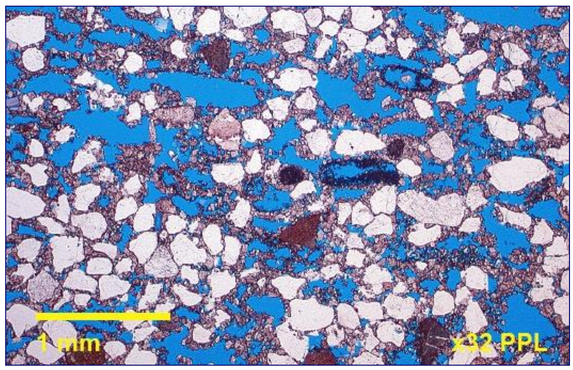
Siliciclastic Diagenesis (Tucker, pages 55-65)

Physical, chemical, and biological changes to sediment *after deposition*, but before metamorphism.

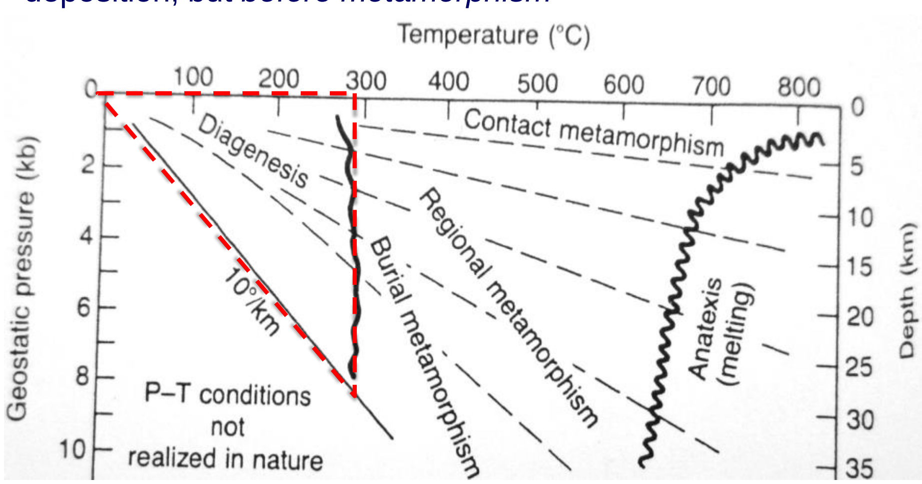
Very important for understanding the distribution of porosity and permeability in rocks.

Ore deposits produced by movement of fluids (*e.g*., uranium), *etc*.



Diagenesis

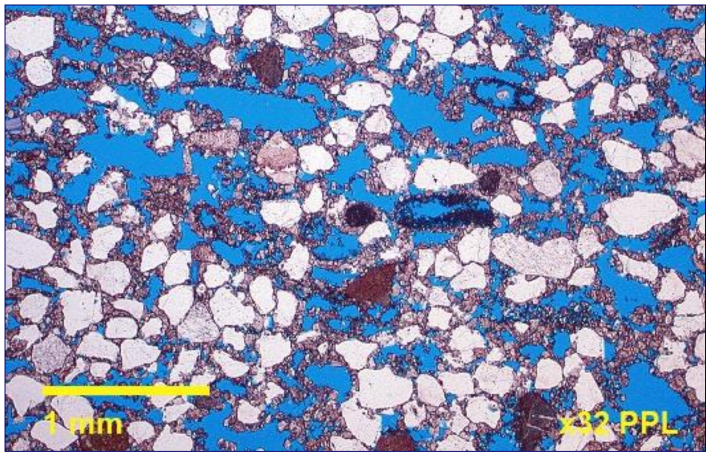
Physical, chemical, and biological changes to sediment after deposition, but *before metamorphism*



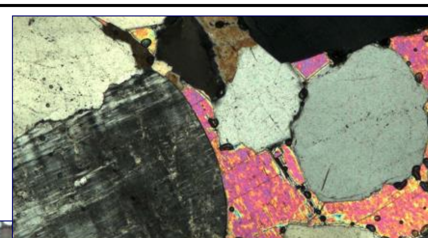
Diagenesis

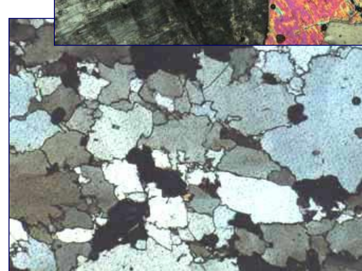
Typically makes provenance studies difficult (sediments altered to equilibrium of diagenetic fluid / environment)

Predicting these reactions is *very* difficult (many controlling factors)



Diagenesis – Main Processes





Compaction

Lithification (cementation)

Generally below 300°C, 1-2 kb pressure

Strongly dependent on provenance/maturity of host rock

General trends are predictable, related to depth

Main ‘Stages’ of Diagenesis

Eogenesis - Immediate changes, following burial
- Largely compaction
- Bioturbation (although much of it is syndepositional or penecontemporaneous)
- Changes in Eh and pH affect reactions (reducing vs. oxidizing) (early cementation)

Mesogenesis - Deeper burial (pressure/temperature)
- Pore fluid compositions change (cementation)
- Chemical stabilities change (alternation/dissolution)
- Compaction-induced dissolution along grain margins

Telogenesis - Uplift & exposure of buried sedimentary rock
- Retrograde reactions (cementation/cement dissolution)
- Oxidizing meteoric pore fluids (mineral alteration/Fe-oxide precipitation)

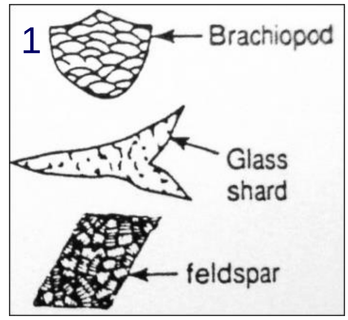
“The physical, chemical or biological alteration of sediments into sedimentary rocks at relatively low temperatures and pressures that can result in changes to the rock’s original mineralogy and texture.”

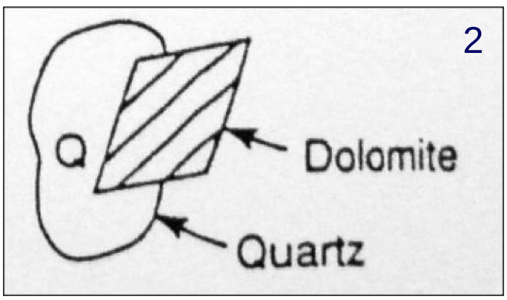
TABLE 6.8 Principal diagenetic processes and changes that occur in siliciclastic sedimentary rocks during burial

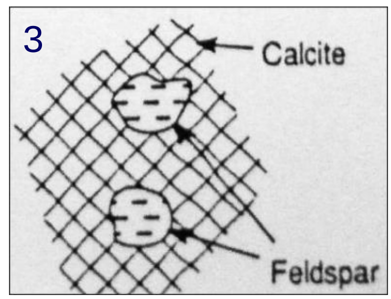
	Diagenetic stage	Diagenetic process	Result
Burial	Eodiagenesis (Early)	Organic reworking (bioturbation)	Destruction of primary sedimentary structures; formation of mottled bedding and other traces
		Cementation and replacement	Formation of pyrite (reducing environments) or iron oxides (oxidizing environments); precipitation of quartz and feldspar overgrowths, carbonate cements, kaolinite, or chlorite
	Mesodiagenesis (Late)	Physical compaction	Tighter grain packing; porosity reduction and bed thinning
		Chemical compaction (pressure solution)	Partial dissolution of silicate grains; porosity reduction and bed thinning
		Cementation	Precipitation of carbonate (calcite) and silica (quartz) cements with accompanying porosity reduction
		Dissolution by pore fluids	Solution removal of carbonate cements and silicate framework grains; creation of new (secondary) porosity by preferential destruction of less stable minerals
		Mineral replacement	Partial to complete replacement of some silicate grains and clay matrix by new minerals (e.g., replacement of feldspars by calcite)
		Clay mineral authigenesis	Alteration of one kind of clay mineral to another (e.g., smectite to illite or chlorite, kaolinite to illite)
Uplift	Telodiagenesis	Dissolution, replacement, oxidation	Solution of carbonate cements, alteration of feldspars to clay minerals, oxidation of iron carbonate minerals to iron oxides, oxidation of pyrite to gypsum, solution of less stable minerals (e.g., pyroxenes, amphiboles)

Indicators of Diagenesis

1) **Pseudomorphs** – replacement of original material, but retain original shape
2) **Cross-cutting grains**
3) **Poikilitic fabrics** (grain fragments floating in cement)





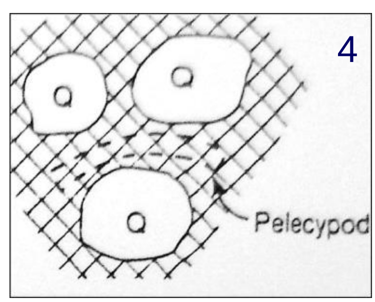


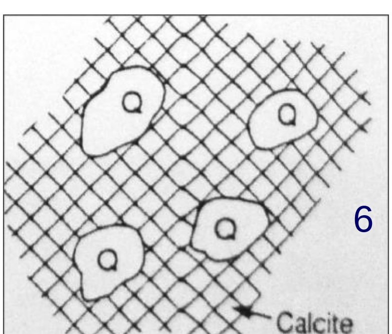
Indicators of Diagenesis

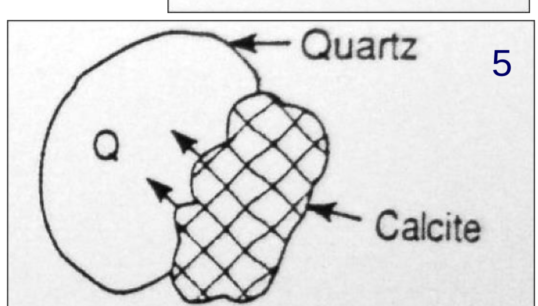
4) **Leached grains**

5) **Deformed grain boundaries** (embayed grain margins)

6) **Anomalous (loose) grain packing**







Compaction Controls

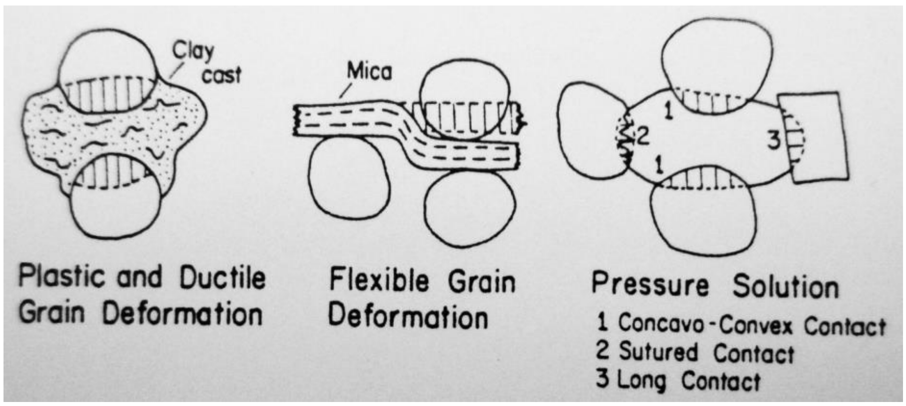
Grain types

Matrix content

Sorting

Burial depth

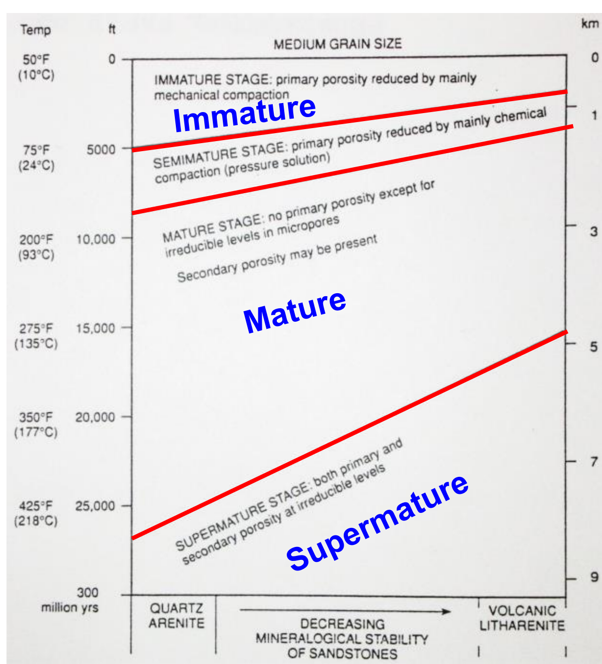
Temperature (grain ductility)



Diagenesis

Maturity *vs*. compaction (pore reduction): mature sediment requires greater temperature and pressure in order to compact media

Greater Burial Depths = pore occlusion *via* compaction; locally coupled with associated cementation (*e.g*., Qtz cement)



Diagenesis

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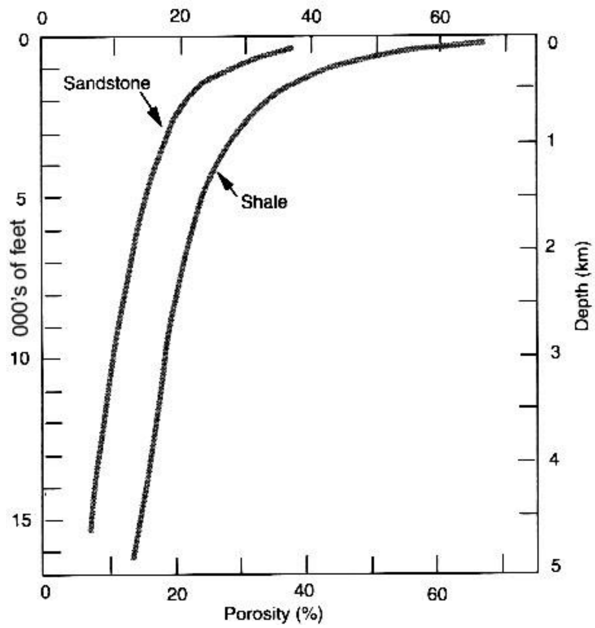


Results of Compaction

Sediment volume reduction

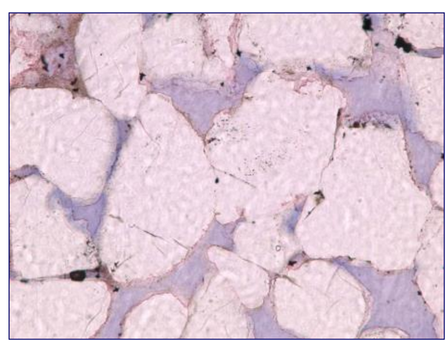
Dewatering (esp. muds)

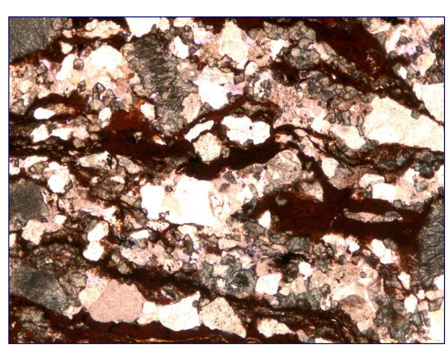
Decrease of pore space

Grain rearrangement

Grain deformation (brittle or ductile)

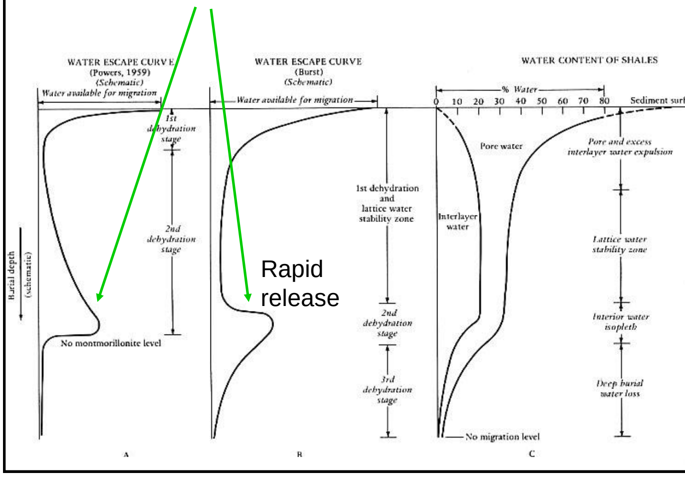
Pressure dissolution (chemical compaction)

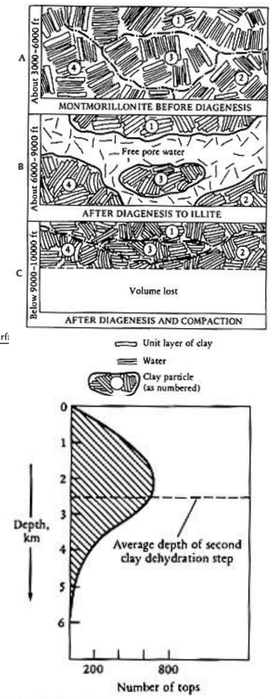




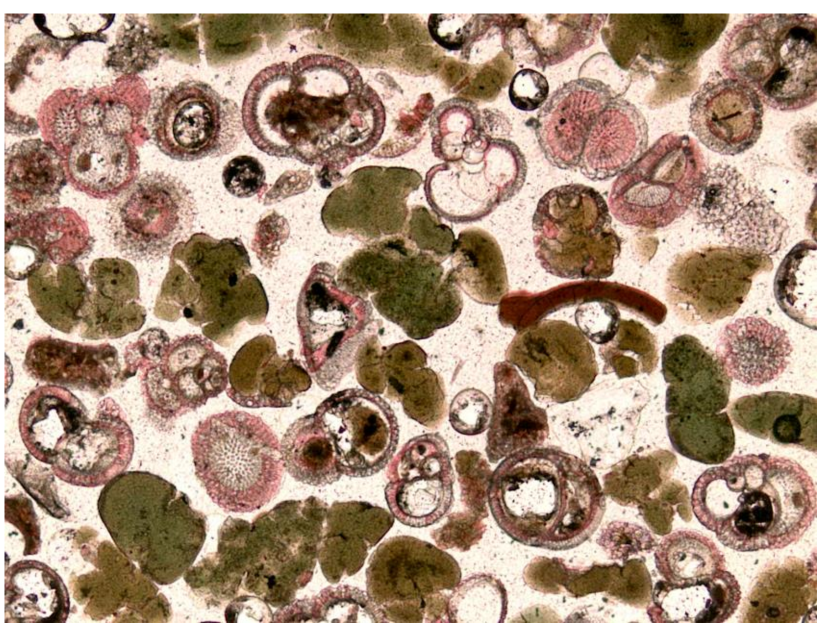
Secondary Clay Dewatering

Free water available for migration

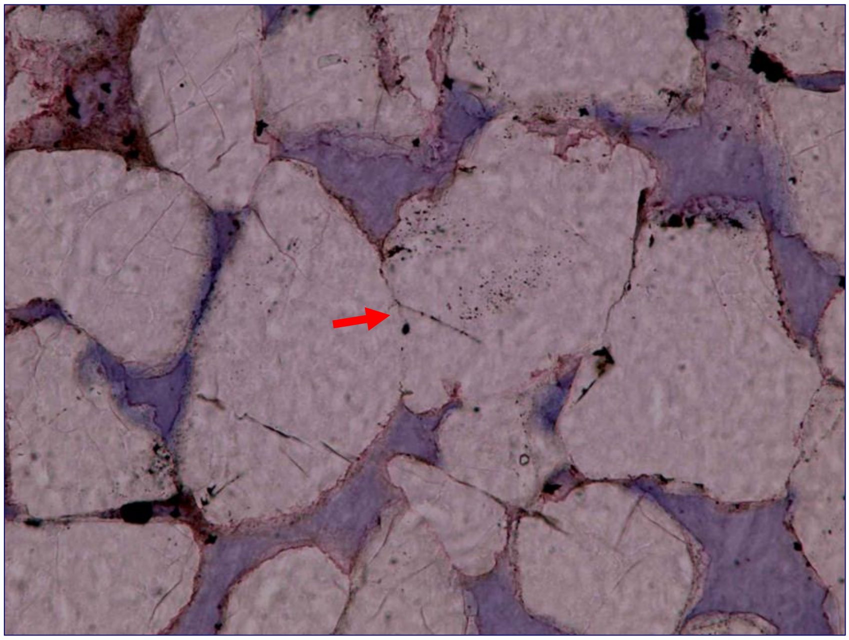




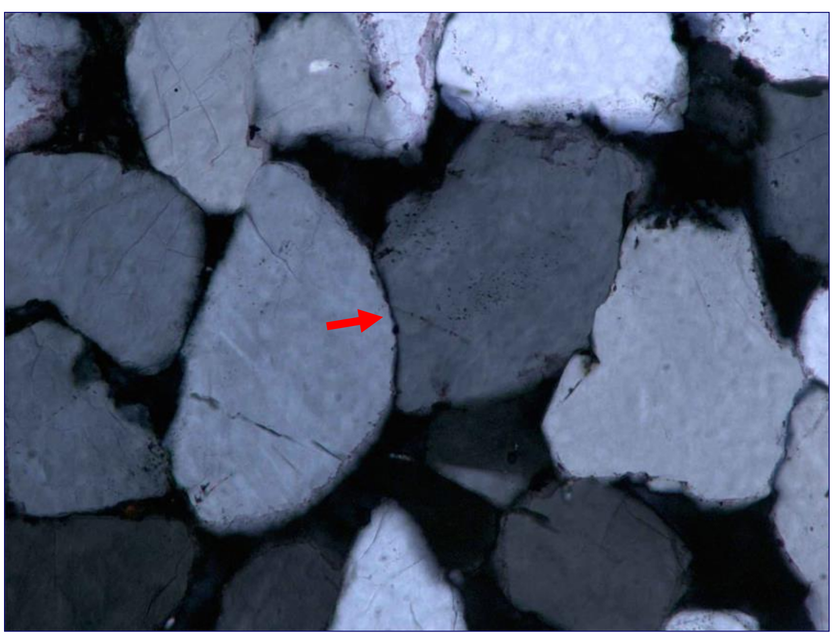
Pre-Burial Diagenesis: Glauconite + Uncompacted



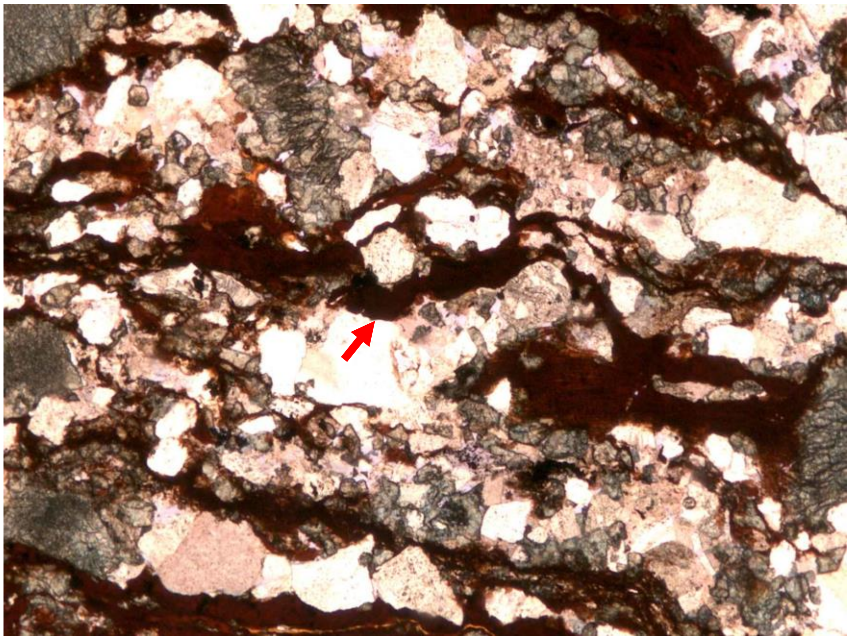
Grain Contacts: Locally no longer epiclastic



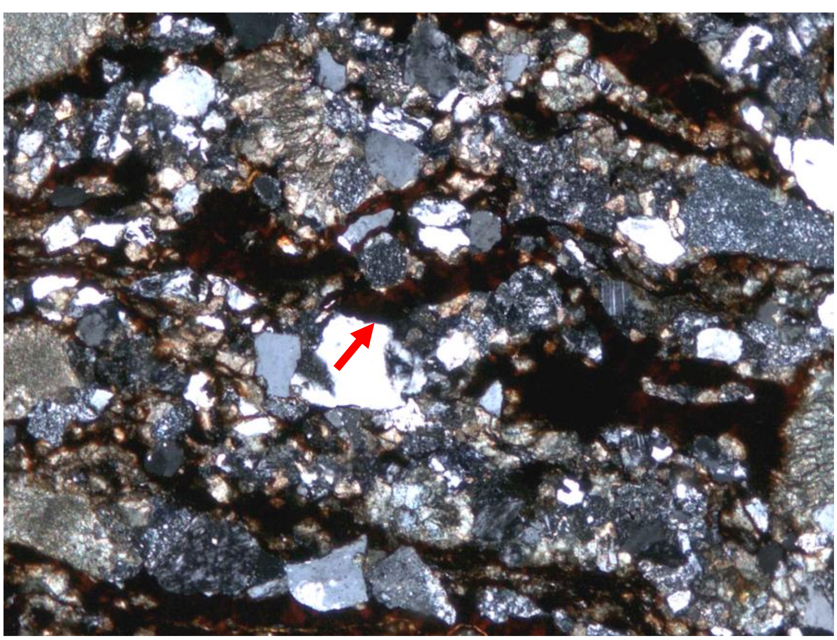
Grain Contacts: Locally no longer epiclastic



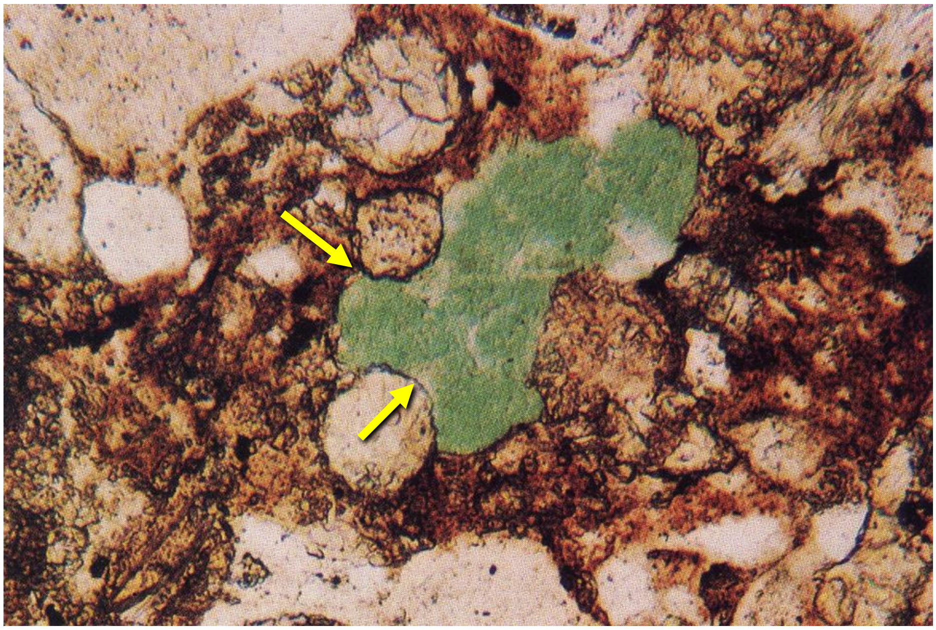
Grain Compaction: Ductile *vs*. Rigid



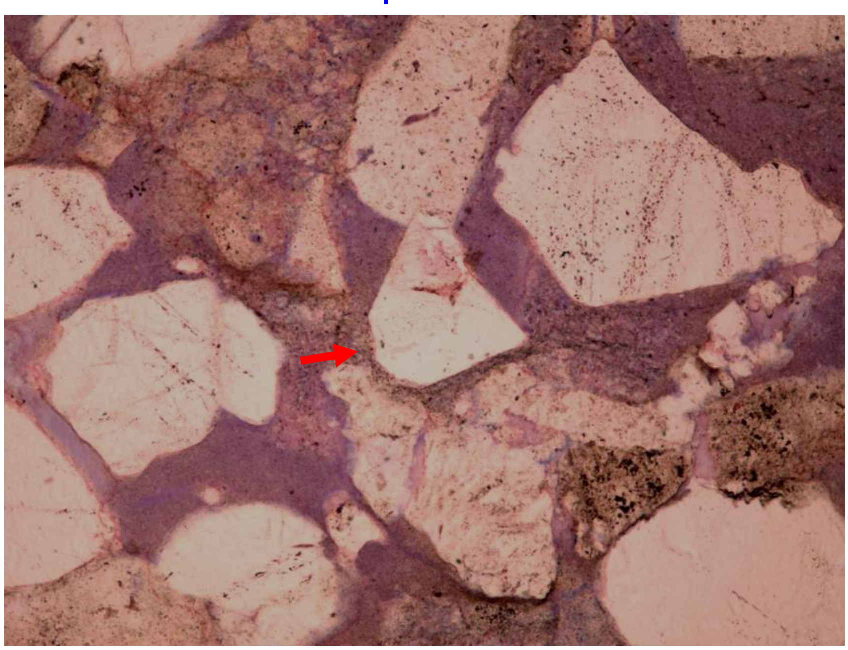
Grain Compaction: Ductile *vs*. Rigid



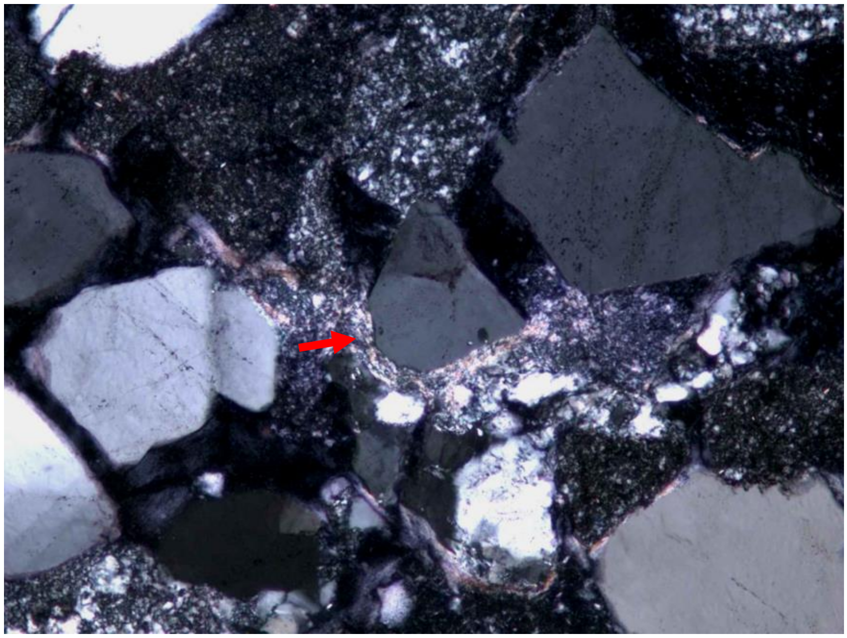
Grain Compaction: Ductile



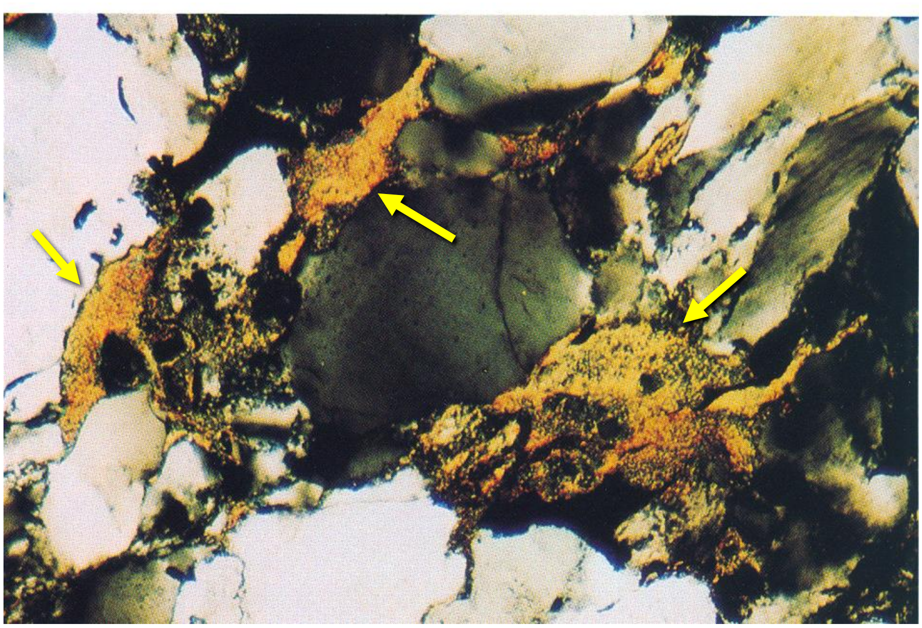
Grain Compaction: Ductile



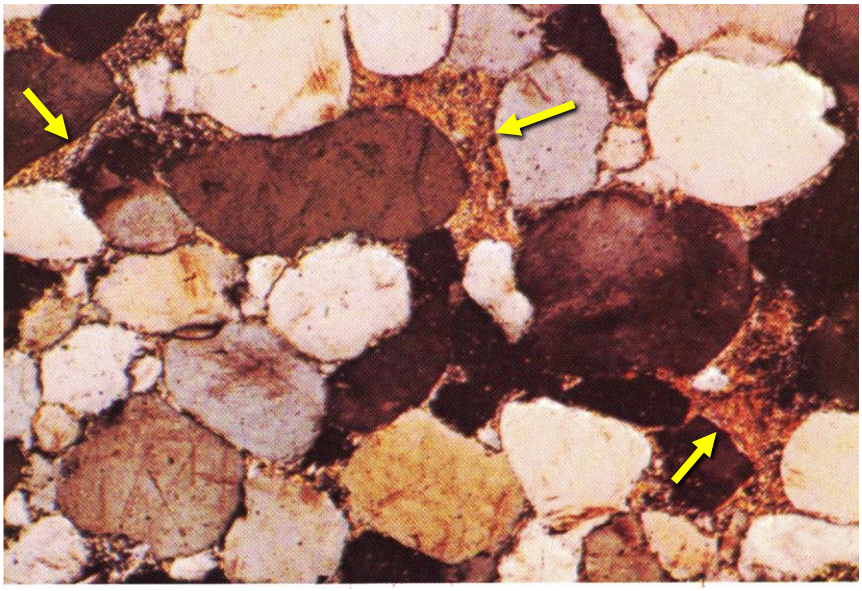
Grain Compaction: Ductile



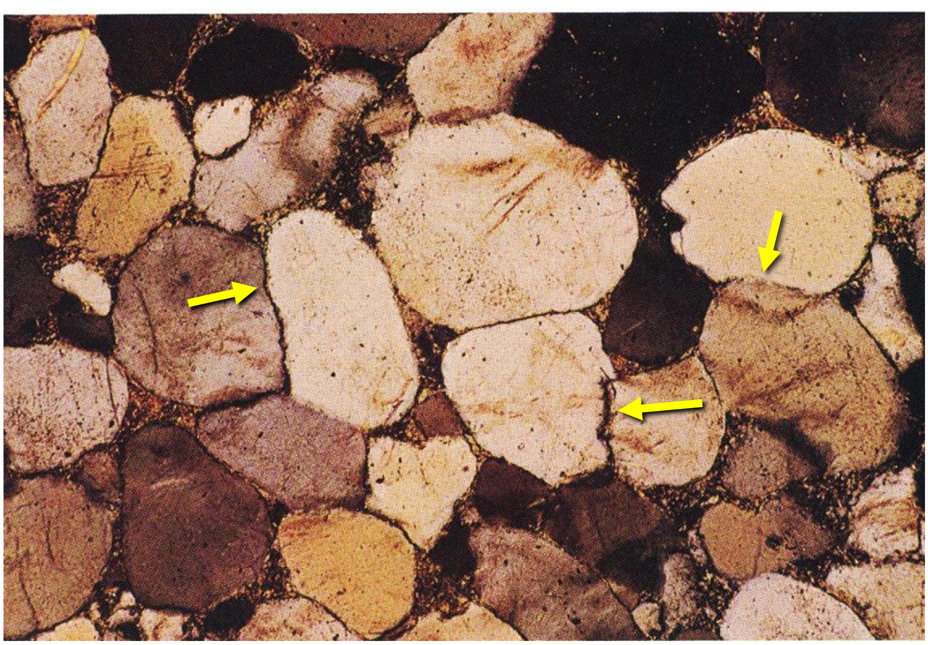
Grain Compaction: Ductile



Grain Compaction: Ductile - Pseudomatrix!



Grain Compaction: Rigid - Embayed Margins



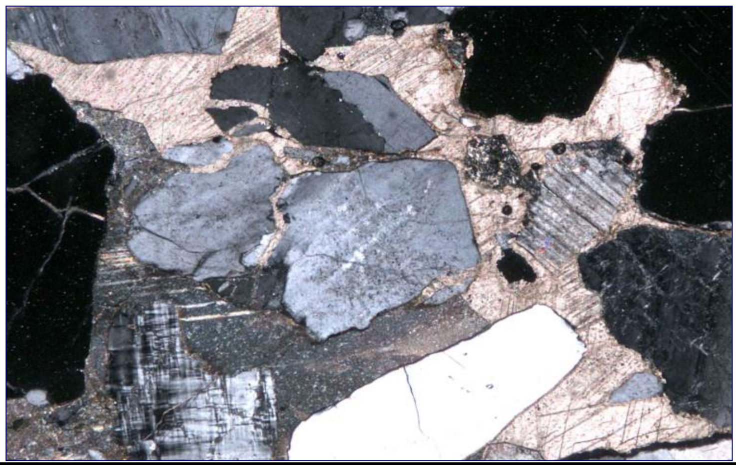
Cements – Precipitated minerals that bind grains (post-depositional in clastics)

Friable: limited cement, easily disaggregated

vs.

Densely cemented: ~ all void space filled

Generally decreases porosity and permeability in clastics (though there are some important exceptions)



Main Cement Types:

Quartz (especially if alkaline fluids)

Calcite or (more rarely) Dolomite: less stable at depth

Clays

- Illite - Common fibrous pore occlusion (commonly grow as other clays destabilize with depth)*
- Kaolinite - (acidic fluids, often from feldspar breakdown)*
- Smectite - Montmorillonite (volcanic glass alteration – may swell if exposed to water-based drilling mud)*
- Chlorite*

Hematite

Anhydrite

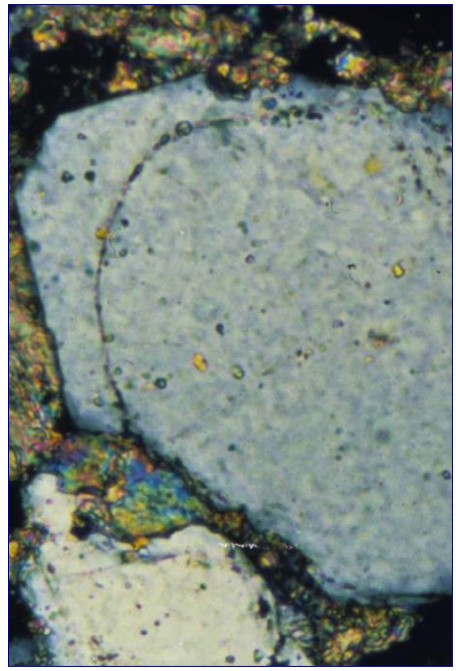
* (clays commonly recrystallize with burial)

Silica Cements

More common in quartz-rich sandstones (hence, passive margins and foreland basins)

Cements may grow in crystallographic continuity with quartz grains (syntaxial overgrowth cement)

If grain has defects, overgrowth will mimic them as well (undulatory extinction zone boundaries)



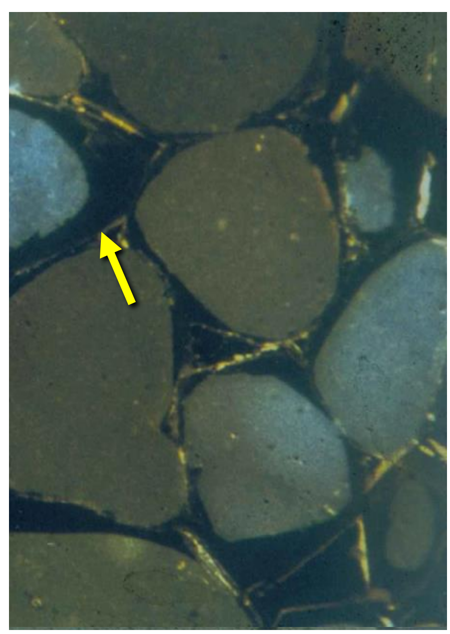
Silica Cements

Commonly only visible from grain coatings (which may inhibit cement growth)

If grain boundaries not visible in quartz arenite and/or grains welded, cements are not readily discernable in thin section.

Use Cathodo-Luminescence: detrital grain formed at higher T and P & contains impurities/inclusions that luminesce.

Cements form at < 300°C and have few impurities - do not luminesce)



Sources of Silica

Subaerial dissolution by meteoric waters

Dissolution of opaline skeletons (radiolaria, diatoms, sponge spicules)

Dissolution of quartz grains by high pH pore waters

Pressure dissolution along grain margins (chemical compaction)

Release during mineral reactions (feldspar dissolution, devitrification of volcanics, clay transformations)

Silica Cement Generation (Precipitation)

Cooling of a hot, saturated solution (50-200°C)

Lowering of pore pressure

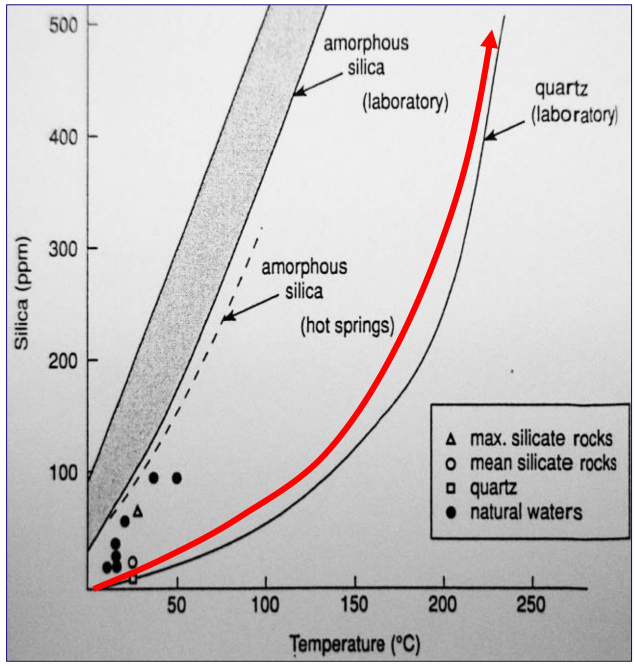
Mixing saturated fluids with saline formation waters

Lowering the pH of saturated solution

Evaporating an under-saturated solution

Silica Solubility

Increases significantly with increasing temperature: (Common precipitate from cooling fluids)



Silica Cement Generation (Precipitation)

Two solid forms of silica:

	Amorphous (Opal)	Crystalline (Quartz)
Solubility:	(variable: 100 -140 ppm)	(constant: 6 ppm)

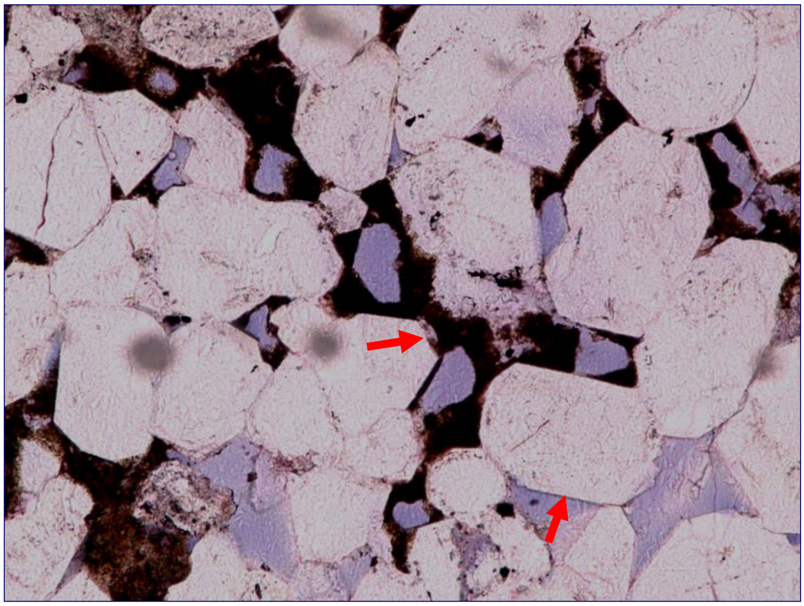
Primarily influenced by temperature

When solubility is very high, easily dissolved but difficult to re-precipitate – Hence, opaline silica is not common

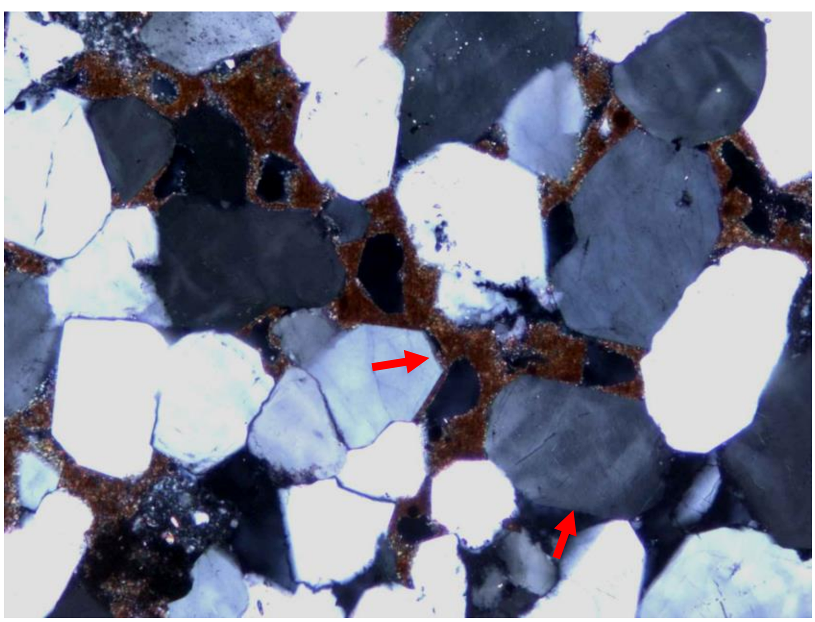
- most silica cements are quartz

Quartz cement requires long-lasting transport of super-saturated fluid through pore spaces in sandstone with good permeability in order to precipitate. Hard to totally occlude pores because the cementing process inhibits fluid migration by reducing pores and pore throat sizes (reduced permeability)

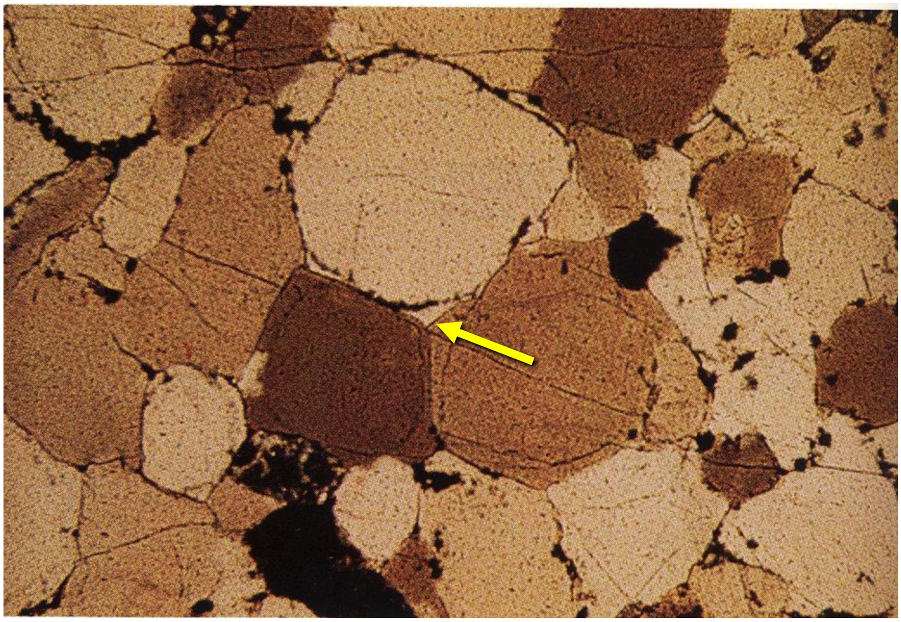
Quartz Cement / Partial Pore Occlusion



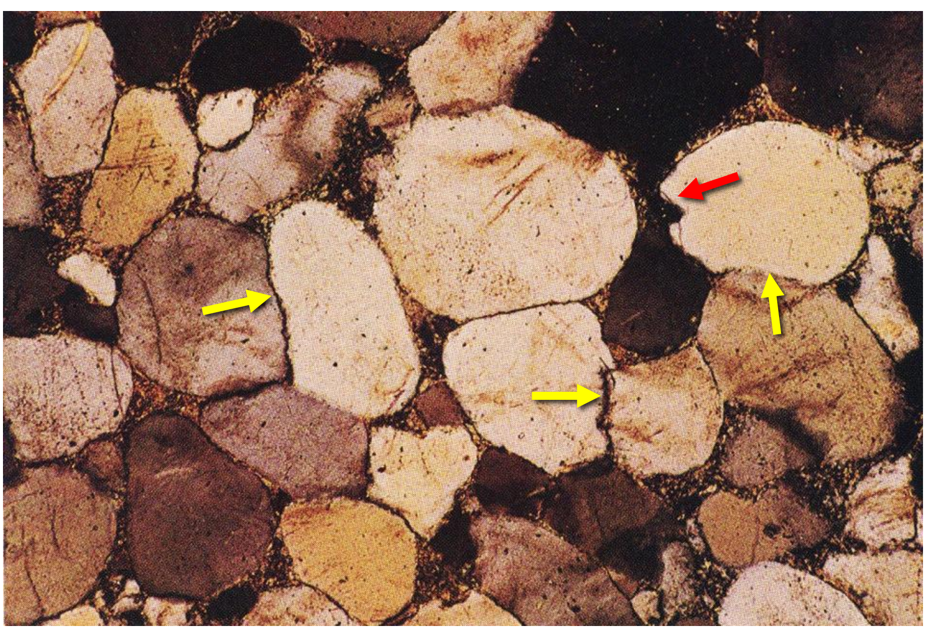
Quartz Cement / Partial Pore Occlusion



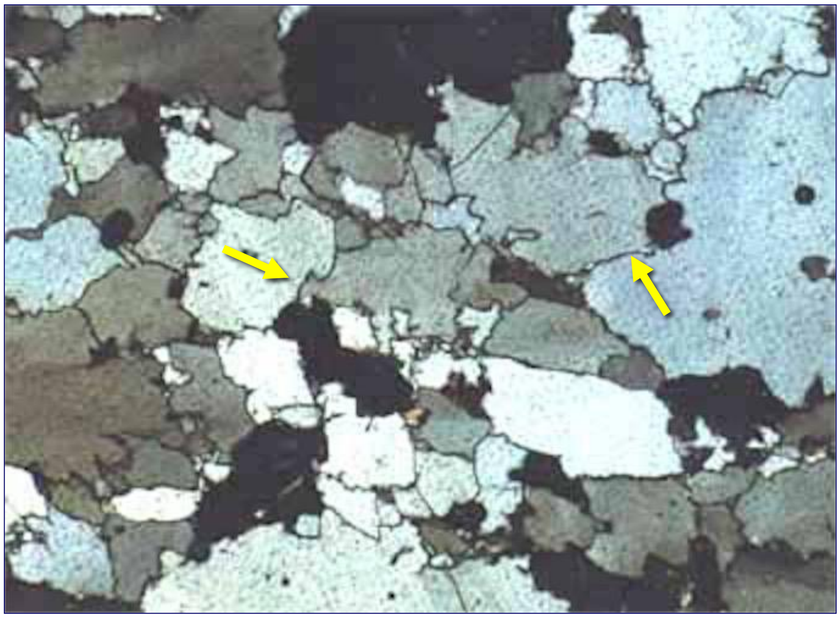
Dense Quartz Cement: Total Pore Occlusion



Source Quartz Cement: Pressure Dissolution

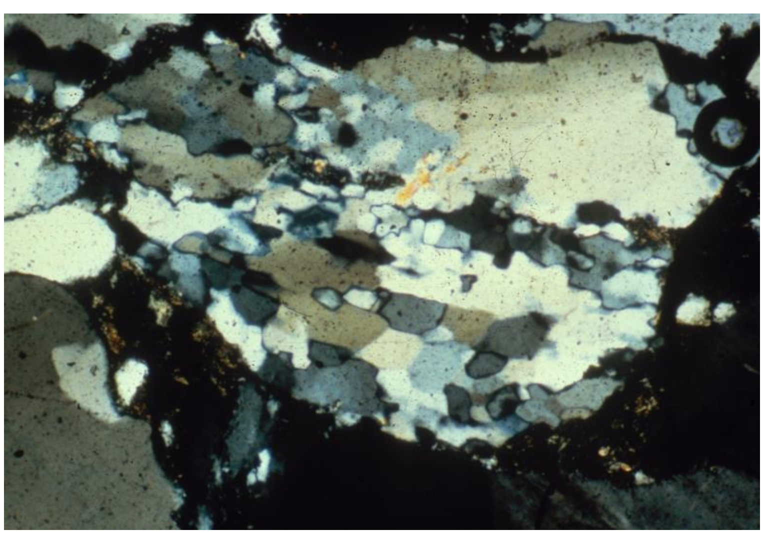


Source Quartz Cement: Pressure Dissolution

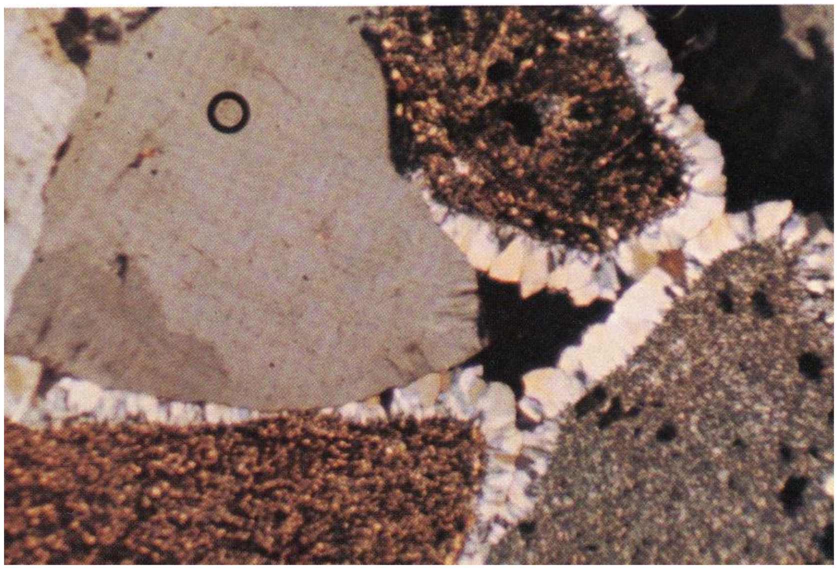


Challenging to Differentiate From **Polycrystalline Quartz**

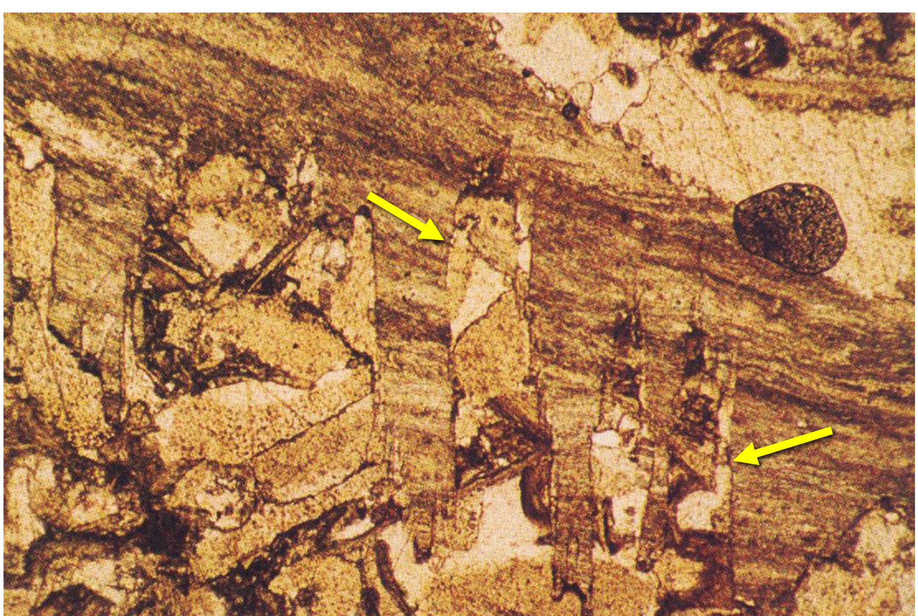
Polycrystalline shows: 1) Multiple crystal sizes; 2) Crystals embedded within crystals; 3) Close extinction between adjacent crystals; 4) Wide range of crystal sizes.



Chert Cement



Pressure Dissolution: Stylolites – rare in siliciclastics



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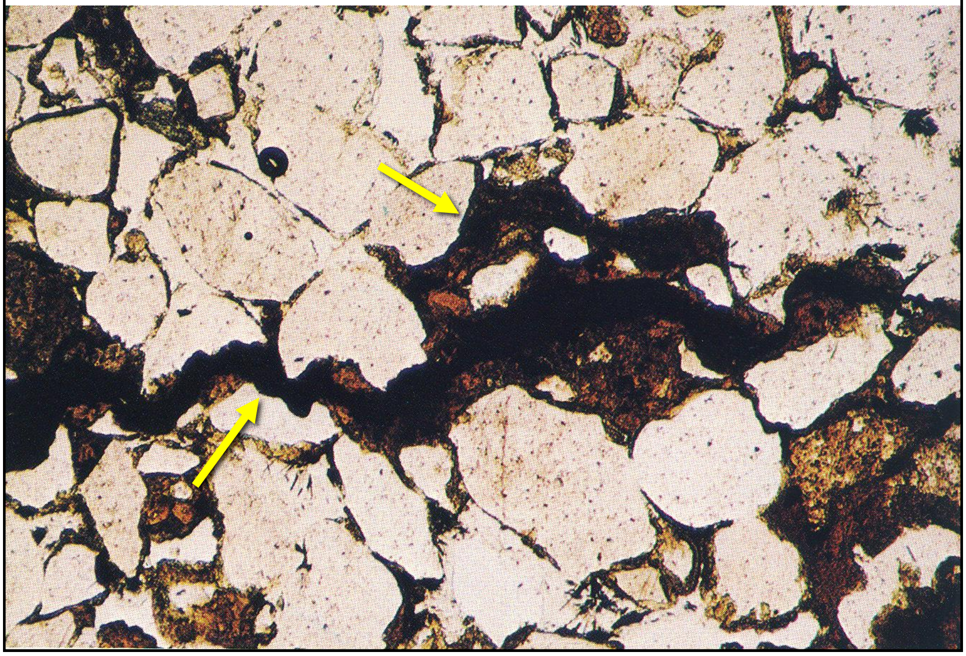
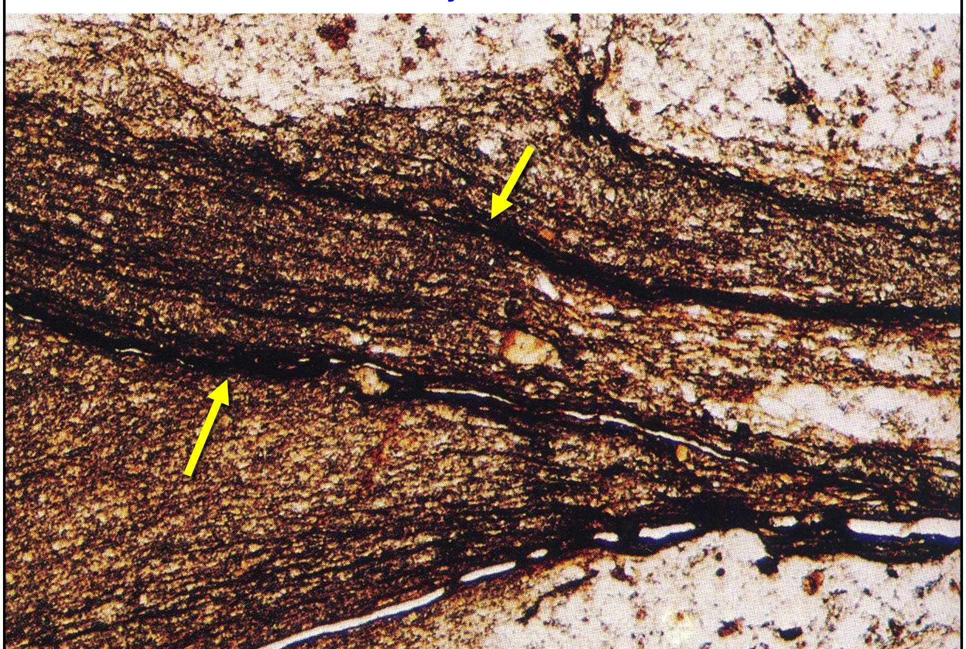


Pressure Dissolution: Stylolites – rare in siliciclastics



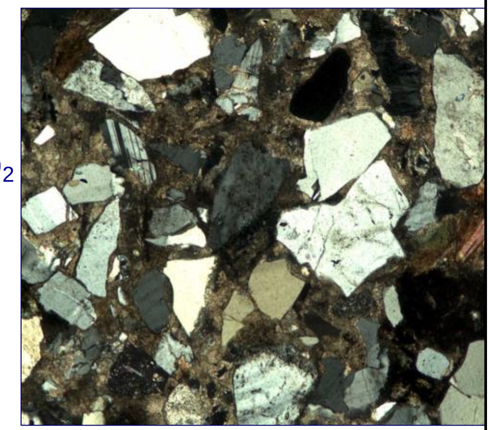
Carbonate Cements

Can occur in all types of sandstones

Primarily calcite

Also includes:

- Dolomite: $(Ca,Mg)(CO_3)_2$
- Ankerite: $Ca(Fe,Mg,Mn)(CO_3)_2$
- Siderite: $FeCO_3$



Microcrystalline calcite most common in sandstones

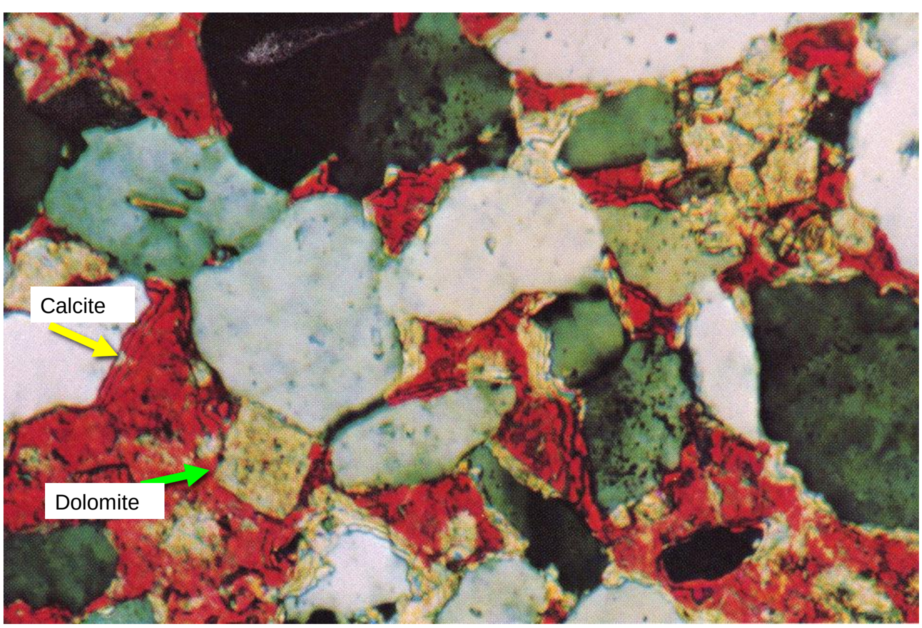
Crystals <20 microns

Grain-lining, crystalline texture

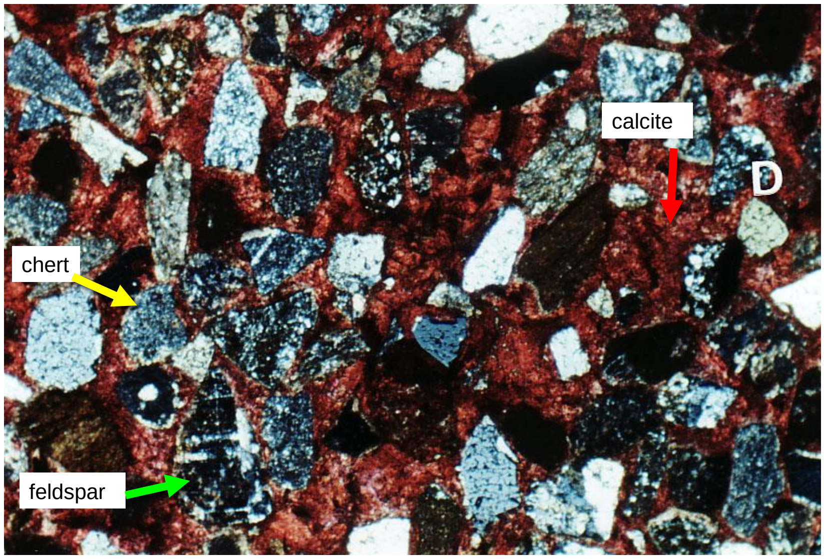
Dolomite typically small pore-filling rhombs.

Locally challenging to tell from calcite, unless stained with Alizarin Red (stains calcite/aragonite, but not dolomite/siderite)

Carbonate Cements



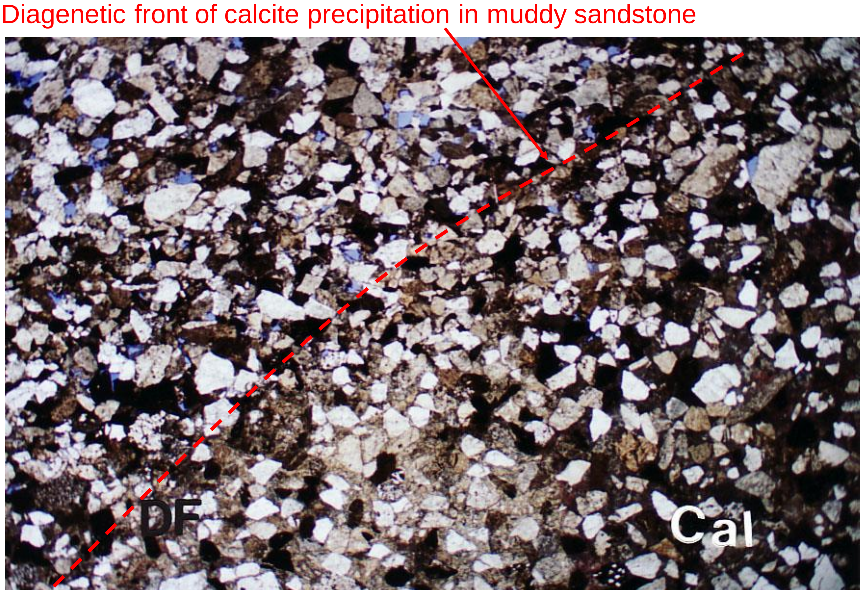
Carbonate Cements



Completely calcite-cemented chert-dominated sandstone
Belly River Fm, 12-4-49-11W5, 1407 m (40 x magnification)

Carbonate Cements

Diagenetic front of calcite precipitation in muddy sandstone



Belly River Fm (6-2-49-12W5, 1509 m, X 40 mag.)

Carbonate Cements

Distribution generally heavily influenced by groundwater

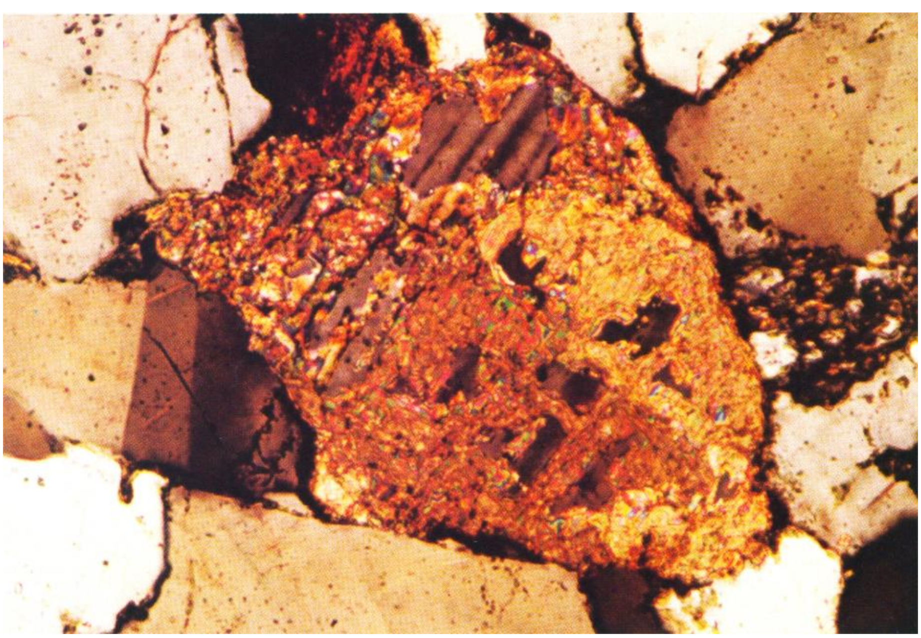
- Very commonly an early cement in this case.
- Typically has a patchy distribution and is difficult to predict.

Also likely with burial of plagioclase grains (alternation product)

Dissolution of early calcite cement often very important in the development of SECONDARY porosity (mesogenesis):

- Corroded cement crystals
- Anomalously packed grains (some loose, some tight)
- Elongated pores (dissolution fronts)
- Pores larger than largest grains (over-sized pores)

Calcite Cement Feldspar Alternation



Carbonate Cements

Conditions favouring precipitation:

- High pH (non-acidic)
- High permeability
- Large aquifer flow (lots of fluid)
- Time
- Source of Ca^{2+} and CO_3^{2-} ions
- Most forms below 80º C

Dolomite much more commonly associated with deeper burial conditions (mesogenesis), often *via* Mg-rich hydrothermal fluids

Generally fine pore-lining rhombs in sandstones

(will discuss more in carbonate section)

Sulphate Cements

Gypsum ($CaSO_4 \cdot 2H_20$)

Anhydrite ($CaSO_4$)

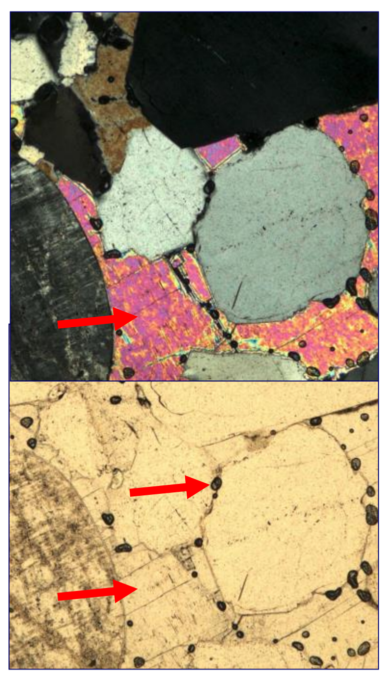
Fairly common, especially in evaporitic settings (alluvial, arid coastal)

Often Eogenetic: very early, near-surface downward percolation of evaporative fluids

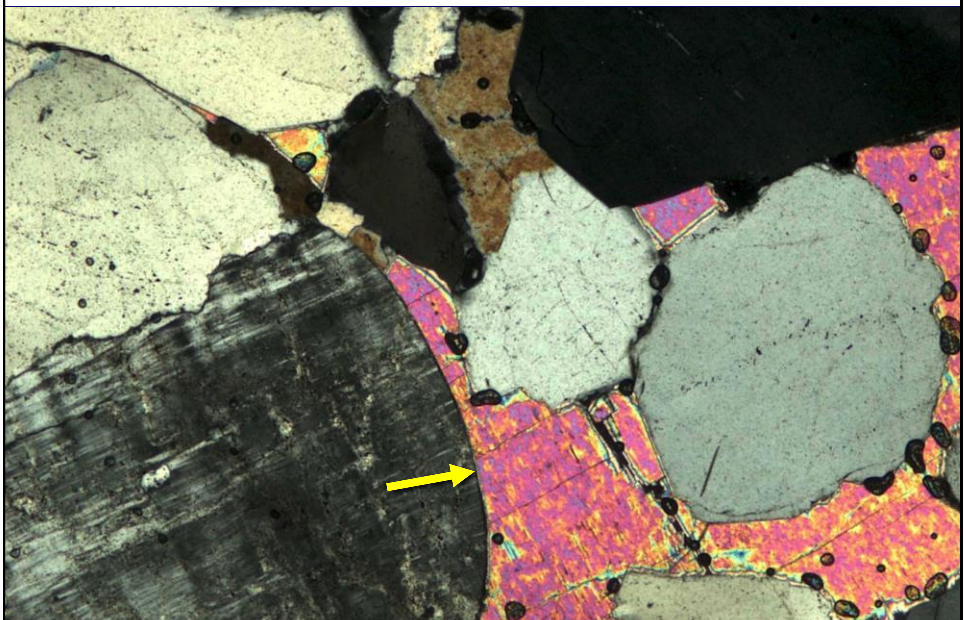
Converts to anhydrite as buried and water driven off – very stable during burial

Also common during burial if evaporites in nearby stratigraphy

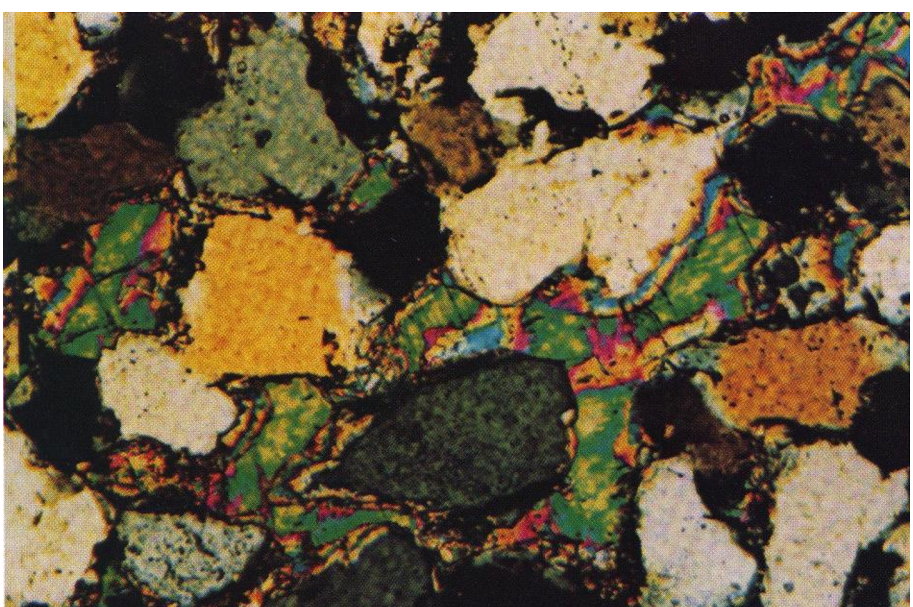
Low relief in PPL



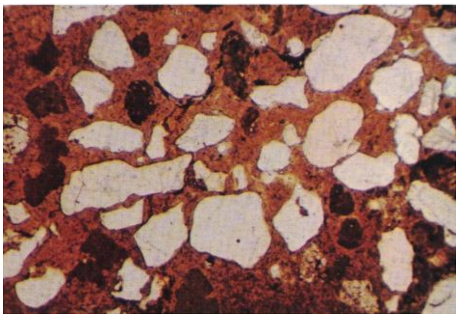
Anhydrite Cement



Anhydrite Cement

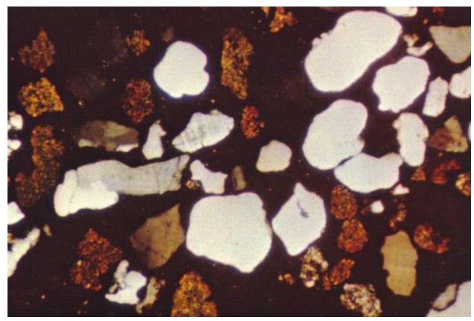


Phosphate Cement



Carbonate hydroxyl fluoroapatites (Francolite & Dahllite): $Ca_{10}(PO_4,CO_3)_6F_{2-3}$

Low birefringence: typically isotropic to grey (up to 1st order blue)



Phosphate Cement: Wavellite

Low birefringence: typically isotropic to grey (up to 1st order blue)

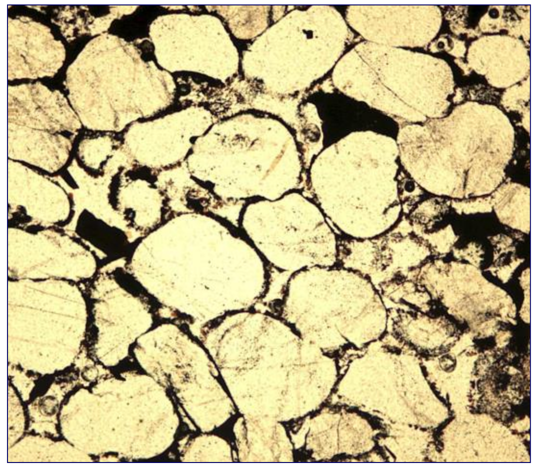
Iron Oxide Cements

Magnetite (Fe_3O_4)
Geothite/Limonite (FeO-OH)
Hematite (Fe_2O_3)

Magnetite preserved only in anoxic conditions

Goethite dehydrates to hematite

Originate from alteration of ferromagnesian minerals (esp. *via* oxidation during surface weathering)

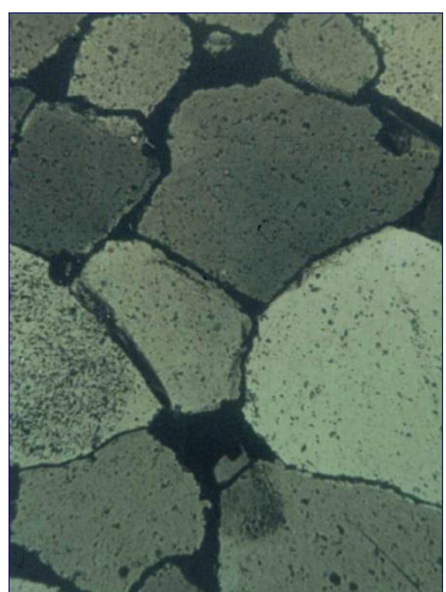


Hematite Cements

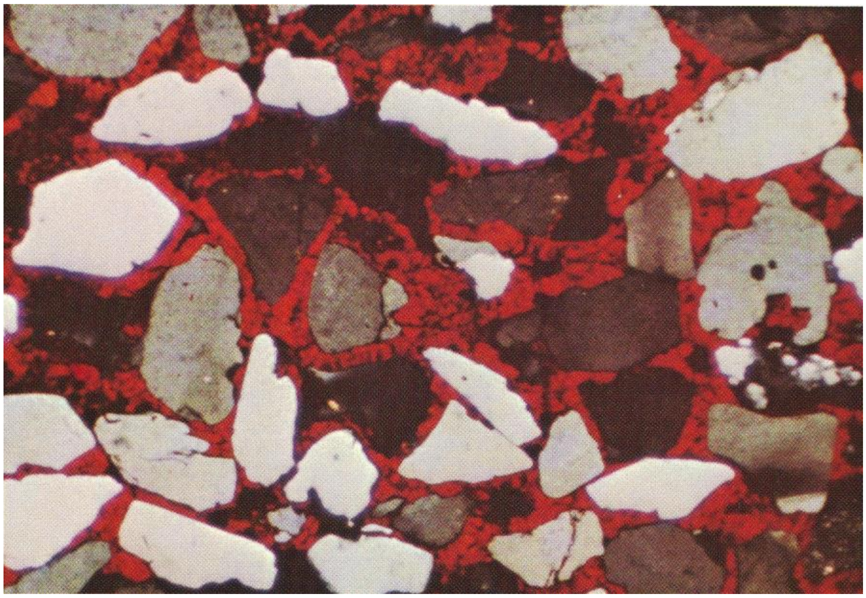
Iron commonly transported as films on clays or grains (can stain grains as rims or veneer before final deposition)

Extremely stable at surface, especially when occurring in highly oxidizing conditions (red beds of floodplains, etc.)

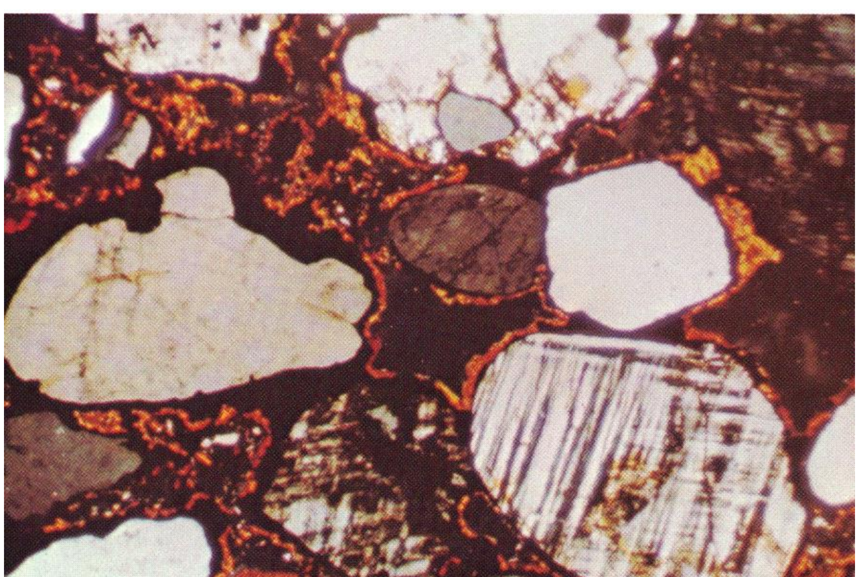
May develop in all diagenetic stages



Hematite Cement



Limonite Cement



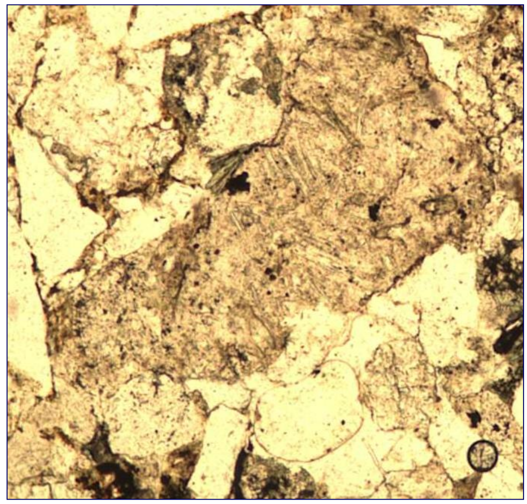
Clay Cements

Very difficult to ID in hand sample.

Often difficult to discern in thin section as well: Is the clay a cement, protomatrix (detrital), or a compacted grain (pseudomatrix)?

With immature lithics (esp. volcanics), there are commonly complex grain alterations to clays

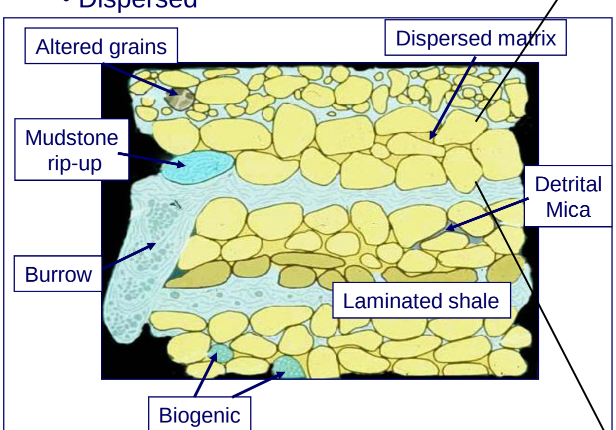
Higher geothermal gradients will speed up alteration of unstable grains to clay



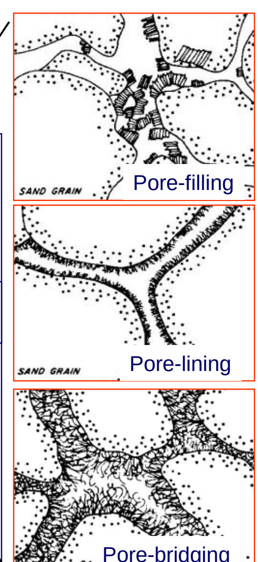
Clay Cements

Clay Distribution in Clastic Sedimentary Rocks

- Laminated
- Structural
- Dispersed



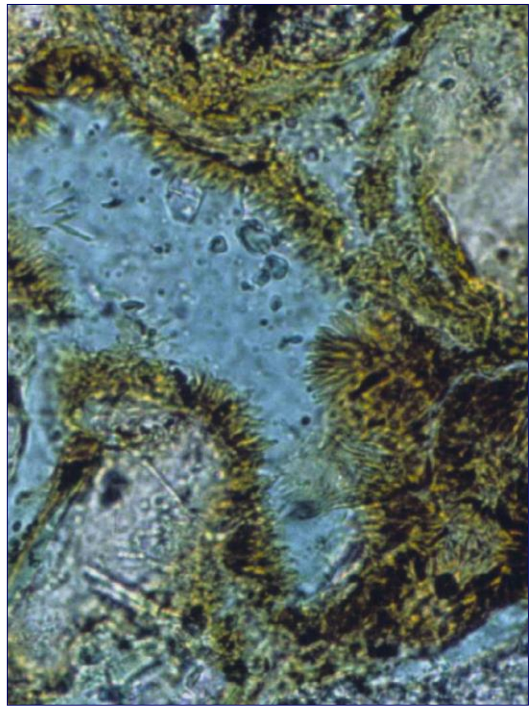
(After Wilson and Pittman, 1977)



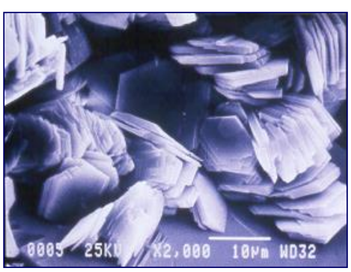
(After Neashan, 1977)

Clay Cements

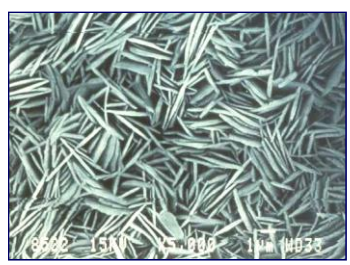
If authigenically formed, should evenly coat grains and line pores with euhedral crystals of clay



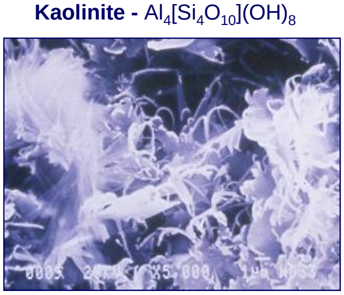
Common Clay Minerals



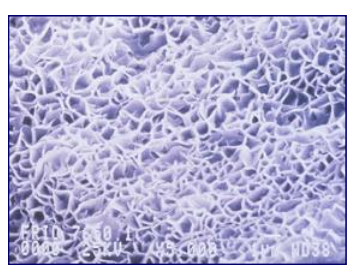
Kaolinite - $Al_4[Si_4O_{10}](OH)_8$



Chlorite - $(Mg,Al,Fe)_{12}[(Si,Al)_8O_{20}](OH)_{16}$



Illite - $KAl_4[Si_7AlO_{20}](OH)_4$



Smectite - $(Ca,Na)(Al,Mg,Fe)_4[(Si,Al)_8O_{20}](OH)_4 \cdot nH_2O$

Clay Cement Reactions

Chlorite	Smectite + (Fe^{2+}, Fe^{3+}) → $(Mg,Al,Fe)_6[(Si,Al)_4O_{10}](OH)_8$ + SiO_2 + Na^+ + Ca^{2+} + H_2O (not balanced)
Na-smectite	$Na_2KCaAl_5Si_{11}O_{32}$ + $MgSiO_3$ + H_2 + $4H^+$ + $4HCO_3^-$ → $Na(Al_5Mg)Si_{12}O_{30}(OH)_6$ + Na^+ + Ca^{2+} + $4HCO_3^-$
Glauconite	Illite + (Fe^{2+}, Fe^{3+}) → glauconite + K^+ + Al_2O_3 (not balanced)
Illite + quartz	$Al_2Si_2O_5(OH)_4$ + $KAlSi_3O_8$ → $KAl_3Si_3O_{10}(OH)_2$ + $2SiO_2$ + H_2O
Kaolinite	$2KAlSi_3O_8$ + $2H^+$ + $9H_2O$ → $Al_2Si_2O_5(OH)_4$ + $4(H_4SiO_4)$ + $2K^+$

Other Reactions

Zeolite growth

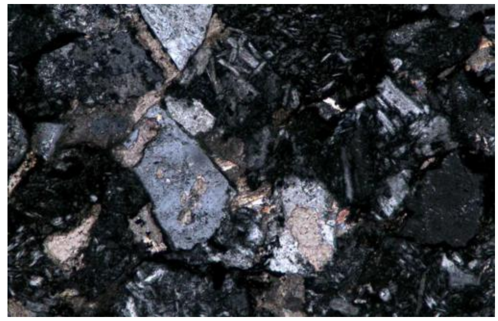
- High temperature (transitional with lowest grade metamorphism
- Near … ons

Zeolite	*Typical formula*
Analcime	$Na_2(Al_2Si_4O_{12})\cdot 2H_2O$
Chabazite	$Ca(Al_2Si_4O_{12})\cdot 6H_2O$
Clinoptilolite	$(Na_2K_2)(Al_2Si_{10}O_{20})\cdot 8H_2O$
Erionite	$(Na_2K_2,Ca,Mg)_{4.5}(Al_9Si_{27}O_{72})\cdot 27H_2$
Ferrierite	$(Na_2Mg_2)(Al_6Si_{30}O_{72})\cdot 18H_2O$
Heulandite	$(Ca,Na_2)(Al_2Si_7O_{18})\cdot 6H_2O$
Laumontite	$Ca(Al_2Si_4O_{12})\cdot 4H_2O$
Mordenite	$(Na_2K_2Ca)(Al_2Si_{10}O_{24})\cdot 7H_2O$
Natrolite	$Na_2(Al_2Si_3O_{10})\cdot 2H_2O$
Phillipsite	$(1/2Ca,Na,K)_3(Al_3Si_5O_{16})\cdot 6H_2O$
Wairakite	$Ca(Al_2Si_4O_{12})\cdot 2H_2O$

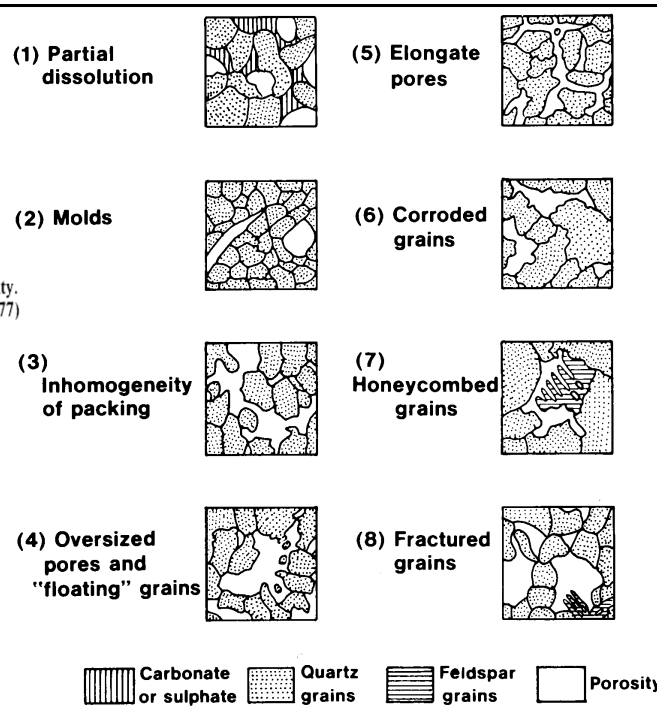
Other Reactions

Grain replacement

- Albitization (Ca exsolved)
- Calcitization
- Silicification
- Organic maturation



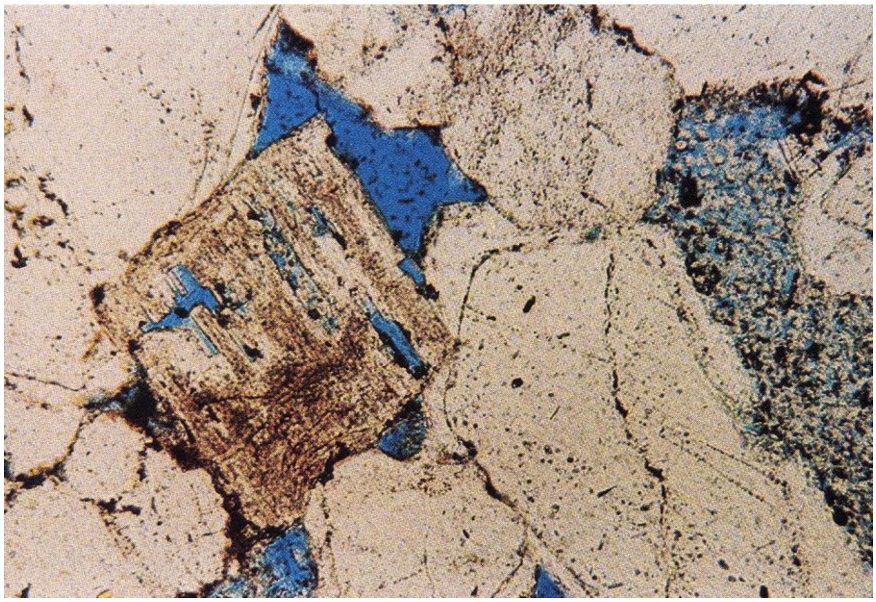
Secondary Porosity Types



Petrographic criteria for secondary porosity.
(from: Schmidt, McDonald, and Platt, 1977)

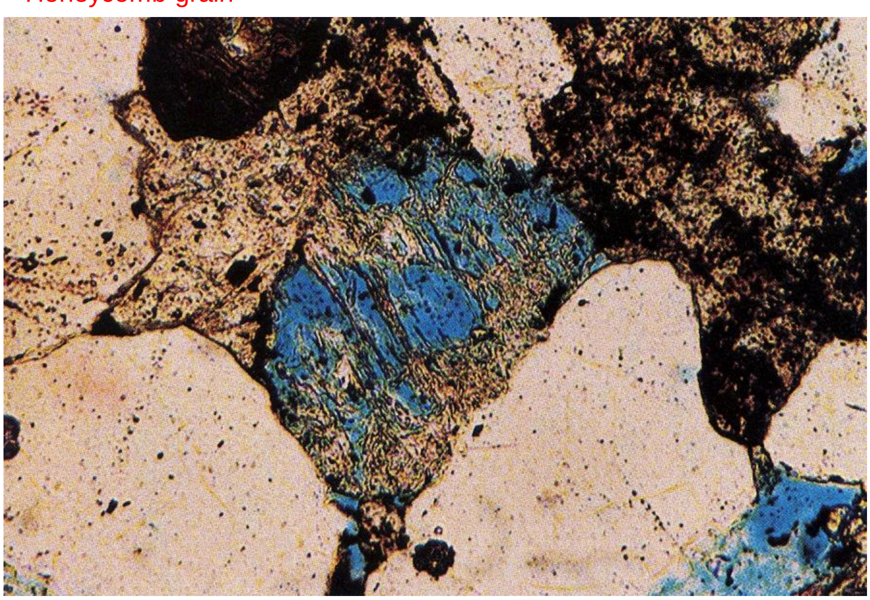
Grain Leaching and Secondary Porosity

Partial dissolution / Honeycomb grain



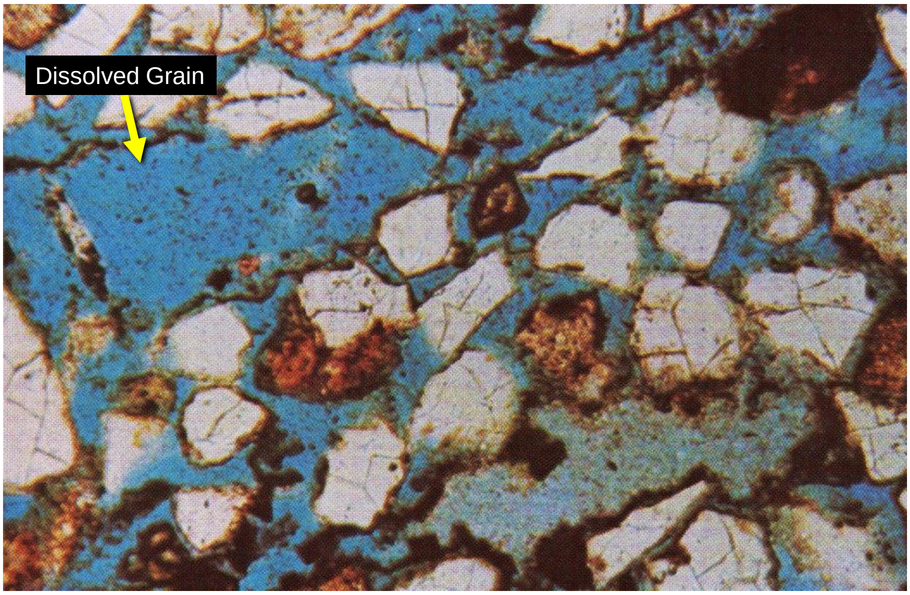
Grain Leaching and Secondary Porosity

Honeycomb grain



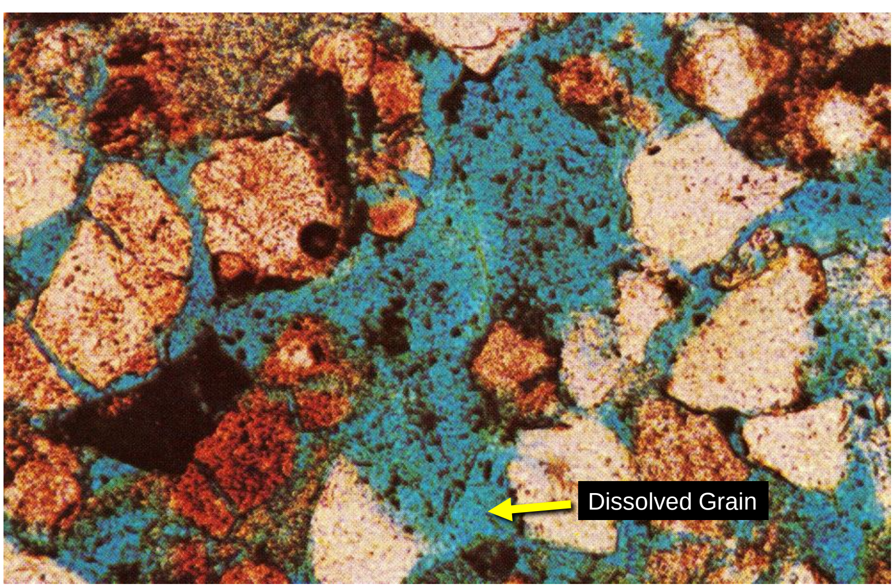
Grain Leaching and Secondary Porosity

Over-Sized Pores



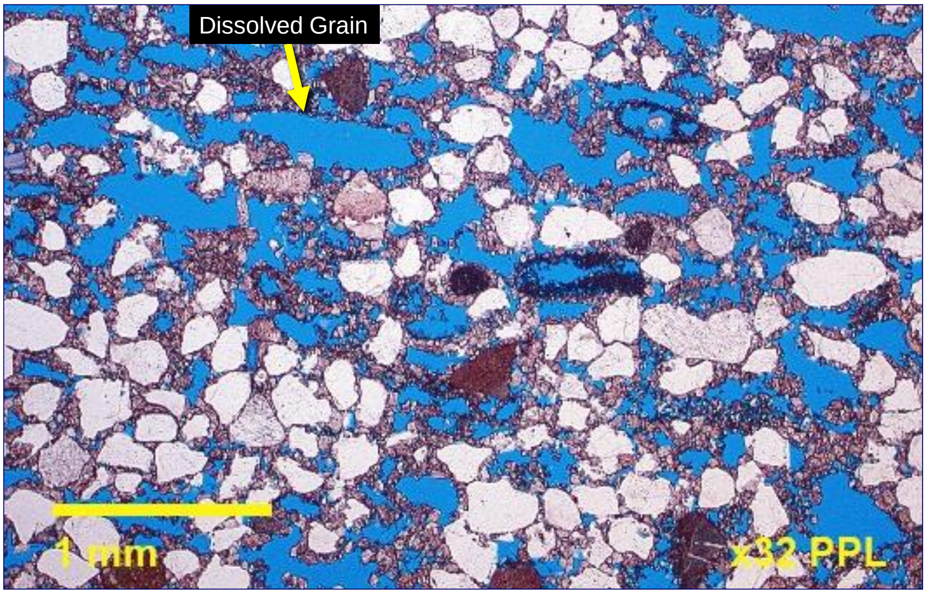
Grain Leaching and Secondary Porosity

Over-Sized Pores



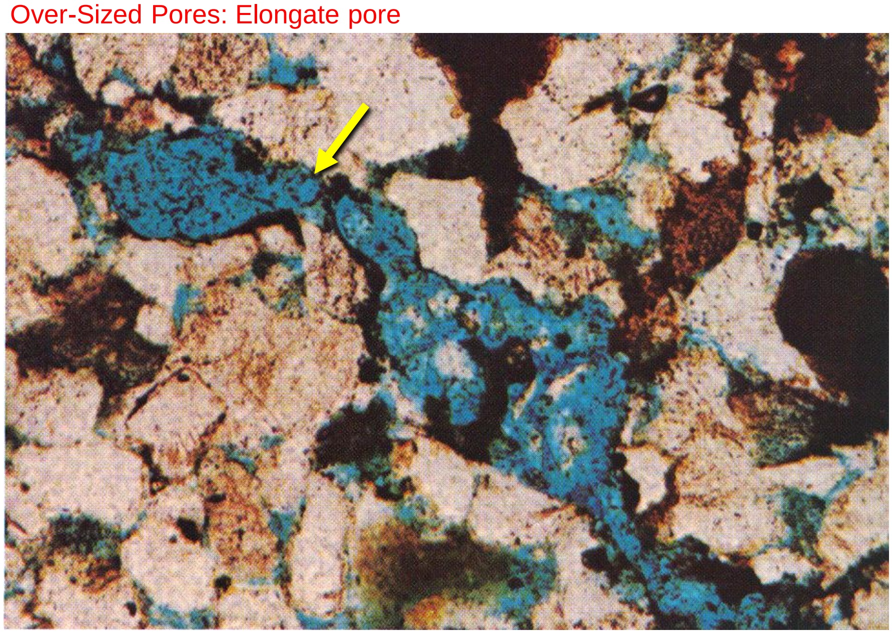
Grain Leaching and Secondary Porosity

Over-Sized Pores / Elongate pores / corroded grains



Grain Leaching and Secondary Porosity

Over-Sized Pores: Elongate pore



Tectonic Influences on Diagenesis of Sst

Can have a strong effect on resulting Diagenetic Reactions:

- Temperature (Geothermal Gradient)
  - Mid-Ocean Ridges (high)
  - Collisional zones (locally high)
  - Rift zones (initially high)
  - Passive Margins (low and declining)
- Burial Rates
  - Subduction zones (rapid)
  - Collisional zones (particularly foreland basins) (rapid)
  - Passive margins (generally slow)
- Mineralogy of Source Terranes
  - Trenches (compositionally unstable)
  - Arc-related (compositionally unstable)
  - Uplifted craton (moderate to compositionally stable)
- Pore Water Composition and Circulation
  - Active margins enriched in total dissolved solids, rapid circulation
  - Passive margins prone to evaporite-rich pore waters; slower circulation
  - Intracratonic basins enriched in total dissolved solids; moderate circulation

General Diagenetic Trends in Siliciclastics