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Microstructure and Deformation Mechanism Analysis of Carbonate Rock located in an Anticline

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Microstructure and Deformation Mechanism Analysis of Carbonate Rock located in an Anticline

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Department of Geology

Honors Research Project

Submitted to

The Honors College

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Microstructure and Deformation Mechanism Analysis of Carbonate Rock located in an Anticline

Senior Honors Research Project

Natalie Zidd

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Abstract

Rock samples were collected from the Tensleep formation in the Seminoe Mountains located in Carbon County, Wyoming. These samples were analyzed to determine the deformation mechanisms operating during small scale displacement faulting. There are three distinct zones included in the sample which includes the undeformed Tensleep, fine grained layers with grain size variation, and porous layers with grain size variation. The microstructures in the fine grained layer were consistent with deformation by crystal plastic deformation mechanisms; whereas, the microstructures in the porous layer were consistent with brittle deformation mechanisms. The microstructures in these rocks are nearly identical to those observed in large displacement carbonate faults, indicating that the evolution of microstructures on carbonate faults occurs at low displacements.

1.0 Introduction

As rocks are loaded due to tectonic forces, they respond by deforming by brittle and/or crystal plastic (ductile) mechanisms. Brittle deformation is caused by stress applied to a rock and results in permanently breaking bonds in crystals or along grain faces (i.e. fractures or faults) when the stress exceeds the strength of the rock. Ductile deformation is caused by breaking and reforming bonds while moving atoms in the crystal lattice in response to applied stress and primarily occurs at high temperature and pressure. Building stress and the subsequent release of stress on rocks is fairly common, but rapid release of stress can cause issues for the human population. Faulting/brittle behavior results in a rapid stress decrease and release of seismic energy (i.e. causes earthquakes). Faults of many scales occur in the crust, from those with less than a meter of displacement to those with many kilometers of displacement.

1.1 Fault Hazards and Earthquakes

Earthquakes are caused by frictional 'stick– slip' instabilities as elastic strain is released by shear failure, almost always on a pre-existing fault (Pulinets et al., 2004). How the faulted rock reacts to the applied shear stress depends on its composition, environmental factors (such as temperature and pressure), fluid presence and strain rate (Fuller et al., 2006). According to Ide et al. (2007), these geological and physical variables determine the shear strength and frictional stability of a fault, and the dominant mineral deformation mechanism. To differing degrees, these effects ultimately control the partitioning between seismic and aseismic deformation, and are recorded by fault-rock textures. The scale-invariance of earthquake slip allows for extrapolation of geological and geophysical observations of earthquake-related deformation. Tremors sometimes can be dangerous to the extent of destroying cities or losing lives. Earthquake magnitudes are measured using devices called seismometers and quantified by the degree of shaking via the Richter or Moment magnitude scales. Earthquake effects are greatest near the epicenter, but can produce far reaching effects on humans such as tsunami and landslides.

Earthquakes are a common occurrence and vary significantly in their intensity. Large-scale earthquakes, such as the recent magnitude 8.3 earthquake off the coast of Chile in September

2015, are observed primarily along plate boundary-scale faults. However, smaller scale earthquakes, such as the magnitude <5 earthquakes observed in Ohio, can occur on small-scale faults away from plate boundaries. These lesser magnitude earthquakes can cause significant damage to property and, therefore, it is important to understand the mechanisms that lead to seismic events on small-scale faults. Small scale faults can form in a variety of settings, such as areas of active folding or slumping/gravity collapse. The small-scale faults that occur in folds are usually associated with over-pressurization of the materials in the core of the fold, which causes a failure of these rocks forming a fault. The microstructures created by these faults will vary depending on the number of slip events (e.g. the amount of wear along the surface) and if secondary mechanisms allow for flow of the materials in the fault in between seismic events.

Small scale earthquakes are caused by strains developed within the wider zone of deformation. This is due to major irregularities such as fault trace. Also, the deformation associate with plate's boundary is divided into nearly solely thrust sense movements to the boundary over a wider zone (Pulinets et al., 2004). Internal stresses in tectonic plates are caused by the interactions between neighboring plates and sedimentary loading such as deglaciation. This stress is enough to cause failure along the tectonic plates leading to an intra-plate earthquake. The damage of this type of earthquake usually depends on factors like number and quality of buildings close and the nature of the soil those buildings are built on. According to (Ide et al., 2007) these types of earthquakes usually have a magnitude of less than five. Moreover there are other causes that can evoke a small scale earthquakes other than been near to plate tectonics. First one been building big water reservoirs can be another cause. This is because by creating such large water holdings you create extra pressure to the ground. This commonly loads it so the less occupied places move down to the ground through cracking clay so you experience minor earthquakes like that. As the ice melts are also another cause. The ground tends to rise gradually like few centimeters a year which build up tension and eventually causing an earthquake.

Earthquakes just like other natural occurrences can be predicted. Although they show variance in variance, mostly large scale earthquakes with a magnitude of above 8, like the one experienced at Chile are mainly due to faults along plate boundaries are a common occurrence and vary significantly in their intensity. On the other hand, smaller magnitudes are observed too, for example the less than 5 in Ohio. These lesser magnitude earthquakes can cause significant damage to property and, therefore, it is important to understand the mechanisms that lead to seismic events on small-scale faults. Small scale faults can form in a variety of settings, such as areas of active folding or slumping/gravity collapse. The small-scale faults that occur in folds are usually associated with over-pressurization of the materials in the core of the fold, which causes a failure of these rocks forming a fault. The microstructures created by these faults will vary depending on the number of slip events (e.g. the amount of wear along the surface) and if secondary mechanisms allow for flow of the materials in the fault in between seismic events.

1.2 Purpose

The purpose of this research paper is to establish whether there is any similarity in the processes that operate in large and small-displacement faults. We would like to answer the question: Are the mechanisms and resulting microstructures the same on large and small displacement faults? If they are similar, then it would indicate that the evolution of the material properties (strength) of the fault is well-evolved at low total displacements. In order to determine the answer to this question I must analyze the microstructures in the a sample fault to determine the mechanisms that allow the faults to slip seismically and if there is evidence of other processes that allow the fault to deform in between seismic events (Örgülü et al., 2011). The methodological approach used in this research is examining the microstructures observed in a sample collected from a fold in the Tensleep formation in the Seminoe Mountains, Wyoming.

1.3 Geologic Setting

The Tensleep Formation is located in the Seminoe Mountains which is located on the Greenstone Belt in Carbon County, Wyoming (Fig. 1; Love and Christiansen, 1985). The Tensleep formation is Pennsylvanian to early Permean in age and is composed of Aeolian sandstone beds as well as limestone and dolomite beds. The sample collected for this research was removed from a carbonate layer within the Tensleep Formation (Fig. 2). The macroscopic structures in the area include open folds and thrust faults, consistent with macrostructures observed in fold and thrust belts.

2.0 Methods

The rock sample collected for analysis from the Tensleep Formation was cut parallel to the lineation in a fine grained layer. The lineation in this fine grained layer is parallel to the slip direction on the fault. I prepared three doubly-polished thin sections ~20 μm thick of this sample in order to analyze the microstructures present in these three zones. I analyzed the type, composition and grain size (shape of materials) present in each of these layers using optical petrography and, where necessary, the scanning electron microscope. Optical microstructures were characterized using a Zeiss AxioScope.A1 POL petrographic microscope. Composition variations and very fine scale (micron to submicron) features present in the thin sections were characterized using a LEO field emission gun scanning electron microscope (SEM). All of the facilities to make and analyze thin sections are in the Department of Geosciences at the University of Akron.

3.0 Results

The sample of the Tensleep formation was collected near the hinge of an anticline above a thrust fault. Displacement along the fault is small (<1m). The sample comes from a limestone bed and contains three distinct zones (Fig. 3): 1) what appears to be relatively undeformed Tensleep formation (thin section TS1, Fig. 4), 2) several thin and uniformly fine-grained layers (thin section TS2, Fig. 4), and 3) a high-porosity zone with wide range of grain particle sizes (thin section TS3, Fig. 4).

3.1 Thin section 1

Three features are present in thin section 1: undeformed micrite with occasional fossils, cross cutting calcite veins and a porous zone with calcite splays (Fig. 5). The undeformed micrite has a grain size <10 um and contains occasional fossils, such as high-spired gastropods (i.e. snails, Fig. 6) and Echinoderms (i.e. sea cucumbers, Fig. 7). The calcite grains in these fossils are untwinned and do not appear to be distorted. Veins in the micrite are filled with coarser grained calcite (30-100 um) than the micrite (Fig. 8). These veins cross cut and displace each other (Figs. 8 and 9). Near the edge of the thin section is the zone with high porosity (Figs. 5 and 10). Fragments of the micrite are found within coarse grained calcite splays (Fig. 10). A linear zone of elongate calcite grains was also observed in the thin section (Figs. 5, 11 and 12). We observed small grains within this zone that are very dark in SEM images (Fig. 12), which appear to be entirely composed of graphite when examined by EDS (Fig. 13).

3.2 Thin Section 2

Thin section 2 has two different zones: a zone of undeformed Tensleep formation and a series of alternating layers with uniform or heterogeneous grain sizes (Fig. 14). The undeformed

Tensleep in this thin section is identical to the undeformed Tensleep observed in TS1 and described above.

The alternating layers of uniform and heterogeneous grain sizes are approximately 1.5 cm thick. The layers with heterogeneous grain sizes contain angular fragments of micrite (30-100 μm) surrounded by fine (~10 μm) calcite grains (Figs. 15 and 16). The angular fragments have the same grain size and appearance as the undeformed Tensleep formation. Smaller grains of twinned calcite (10-30um) were also observed. The uniformly fine-grained layers are almost all calcite grains (Fig. 17).

<u>3.3 Thin section 3</u>

Thin Section 3 (TS3) contains three zones (Fig. 18): undeformed Tensleep that is consistent with the undeformed Tensleep observed in TS1, fine-grained calcite layers consistent with those observed in TS2 (Fig. 19) and a high porosity layer that contains fragments of undeformed Tensleep mixed with calcite splays similar to those observed in TS1 (Fig. 5). This layer is composed of very fine grained micrite (<10um) as well as twinned calcite inclusions and grains (10-30um). Calcite precipitation was also included in this porous layer (Fig. 3.14).

4.0 Discussion

The microstructures observed in the deformed portions of the sample analyzed above include 1) zones of high porosity with fragments of Tensleep formation cemented with calcite splays, 2) layers with large angular fragments of Tensleep formation surrounded by fine-grained calcite with low porosity and 3) layers of uniformly fine-grained calcite. These different microstructures indicate that the deformation mechanisms operating in these faults have evolved.

The microstructures in the uniformly fine-grained layers are consistent with microstructures observed in fine-grained calcite aggregates that have deformed by diffusion creep (Wells et al., 2014). Grain boundaries in this layer are interlocking and extinction is straight. Diffusion creep in calcite is possible at low temperatures (100-150^{o}C) if the grain size is very small, which indicates that this fault occurred at moderate depths assuming a moderate geothermal gradient (25^{o}C; Wells et al., 2014).

The fine-grained layers are adjacent to layers with angular fragments of the host rock surrounded by fine-grained calcite. These microstructures are consistent with cataclastic deformation, a brittle process that creates a large variety of grain sizes during fracturing and grinding of fault gouge. Cataclasis increases porosity via cracking and these layers do not have significant porosity. However, if the temperature and pressure was high enough or fluids were present, it is possible for the fine-grained calcite in the cataclasis layer to grow together and reduce porosity.

The porous layers contain microstructures consistent with the cataclastic layers above, including angular fragments of Tensleep with a range of sizes (30-300 μm). However, these layers are very porous (>25%), which is very different from the cataclastic layers above. In some places, the spaces in between fragments are filled by calcite splays, which are consistent with growth in the presence of a fluid.

The variety of microstructures observed in this sample from the Tensleep indicate that the temperature conditions during deformation changed as this rock was formed. The layers of cataclastic and uniformly fine-grained calcite are consistent with those observed by Wells et al. (2014). They investigated the processes operating during deformation along a calcite-shale thrust fault with a total displacement of ~20 km, but a thickness of ~2 cm. Wells' sample was ultra fine grained (<0.3um) but also contained larger grains of calcite. In her research she found that there were distinct regions of different deformation mechanisms. The ultra-fine grained areas primarily were involved with ductile deformation mechanisms while the coarser grained areas and areas that contained veins showed signs of brittle deformation (Wells et al., 2014). Wells et al. (2014) inferred that the ductile deformation mechanisms operated during interseismic periods between the earthquake producing events that formed the cataclastic materials, similar to those observed in this study.

5.0 Conclusions

In conclusion the rock sample that was analyzes contains three distinct zones. These zones include: a) undeformed tensleep b) fine grained layers with grain size variation c) porous layers with grain size variation. The fine grained layer was consistent with deformation by brittle deformation mechanisms. The porous layer was consistent with ductile deformation mechanisms. Similar microstructures observed in small and large displacement faults indicates that the mechanisms and seismic activity are similar.

6.0 References

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Wells, Rachel K., Newman, Julie., Wojtal, Steven. "Microstructures and rheology of a calcite-shale thrust fault." *Journal of Structural Geology* 65 (2014): 69–81.

Figures:

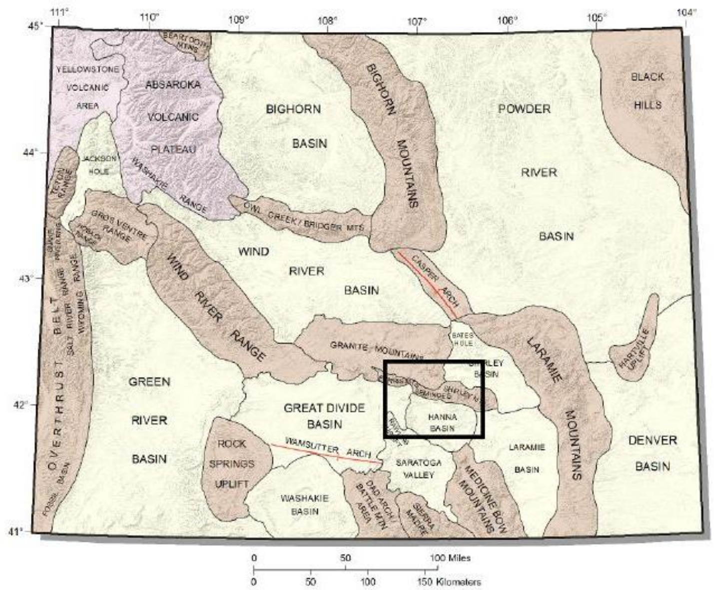

Figure 1 - Geologic provinces of Wyoming (Love and Christiansen, 1985). The area in Fig. 2 is indicated by the black box.

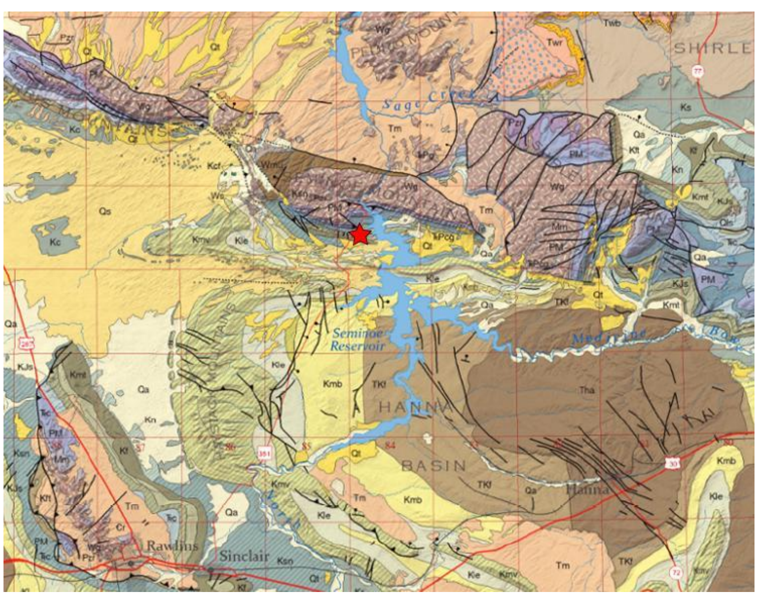

Figure 2 - The sample examined in this study was collected at the location indicated by the red star. This map is cut from the Geologic map of Wyoming (Love and Christiansen, 1985).

Figure 3 – Three zones are present in the sample after cutting. A mottled grey/tan micrite, fine grained multi-colored layers near the base of the sample and a black, porous layer around the upper edges. (Ruler width is ~15 cm)

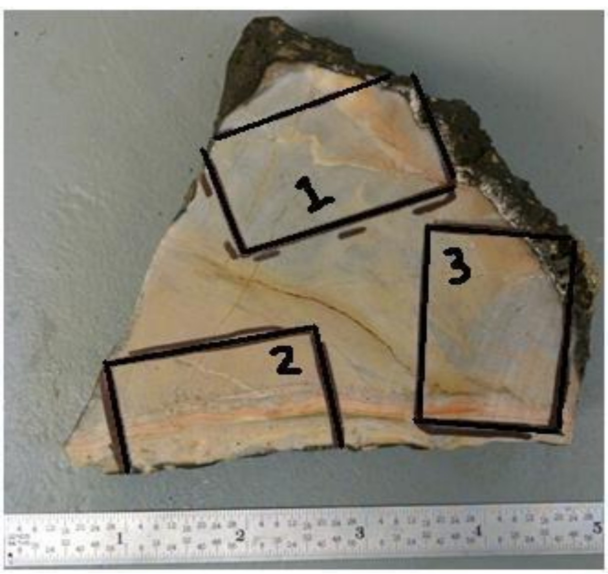

Figure 4 – Thin section billets were cut from the locations indicated above in order to analyze each of the zones described in Fig. 3. (Ruler width is ~12.5 cm)

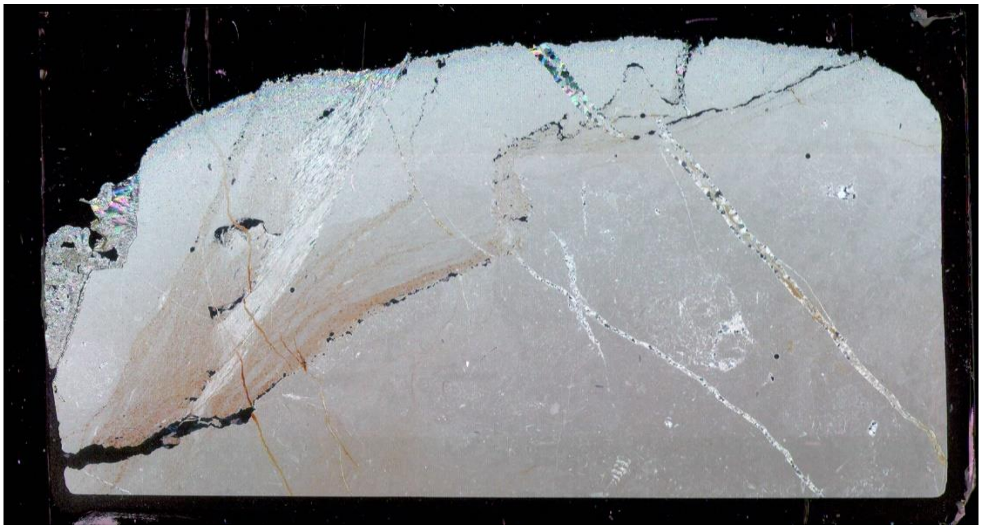

Figure 5 – Features present in a scan of thin section 1 (cross polarized light) are undeformed micrite, offset calcite veins that cross cut the thin section and a porous region (upper left corner). Width of the scan is ~5 cm.

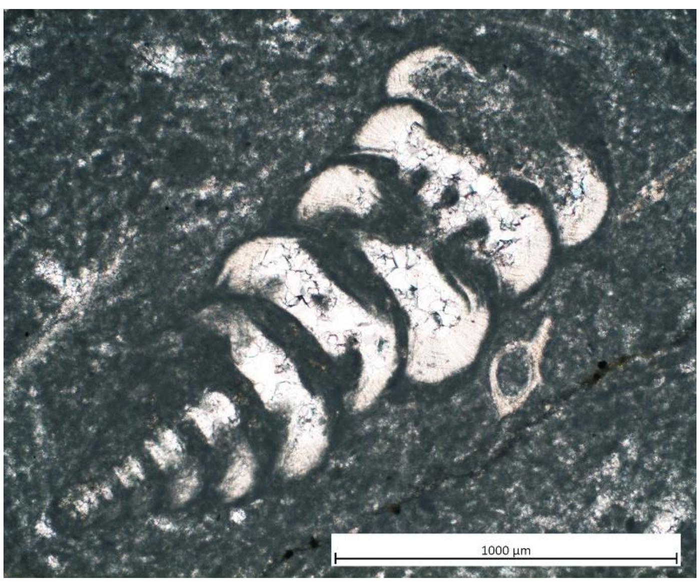

Figure 6 - High spired gastropod observed in undeformed micrite (TS1, cross polarized light).

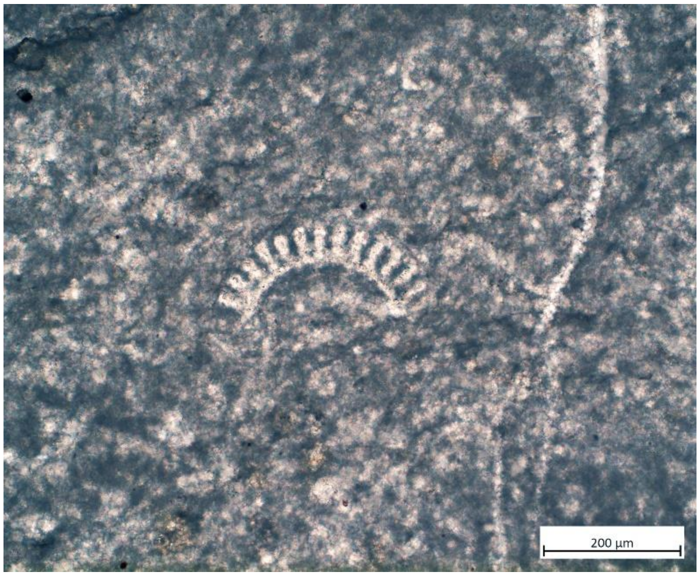

Figure 7 – Partial echinoderm observed in micrite (TS1, plain polarized light).

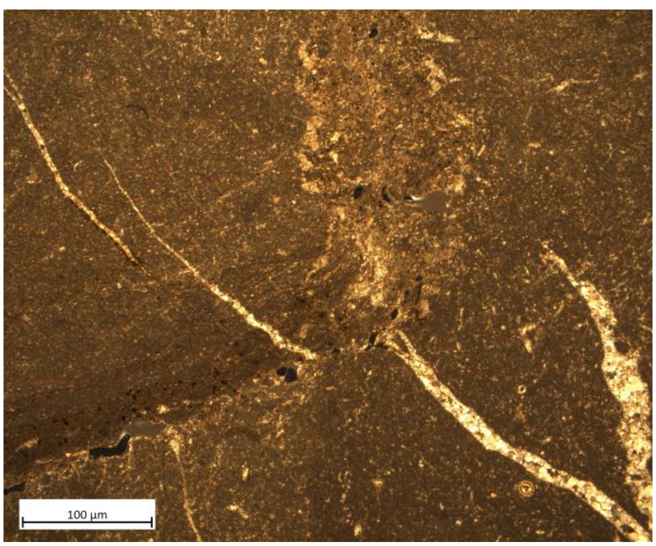

Figure 8 – Offset calcite vein (TS1, cross polarized light)

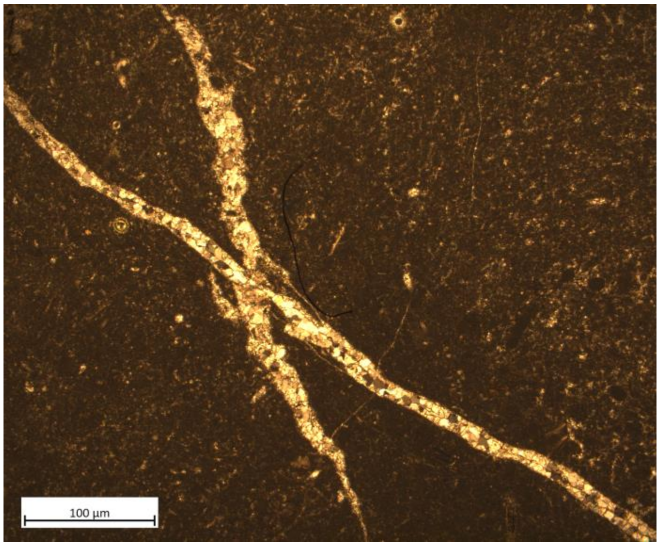

Figure 9 – Cross-cutting calcite veins (TS1, cross polarized light).

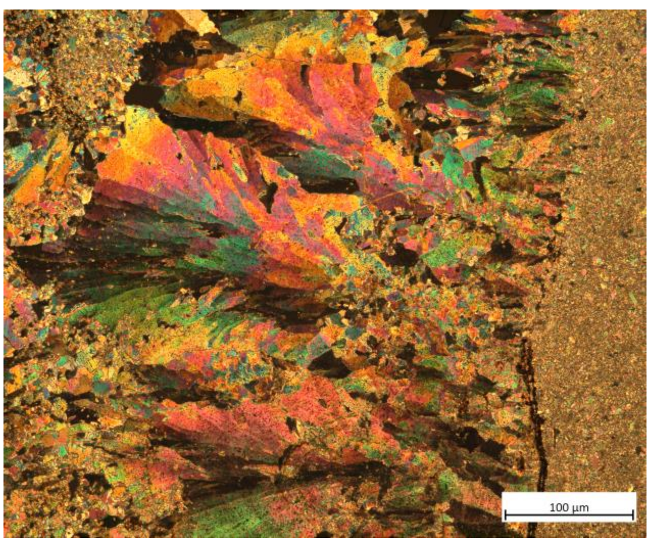

Figure 10 - Calcite splays in between fragments of micrite (left side of image) and undeformed micrite (right side of image; TS1, cross polarized light).

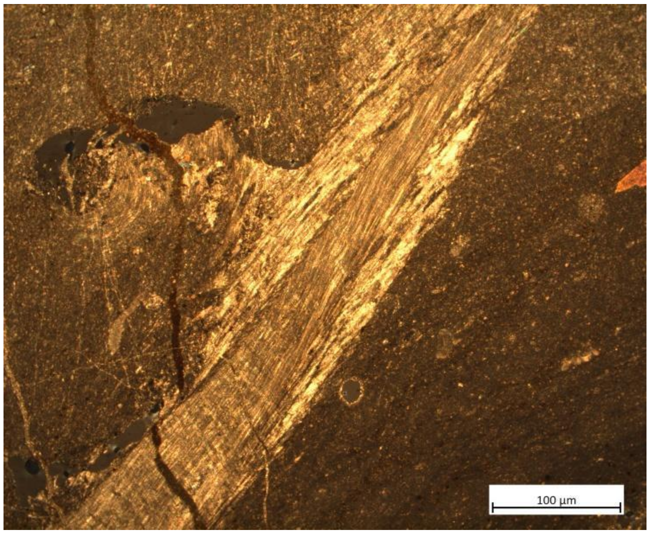

Figure 11 – linear zone of elongate calcite grains (TS1, cross polarized light).

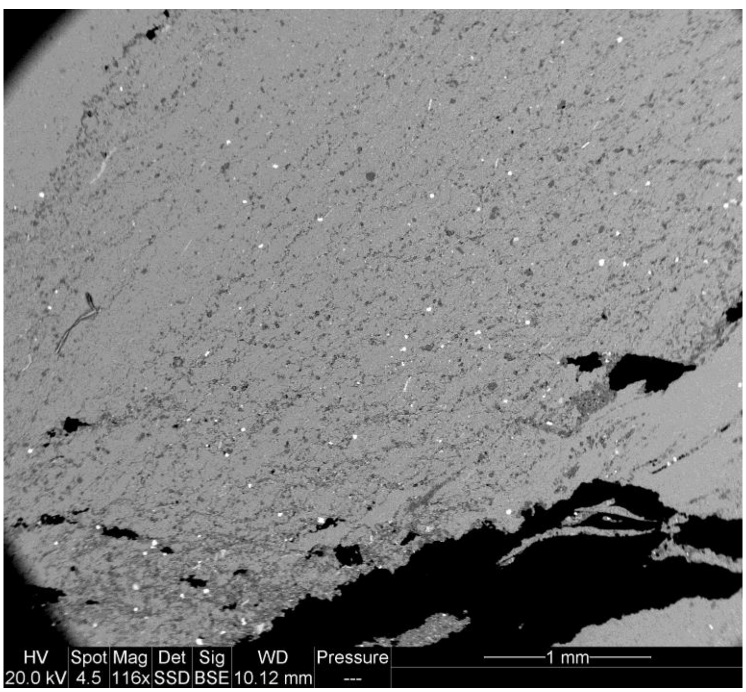

Figure 12 – SEM image of the zone of elongate calcite grains (grey) in TS1. Oxides are white grains. Large black spots are the thin section, but small black grains in the calcite are graphite.

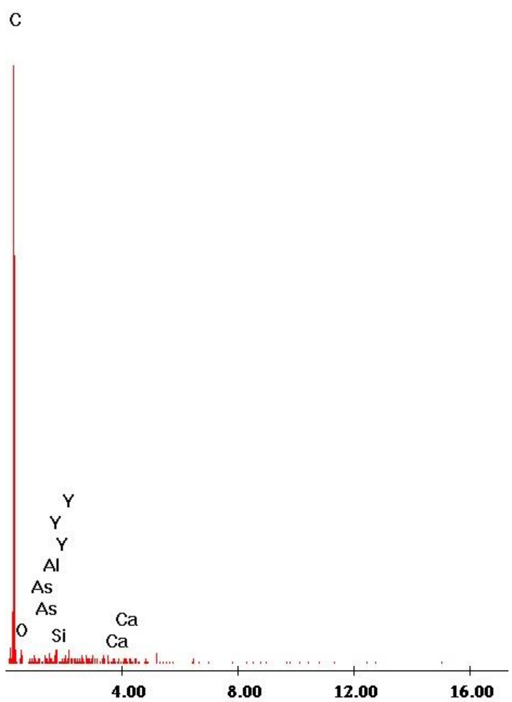

Fig 13 – EDS analysis of the fine-grained dark spots observed in Figure 12 were entirely composed of carbon, indicating they are graphite.

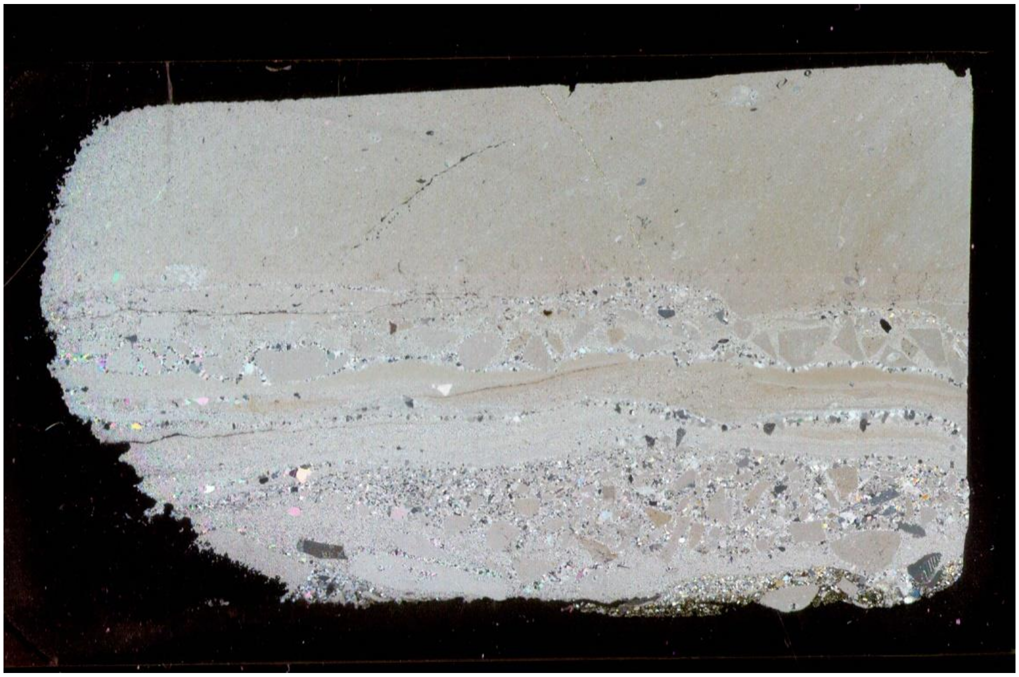

Figure 14 – The upper portion of this scan of thin section 2 is the undeformed micrite. The lower half of the section is composed of layers of uniformly fine-grained calcite in between layers of cataclastic breccia (larger angular fragments surrounded by fine-grained matrix). Width of the scan is ~5 cm.

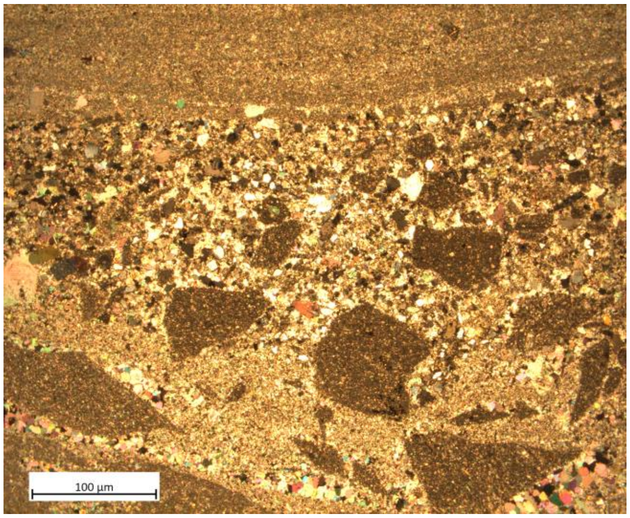

Figure 15 – Grain sizes in the cataclastic layers are highly variable (1-200 μm), but are very uniform (1-10 μm) in adjacent layers. The large, darker, angular grains are pieces of the micrite (TS2, cross polarized light).

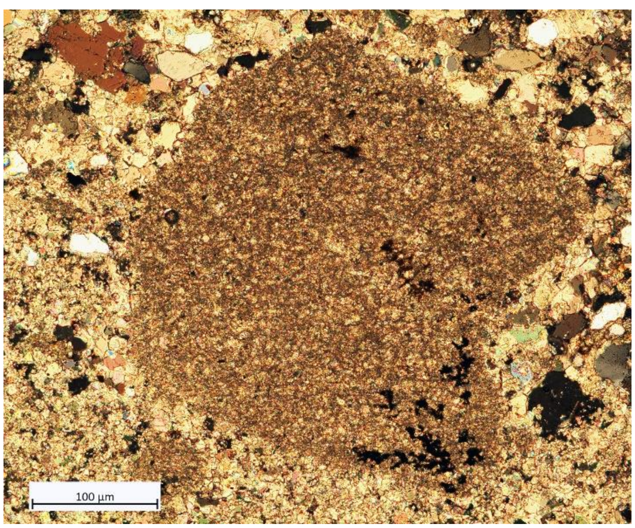

Figure 16 – The large fragments of micrite are surrounded by fine-grained calcite (TS2, cross polarized light).

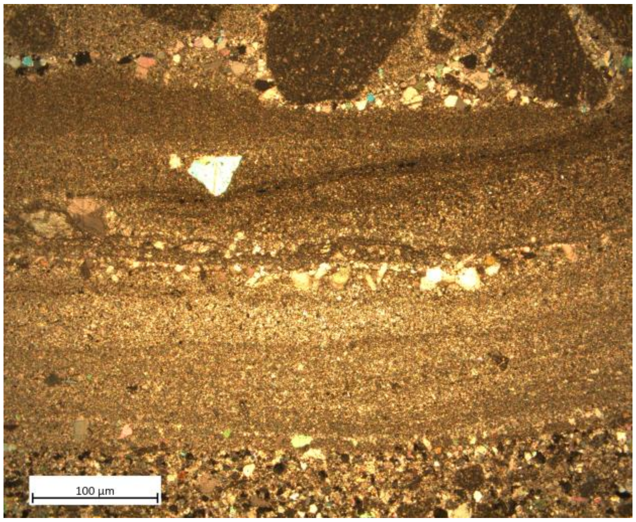

Figure 17 – Adjacent to the cataclastic layers are uniformly fine-grained layers of calcite (TS2, cross polarized light).

Figure 18 – Thin section 3 contains undeformed micrite with calcite veins, a layer of the porous material (upper right corner) also observed in thin section 1 and the fine-grained layers of calcite (left edge) also observed in thin section 2.

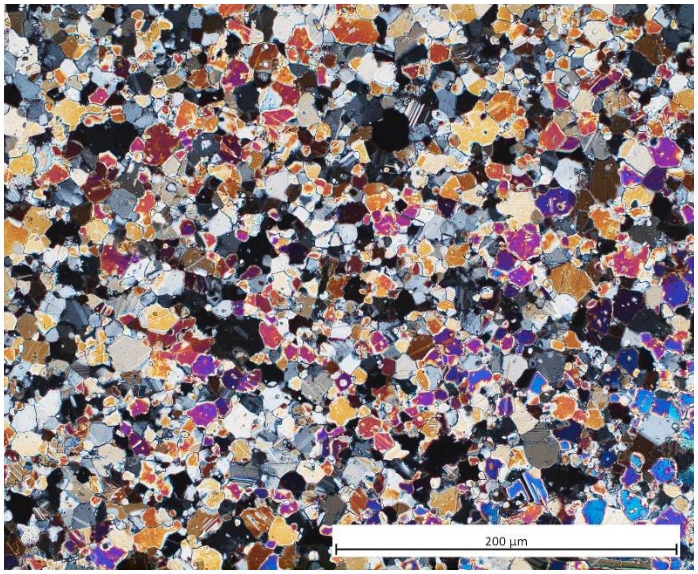

Figure 19 – The grain size in the fine grained layer is very uniform and some twins are present in these small grains (TS3, cross polarized light, ultra-thin portion of section).