 X 320 plane light: Close-up view of quartz-vein and open fracture. An intact rim of calcite adheres to the lower edge of the quartz fill.
The open fracture has diverged from the earlier vein and has no filling or calcite rim.

Formation: Palliser
Outcrop: Jura Creek
Sample Number: 6531, elevation 1509.1 metres
Summary: Thin section with cover slip. Stained for calcite. Limestone: Partially dolomitized sparse biomicrite.

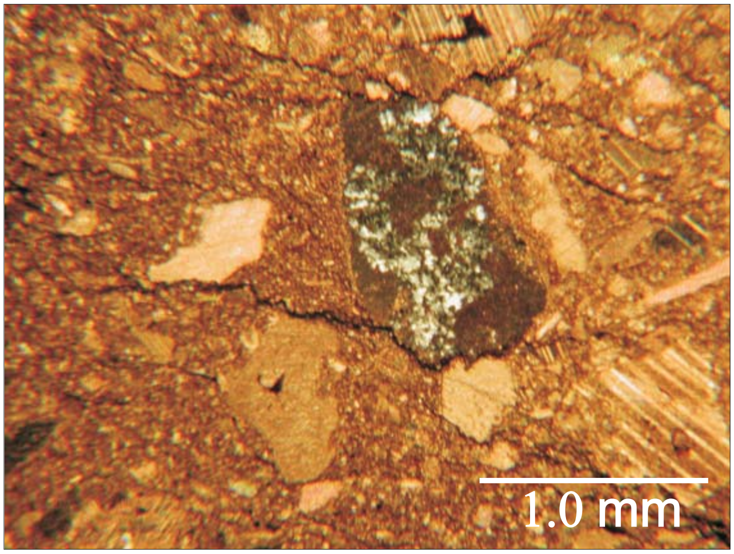

Plate 1 X 2 0Cross Polarized light: Overview of a sparse rudaceous biomicrite. A poorly sorted assemblage of allochems ranging in size from medium silt (0.03mm) to fine gravel (1.5mm) in a micritic matrix. Many of the allochems have been replaced by large twinned calcite crystals. Mottled, patchy chert has replaced part of the large grain, at centre.
Dark organic matter is present in intragrain voids and concentrated as stylolites.
Visible porosity in the sample is in the form of sinuous, open microfractures (channel porosity).

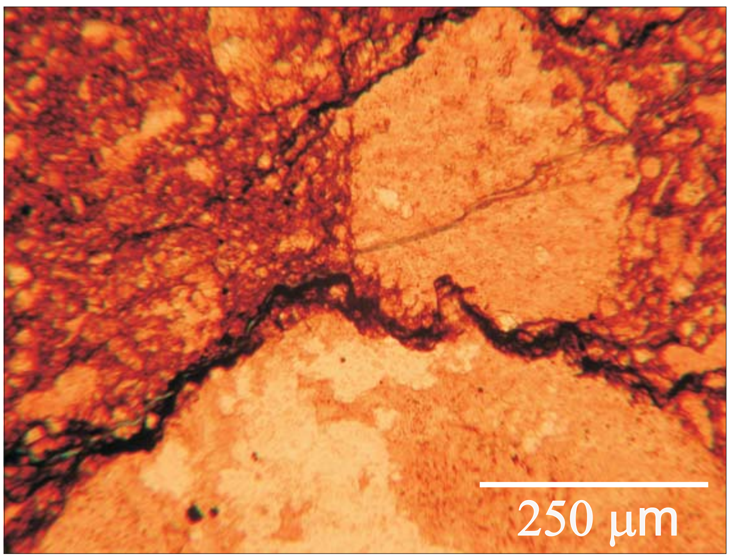

Plate 2 X 8 0Plane Polarized light: Organic matter concentrated in stylolites following grain boundaries in a coarse-grained facies (calcirudites). There are numerous open microfractures in the sample, with apertures from 0.1mm to <0.002mm. Note the presence of an open fracture approximately following the stylolite then diverging, upward to the bisect upper grain. White patches in the large lower grain are chert.

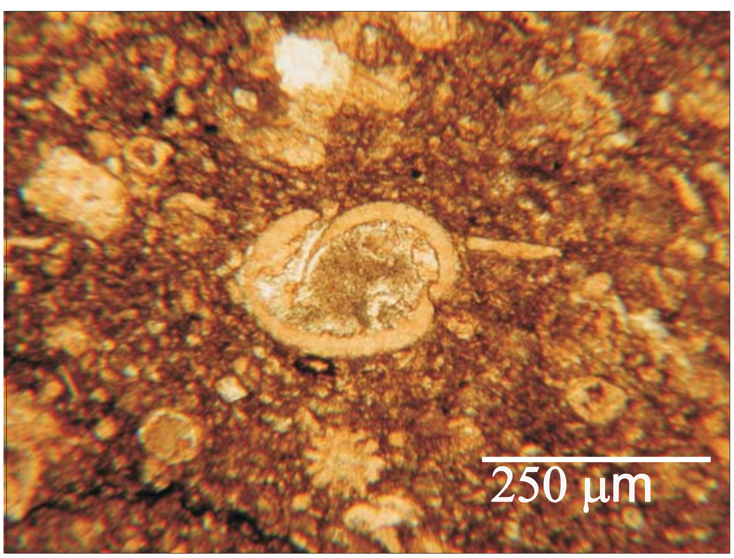

Plate 3 X 8 0 Plane Polarized light: Diverse assemblage of detrital allochems (fossil grains including bryozoans, pelecypods) suspended in a micritic matrix. Original cavity in the central shell fragment is filled with chert. Dolomite rhombs are scattered throughout the micrite matrix.

Formation: Exshaw
Outcrop: Nordegg Railroad section
Sample Number: 6541, elevation 1327.0 metres
Summary: Thin section with cover slip. Stained for calcite. Partially dolomitized silty calcilutite / calcarenite.

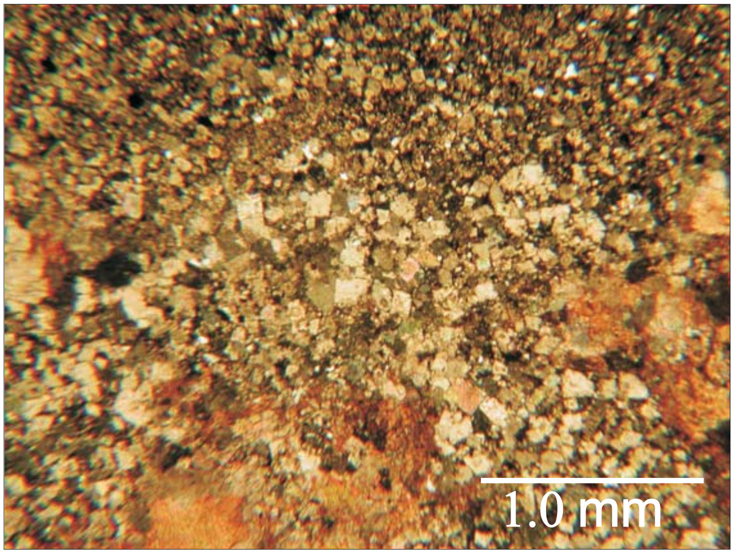

Plate 1 X 2 0 Cross Polarized light: Overview of partially dolomitized calcilutite (top - a coarse dolomitic siltsone) and calcarenite. Grains are predominantly dolomite and, in the silt-sized component, common subangular quartz.
Dark organic matter is disseminated throughout the matrix, and concentrated in stylolites. It is also present within dissolution cavities in dolomite grains and rhombs.There is no visible primary or secondary porosity.

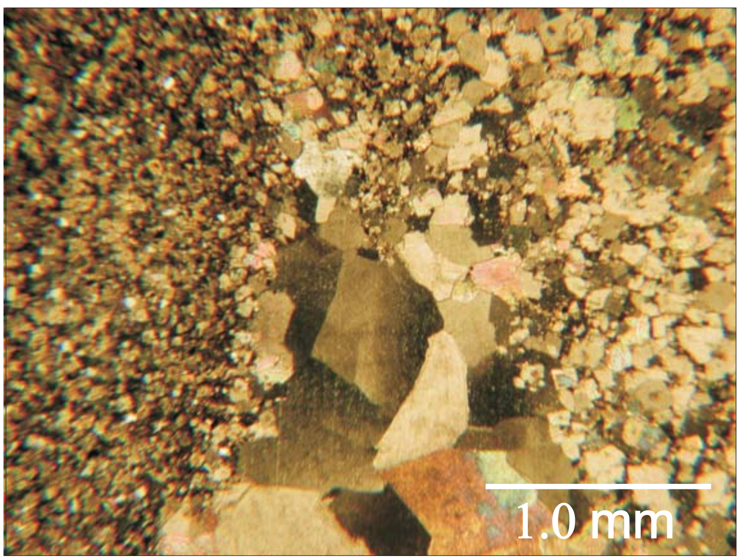

Plate 2 X 2 0 Cross Polarized light: Formation of a dolomitic mosaic. Saddle dolomite, characterized by sweeping extinction of large crystals, is a late-stage dolomitic texture. Very fine calcite rims can be seen along some of the crystal boundaries (see below).

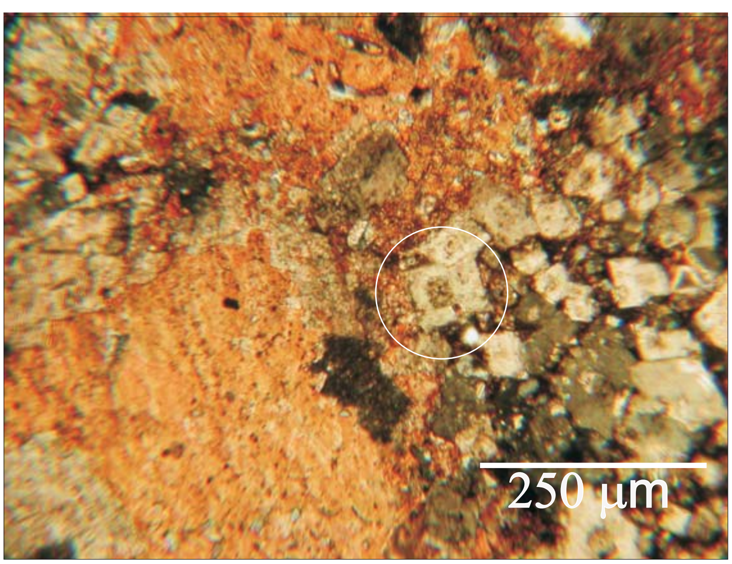

Plate 3 X 80 XN: Partial replacement of dolomite by calcite (red stain)? Selective de-dolomitization is suggested both in these patchy areas and in the cores of zoned dolomite rhombs (circled in centre of view).

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 6548, elevation 1307.0 metres
Summary: Thin section with cover slip. Stained for calcite. Partially dolomitized and partialy silicified sparse biomicrite / calareous siltstone.

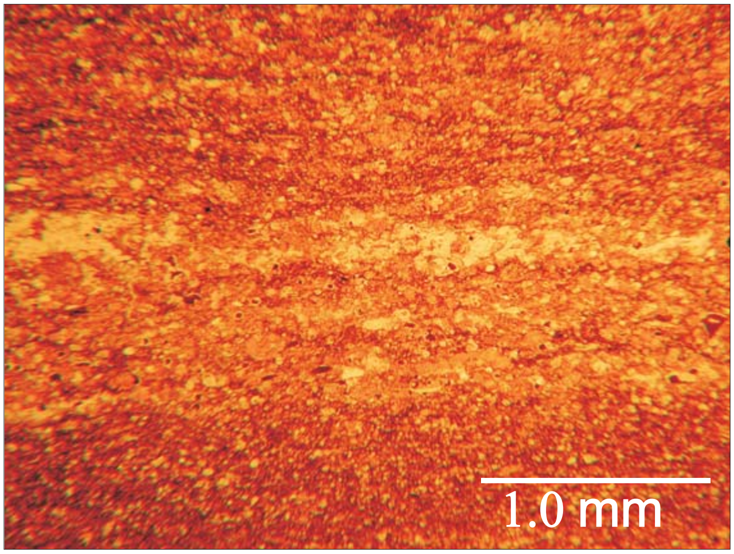

Plate 1 X 2 0 Cross Polarized light: Overview of faintly laminated, partially dolomitized and partially silicified biomicrite and calcareous siltstone. Laminae are defined by the variable size of allochems (clasts) and variations in dolomitization, organic matter, and chert content. Bright irregular lenses are chert, and dark brownish specks are chalcedony. Many of the larger grains are dolomitized bioclasts. Red stain is calcite.

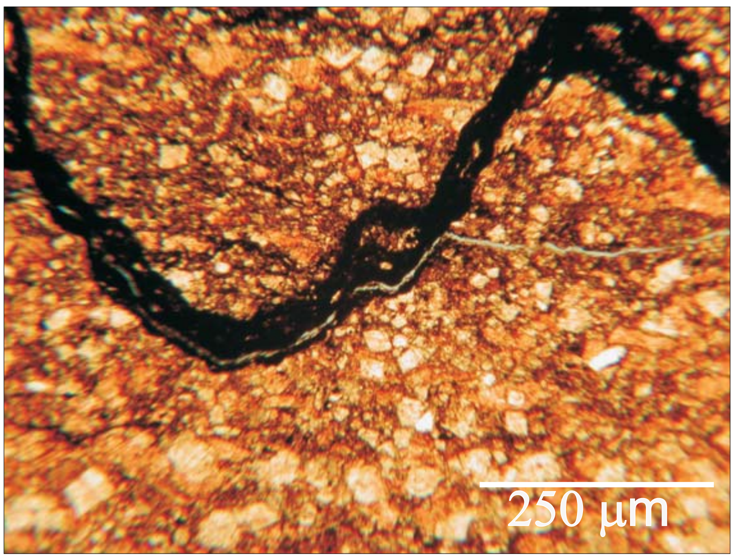

Plate 2 X 8 0 Plane Polarized light: Concentration of opaque, insoluble material (organic matter) in stylolites, and variably dispersed within the dominantly neomorphic micritic calcite matrix. Note the presence of abundant dolomite rhombs scattered within the matrix.
Fractures can be seen following and then diverging from stylolites The absence of authigenic mineralization within these fractures suggests that they open as a result of sample preparation. The aperture of the fracture is 0.006mm.

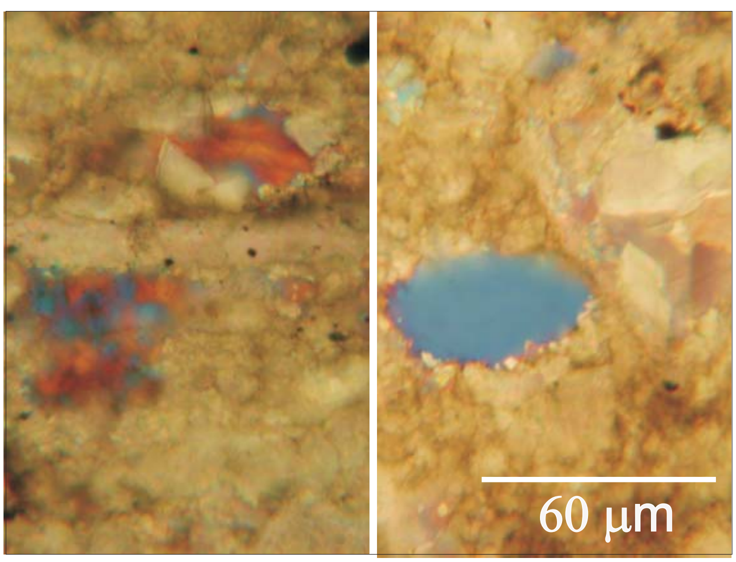

Plate 3 X 320 XN: Two high magnification views of pores (blue epoxy) within the matrix. These intergranular pores display variable degrees of authigenic calcite (left, red stain) and dolomite (right, bright white) crystalline infilling. Dolomitization of larger bioclasts can be seen, at left in the elongate fragment bisecting the view, and right in the large grain to the right of the open pore.
Pores are rare, occasionally connected, and have apertures generally < 0.03mm.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 6549, elevation 1307.0 metres
Summary: Thin section with cover slip. Stained for calcite. Limestone: Partially dolomitized and partialy silicified sparse biomicrite / biosparite.

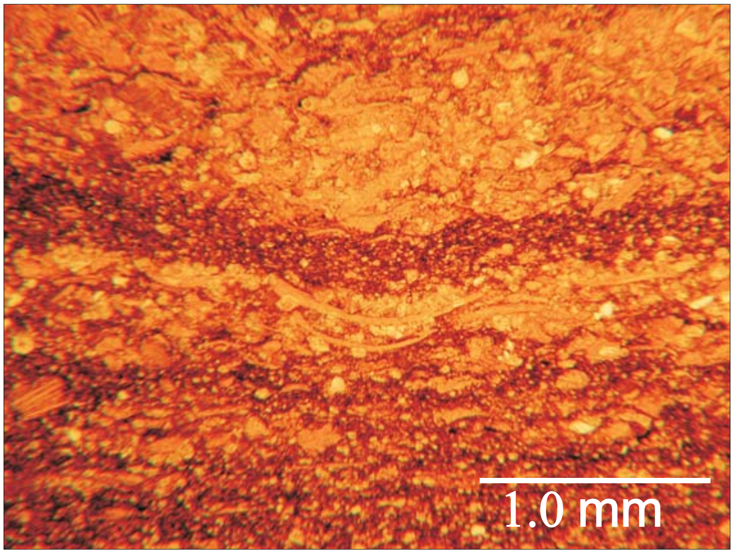

Plate 1 X 2 0 Cross Polarized light: Overview of laminated, partially dolomitized and partially silicified biomicrite - bisparite and calcarenite. Largest bioclasts (allochems) are medium to coarse sand-sized, mainly replaced by secondary calcite, dolomite or chert. Red stain is calcite.

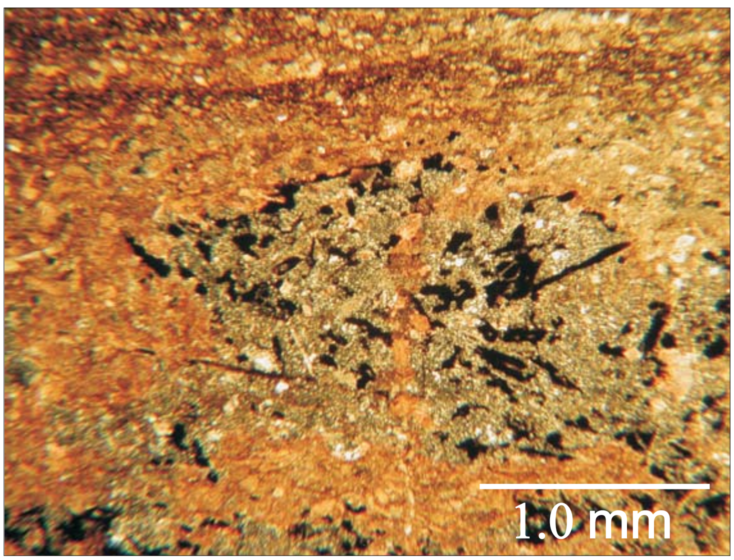

Plate 2 X 2 0 X N : Large lense of chert cut by a vertical vein. Vein fill is both calcite and dolomite. The lense has inclusions of dolomite, calcite and opaque material (organic matter) plus minor chalcedony. The vein is completely closed.

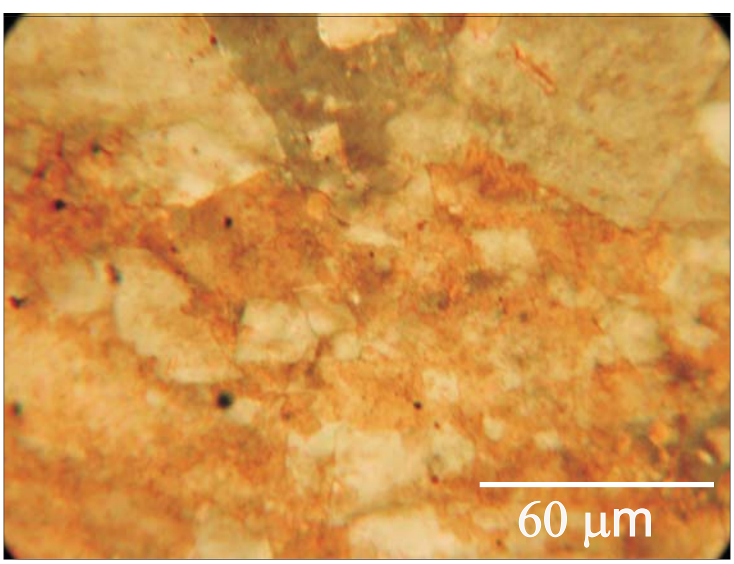

Plate 3 X 320 XN: Partial replacement of calcite spar cement (red stain) by dolomite. There is no visible primary or secondary porosity in the sample.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 6550, elevation 1307.0 metres
Summary: Thin section with cover slip. Stained for calcite. Interbedded calcarenite and chert.

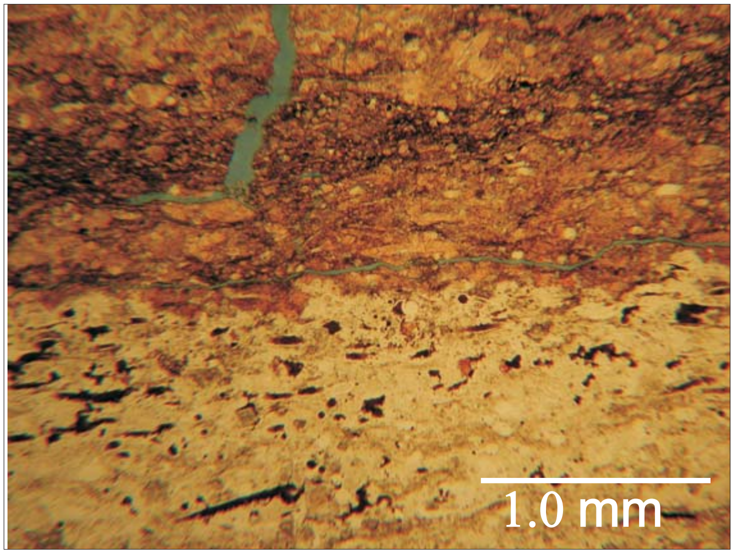

Plate 1 X 2 0 Plane Polarized light: Limestone (top) and chert (bottom). The calcarenite is interlaminated, packed biomicite with wisps of disseminated organic matter, and coarse biosparite with abundant coarse-grained shell and bryozoan fragments. Both cement and grains are partially dolomitized. Chert (bottom half of frame) has abundant fragments of opaque organic matter as well as common dolomite rhombs and occasional calcite grains 'floating' in the cryptocrystalline matrix.

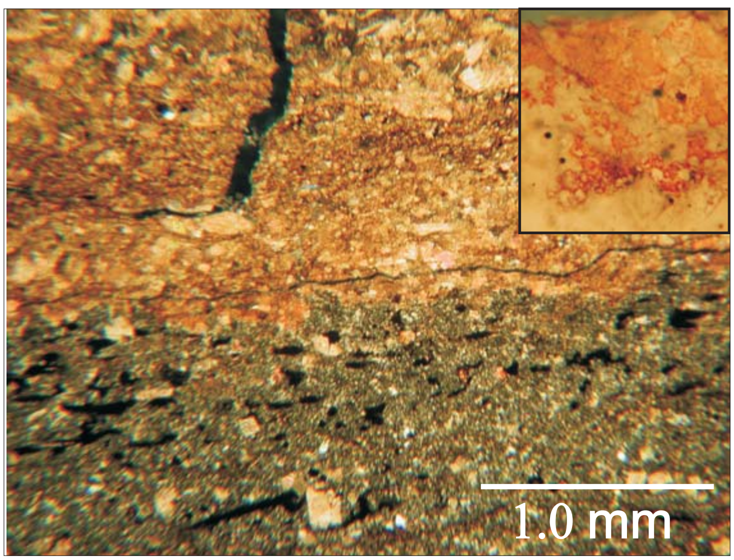

Plate 2 X 2 0X N : Same view as above in crossed polarizers. Sinuous open fractures can be seen following and cross-cutting bedding in this and the previous plate. Most fractures display no authigenic mineralization and thus are likely a product of sample preparation (see below).
The contact between chert and limestone suggests the chert is a replacement of original calcite (see inset upper right X320 PP).

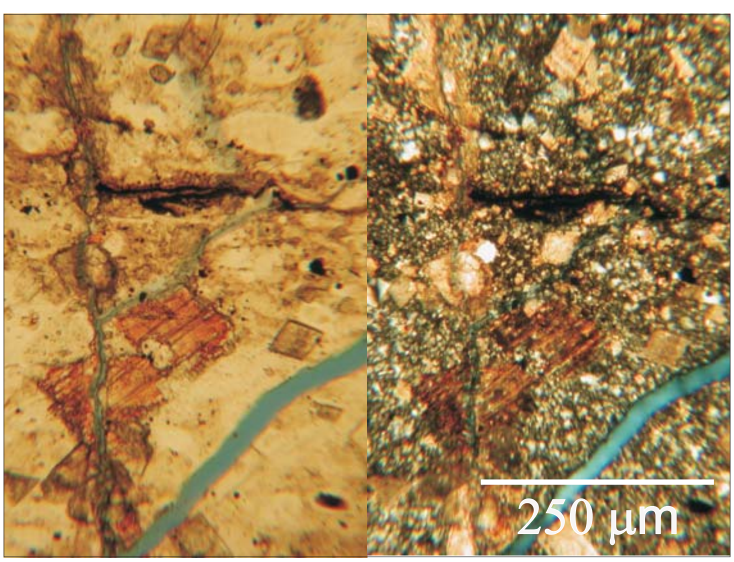

Plate 3 X 8 0 Plane Polarized (left) and Crossed Nichols: Same view of intersecting fractures within chert. The vertical and diagonal fractures are open and display no mineralization (apertures are 0.01mm and 0.03mm). The vertical fracture penetrates and displaces embedded calcite grains.
The sinuous horizontal fractures are filled with dark organic matter. There is no visible primary or dissolution porosity in the sample.

Strata: Colorado Group, Blackstone Formation
Outcrop: Cadomin Railroad section
Sample Number: 7254, elevation 1522.2 metres
Summary: Thin section with cover slip. Stained for calcite. Massive to faintly laminated medium- to coarse-grained siltstone.

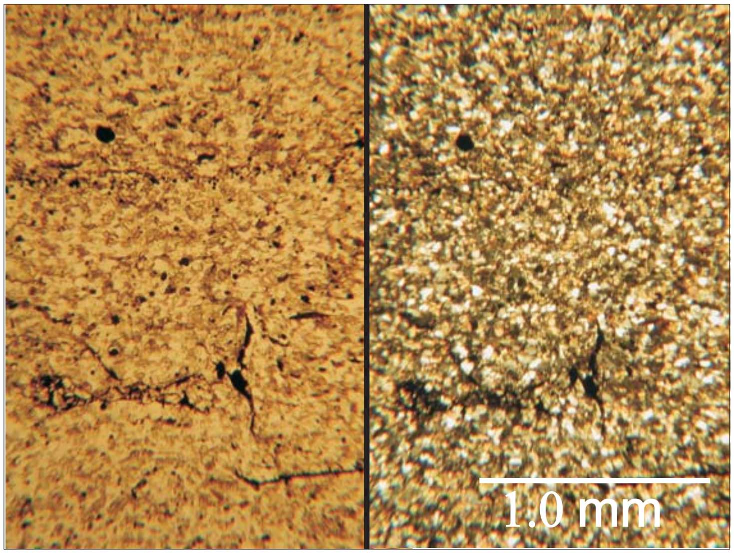

Plate 1 X 20: Two views (left in plane polarized light, right in cross nicols) of faintly laminated massive medium- to coarse-grained siltstone. Laminae are defined by an increase in clays, mica and opaques (both wisps of organic matter and pyrite framboids). Grains are predominantly angular to subangular quartz, with abundant mica (biotite), common detrital calcite and dolomite along with other detrital minerals. Rock is cemented with chert and minor chlorite +/- clays and displays no fissility (orientation of clay minerals).

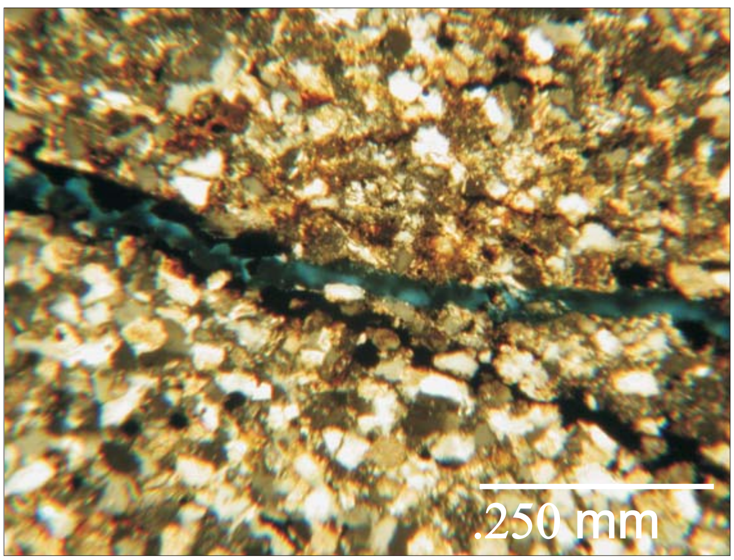

Plate 2 X 80 Cross Polarized light: Fracture roughly paralleling inclined bedding in muddy siltstone. Large fracture appears to have opened in part along a concentration of organic matter on bedding plane. Mica and elongate silt grains display moderate imbrication. Most fractures in the sample are not continuous or penetrative, and do not cleave grains.

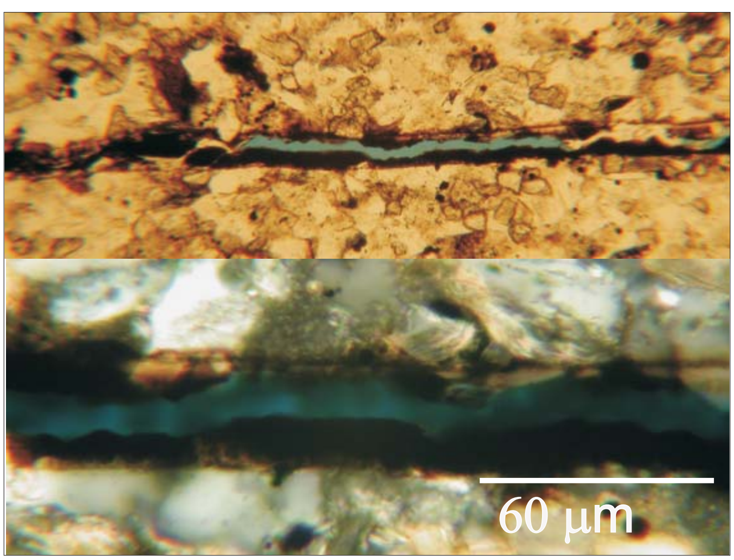

Plate 3 X 80 PP (top) and X 320 XN (bottom): Discontinuous fracture porosity. Fracture (blue epoxy) is partially filled by chert, and also by OM (bitumen?) Lower frame shows some apparent smearing of bitumen.
There is no visible primary or dissolution porosity in the sample.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 7301, elevation 1307.0 metres
Summary: Thin section with cover slip. Stained for calcite. Coarse-grained calcisiltite.

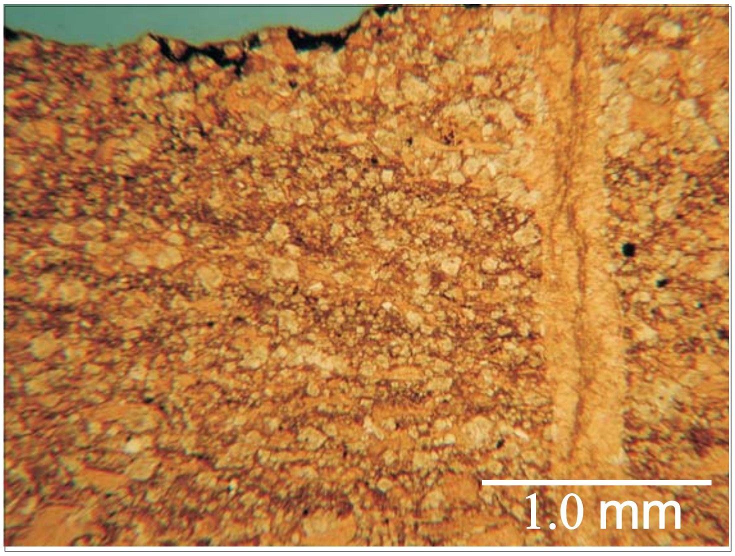

Plate 1 X 2 0 Plane Polarized light: Overview of coarse-grained calcisiltite (calcareous muddy siltstone). The sample is composed of detrital calcite and dolomite allochems and grains, with minor amounts of disseminated opaque organic matter. Cements are both micrite and sparry calcite and occasional dolomite. The sample is cut vertically by numerous veins of calcite with minor dolomite. The Red stain indicates calcite.

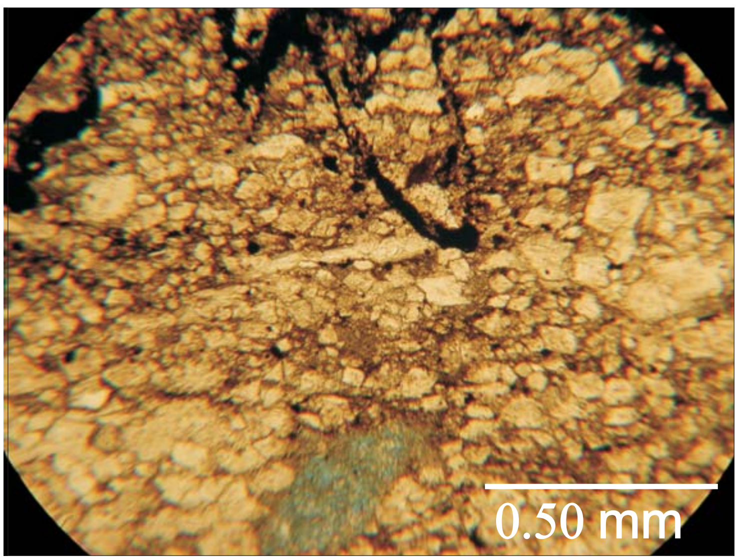

Plate 2 X 4 0Plane Polarized light: Opaque organic matter (bitumen?) in stylolite-like concentrations occuring along the fractured upper margin of sample. Rare open pores range from 0.02 to 0.5mm in diameter, and show no authigenic mineral growth into the pore space.

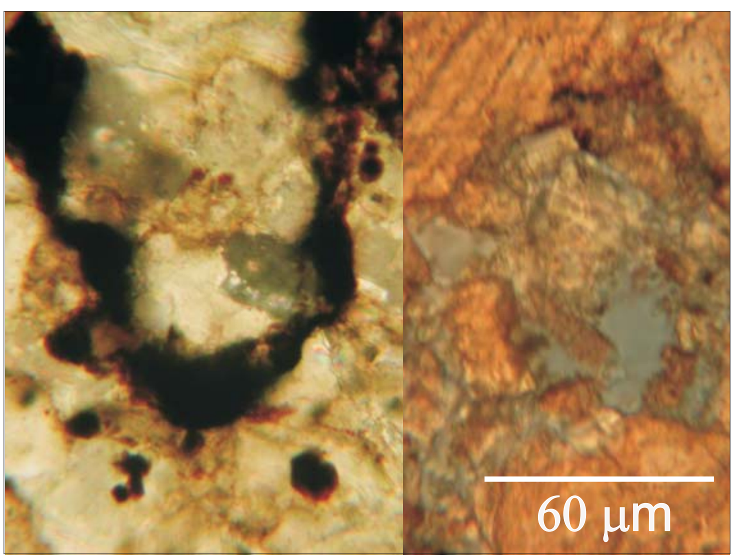

Plate 3 X 320 Cross Polarized light: Left slide: high magnification view of stylolite-like organic matter (bitumen?) concentration. There is little other evidence of dissolution along the sinuous path of this stylolite. Right slide: an open intergranular pore showing some debris within the pore space but no indication of organized authigenic mineral growth or of organic matter accumulation. These pores may thus be an artifact of sample preparation.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 7303, elevation 1315.0 metres
Summary: Thin section with cover slip. Stained for calcite. Limestone: biomicrite and biosparite

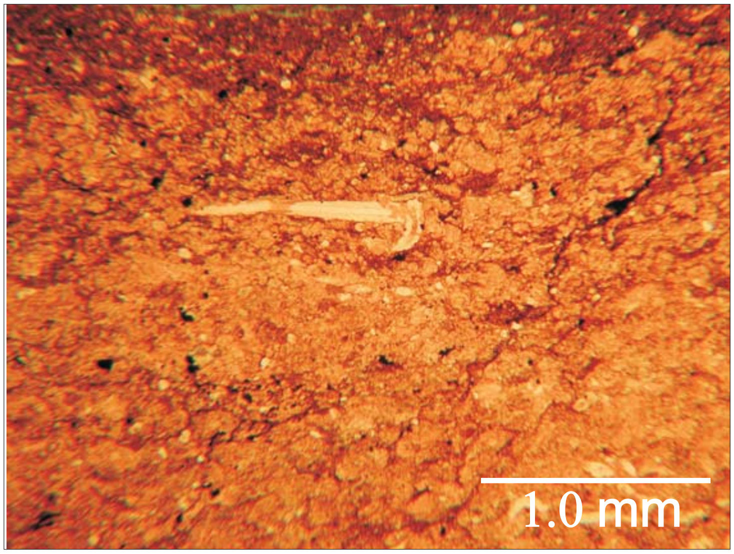

Plate 1 X 2 0 Plane Polarized light: Overview of biomicrite (top) and biosparite composed of poorly sorted detrital allochems, many of which have been replaced by chert, within a massive matrix of spar and micrite with rare dolomite grains. The large, bright skeletal fragment above centre has been almost completely replaced by chert.
Grains include skeletal fragments or tests, along with detrital clasts of calcite and dolomite. There is a minor amount of very fine, disseminated opaque matter, some clearly amorphous organic matter, and some apparently crystalline.

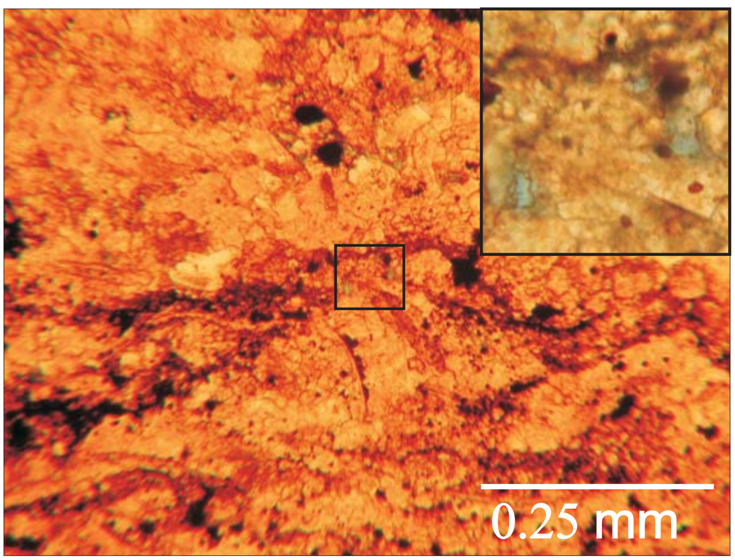

Plate 2 X 8 0 Plane Polarized light: View showing thin, unoriented tests or shells with associated concentrations of organic matter, and numerous, very fine, open pores (micro-vugs, see enlargement of central box at top right X 320). The aperture of pores is around 0.005mm. The micritic / sparry matrix was probably originally bioturbated.

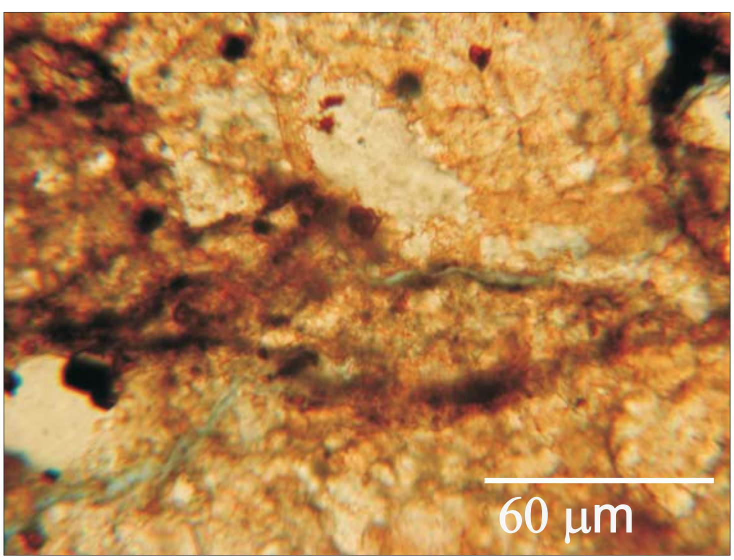

Plate 3 X 320 XN: Channel porosity - Very fine, sinuous fracture (aperture <0.002mm) associated with concentrated opaque organic matter. The bright patches are chert. Note that the fracture penetrates chert at the right side of frame.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 7304, elevation 1315.0 metres
Summary: Thin section with cover slip. Stained for calcite. Limestone: Biomicrite and biopsparite with minor dolomite and chert.

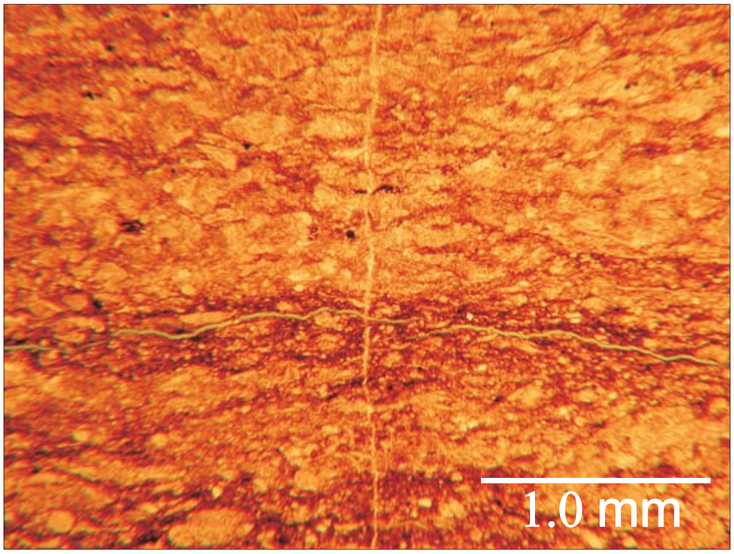

Plate 1 X 2 0 Plane Polarized light: Overview of mainly biosparite (red stain for calcite) with lesser micritic laminae. View shows a penetrative, vertical calcite vein (width 0.02mm). The horizontal fracture through the micritic zone, one of many in this sample, exhibits no authigenic mineralization and is likely an artifact of sample preparation.
The bright patches in this view are chert, while the light grey areas are generally dolomite rhombs. The opaque grains are likely pyrite.

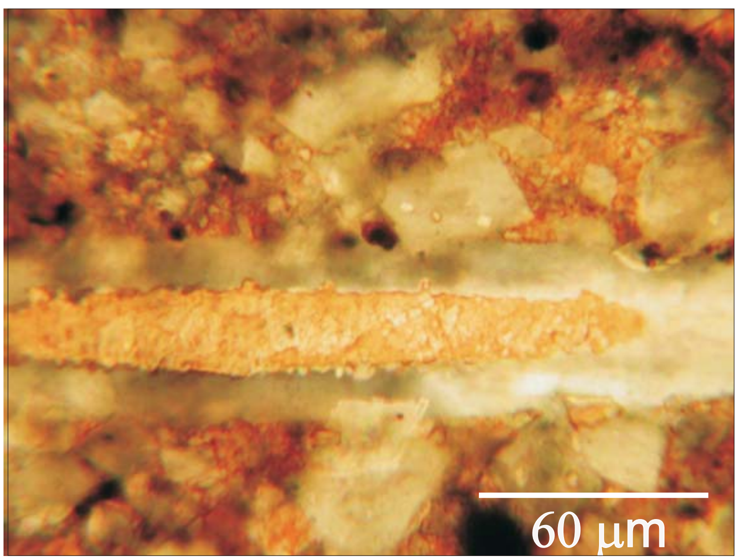

Plate 2 X 320 Plane Polarized light: There have been several phases of replacement and growth of authigenic minerals. The plate shows a skeletal fragment, likely originally calcite, most of which has been replaced by chert. A core of partly dolomitized calcite remains. Dolomite rhombs have also grown within the enclosing micrite cement. The opaque spots are likely pyrite.
There is no visible primary or secondary porosity in the sample (see below).

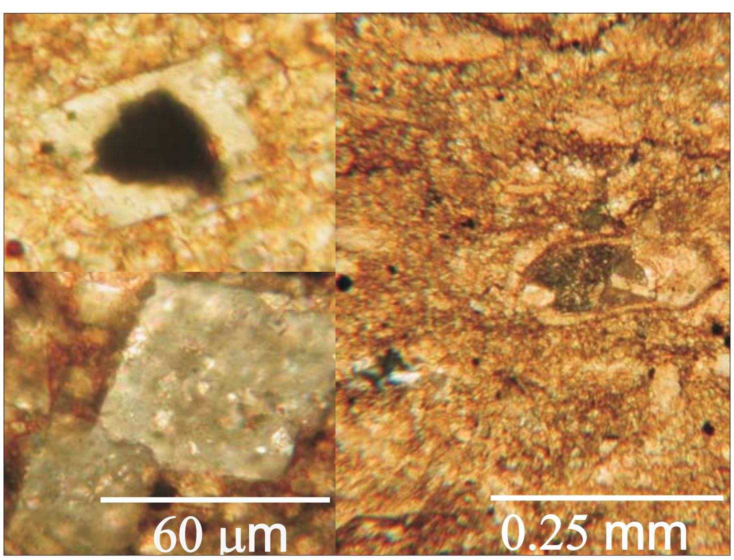

Plate 3 Replacement textures and authigenic minerals have occluded all porosity.

Left X 320 XN: View at top left: a corroded dolomite rhomb with a core of authigenic pyrite is present.
Left bottom view: originally intergrown dolomite rhombs in a micrite matrix are replaced by chert with small dolomite inclusions (dedolomitization).
Right X 80 XN: Occluded intragranular porosity; an intact pelecypod (or ostracode?) shell now filled with chert. Calcite of shell contains abundant authigenic pyrite.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 7305, elevation 1315.0 metres
Summary: Thin section with cover slip. Stained for calcite. Partially silicified limestone, biomicrite / biosparite.

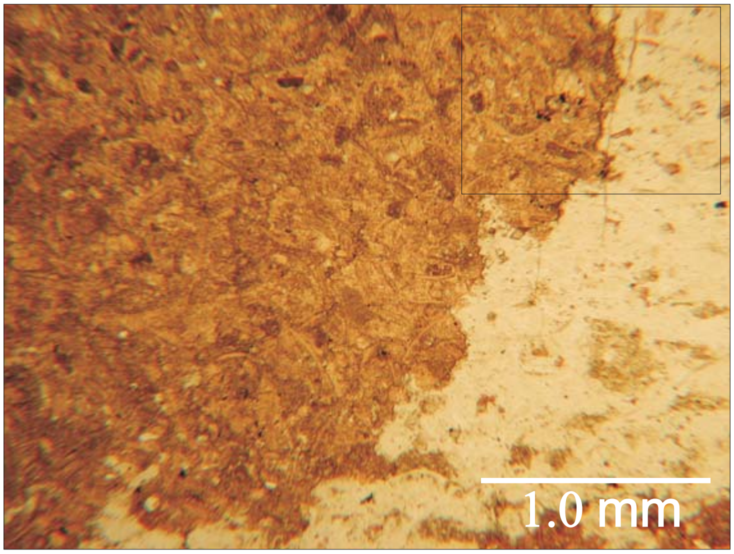

Plate 1 X 2 0 Plane Polarized light: Limestone (calcite stained red) is a poorly sorted coarse-grained calcisiltite with unsorted skeletal fragments, tests, shells and other allochems cemented by both micritic and sparry calcite cement. Much of the calcite has been replaced by chert (bright area at the right side of the frame), although patches of calcite and calcite 'shadows' surrounding silicified skeletal fragments can still be seen. The chert is fractured, with most of the fractures being filled with calcite, although some are unfilled (see the rectangle in upper right enlarged below).

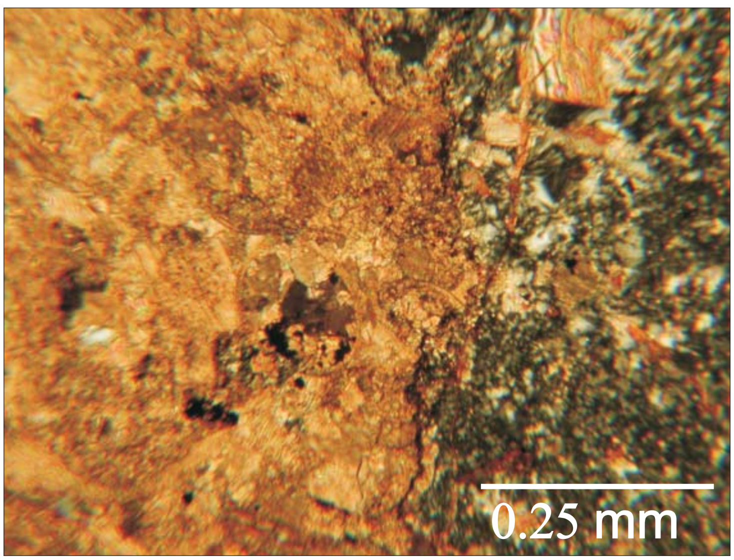

Plate 2 X 8 0 Cross Polarized light: Close-up of a part of Plate 1 under crossed-nicols (XN). Variable textures can be seen in the chert (right side) and a calcite-filled vertical vein is just right of centre. Just left of centre is an intact bivalve (or ostracode?) test is partially filled with chert. Fractures do not appear to propagate from chert into the limestone.
A small amount of organic matter is present as pore fillings, disseminated, and concentrated in stylolite-like 'veins'.

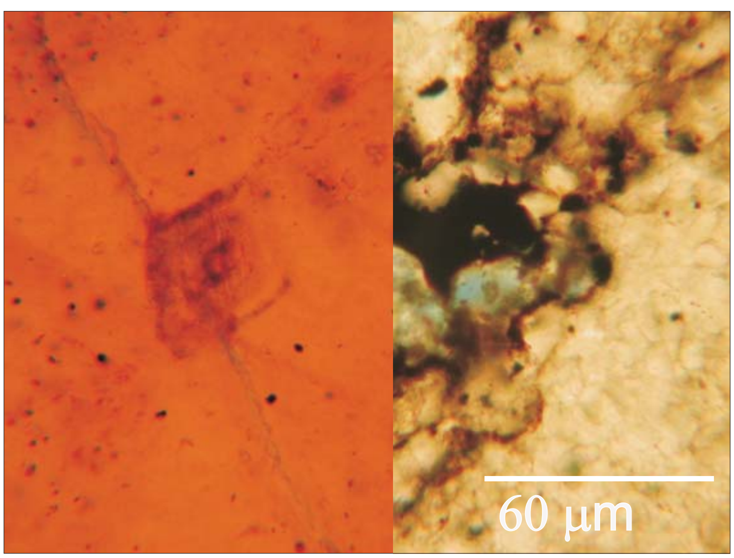

Plate 3 X 320 Plane Polarized light: Views of Porosity.
At left, a high magnification view of a sinuous, anastomozing open micro-fracture in chert. The fracture penetrates an included dolomite rhomb. The width of the fracture <0.002mm.
At right, a 0.02mm open pore associated with a corroded skeletal fragment partially filled with organic matter.
Note the interlocking crystal fabric (neomorphic fabric) of the micrite cement, lower right. Porosity is generally very low in the sample.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 7307, elevation 1315.0 metres
Summary: Thin section with cover slip. Stained for calcite. Faintly laminated medium- to coarse-grained calcisiltstone.

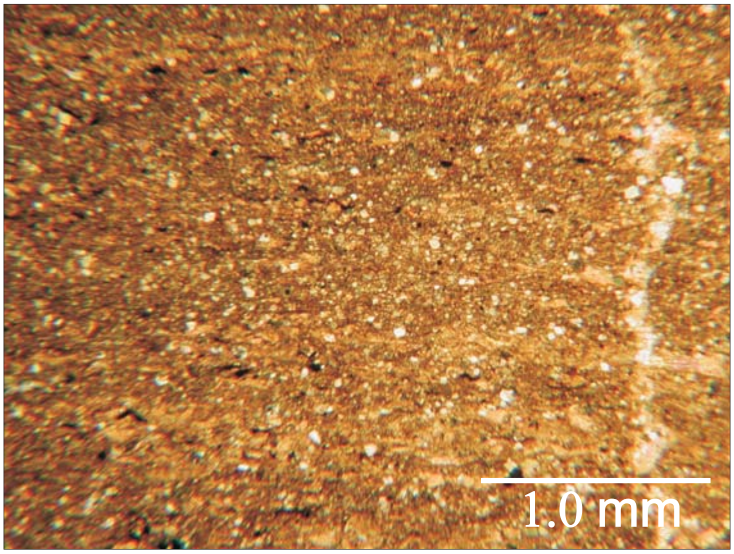

Plate 1 X 2 0 Cross Polarized light: Overview of weakly laminated medium- and fine-grained calcisiltite. Laminae record variations in the size of detrital allochems (skeletal grains, shells and tests) and the proportion of mud (micrite). There is common partial replacement of calcite with chert in many of the grains and within calcite cement. There is also common dolomite within the cement. Many of the bright visible, silt-sized grains are authigenic dolomite and chert.
Note the vertical 0.1mm wide calcite vein, with some chert.

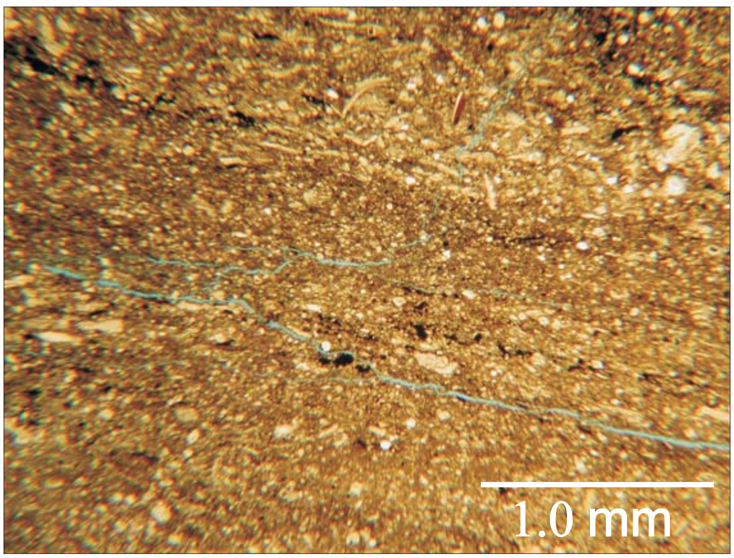

Plate 2 X 2 0 Plane Polarized light: Inclined bedding planes and chaotic bedding are viewed in a coarse-grained calcisiltite (biomicrite). Laminae within fine-grained units have concentrated organic matter on bedding planes. Fracture patterns occur both parallel and cross bedding, and do not appear to reflect fissility ('shaliness') in the rock, but this is easier to determine from hand sample.
Open fractures appear to be an artifact of sample preparation. Rare dissolution or micro-vug porosity is present (see below).

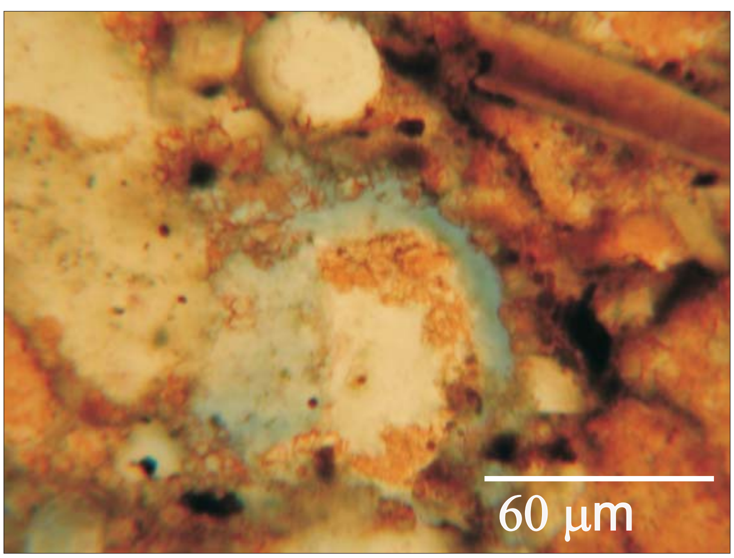

Plate 3 X 320 XN: View of dissolution porosity. Central grain has chert mostly replacing calcite, as does algal sphere at top. Brownish allochem is a phosphatic (bone) fragment. Red stain is calcite. Such open pores are rare in the sample.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 7308, elevation 1315.0 metres
Summary: Thin section with cover slip. Stained for calcite. Limestone: Medium- to fine-grained calcisiltite (biomicrite / biosparite).

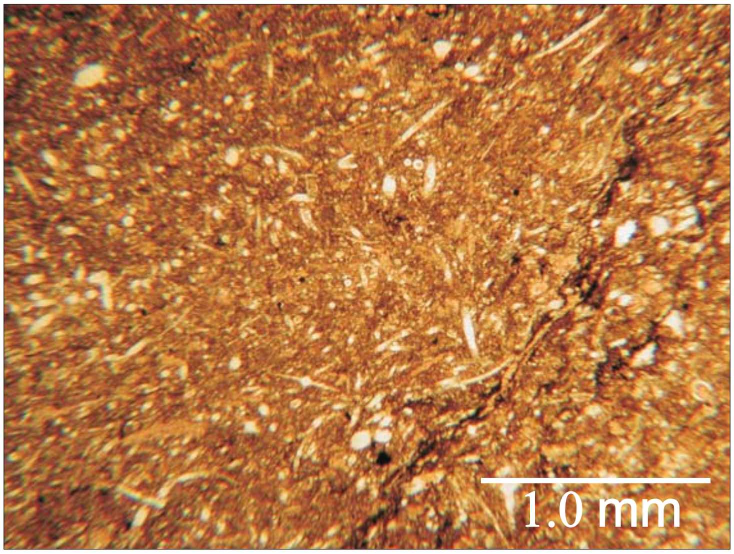

Plate 1 X 2 0 Plane Polarized light: Overview of medium to fine grained calcisiltite (biomicrite and biosparite) composed of poorly sorted allochems (shells, tests, bryozoan fragments, etc) cemented by micrite and ro a lesser degree, sparry calcite. Chert has replaced much of the calcite in allochems and to a lesser extent in the matrix. In this view, a vein of calcite, generally with quartz, cuts diagonally on the right, associated with a concentration of dark organic matter.
Chaotic bedding suggests original bioturbation.
All bright grains are chertified.

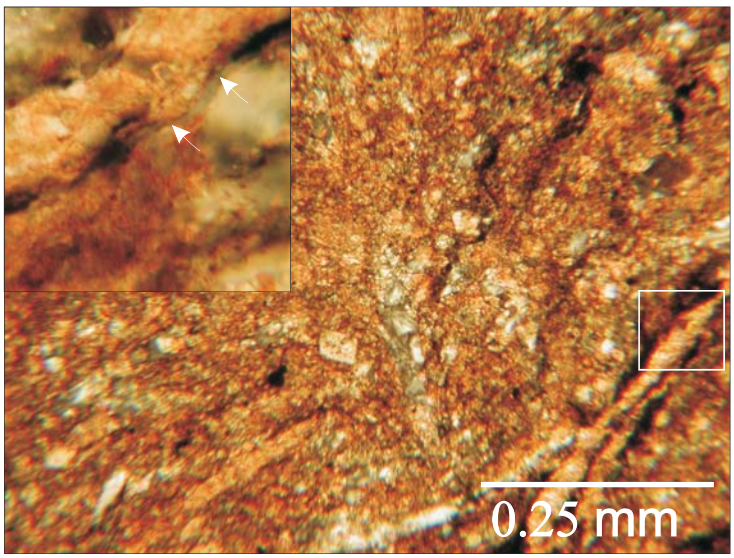

Plate 2 X 8 0 Cross Polarized light: Magnified view of part of the calcite vein in Plate 1. Paralleling the vein is a fine (<0.002mm), open fracture, shown also at upper left (X 320 XN) by arrows. Other very fine fractures are present in the rock (see Plate 3).
Also visible are common rhombs of dolomite and abundant chertified allochems.

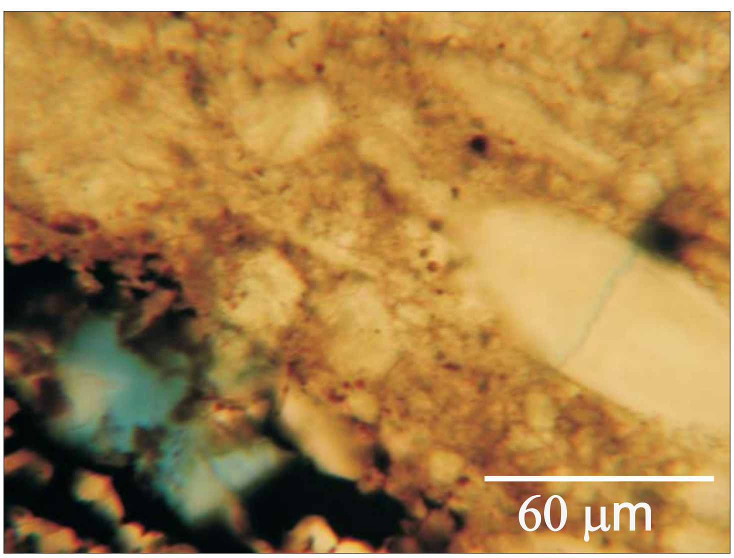

Plate 3 X 320 XN: Vuggy porosity, often associated with concentrated organic matter as at lower left, is present particularly in the coarser-grained units. Note also a very fine open fracture within the chertified allochem right centre. This fracture propagates a short distance into the neomorphic micrite (calcite) matrix. Larger, open fractures within this sample appear to be a product of sample preparation.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 7309, elevation 1315.0 metres
Summary: Thin section with cover slip. Stained for calcite. Limestone: Coarse-grained calcisiltite (biomicrite / biosparite).

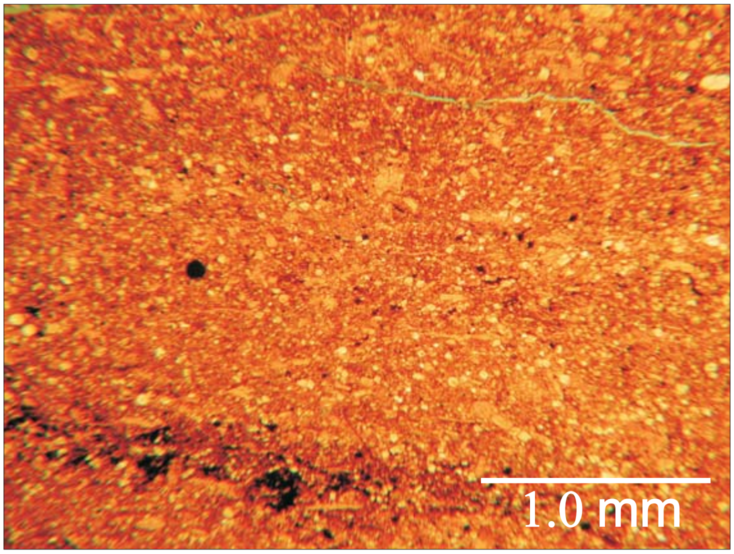

Plate 1 X 2 0 Plane Polarized light: Overview of coarse calcisiltite and very fine-grained, poorly sorted muddy calcarenite. This sparse biomicrite is composed of poorly sorted allochems (shells, tests, algal cysts) in neomorphic micrite cement. Minor chert has replaced some of the calcite in grains and to a lesser extent in the matrix. Chaotic bedding suggests bioturbation. Bright grains are chertified.
There are many sinuous, open fractures in the sample, most of which display no authigenic mineralization and are likely an artifact of sample preparation.

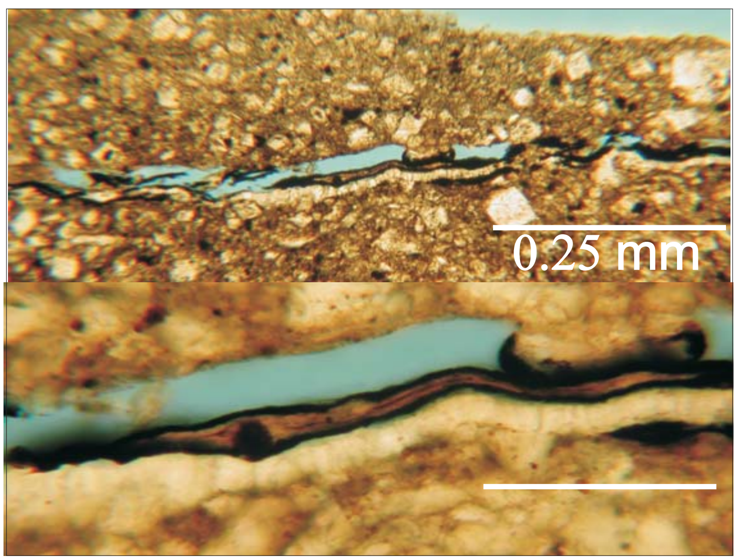

Plate 2 X 8 0 Plane Polarized light:
Upper view: Part of an open fracture associated with both a calcite vein and a concentration of dark organic matter.
Lower half of frame X 320 PP: Close up of open fracture and rim of organic matter. Calcite vein fill appears to have formed in a single phase. Other fractures in the sample have no veins or organic matter associated with them.
The rock fabric does not appear to be fissile (shaley) in thin section.

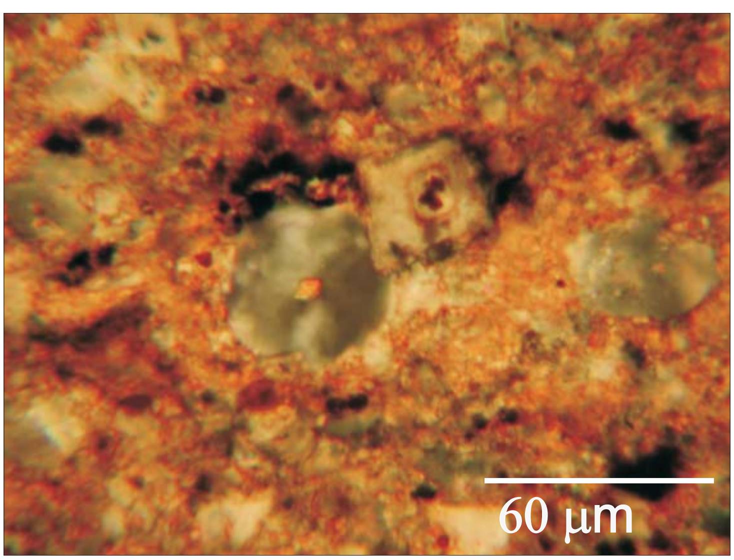

Plate 3 X 320 XN: Micritic cement matrix partially replaced by neomorphic calcite (red stain) and partially chertified (grey mottled texture). At the centre is a coarse grained, silt-sized, chertified allochem with a remnant calcite core, intergrown with a zoned dolomite rhomb with an opaque (due to organic matter) core.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 7310, elevation 1315.0 metres
Summary: Thin section with cover slip. Stained for calcite. Limestone: Coarse-grained calcisiltite and very fine-grained muddy calcarenite (biomicrite / biosparite).

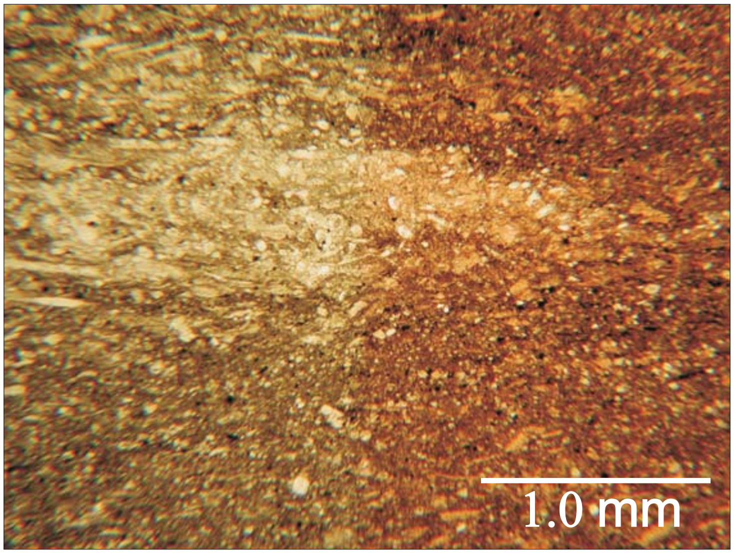

Plate 1 X 2 0   Plane Polarized light: Overview of coarse calcisiltite and very fine grained, poorly sorted muddy calcarenite. The right side was stained red for calcite identification. This sparse biomicrite is composed of poorly sorted detrital allochems (shells, tests, algal cysts) and common dolomite rhombs in neomorphic micrite cement. Minor chert has replaced some of the calcite in grains and to a lesser extent in the matrix. Chaotic bedding suggests bioturbation. Bright grains are chertified. Large sinuous open fractures in the sample, display no authigenic mineralization and are likely an artifact of sample preparation.

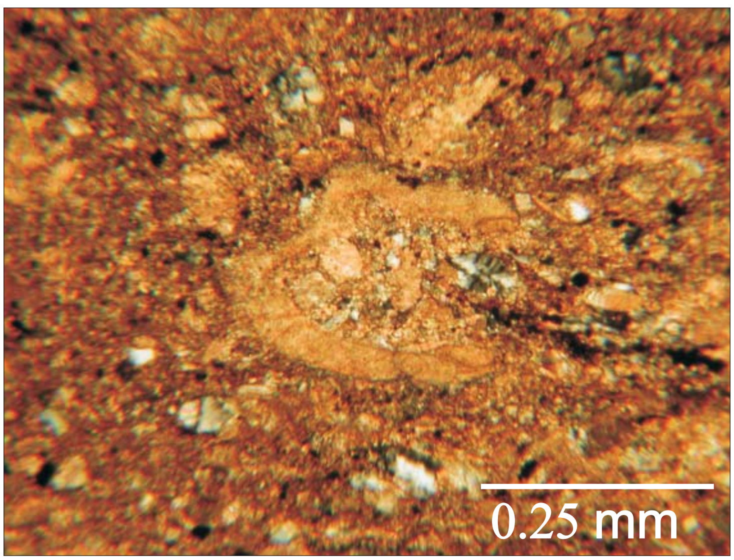

Plate 2 X 8 0 Plane Polarized light: A view fabric of the finer grained facies. The central skeletal grain has been replaced with neomorphic, micritic calcite cement. The cavity fill includes authigenic sparry calcite and micrite cement as well as chert and dolomite. Along the upper and lower margins of the grain are very fine open channels (see below).

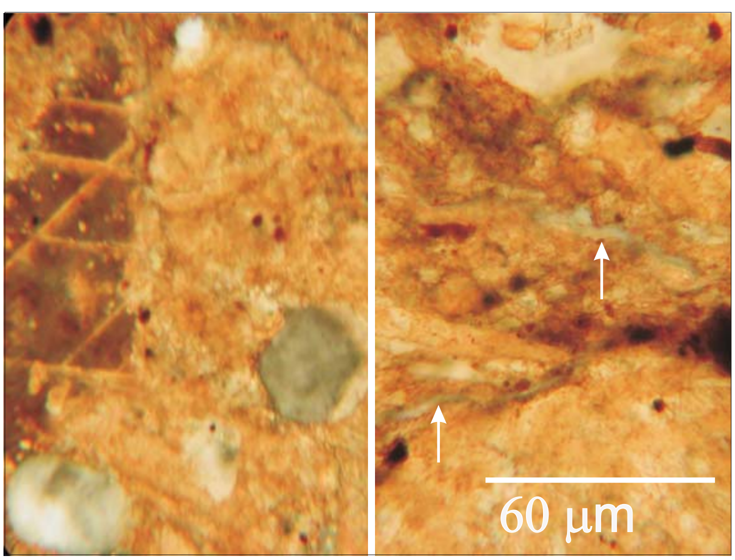

Plate 3 X 320 XN: Left view: Multiple replacement textures and authigenic mineral growth. Original micrite (lime mud) has been replaced by neomorphic micrite, with lesser amounts of sparry calcite and chert. Many of the allochems have undergone partial or complete replacement with chert.
Right view: Arrows indicate microfractures. Porous micro-channels, such as these marginal to the altered shell fragment in Plate 2, are present throughout the sample but difficult to resolve or quantify. Aperture here is < 0.002mm. Similar pores are found marginal to dolomite rhombs.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 7311, elevation 1315.0 metres
Summary: Thin section with cover slip. Stained for calcite. Limestone: Fossiliferous biomicrite.

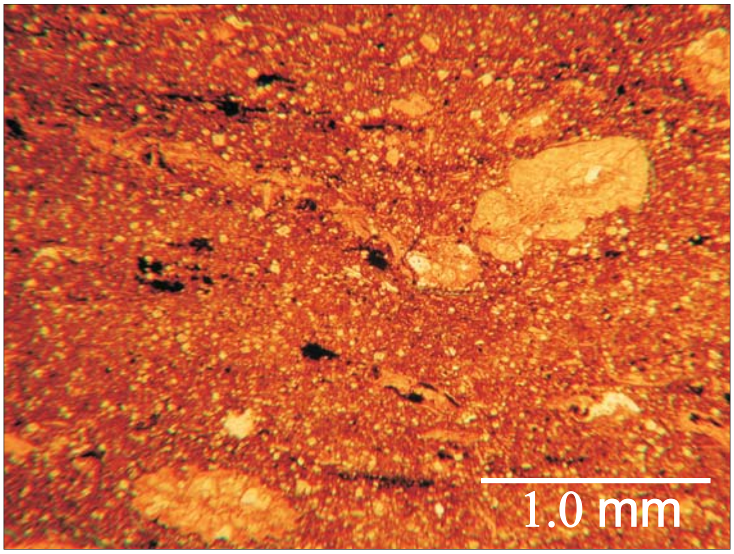

Plate 1 X 2 0 Plane Polarized light: Overview of micritic limestone with scattered skeletal calcite fragments. Micrite (lime mud) is partially altered to neomorphic micrite and partially dolomitized. There is patchy chertification (bright patches) in the micrite cement, and more extensive chertification of cavity fill, and some skeletal fragments.

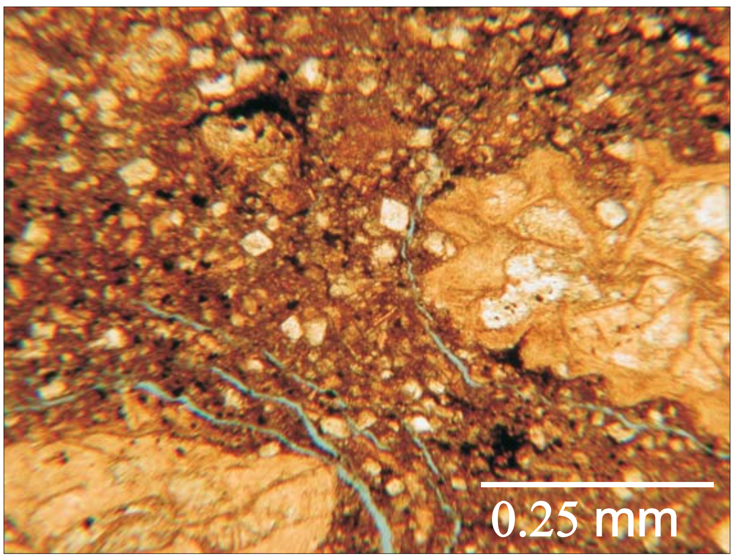

Plate 2 X 8 0 P P : Porosity viewed as concentric open fractures within cement surrounding most of the large allochems. Some secondary (fracture) porosity is present within cavities. Primary porosity (cavities) is occluded by chert and authigenic calcite. Calcite is stained red.

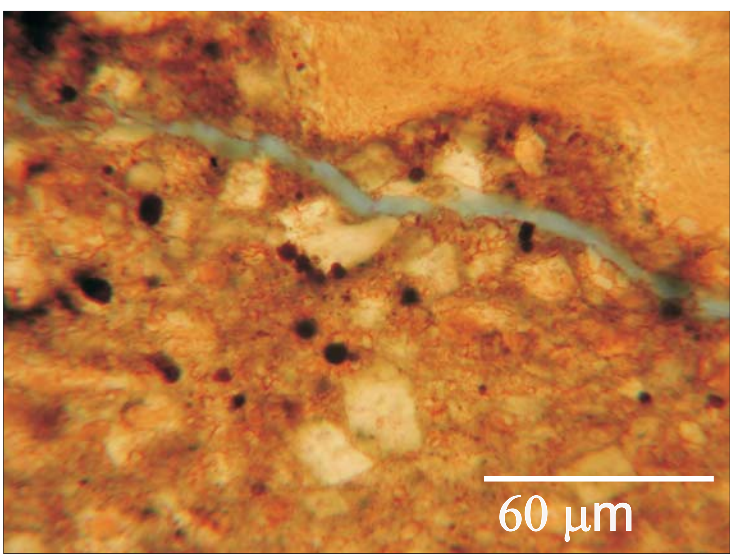

Plate 3 X 320 XN: Fine discontinuous fractures associated with allochems. Fractures do not cleave grains (note displaced dolomite rhomb) and have no associated authigenic mineralization, thus may in part be an artifact of sample preparation.
Fibrous calcite is part of large skeletal fragment in Plate 2 (right). Note common authigenic dolomite in micritic calcite cement.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 7312, elevation 1315.0 metres
Summary: Thin section with cover slip. Stained for calcite. Limestone: Partially silicified biomicrite.

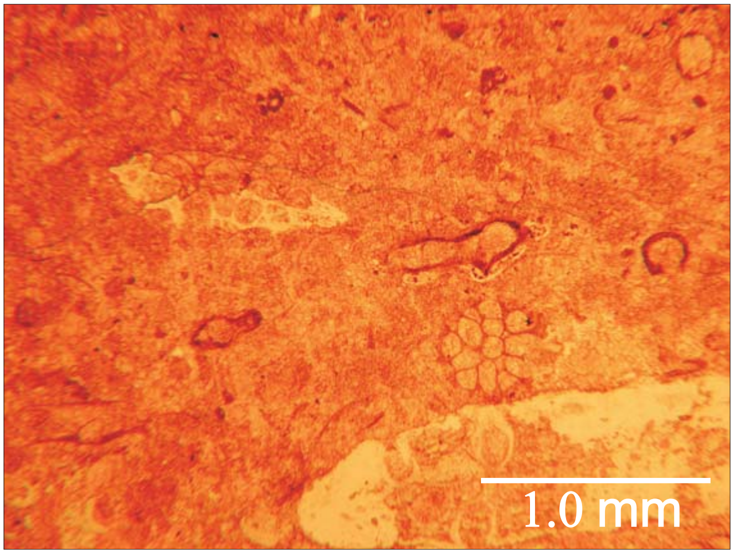

Plate 1 X 2 0 Plane Polarized light: Overview of micritic limestone packed with detrital skeletal calcite fragments. Micrite (lime mud) is partially altered to neomorphic micrite and sparry calcite, and partially silicified. There is extensive chertification (bright patches) in the micrite cement along with more extensive chertification of cavity fill and most skeletal fragments (large fragment at lower left and gastropod left centre).

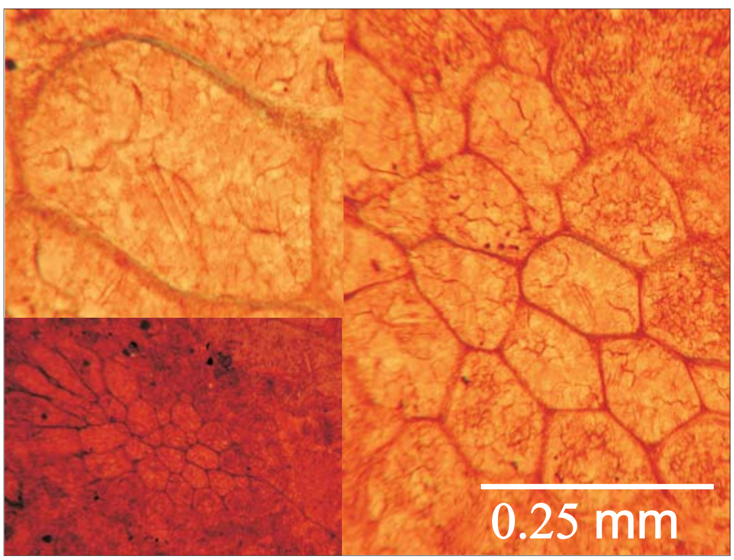

Plate 2: Three views are displayed of secondary porosity associated with large skeletal fragments.
Bottom left X20 PP is a large fan-shaped algal fragment with a network of open fractures following the cell walls and propagating into the rock matrix.
Right side of view (X 80PP) shows the interconnected fracture porosity.
Top left view (X 320) shows the fractures to be anastomozing with an aperture of about 0.002mm. Note mix of micritic and sparry calcite cavity filling.

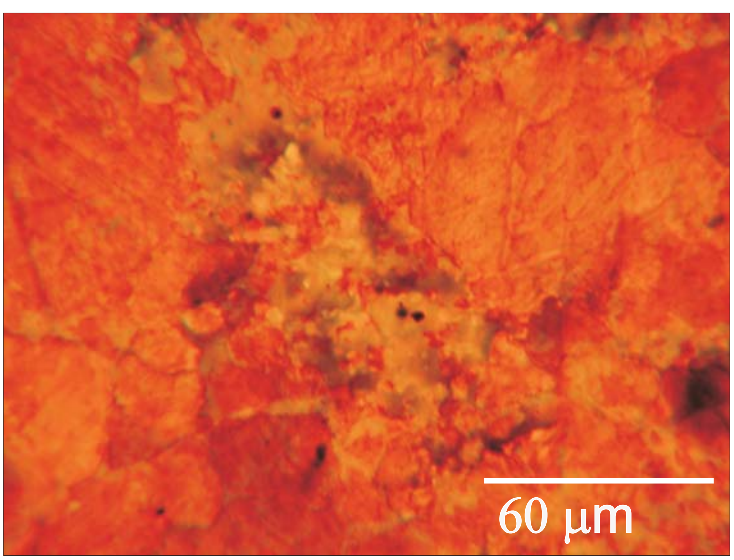

Plate 3 X 320 XN: Replacement fabric of limestone matrix (cement) is composed of neomorphic micrite, sparry calcite cement, and chert. All of the original carbonate has been replaced.

Formation: Lower Banff
Outcrop: Nordegg Railroad section
Sample Number: 7313, elevation 1316.0 metres
Summary: Thin section with cover slip. Stained for calcite. Limestone: Partially silicified biomicrite.

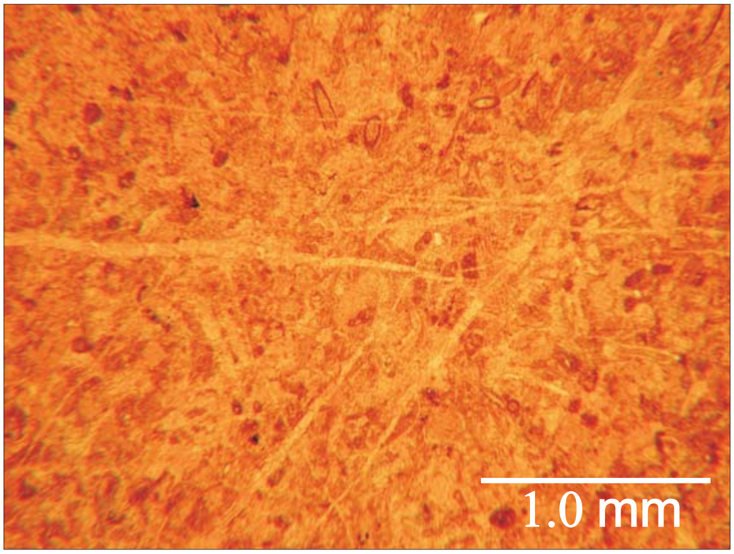

Plate 1 X 2 0Plane Polarized light: Overview of micritic limestone packed with detrital skeletal calcite fragments. Micrite (lime mud) is partially altered to neomorphic micrite and sparry calcite, and partially silicified. There is minor chertification in the micrite cement and more extensive chertification of cavity fill and skeletal fragments. Allochems range in size from fine grained silt-sized to medium grained sand-sized. There is a network of veins criss-crossing the entire sample.

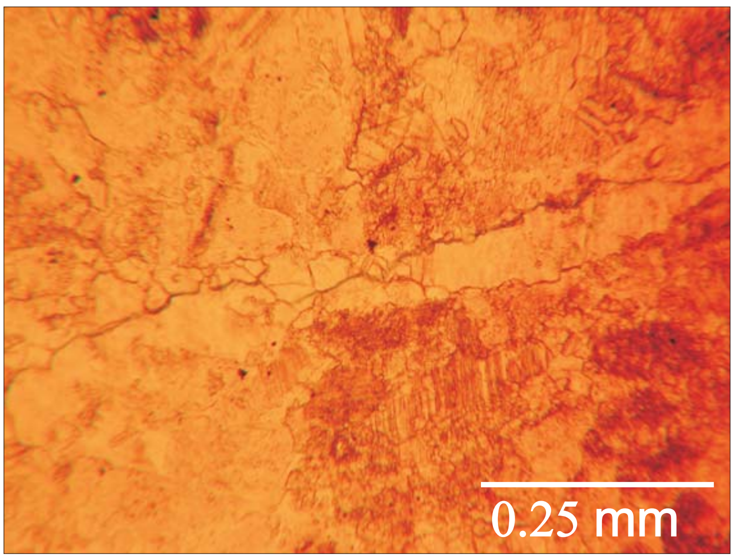

Plate 2X 80 PP: Close-up of vein. An irregular open fracture penetrates the vein fill. This fracture averages about 0.002mm wide; such fractures are present throughout the sample. The vein fill is a complex combination of sparry calcite, euhedral calcite, megaquartz and chert. The sequence of authigenesis and replacement is not clear. Fractures tend to follow grain contacts. The cement is both neomorphic micrite and sparry calcite. Dark patches on the right are partially chertified.

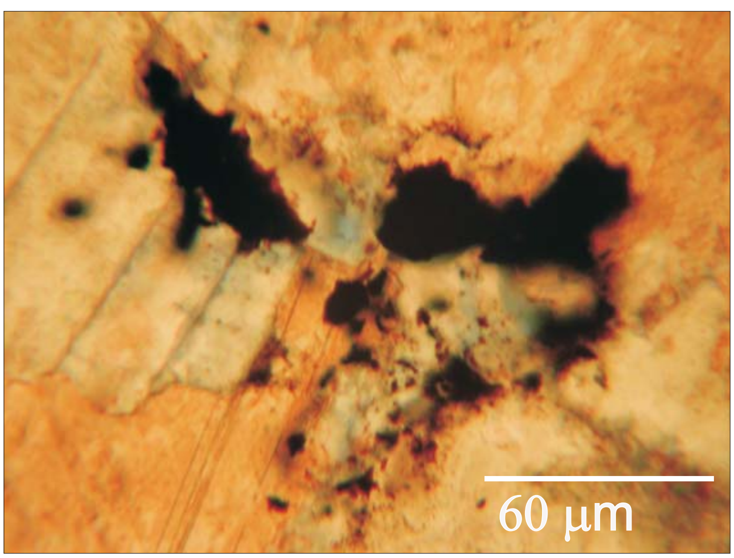

Plate 3 X 320 XN: A large, open secondary pore within the micrite / sparry calcite cement. The organic matter that fills part of this pore is rare in this sample. Similar open pores are fairly common both within the matrix and in vein fill.
There is no apparent primary porosity in this rock, and secondary open pores are not exclusive to particular facies.

Strata: Colorado Group, Second White Specks
Outcrop: Birch Mountains
, Asphalt Creek
Sample Number: 7329, elevation 652.2 metres
Summary: Thin section with cover slip. Stained for calcite.
Sandstone: Fine-grained calcareous quartz wacke with common phosphatic grains (collophane bone fragments).

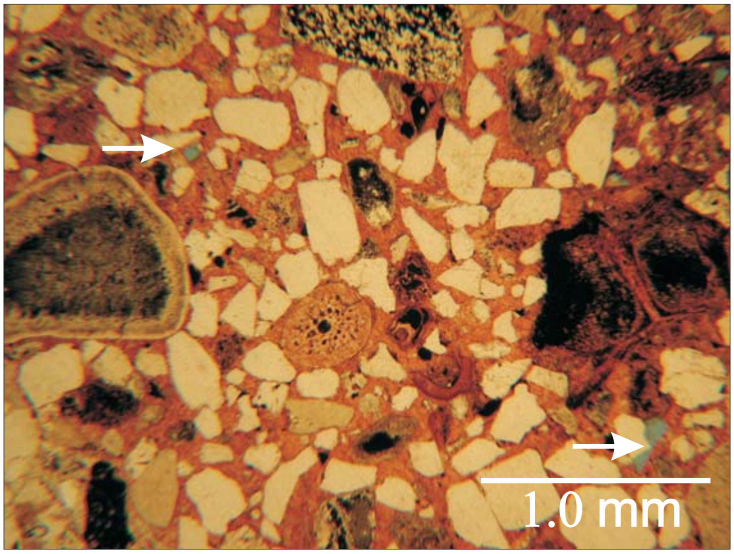

Plate 1 X 2 0 plane polarized light: Fine to very fine sandstone composed of 70% quartz grains, 15% phosphatic bone fragments and 15% grains of chert and occasional bituminous siltstone in a matrix of calcite which has altered to sparry calcite cement (red stain).
Arrows indicate scattered open coarse grained silt-sized pores.

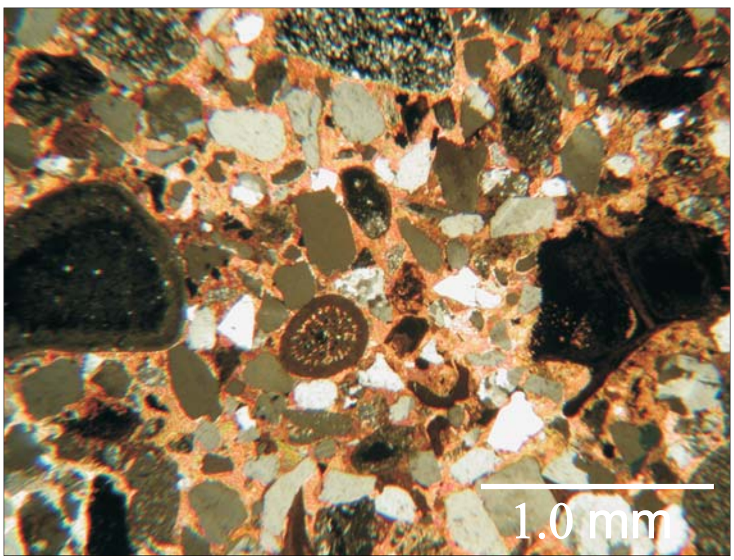

Plate 2 X 20 cross polarized light: Same view as above showing predominance of sub-rounded to sub-angular, slightly pitted monocrystalline quartz grains. Bone fragments (collophane) are well preserved and pores or lacunae filled with both calcite and organic matter.

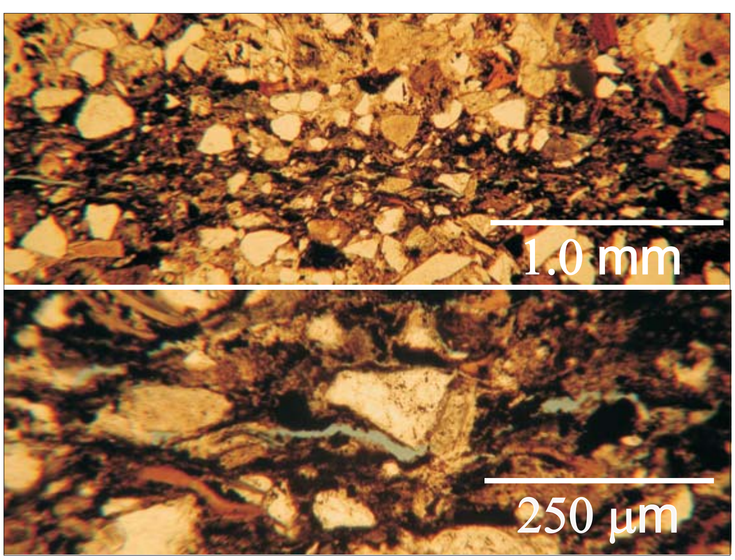

Plate 3: Channel porosity.
Top X 20 PP: Lamina of concentrated organic matter has a sinuous open fracture threading through the calcite matrix parallel to bedding .

Bottom X 80 PP: Close up view showing sinuous fracture, partially filled with opaque organic matter. Open fractures are also seen within bone fragments, and in detrital siltstone clasts. Maximum width of the fracture is .02mm.