

# **The Ordovician Tøyen Shale, and its Eight Steps through Diagenesis - An Overview\***

**Sven O. Egenhoff<sup>1</sup> and Neil S. Fishman<sup>2</sup>**

Search and Discovery Article #51358 (2017)\*\*

Posted February 6, 2017

\*Adapted from oral presentation given at SEPM-AAPG 2016 Hedberg Research Conference, Santa Fe, New Mexico, October 16-19, 2016

\*\*Datapages © 2017 Serial rights given by author. For all other rights contact author directly.

<sup>1</sup>Colorado State University, Fort Collins, Colorado, USA ([sven.egenhoff@colostate.edu](mailto:sven.egenhoff@colostate.edu))

<sup>2</sup>Hess Corporation, Houston, Texas, USA

## **Abstract**

The Lerhamn core, drilled in south-western Scania, southern Sweden, contains an approximately 70 m thick succession of the Early to Middle Ordovician Tøyen Shale. The succession was deposited in an outer shelf environment, likely below storm wave base based on a lack of wave induced sedimentary structures. The unit consists entirely of siliciclastic mudstones with varying amounts of diagenetic carbonate, phosphatic, siliceous, and sulfide cements. Prior to this study, diagenetic phases in this unit and their temporal relationships had not been described even though the Tøyen Shale as well as the underlying Alum Shale have the potential to be good source rocks and unconventional reservoirs. In addition, the nature and temporal relationships of diagenetic cements in the Tøyen were considered relative to those in the underlying Bjørkåsholmen Formation and overlying Huk Formation (both carbonate rocks) to evaluate the role, if any, in interformational fluid flow as it bears on Tøyen diagenesis. Seven temporally distinct diagenetic phases have been observed in the Tøyen, as determined from petrographic and SEM observations on thin sections (n = 53). Based on paragenetic relations between authigenic phases, the earliest-formed diagenetic mineral was chalcedony that exclusively exists as a cement within roundish organic-shelled microfossils and comprises less than 1 vol% of the rock based on visual estimations. In turn, the chalcedony is variably replaced by the paragenetically earliest generation of calcite observed in the Tøyen (Calcite 1). The chalcedony-calcite 1 cemented microfossils are preserved inside of centimeter-scale phosphatic concretions, with phosphate mineralization representing the third diagenetic mineral to have formed in the Tøyen. Fractures in the phosphatic concretions are rare, but where present they are filled with a coarsely-crystalline calcite (Calcite II); this generation of calcite clearly post-dates phosphate precipitation. Additionally, small phosphate crystals line the perimeter of presumed primary intergranular pores, and these pores were subsequently filled with coarsely-crystalline calcite (?),

which is inferred to also be calcite II. Replacement of calcite II crystals by very fine grained calcite (Calcite III) has been documented, and calcite III is generally observed adjacent to or within pyrite concretions. The relative timing of calcite III versus concretionary pyrite is unclear, and so is the relationship between the pyrite to most other cements. Nevertheless, at least two pyrite generations (plus one sphalerite generation?) are recognized. One of the generations of pyrite, here referred to as pyrite I, consists of isolated or multiple euhedral crystals and roundish sub-mm-scale pyrite aggregates or clumps of aggregates in the matrix. A second, texturally distinctive generation of pyrite (pyrite II), are up to mm-scale roundish or elongate masses, and are inferred to have formed as pyrite concretions. The outer margins of these concretionary pyrite masses are either irregularly bulbous or crystal facets.

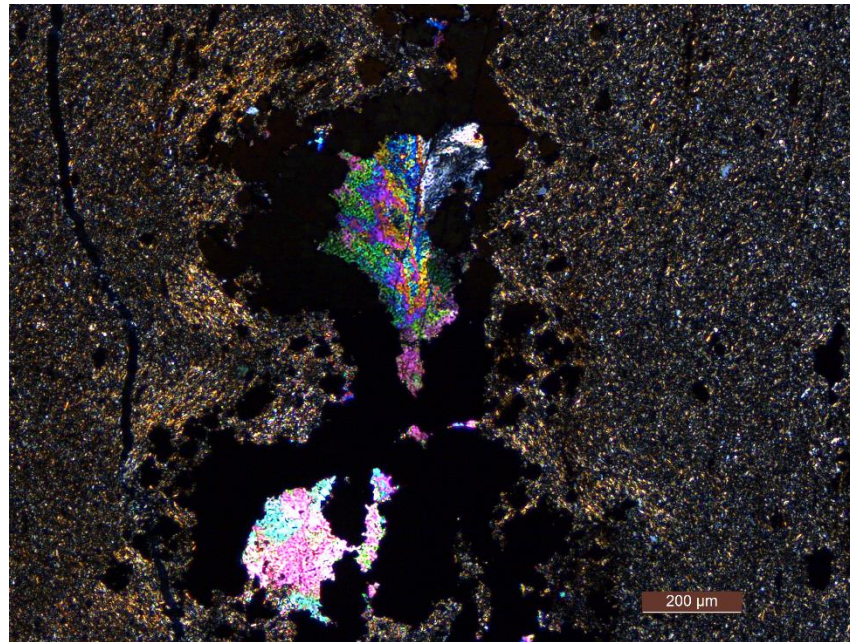
Even though the Tøyen Shale is stratigraphically separated from the underlying high-TOC Alum Shale by the 1 m thick carbonate Bjørkåsholmen Formation, diagenesis in the Bjørkåsholmen shows significant differences from the Tøyen in the number of cement phases, and their relative paragenetic sequence: preliminary results from adjacent outcrops and core sample in Scania show that the Bjørkåsholmen Formation contains 3-5 carbonate and one pyrite generations of cement. The pyrite pre-dates the latest carbonate cement. However, the Bjørkåsholmen Formation lacks any quartz or phosphate cements. Our first data from the Huk Formation in Scania, a fine-grained carbonate unit directly overlying the Tøyen, also shows exclusively carbonate cements (3 generations?) and pyrite similar to the Bjørkåsholmen Formation but markedly dissimilar from the Tøyen. This study therefore suggests that shale units, even though in close proximity to carbonate units, seem to generally undergo independent diagenetic pathways and thus, interformational fluid flow does not seem to effect shale diagenesis. Therefore, unconventional reservoirs, even though they may be adjacent stratigraphically and regionally, should be expected to show very different diagenesis and geo-mechanical behavior, and behave as entirely separate units when subjected to hydraulic fracturing.

### **Selected Reference**

Bruton, D.L., and S.H. Williams (eds.), 1982, Field Excursion Guide IV International Symposium on the Ordovician System: Paleontological Contributions from the University of Oslo 279, 217 p.

# The Ordovician Tøyen Shale

and its eight steps through diagenesis – an overview



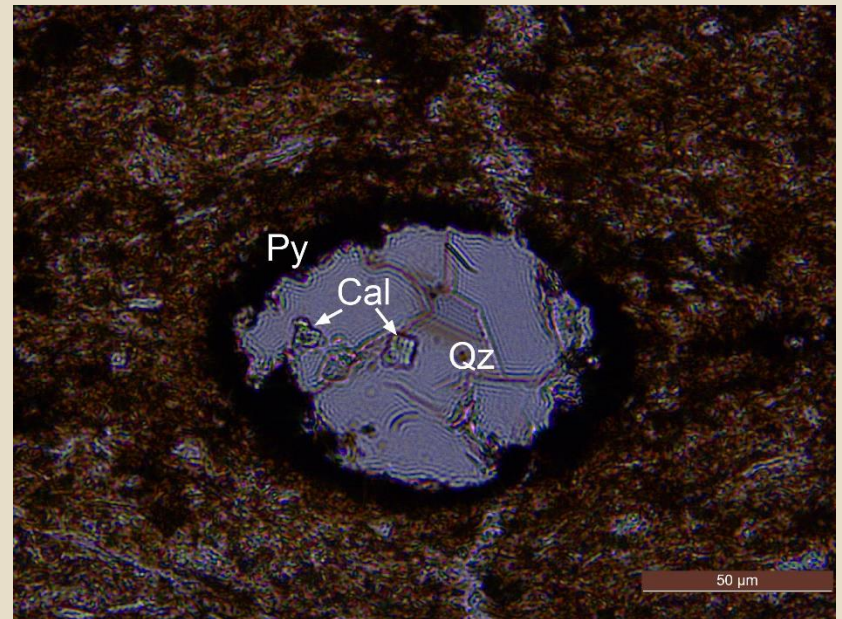
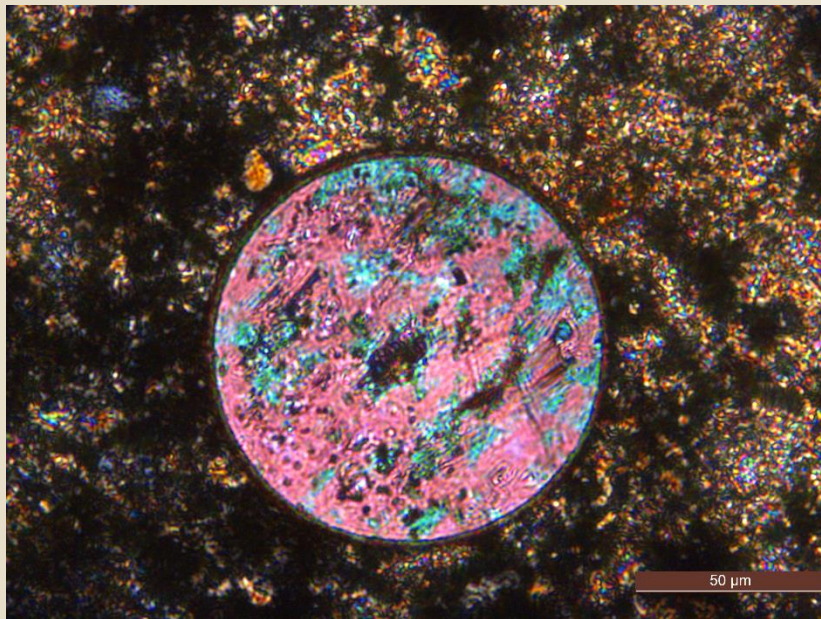
**SVEN EGENHOFF & NEIL FISHMAN**

Thursday, October 13, 2016

# Introduction and problem



- Mudstones – often undergo heavy diagenesis
- But: how much different is diagenesis of directly adjacent shale units?

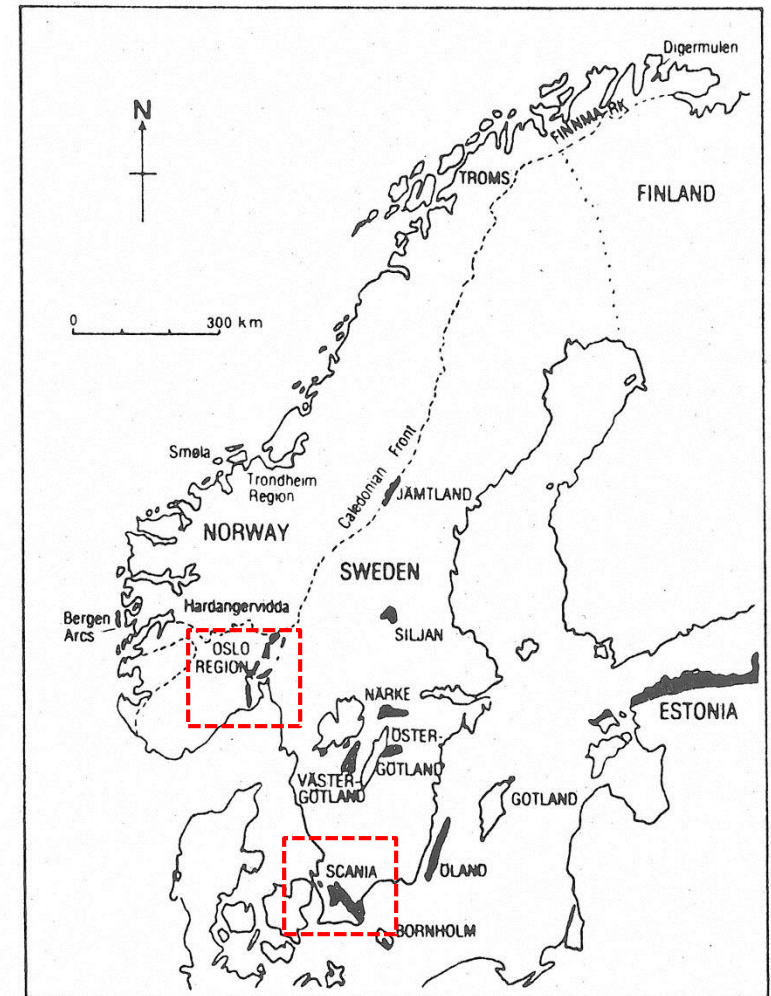




# Distribution of Ordovician Sediments in Scandinavia

- Cambrian to Ordovician succession in Sweden/Norway
  - Scattered large and small outcrops in southern and central Sweden
  - One relatively continuous outcrop area around Oslo in Norway

Bruton and Owen 1982

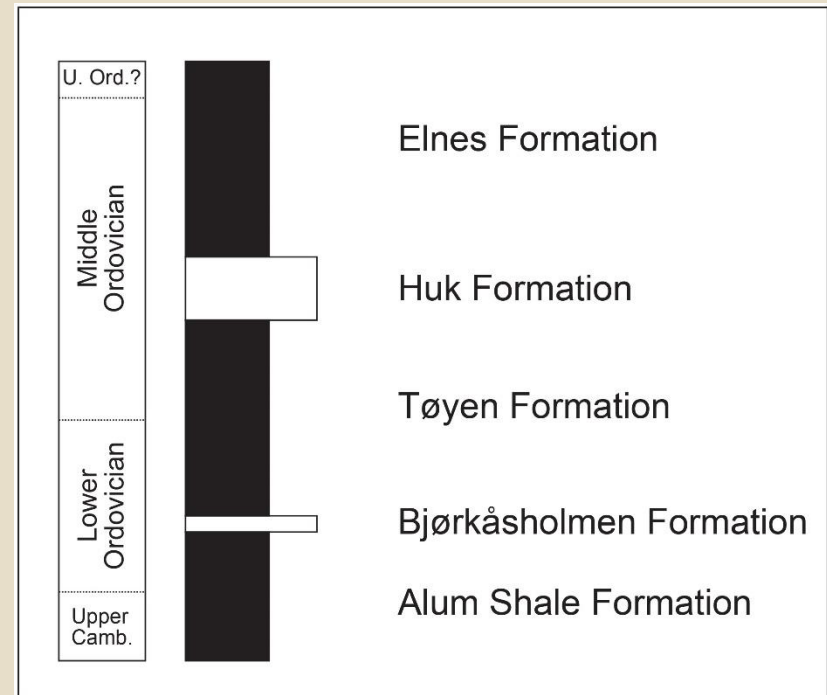


# Stratigraphic Framework

## Ordovician succession of Scandinavia



- Lower part of succession
  - Middle Cambrian to Lower Ordovician Alum Shale Formation (~100 m thick)
  - Thin carbonate unit above, Bjørkåsholmen Fm. (~1 m)
  - Lower to Middle Ordovician Tøyen Formation (5-20.5 m thick in Oslo area)
  - Huk Formation (2.5-13.5 m)
  - Elnes Formation (~60 m); partly Upper Ordovician?



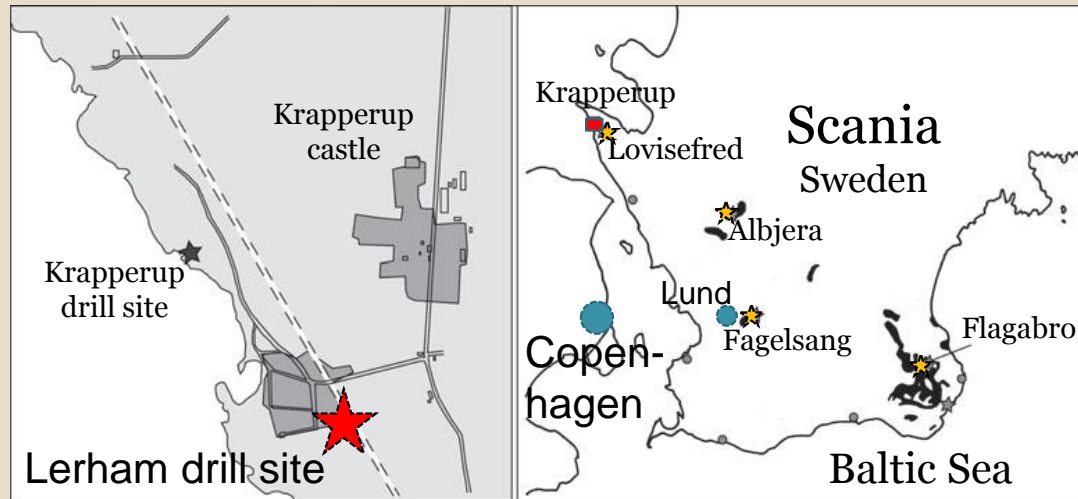
Modified after Bruton and Williams 1982

# Study Area: Lerham core, Scania

Southern Sweden



- Observations presented here: Based on one core
- Lerham core – Scania (southern Sweden), ~70 m Tøyen Fm.
- One of several cores in Lower Paleozoic sediments

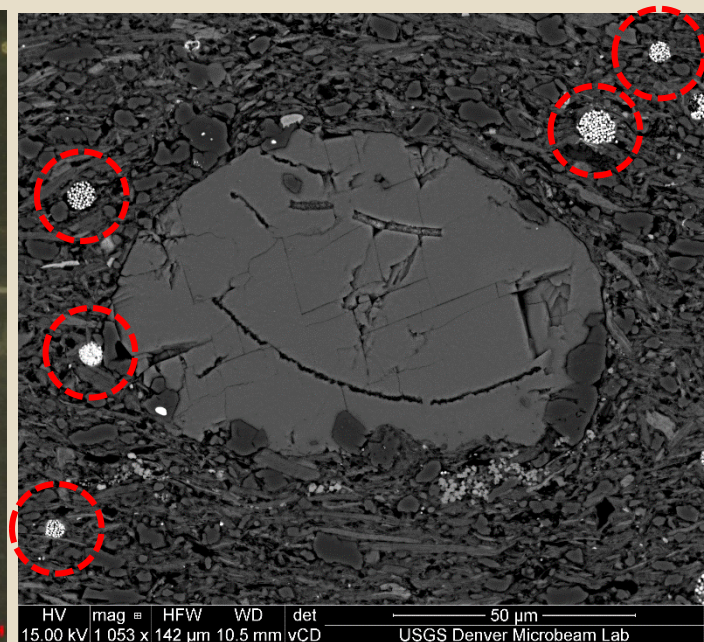
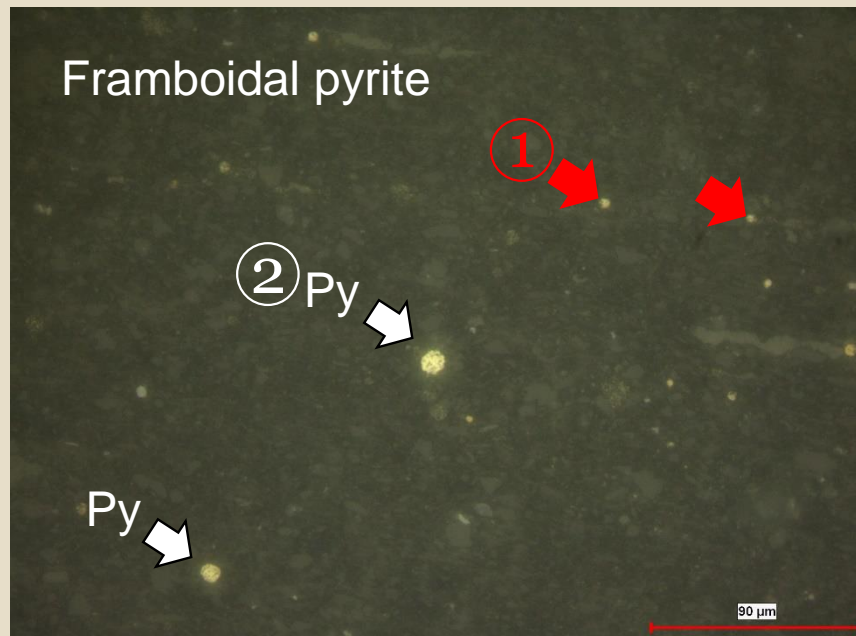


- Total of 76 thin sections of siliciclastic mudstones (Tøyen Fm.)
- Compare observations to underlying units, especially Alum Shale

# Pyrite



- Several generations: (1) isolated, individual pyrite crystallites ( $\sim 3\text{-}6\mu\text{m}$  in diameter, red arrows), (2) matrix framboids (white arrows and red circles, up to  $5\text{-}12\mu\text{m}$ )

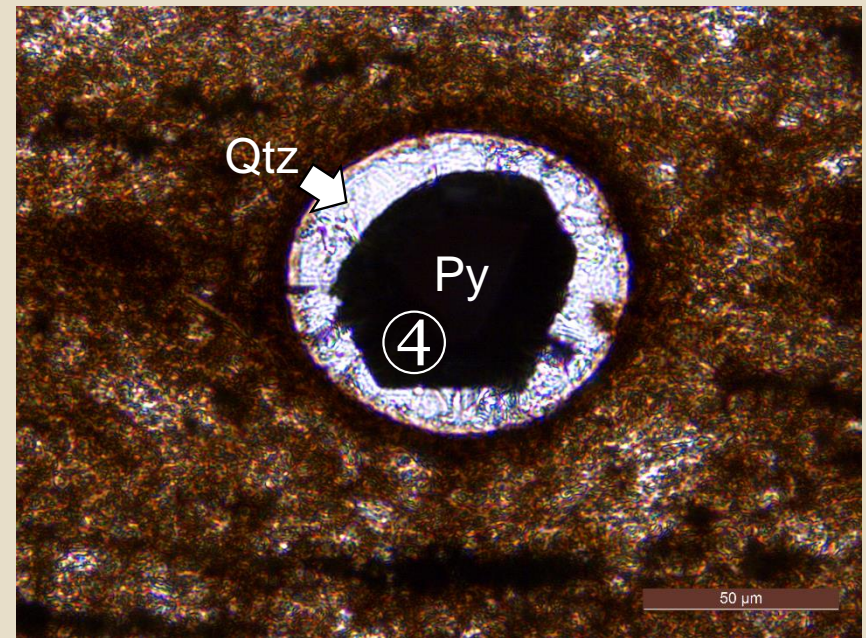
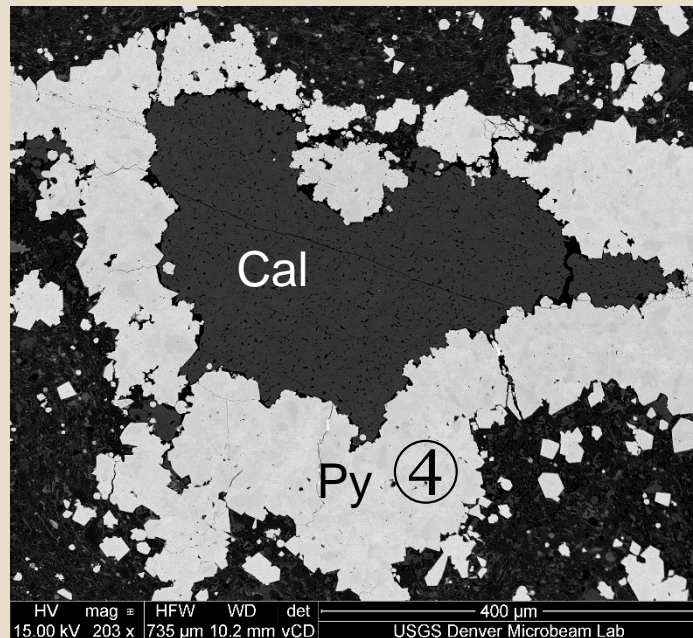




# Pyrite



- Several generations (continued): (3) framboid concretions, (4) euhedral pyrite (several generations) → likely succession of pyrites

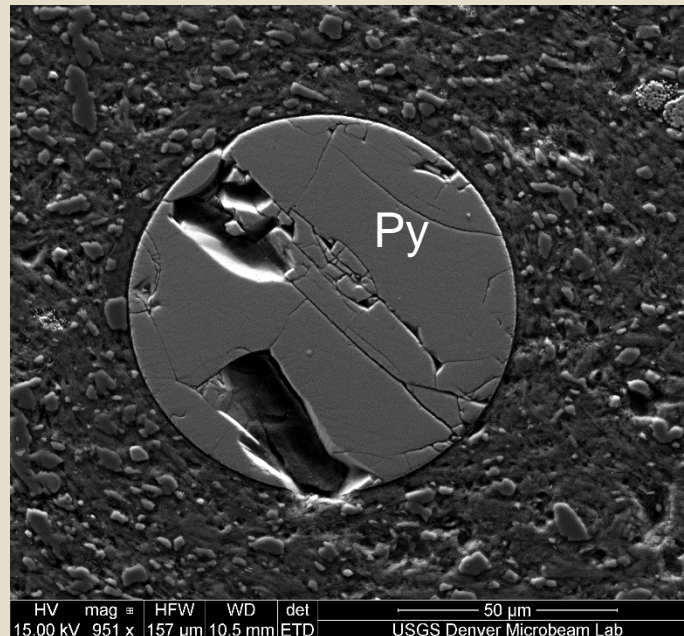


# Pyrite generations

What do we know?



- First three generations – crystallites and framboids – all early, no temporal framework
- Euhedral: (4a) Round microfossil completely filled with pyrite (others are slightly compacted)



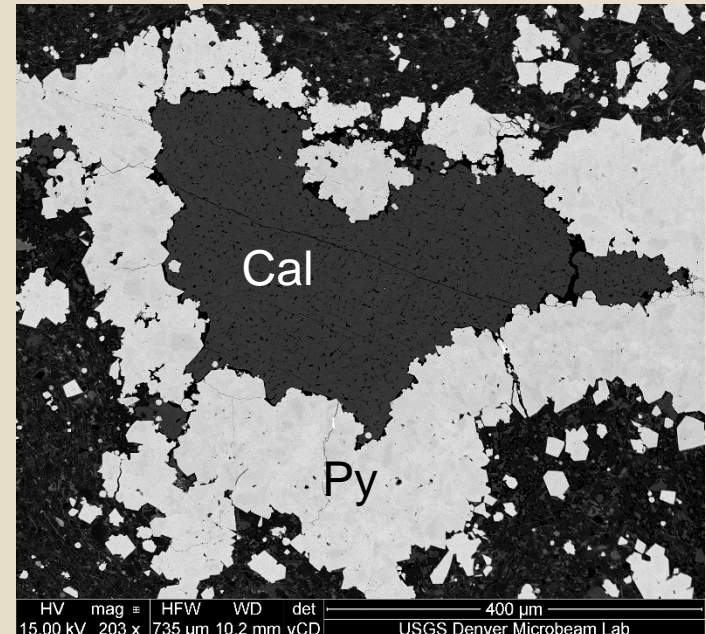
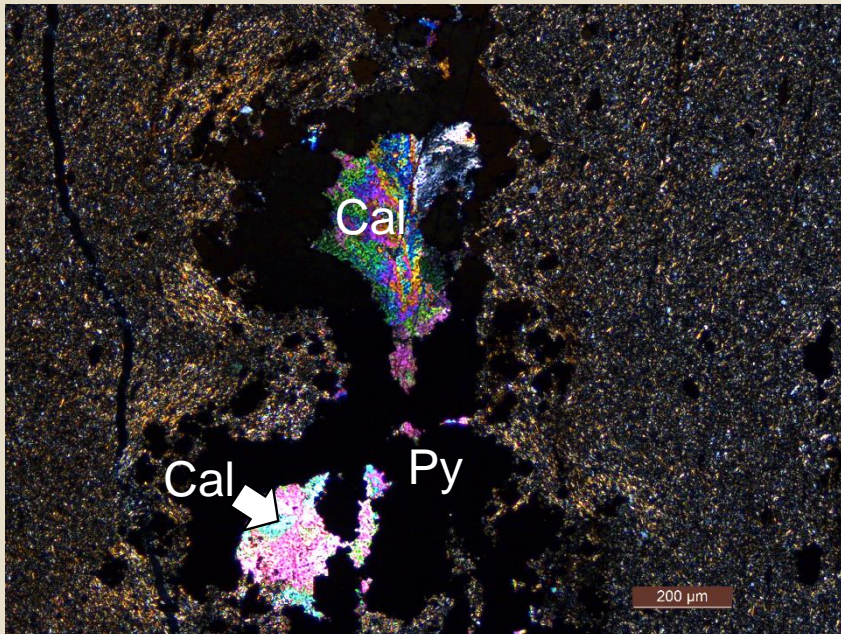


# Pyrite generations

What do we know?



- Euhedral: (4b) two? pyrite generations - pre-date calcite  
→ different grey shadows in SEM – but no chemical difference detectable

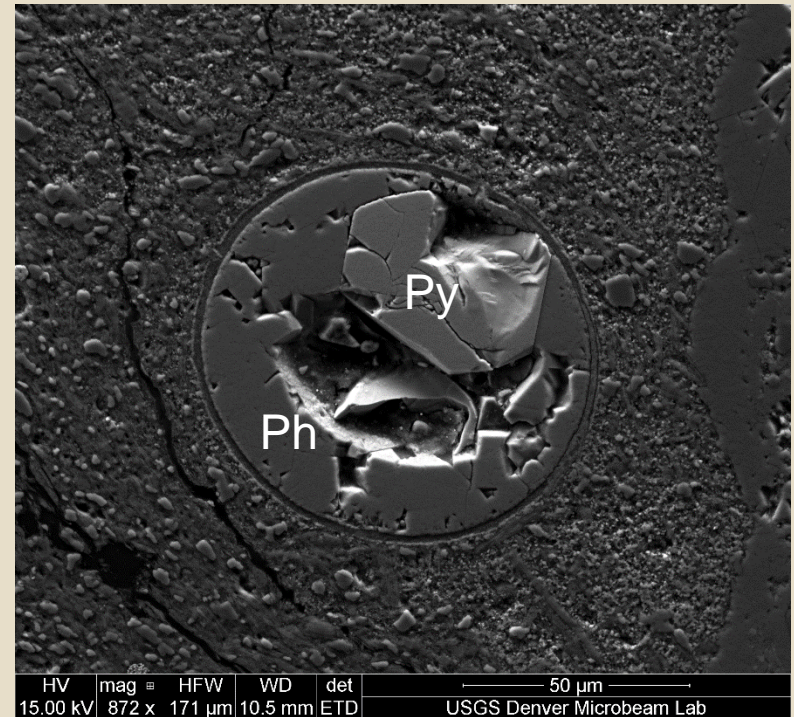
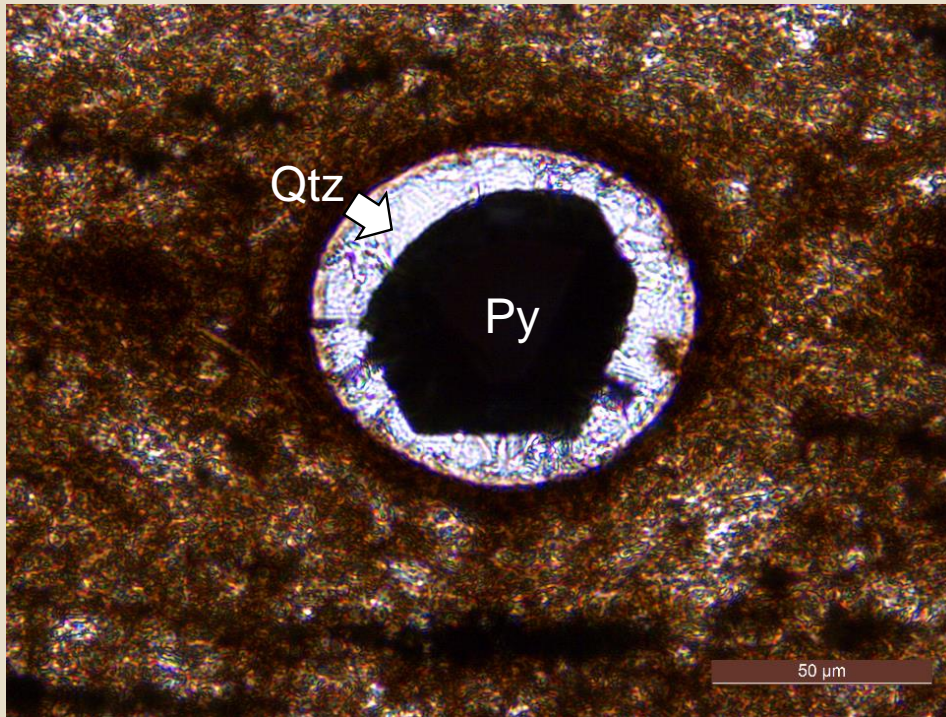




# Pyrite



- Euhedral: (4c) Pyrite that post-dates quartz – and (if the same, or 4d) post-dates apatite recorded in slightly compacted calcispheres

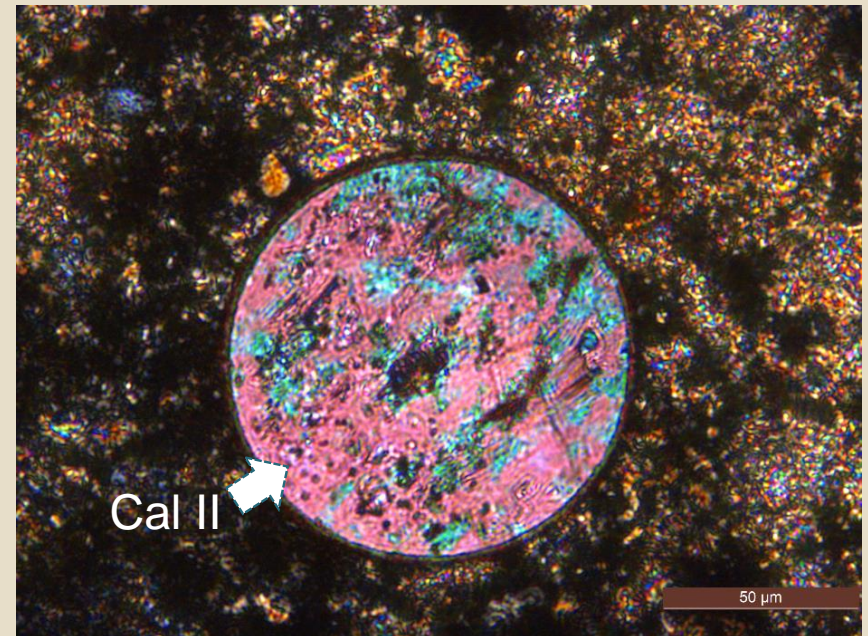
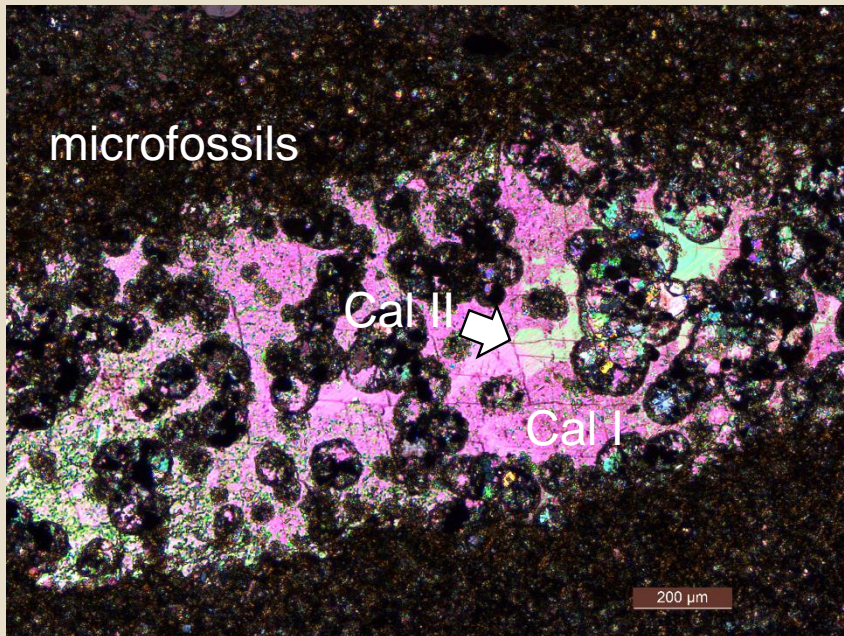




# Carbonate cement



- Two generations of calcite in concretions – outer rim of concretion = cloudy, inner part = clear
- Cloudy calcite I – not present otherwise
- Clear calcite II – also filling microfossils

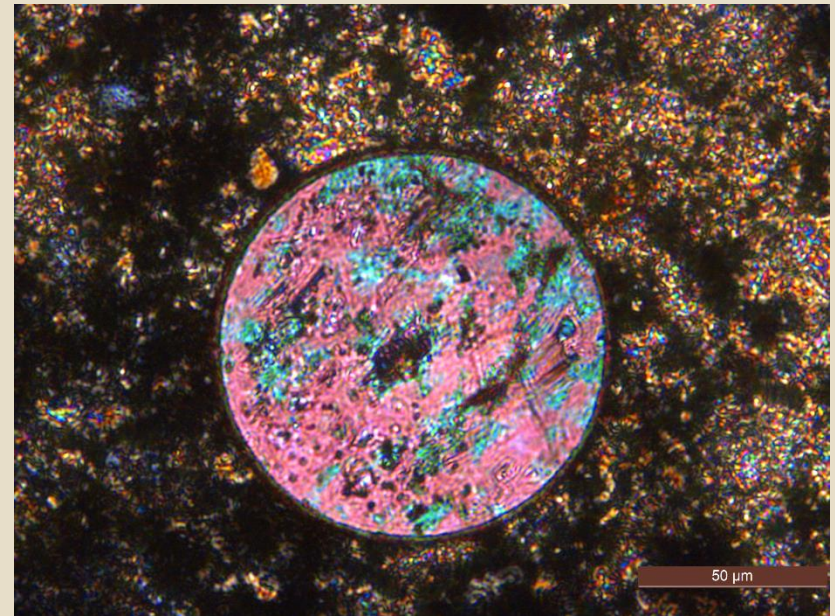
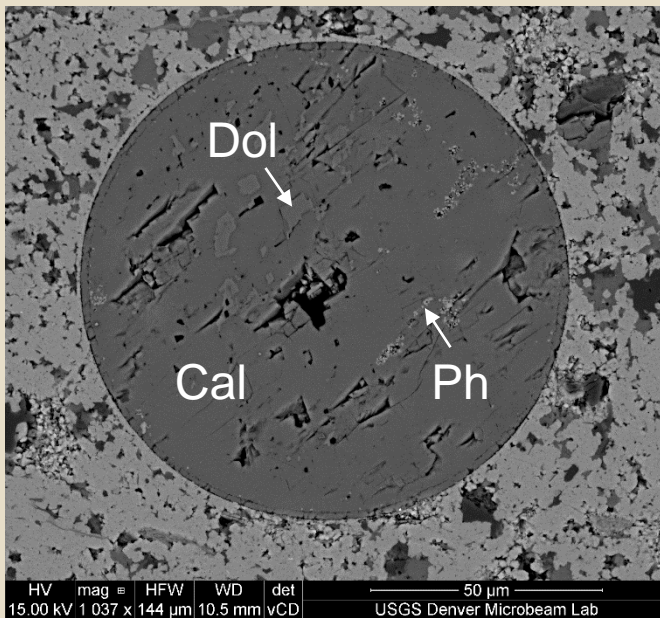
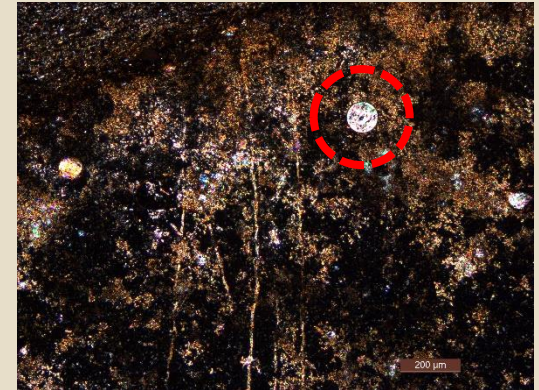




# Carbonate cement



- Calcite in round calcispheres – pre-compaction!
- Fill: calcite, some dolomite, minor phosphate
- Dolomite earliest (filled entire cavity, extinguishes all at once), then clear calcite (II?), then phosphate (concretion)

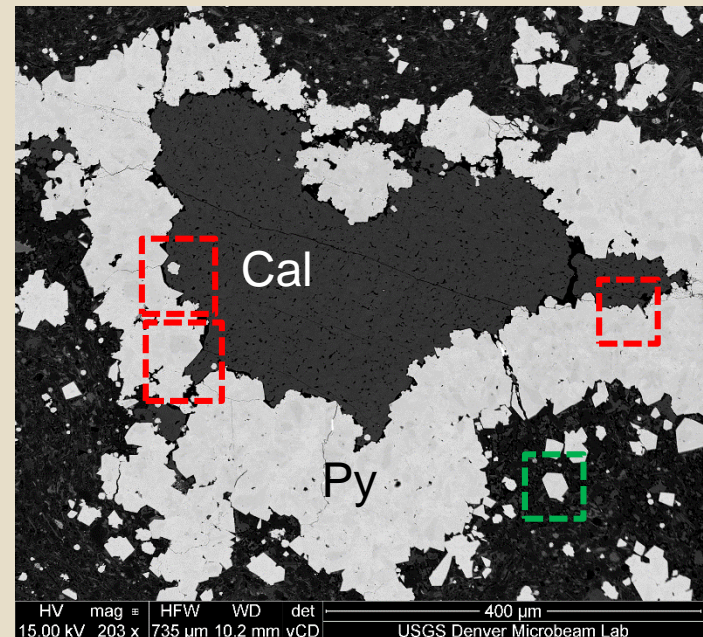
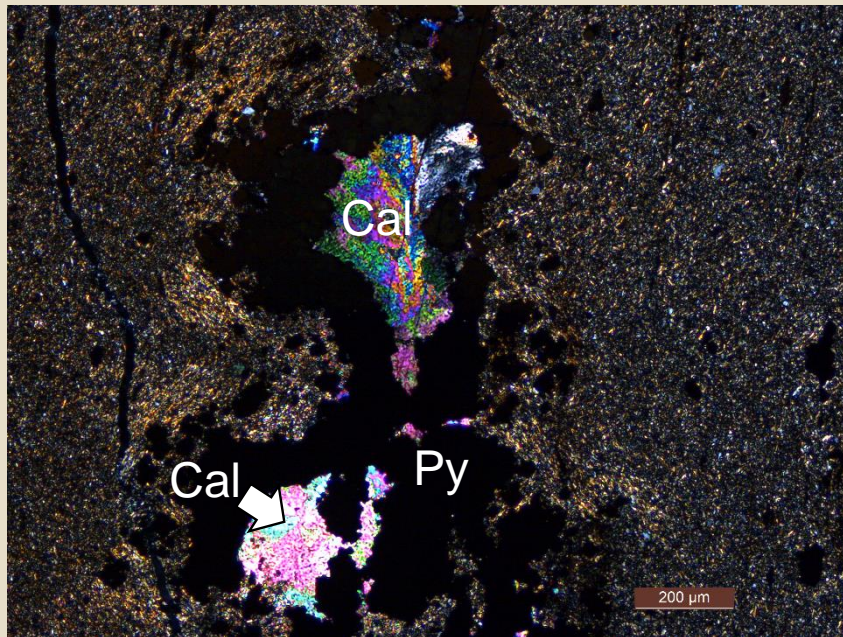




# Carbonate cement



- Calcite inside pyrite concretions – clear calcite II?
- Later than two of the euhedral pyrite generations
- Also as isolated euhedral pyrite crystals in the matrix (green boxes)

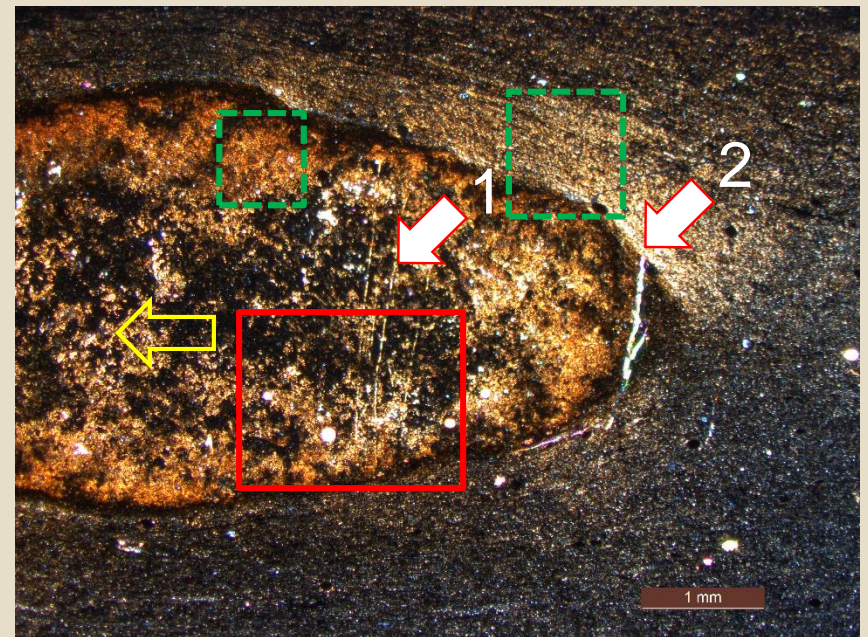
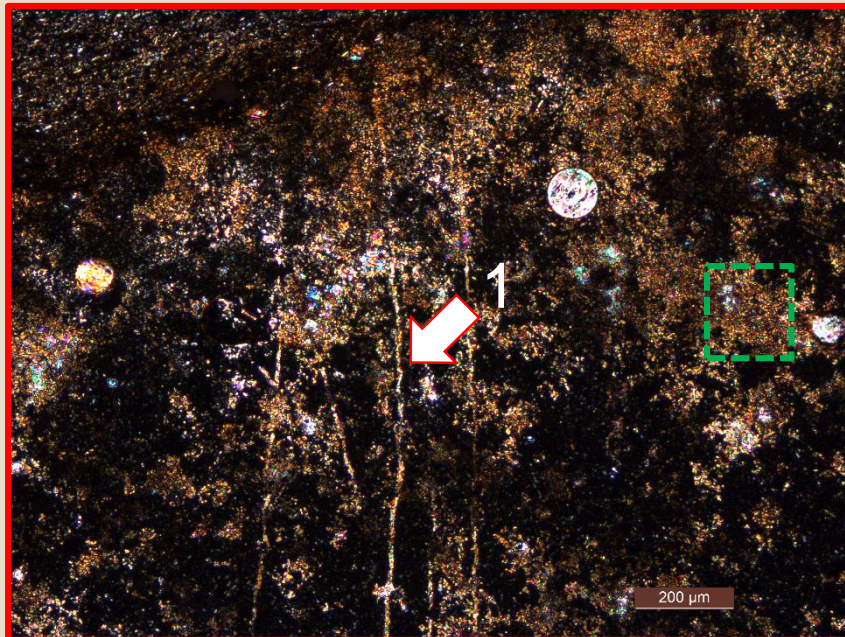




# Carbonate fractures



- Carbonate-filled fractures – 2 generations?
- Microcrystalline carbonate in and outside concretion (green boxes); all optically in tune

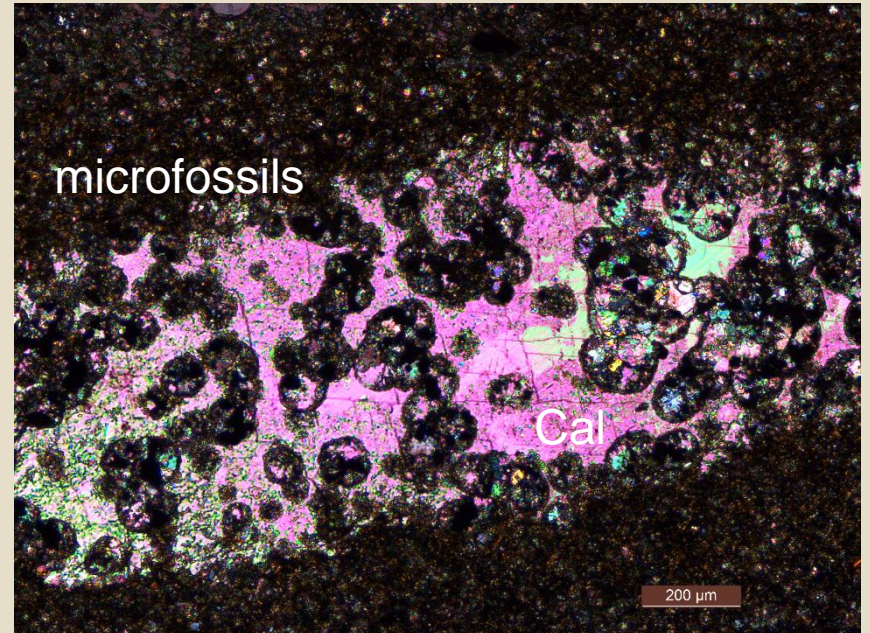
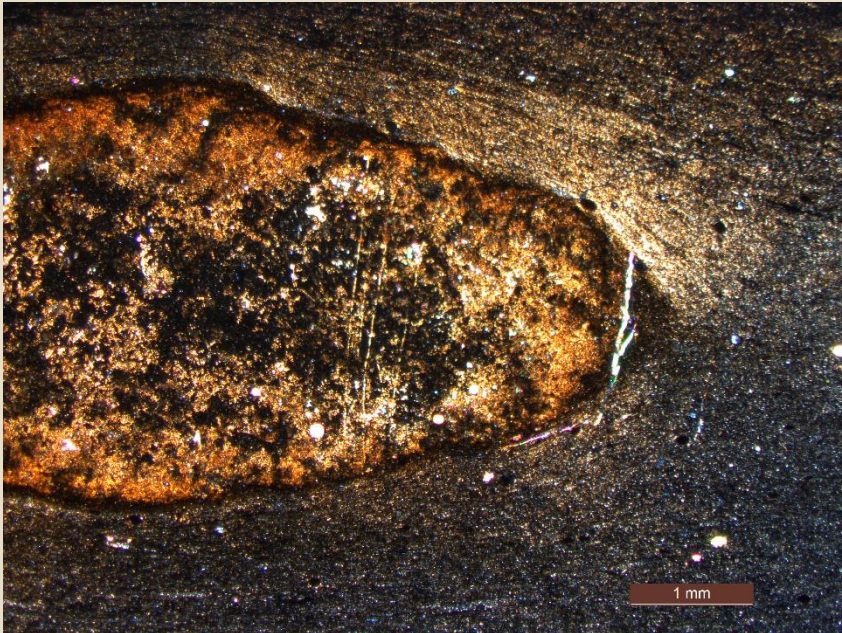




# Recrystallization of carbonate [cement]



- Calcite is likely recrystallized – undulose extinction throughout concretions and beyond
- # of calcite generations therefore unclear: microcrystalline, fractures (2?), outside concretion

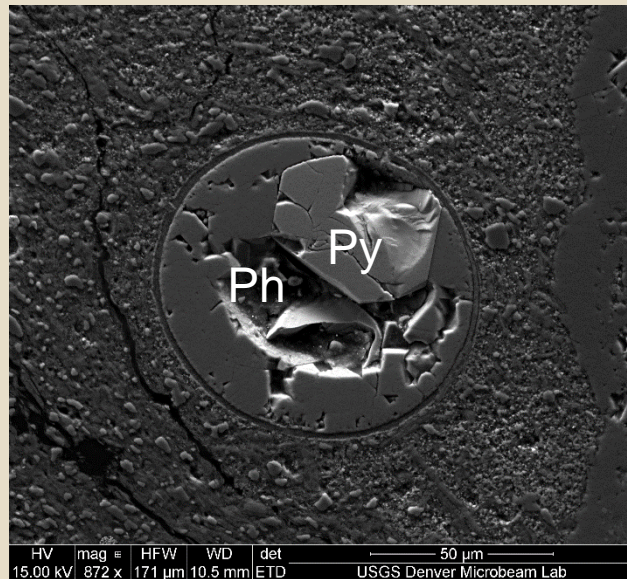




# Phosphate



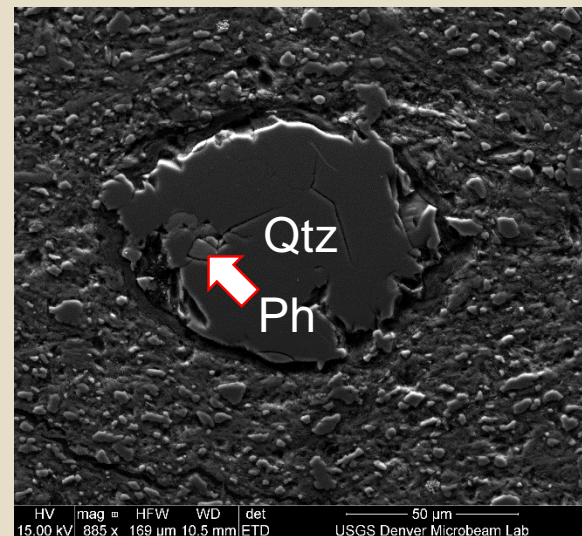
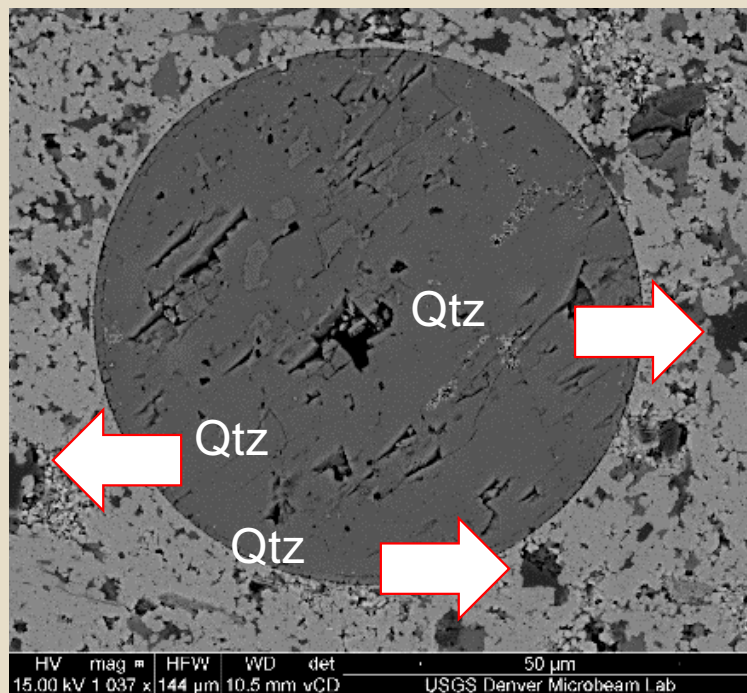
- Phosphate, generally in concretions
- Often substituted by carbonate (calcite)
- In places fills concretions, it is locally replaced by pyrite



# Quartz



- In concretion, filling microfossils, in places replacing (?) phosphate
- Not abundant; likely post phosphate

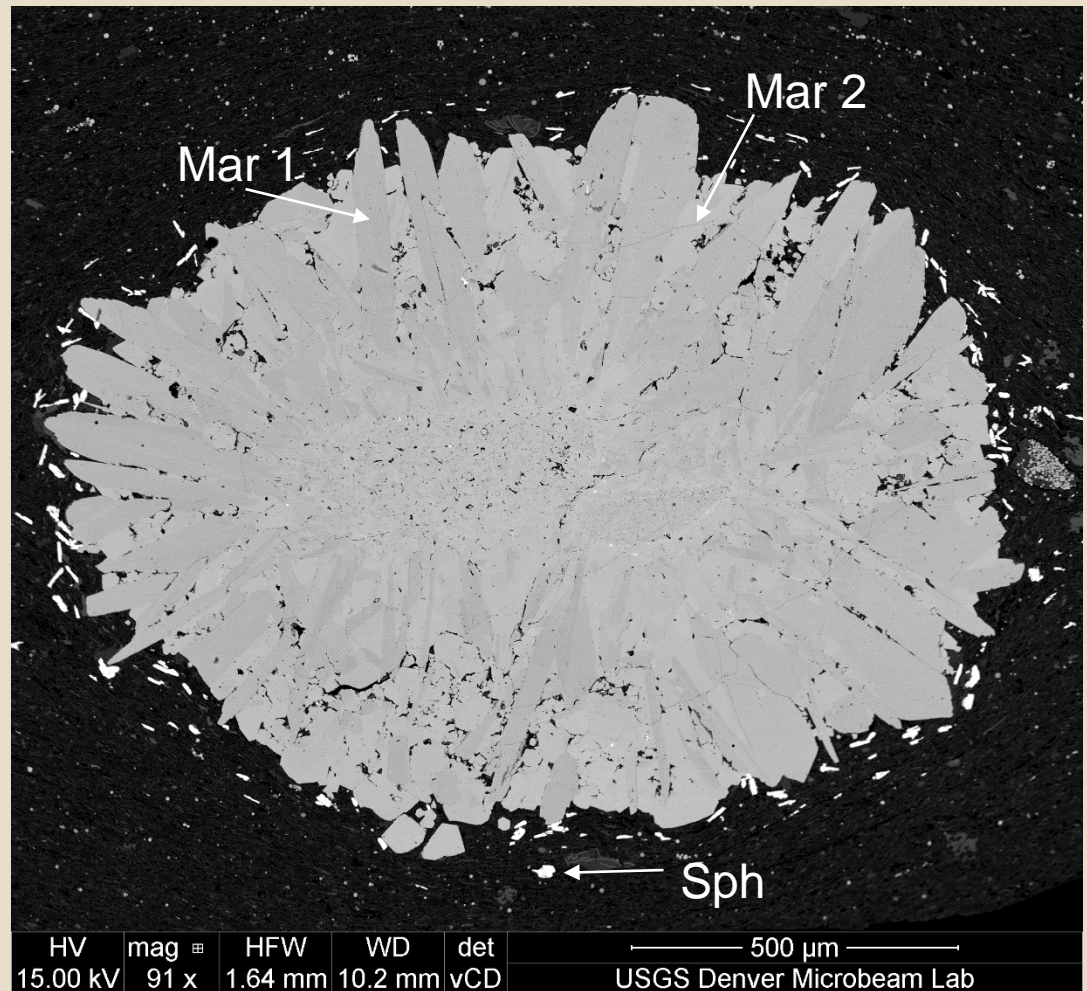




# Markasite



- In concretions only
- Two types of marcasite;
- (1) = dark grey, intergrown with (2) = light grey
- Sphalerite around concretion
- Likely sphalerite after marcasite

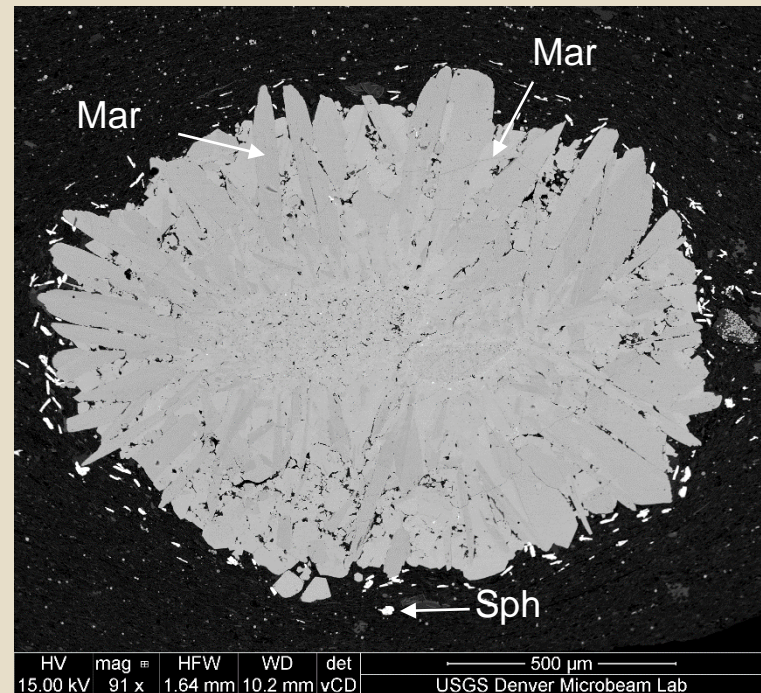
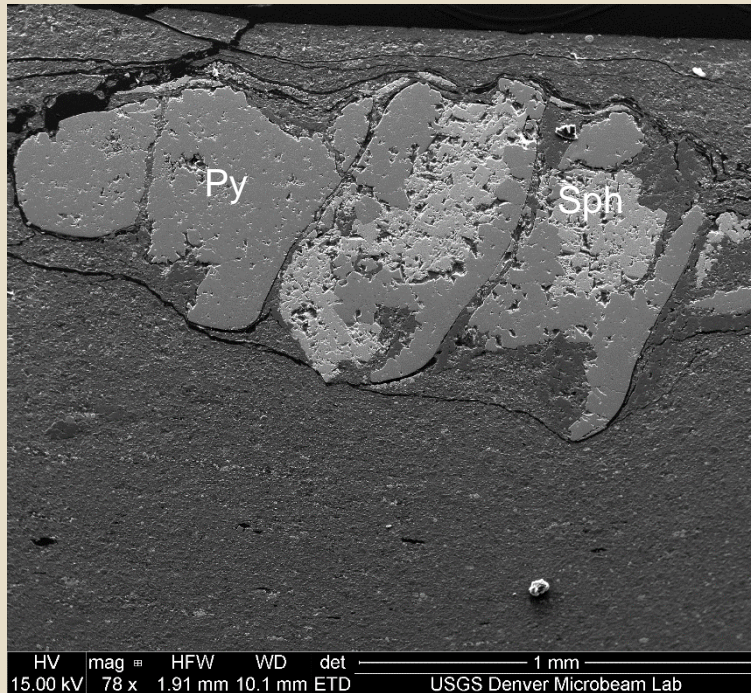




# Sphalerite



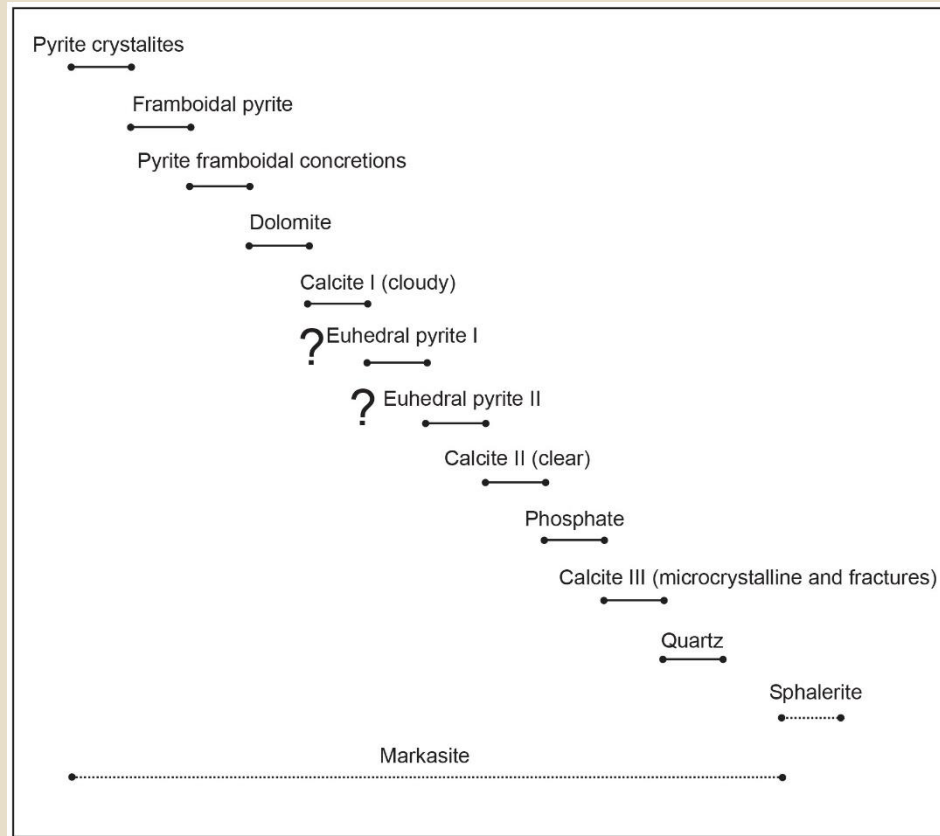
- In and outside of concretions
- Anhedral
- After marcasite, after pyrite



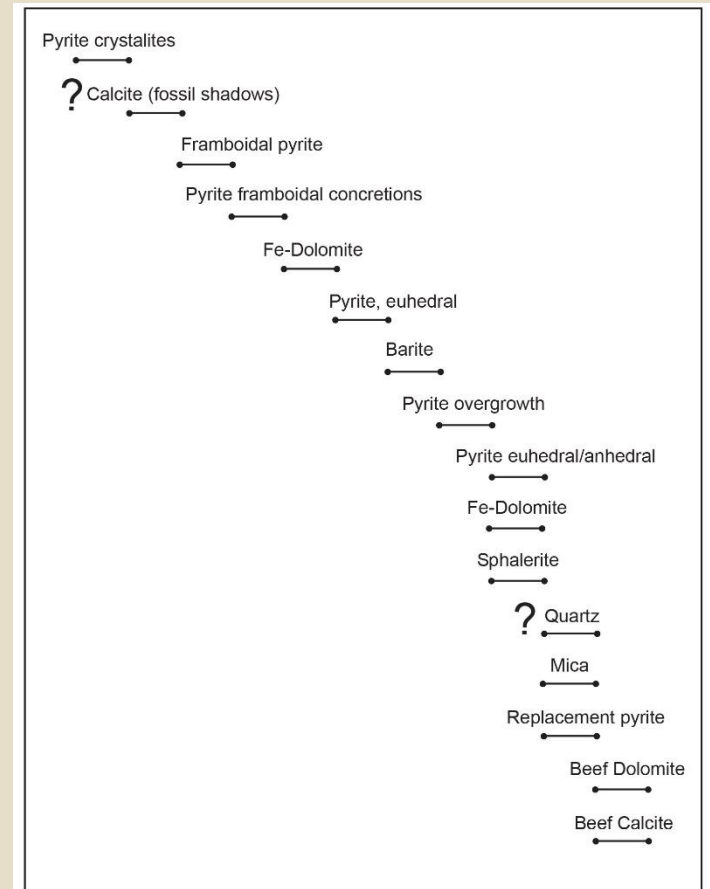
# Cement Succession



## Tøyen Formation



## Alum Shale



# Conclusions



1. Pyrite, dolomite, calcite, phosphate, quartz, marcasite and sphalerite cements present in Tøyen Formation
2. Crystallites and framboidal pyrite earliest, Sphalerite last
3. Diagenesis in Tøyen Shale different from (nearly) directly underlying Alum Shale → shales are closed systems

