Part III: Composition, Classification, and Diagenesis of Sedimentary Rocks

Classification of sedimentary rocks based on (1) Particle composition: mineralogy; and (2) chemical composition: bulk chemistry. **Sedimentary Petrology (岩象學)**: study of the mineralogy of sedimentary rocks

Sedimentary rocks

A. Siliciclastic sedimentary rocks (sandstones, conglomerates, shales)
B. Carbonate rocks (limestones and dolomites)
C. Other biochemical/chemical rocks (evaporites, cherts, iron-rich sedimentary rocks, phosphorites)
D. Carbonaceous sedimentary rocks (oil shales and coals)

5. Siliciclastic Sedimentary Rocks

Make up about ¾ of sedimentary rocks

5.2 Sandstones

Albite:鈉長石
Oligoclase:奧長石,鈉鈣長石
Andesine:中性長石
Labradorite:拉長石;鈣鈉斜長石
Bytownite:培斜長石;鈉鈣長石
Anorthite:鈣斜長石
Sericite: 絹雲母

Table 5.1 Common Minerals and Rock Fragments in Siliciclastic Secimentary Rocks

5.2.1 Framework Mineralogy

Boggs (2006) p.121

Major minerals (abundance >~1%-2%)
Stable minerals (greatest resistance to chemical decomposition):
Quartz—makes up approximately 65% of framework grains in average sandstone, 30% of minerals in average shale.
Less stable minerals:

正長石   微斜長石   透長石   鈉微斜長石

Feldspars—include K-feldspars (orthoclase, microcline, sanidine, anorthoclase) and plagioclase feldspars (albite, oligoclase, andesine, labradorite, bytownite, anorthite); make up about 10–15% of framework grains in average sandstone, 5% of average shale.
Clay minerals and fine micas—clay minerals include the kaolinite group, illite group, smectite group (montmorillonite a principal variety), and chlorite group; fine micas are principally muscovite (sericite) and biotite; minor abundance in sandstones, where they occur as matrix minerals, but comprise >60% of the minerals in average shale.

Common minerals and rock fragments in siliciclastic sedimentary rocks (continued)

Zircon:鋯石
Tourmaline:電氣石
Rutile: 金紅石
Anatase:銳鈦礦
Apatite:磷灰石
Staurolite:十字石
Epidote:綠簾石
Sphene:榍石
Zoisite:黝簾石
Clinozoisite:斜黝簾石
Topaz:黃晶
Monazite:獨居石
Hematite:赤鐵礦
Limonite:褐鐵礦
Magnetite:磁鐵礦
Ilmenite:鈦鐵礦
Leucoxene:白榍石
Zeolite:沸石
Aragonite:霰石(文石)
Dolomite:白雲石
Siderite:菱鐵礦
Goethite:針鐵礦
Anhydrite:硬石膏
Gypsum:石膏
Barite:重晶石

Accessory minerals (abundances <~1–2%)
Coarse micas—principally muscovite and biotite
Heavy minerals (specific gravity >~2.9):
Stable nonopaque minerals—zircon, tourmaline, rutile, anatase.
Metastable nonopaque minerals—amphiboles, pyroxenes, chlorite, garnet, apatite, staurolite, epidote, olivine, sphene, zoisite, clinozoisite, topaz, monazite, plus about 100 others of minor importance volumetrically.
Stable opaque minerals—hematite, limonite
Metastable opaque minerals—magnetite, ilmenite, leucoxene.

Rock Fragments (make up about 10–15% of the siliciclastic grains in average sandstone and most of the gravel-size particles in conglomerates; shales contain few rock fragments).

Igneous rock fragments—clasts of any kind of igneous rock possible in conglomerate; however, fragments of fine-crystalline volcanic rock are most common in sandstones.
Metamorphic rock fragments—may include clasts of any kind of metamorphic rock; however, metaquartzite, schist, phyllite, slate, and argillite clasts are most common in sandstones.
Sedimentary rock fragments—clasts of any kind of sedimentary rock possible in conglomerates; clasts of fine sandstone, siltstone, shale, and chert are most common in sandstones; limestone clasts are comparatively rare in sandstones.

Chemical Cements (abundance variable)
Silicate minerals—predominantly quartz; others may include microquartz (chert), opal, feldspars, and zeolites.
Carbonate minerals—principally calcite; less commonly aragonite, dolomite, siderite.
Iron oxide minerals—hematite, limonite, goethite.
Sulfate minerals—anhydrite, gypsum, barite.

Note: The terms stable and metastable refer to chemical stability.

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Boggs (2006) p.121

Major framework grains in sandstone

A. Monocrystalline quartz
B. Polycrystalline quartz
C. Potassium feldspar or K-feldspar (microcline)
D. Plagioclase
E. Muscovite (mainly derived from metamorphic rocks and some plutonic igneous rocks)
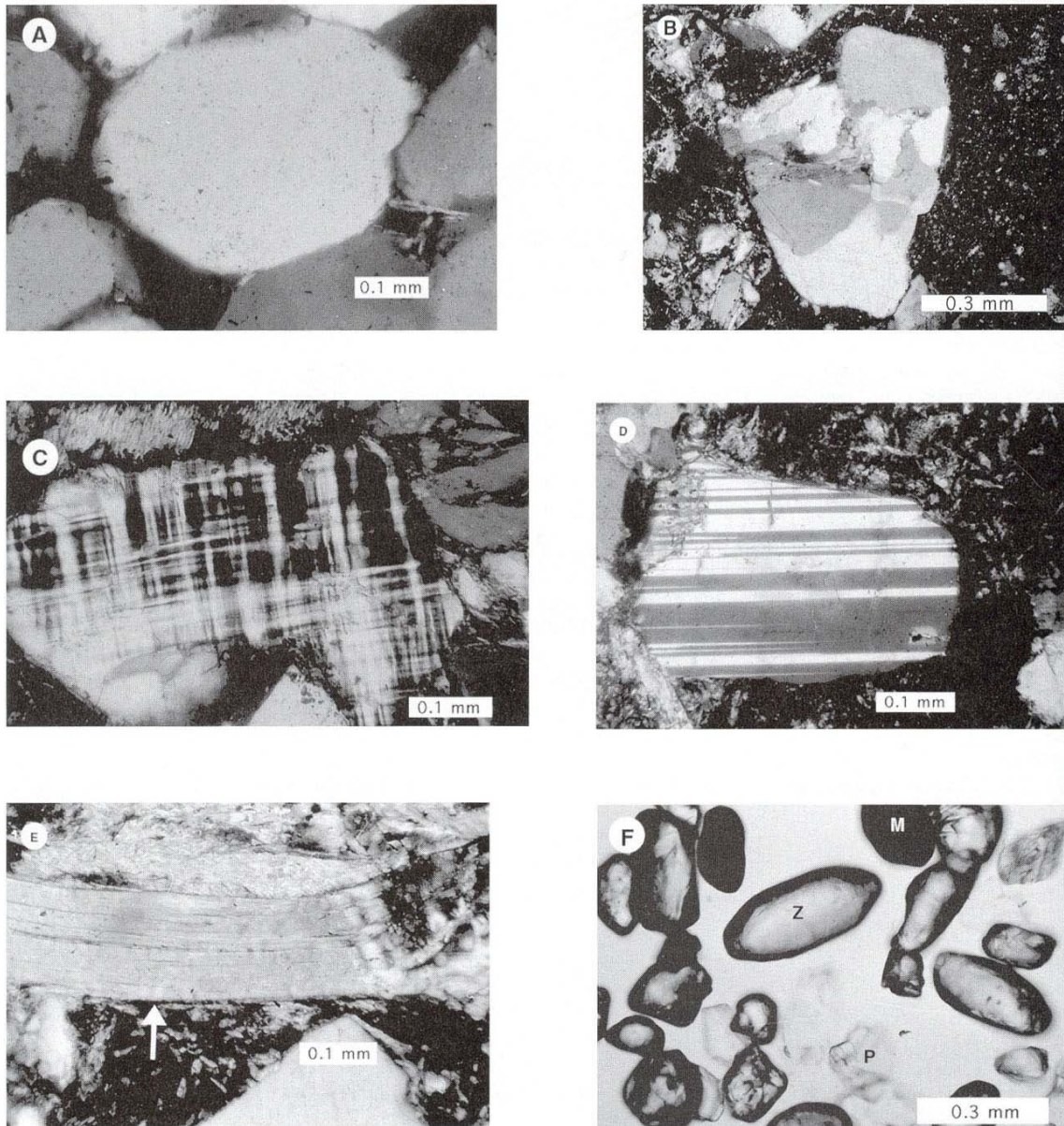F. Heavy minerals: Zircon (Z); Magnetite (M); Pyroxene (P)

Figure 5.1
Principal kinds of framework grains in sandstones. (A) monocrystalline quartz, Roubidoux Fm. (Ord), Missouri; (B) polycrystalline quartz, Miocene sandstone, Japan Sea; (C) potassium feldspar (microcline), Bateman Fm. (Eocene), Oregon; (D) plagioclase feldspar, Bateman Fm. (Eocene), Oregon; (E) Mica (muscovite), Bateman Fm. (Eocene), Oregon (F) heavy minerals (Z = Zircon; M = magnetite; P = pyroxene), India. Crossed nicol photomicrographs.

Boggs (2006) p.122

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Rock Fragments

A. Plutonic grain (granite)
B. Volcanic grain
C. Metamorphic grain (schist)
D. Metamorphic grain (quartzite)
E. Sedimentary grain (sandstone)
F. Sedimentary grain (chert/ microcrystalline quartz)

Rock fragments are reliable indicators of source rock type than are quartz or feldspar, which can be derived from different types of source rocks.
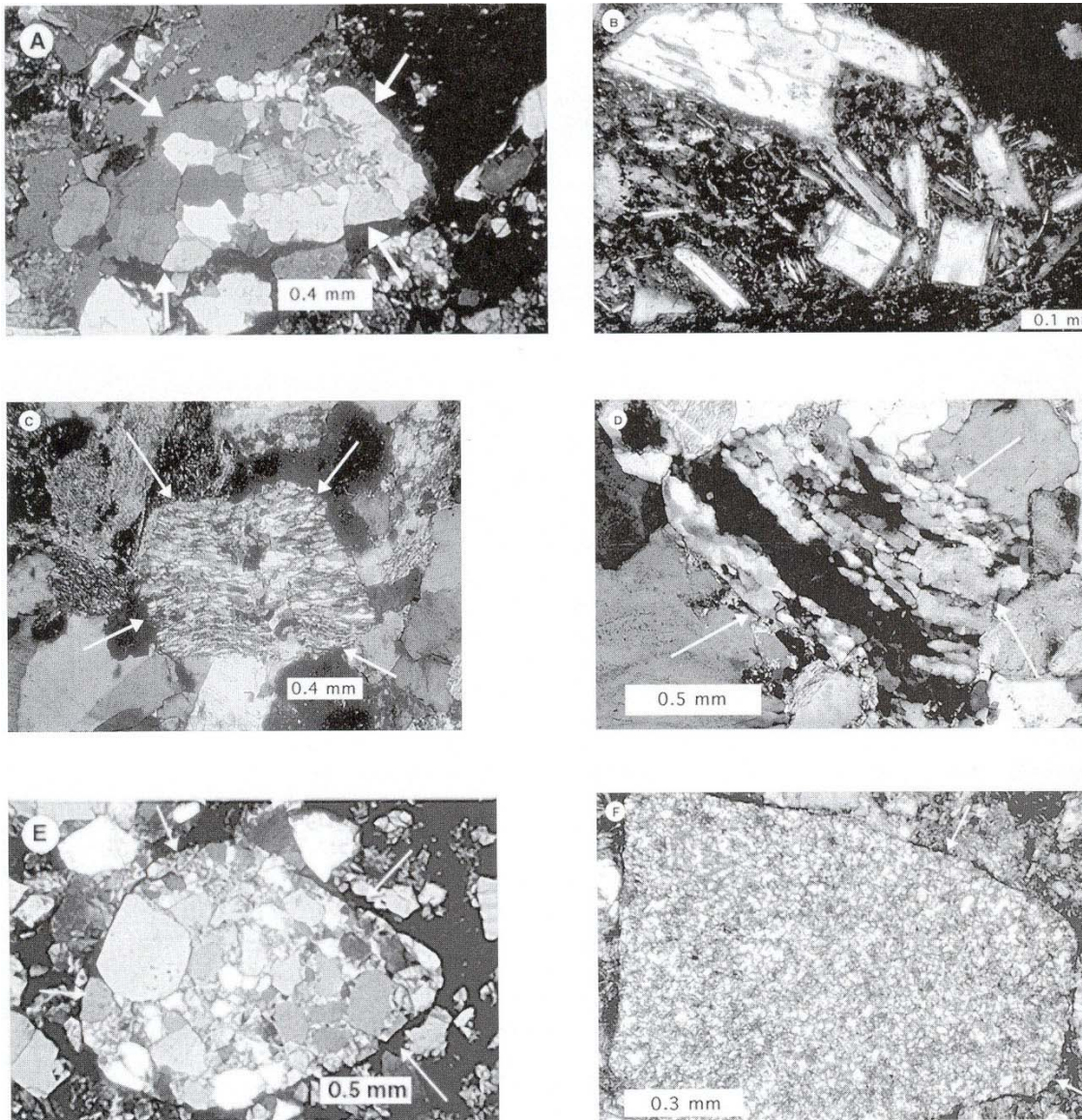
Figure 5.2
Common kinds of rock fragments in sandstones. (A) plutonic (granite; arrows), Batema Fm. (Eocene), Oregon; (B) volcanic, Miocene sandstone, Japan Sea; (C) metamorphic (schist; arrows), Pottsville Group (Penn), Eastern Pennsylvania; (D) metamorphic (quartzite; arrows) Pottsville Group (Penn), Eastern Pennsylvania, (E) sedimentary (sand stone; arrows; note rounding of grains within this clast), Bateman Fm. (Eocene), Oregc (F) sedimentary (chert; arrows), Otter Point Fm. (Jur.), Oregon. Crossed nicol photomi-crographs.
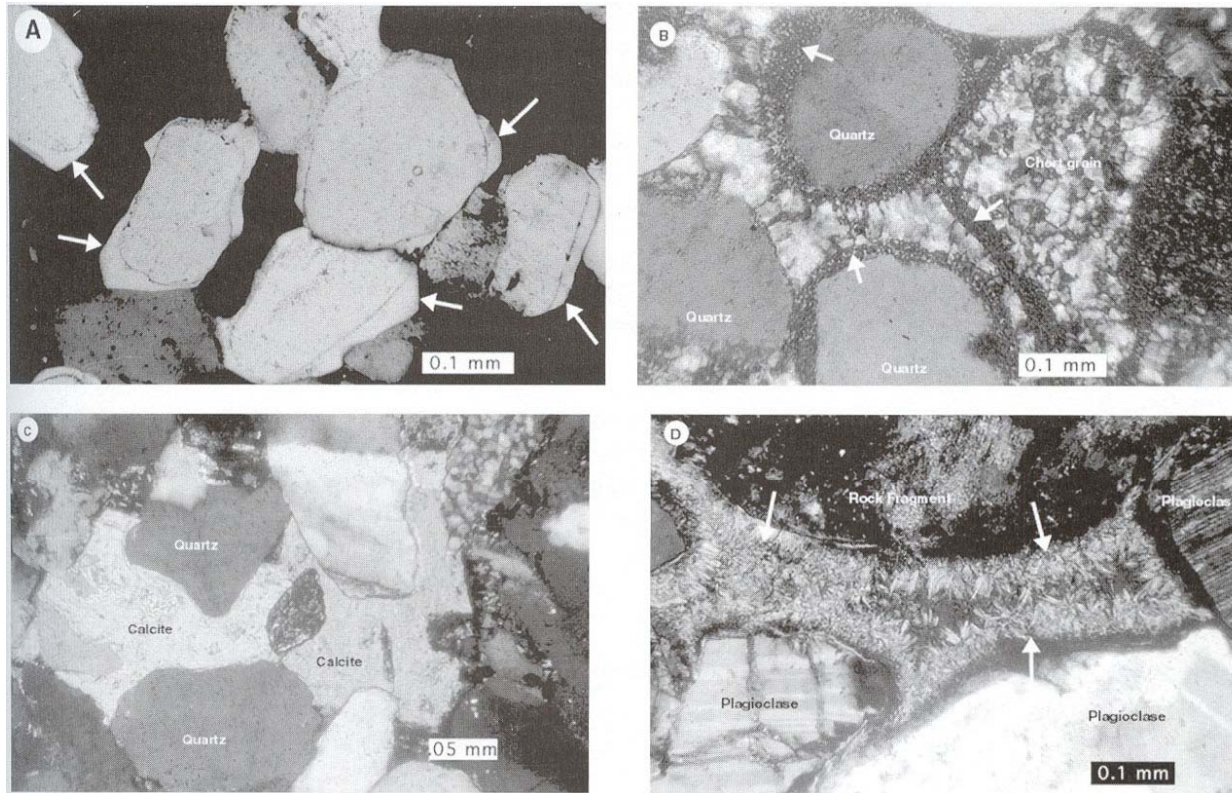
Boggs (2006) p.124

Figure 5.3

Common cements in sandstones. (A) quartz overgrowths (arrows), Lamotte Sandstone (Camb), Missouri; (B) microquartz (chert; arrows) cementing quartz and chert grains, Jefferson City Fm. (Ord), Missouri; (C) Calcite, Kayenta Fm. (Trias.), Utah; (D) Clay mineral (chlorite; arrows), Miocene sandstone, Japan Sea. Crossed nicol photomicrographs.

Boggs (2006) p.125

5.2.2 Mineral Cements

Cements: Authigenic minerals in the pore spaces that bound together framework grains.

Common cements in sandstones:
A. Quartz overgrowths
B. Microquartz (chert)
C. Calcite
D. Clay minerals (chlorite)

5.2.3 Matrix Minerals

Grains in sandstones smaller than about 0.03 mm, which fill interstitial spaces among framework grains. Matrix minerals may include: clay minerals (most common), micas, quartz, feldspars.

Cements in sandstones:

Quartz overgrowths: quartz cement is chemically attached to the crystal lattice of existing quartz grains, forming rims of cement. Overgrowth retains crystallographic continuity of a grain and this is called syntaxial.

Microcrystalline quartz (less common) : Fine-grained, crystalline texture similar to that of chert.

Opal (蛋白石) (more rarely): Amorphous, because of containing water and lacking a definite crystal structure.

Calcite: Forming a mosaic of smaller crystals in pore spaces.

Dolomite and siderite (less common)

Other minerals: Hematite, limonite, feldspars, anhydrite, gypsum, clay minerals…

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5.2.4 Chemical Composition

Table 5.2 Average Chemical Composition (Weight Percent) of Sandstones from Some North American Formations*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$n =$	11	23	30	16	18	12	119	12	59
SiO_2	86.5	67.8	65.6	56.9	56.2	68.4	70.6	37.3	50.3
TiO_2	0.53	0.95	0.91	1.42	0.89	0.69	0.64	0.34	0.64
Al_2O_3	5.71	15.4	15.1	12.3	15.3	13.5	12.6	7.91	14.0
Fe_2O_3 (t)	2.69	6.46	6.09	6.18	6.48	5.30	4.97	3.18	6.40
MnO	0.02	0.07	0.15	0.11	0.07	0.09	0.08	0.10	0.13
MgO	0.69	1.73	1.82	4.20	2.35	1.68	1.51	1.07	3.25
CaO	0.05	0.42	1.94	5.82	5.74	2.38	1.61	26.0	9.90
Na_2O	0.02	1.07	0.87	1.92	1.28	3.15	2.76	0.92	—
K_2O	1.55	2.74	3.03	1.90	2.80	2.62	2.20	0.51	2.09
P_2O_5	0.02	0.16	0.17	0.17	0.17	0.18	0.02	0.10	0.21
V (ppm)	51	123	159	100	126	71	79	103	—
Cr	55	82	88	225	71	55	44	31	—
Ni	19	231	58	130	49	30	8	5	49
Zn	29	52	104	84	114	69	—	66	91
Rb	60	123	133	72	125	93	—	10	79
Sr	29	134	113	233	168	310	110	879	267
Y	17	31	40	21	35	36	37	15	29
Zr	417	238	260	191	187	333	413	58	118

Source: Argast and Donnelly, 1987, *Jour. Sed. Petrology*, v. 57, p. 813–823: Society Economic Mineralogists and Paleontologists, Tulsa, OK.

Note: Iron is reported as total Fe_2O_3; n is the number of samples in each average. A dash indicates no reported value.

*(1) Shawangunk Formation near Ellenville, New York (quartz arenite)
(2) Millport Member of the Rhinestreet Formation, Elmira, New York (lithic arenite/wacke)
(3) Oneota Formation, Unadilla, New York (lithic arenite/wacke)
(4) Cloridorme Formation, St. Yvon and Gros Morne, Quebec (lithic arenite/wacke)
(5) Austin Glen Member of Normanskill Formation, Poughkeepsie, New York (lithic arenite/wacke)
(6) Renessalaer Member of the Nassau Formation, near Grafton, New York (feldspathic arenite/wacke)
(7) Renesselaer Member, averages of analyses from Ondrick and Griffiths (1969) (feldspathic arenite/wacke)
(8) Rio Culebrinas Formation, La Tosca, Puerto Rico (fossiliferous volcaniclastics)
(9) Turbidites from DSDP site 379A (lithic arenites/wacke)

→ Quartz

→ Feldspars

Due to weathering and diagenesis, sedimentary rocks are enriched in silica and deplted in iron, magnesium, calcium, sodium, and potassium compared to the parent rocks.

Bulk chemical composition and trace-element composition of individual minerals are applied to provenance studies.

Boggs (2006) p.128

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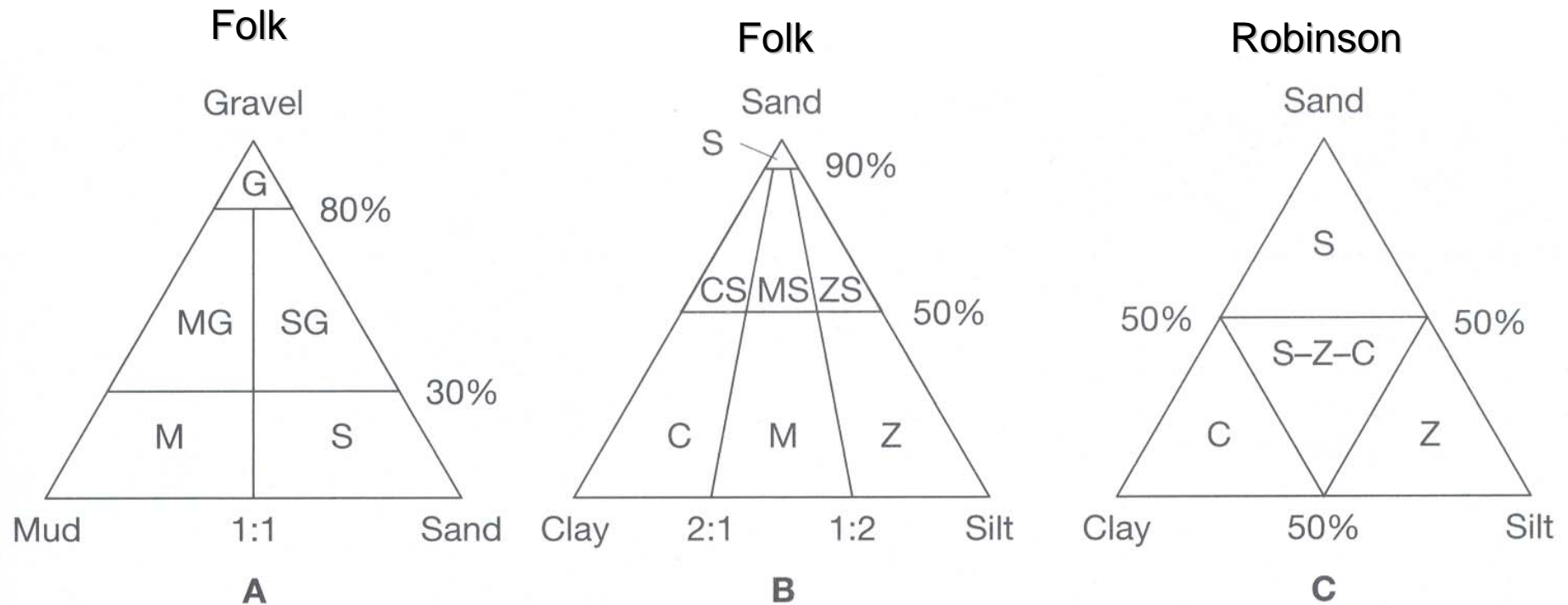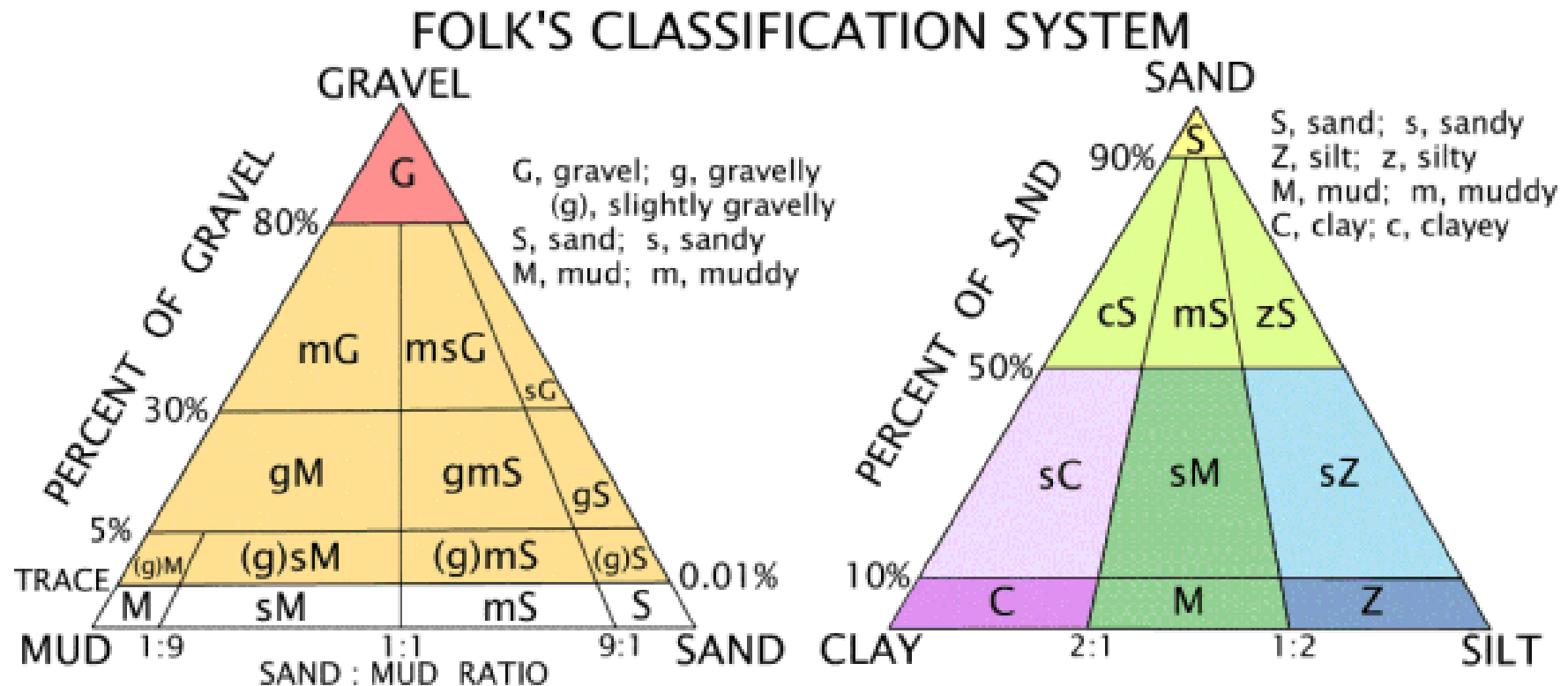6

Textural nomenclature of mixed sediments

Fig. 5.4 Nomenclature of mixed sediments. A, B. Simplified from Folk. C. After Robinson. C= clay, CS= clayey sand, G= gravel, M= mud, MG= muddy gravel, MS= muddy sand, S= sand, SG= sandy gravel, Z=silt, Zs= silty sand.

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For your reference

The system devised by Folk (**1954**, **1974**) is also based on two triangular diagrams, but it has 21 major categories, and uses the term mud (defined as silt plus clay). The patterns within the triangles of both systems differ, as does the emphasis placed on gravel. For example, in the system described by Shepard, gravelly sediments have more than 10 percent gravel; in Folk's system, slightly gravelly sediments have as little as 0.01 percent gravel. **Folk's classification scheme** stresses gravel because its concentration is a function of the highest current velocity at the time of deposition, together with the maximum grain size of the detritus that is available.

FOLK'S CLASSIFICATION SYSTEM

G, gravel; g, gravelly
(g), slightly gravelly
S, sand; s, sandy
M, mud; m, muddy

S, sand; s, sandy
Z, silt; z, silty
M, mud; m, muddy
C, clay; c, clayey

From: USGS: http://pubs.usgs.gov/of/2006/1046/htmldocs/nomenclature.htm
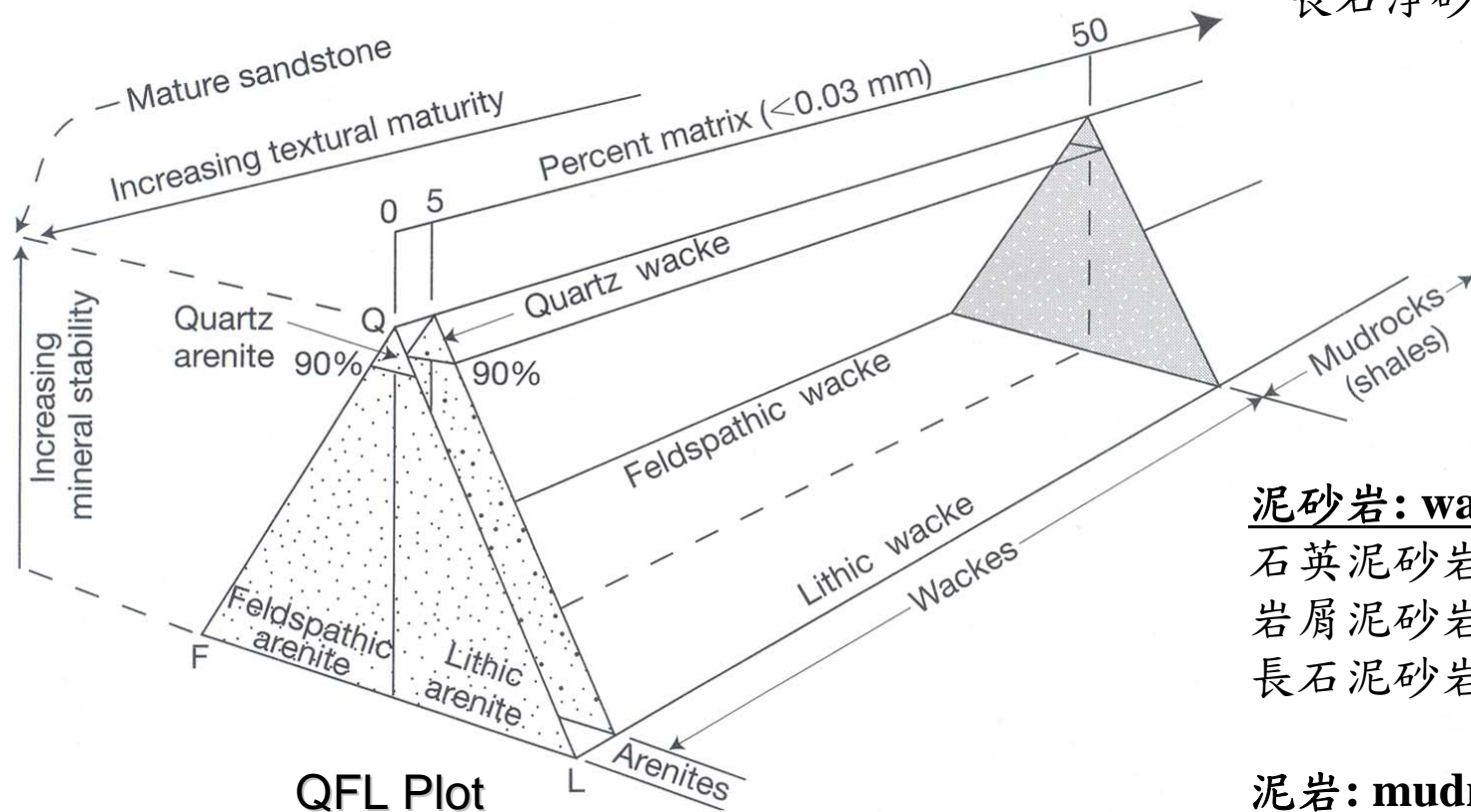
For your reference

To describe the approximate relationship between the size fractions, most sedimentologists use one of the systems described either by Shepard (**1954**) or Folk (**1954**, **1974**). The original scheme devised by Shepard (**1954**) utilized a single ternary diagram with sand, silt, and clay in the corners to graphically show the relative proportions among these three grades within a sample. This scheme, however, does not allow for sediments with significant amounts of gravel. Therefore, **Shepard's classification scheme** was subsequently modified by the addition of a second ternary diagram to account for the gravel fraction (Schlee, **1973**).
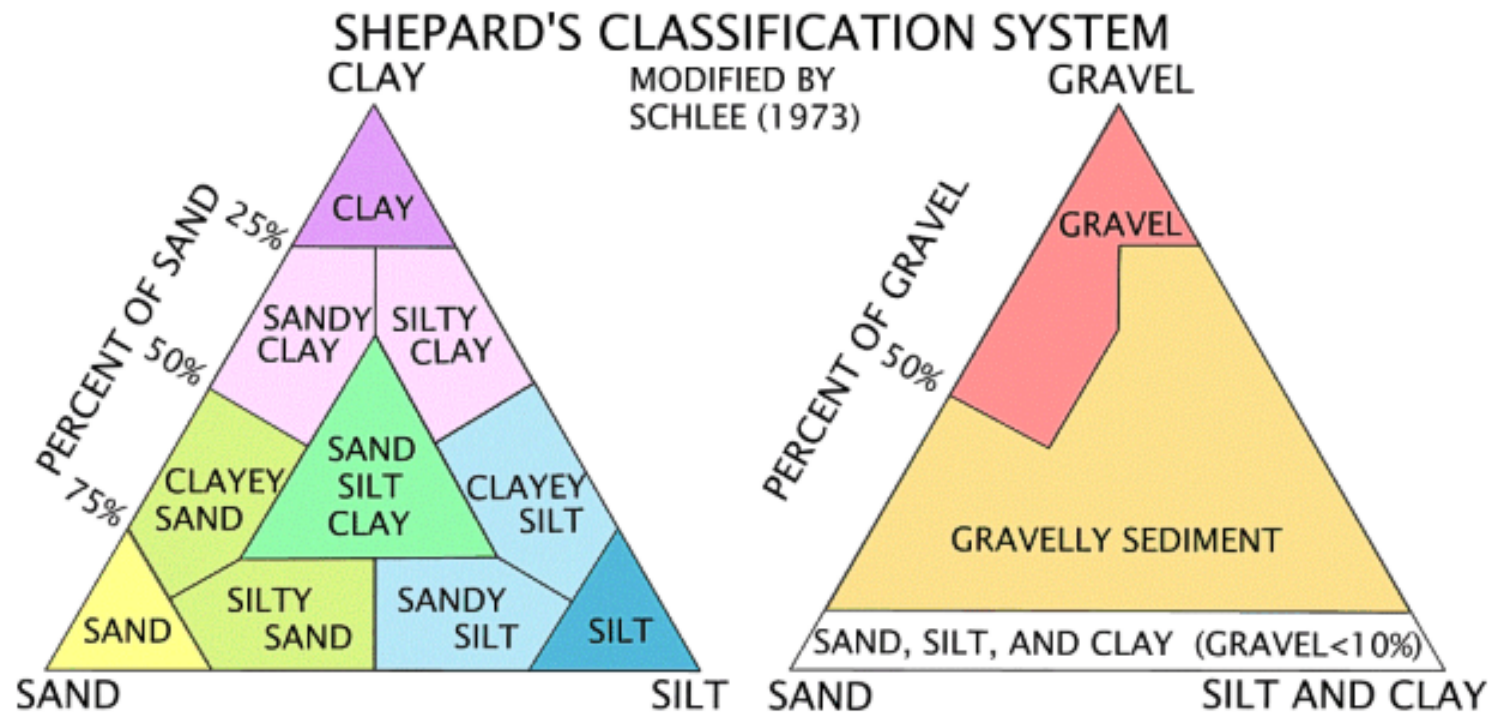
Shepard's classification scheme emphasizes the ratios of sand, silt, and clay because they reflect sorting and reworking (Poppe and others, **2005**).

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From: USGS: http://pubs.usgs.gov/of/2006/1046/htmldocs/nomenclature.htm

Minerallgical Classification

Gilbert's (1982) classification

淨砂岩:arenite
石英淨砂岩(quartz arenite);
岩屑淨砂岩(lithic arenite);
長石淨砂岩(feldspathic arenite)

QFL Plot

泥砂岩: wacke
石英泥砂岩(quartz wacke);
岩屑泥砂岩(lithic wacke);
長石泥砂岩(feldspathic wacke)

泥岩: mudrock

Fig. 5.5 Classification of sandstones on the basis of three mineral components: Q=quartz, chert, quartzite fragments; F=feldspars; L=unstable, lithic grains (rock fragments). Points within the triangles represent relative proportions of Q, F, and L end members. Percentage of argillaceous matrix is represented by a vector extending toward the rear of the diagram. The term arenite is restricted to sandstones containing less than about 5 percent matrix; sandstones containing more matrix are wackes.

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Informal names:

Arkose (長石砂岩): feldspathic arenite rich (>~25%) in feldspars.

Graywacke (混濁砂岩): Matrix-rich sandstones of any composition that have undergone deep burial, have a chloritic matrix, and are dark gray to dark green, very hard, and dense. This term has been much misused and should be abandoned.

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5.2.6 Sandstone maturity

● **Compositional maturity**: relative abundance of stable and unstable framework grains (mature: abundant quartz; immature: abundant feldspar or rock fragments)
● **Textural maturity**: relative abundance of matrix and the degree of rounding and sorting of framework grains.
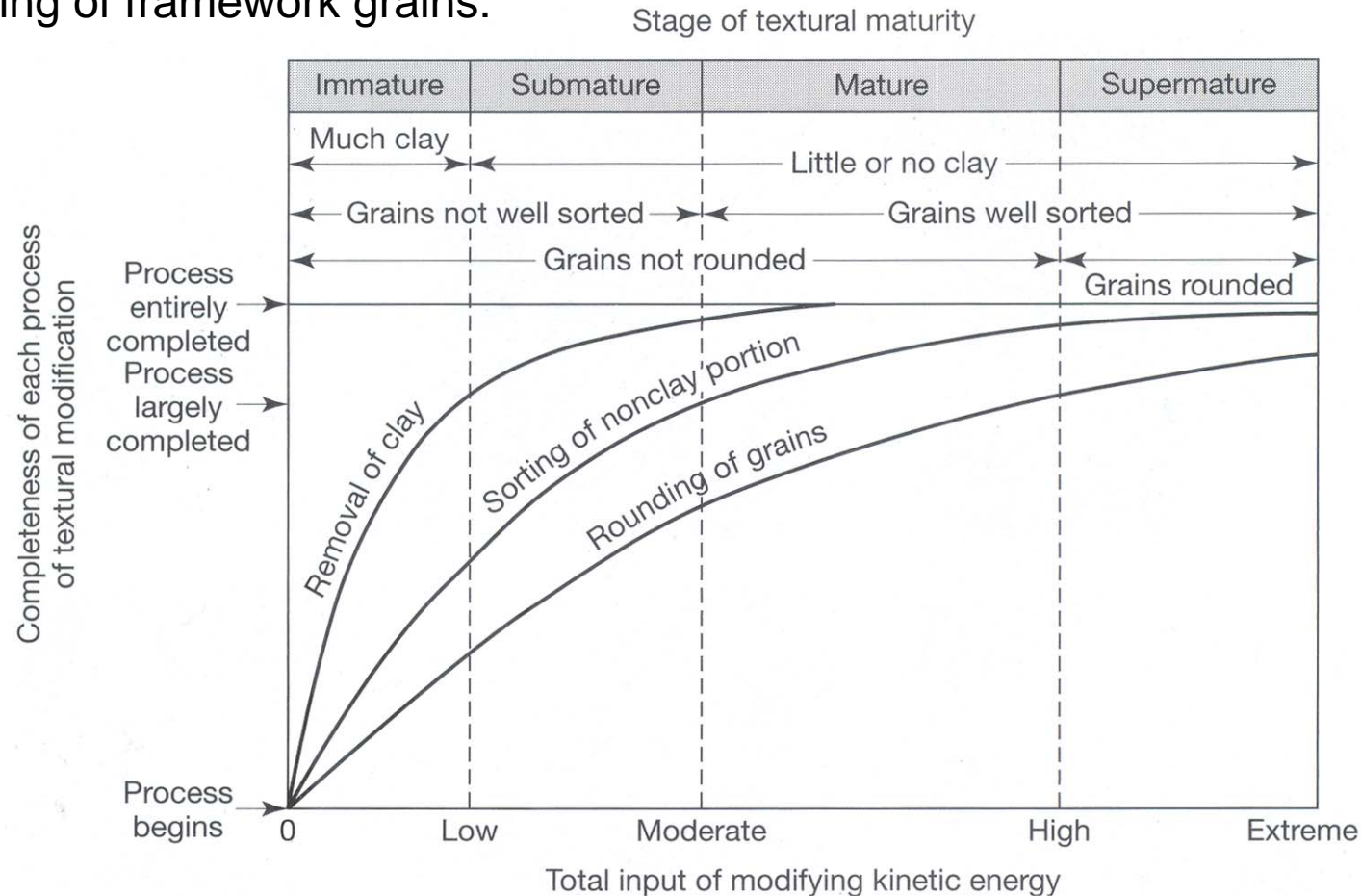
Fig. 5.6 Textural maturity classification of Folk. Textural maturity of sands is shown as a function of input of kinetic energy.

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Quiz: Describe the texture of the sandstone under microscope.
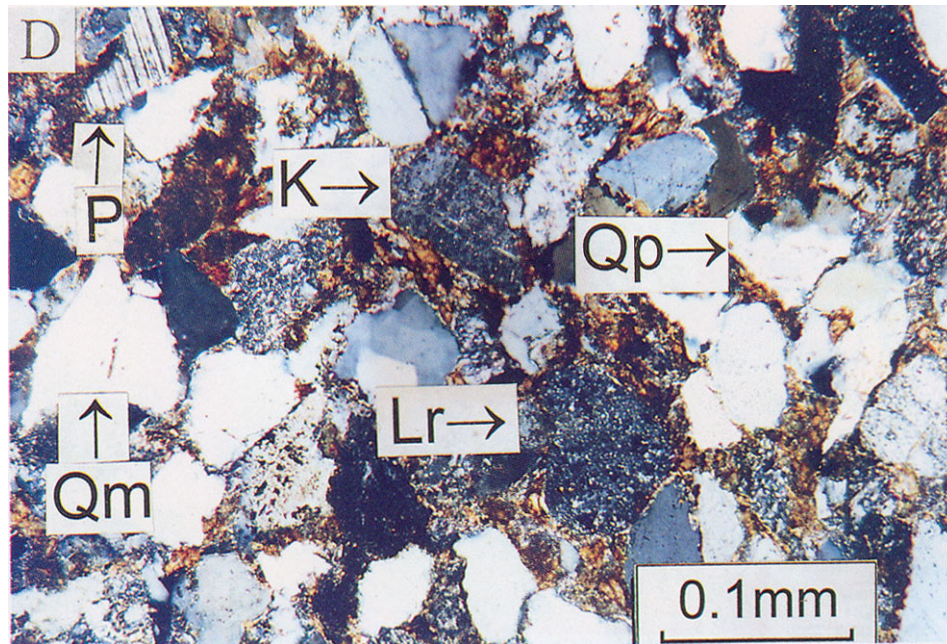
My answer:

K: K-feldspar; Lr: Lithic fragment; P: plagioclase; Qp, Qm: quartz
五指山層(鄧屬予, 1997)

Percentage chart

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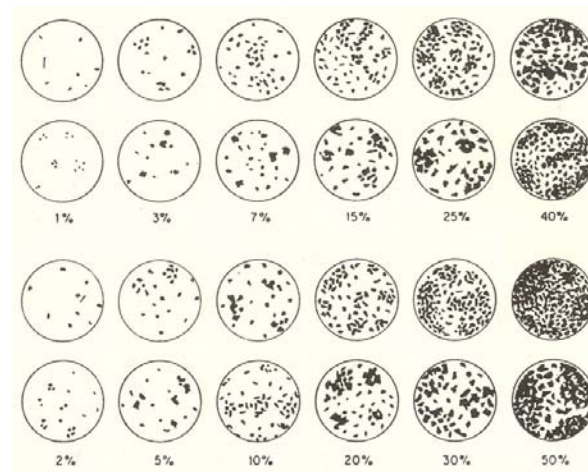
Fig. 5.7 Representative photomicrographs illustrating major classes of sandstones. A. Quartz arenite (>90% quartz), Roubidoux Fm. (Ordovician), Missouri. B. Feldspathic arenite (F=feldspar; Q=quartz), Belt Group (Precambrian), Montana. C. Lithic arenite (V=volcanic rock fragment; Q=quartz; Ch=chert— some apparent chert grains may actually be silicified volcanic rock fragments), Otter Point Fm. (Jurassic), Oregon. D. Volcaniclastic sandstone (V= volcanic rock fragment; P=plagioclase; M=matrix), Miocene sandstone, Japan Sea. Crossed nicols.

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5.3 Conglomerates

Make up less than 1% of sedimentary rocks.

Conglomerates: Sedimentary rocks that contain a substantial fraction (at least > 30%) of gravel-size (>2 mm) particles.

Breccias: composed of very angular, gravel-size fragments.

5.3.1 Particle compositions

Mainly rock fragments (clasts) and sand- or mud-size mineral grains are commonly present as matrix minerals.

Rock fragments of quartzite, chert, vein-quartz are stable and durable clasts.

Oligomict conglomerates: composed mainly of a single durable clasts, e.g., quartzite.

Polymict conglomerates: composed of many kinds of clasts.

If the grains are largely unstable or metastable clasts such as basalt, limestone, shale, and metamorphic phyllite it is called **petromict conglomerates.**
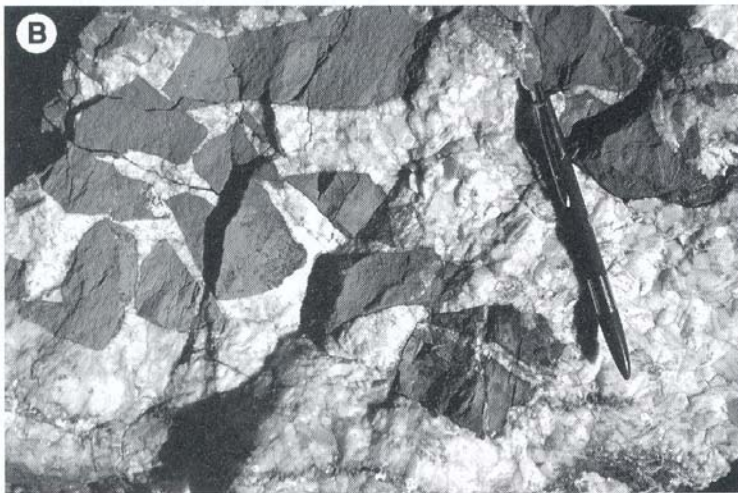
Fig. 5.8 A. Clast-supported conglomerate underlying laminated sands. Terrace deposits (Holocene) of the Umpqua River, southwest Oregon. B. Large breccia clasts (dark) cemented with calcite. Nevada Limestone (Devonian), Treasure Peak, Nevada. Photograph courtesy of Walter Youngquist.

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Table 5.3 Fundamental genetic types of conglomerates and breccias

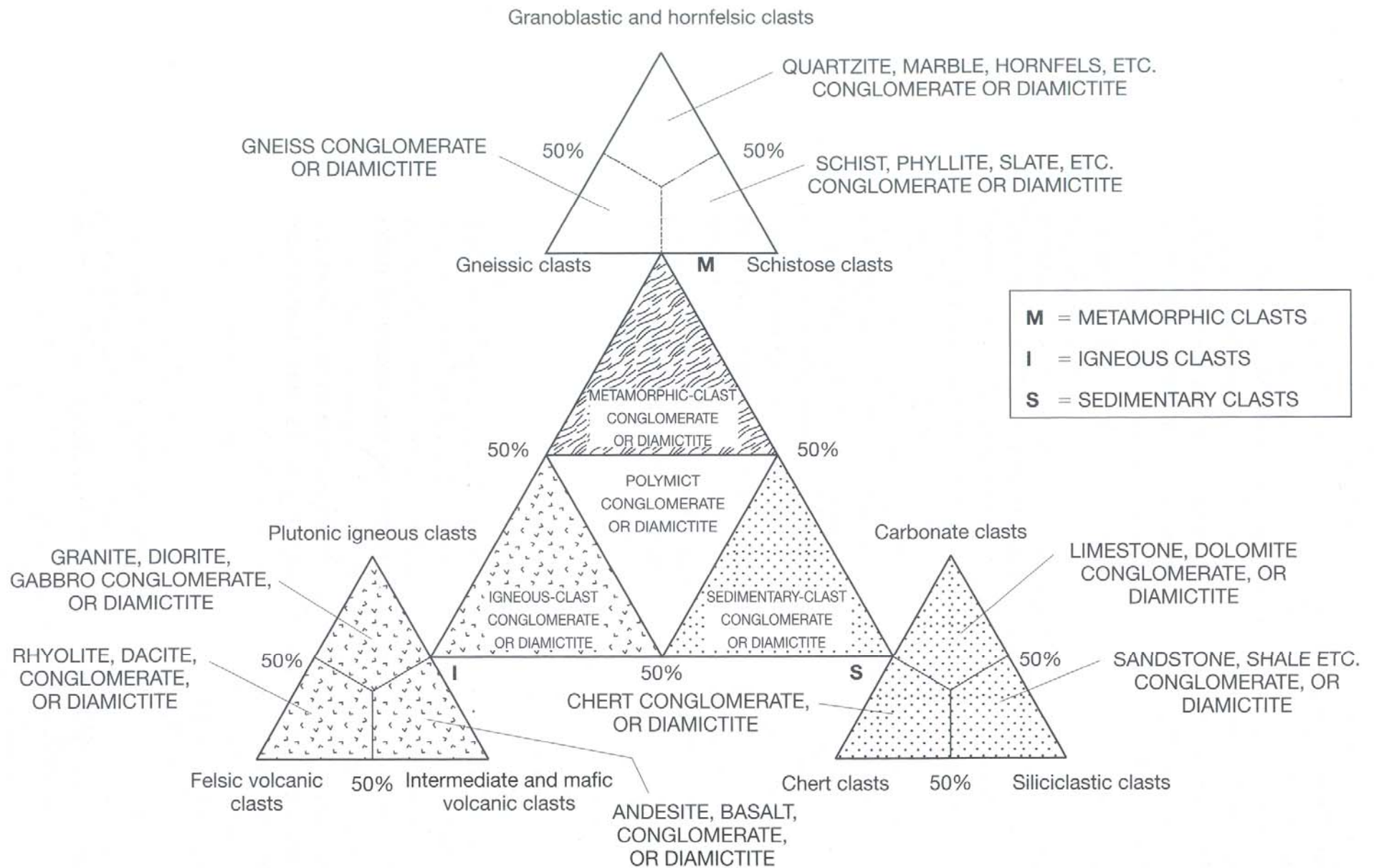| Major types	Subtypes	Origin of clasts
Epiclastic conglomerate and breccia	Extraformational conglomerate and breccia	Breakdown of older rocks of any kind through the processes of weathering and erosion; deposition by fluid flows (water, ice) and sediment gravity flows
	Intraformational conglomerate and breccia	Penecontemporaneous fragmentation of weakly consolidated sedimentary beds; deposition by fluid flows and sediment gravity flows
Volcanic breccia	Pyroclastic breccia	Explosive volcanic eruptions, either magmatic or phreatic (steam) eruptions; deposited by air-falls or pyroclastic flows
	Autobreccia	Breakup of viscous, partially congealed lava owing to continued movement of the lava
	Hyaloclastic breccia	Shattering of hot, coherent magma into glassy fragments owing to contact with water, snow, or water-saturated sediment (quench fragmentation)
Cataclastic breccia	Landslide and slump breccia	Breakup of rock owing to tensile stresses and impact during sliding and slumping of rock masses
	Tectonic breccia: fault, fold, crush breccia	Breakage of brittle rock as a result of crustal movements
	Collapse breccia	Breakage of brittle rock owing to collapse into an opening created by solution or other processes
Solution breccia		Insoluble fragments that remain after solution of more soluble material; e.g., chert clasts concentrated by solution of limestone
Meteorite impact breccia		Shattering of rock owing to meteorite impact

Source: Modified from Pettijohn, F. J., 1975, *Sedimentary rocks*, 3rd ed., Harper & Row, New York, p. 165.

Boggs (2006), p.136

Fig. 5.9 Classification of conglomerate on the basis of clast lithology and fabric support.

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Clast-supported conglomerate: gravel-size grains touch and form a supporting framework.
Matrix-supported conglomerate: gravel-size grains do not touch and are supported in a mud/sand matrix. This type of conglomerate may be referred to as diamictites.

Note: Other meaning for diamictites: poorly sorted glacial deposits.

5.3.3 Origin and Occurrence of Conglomerate

Quartzose (oligomict) conglomerate (less common): derived from metasedimentary rocks, containing quartzite beds, igneous rocks containing quartz-filled veins, and sedimentary successions, particularly limestones, containing chert beds.

Petromict conglomerate (more common): derived from many kinds of plutonic igneous, volcanic, metamorphic and sedimentary rocks, although the clasts in a particular conglomerate may be dominantly one or another of these rock types. For example, limestone conglomerate, basalt conglomerate …

Resedimented conglomerates: retransported from nearshore areas by sediment gravity-flow process and deposited in deep-marine settings.

Intraformation conglomerates: composed of clasts of sediments formed within depositional basins, e.g., mud clasts.

Boggs (2006), p.137

Table 5.4 Classification of conglomerates and diamictites on the basis of clast stability and fabric support

Percentage of ultrastable clasts	Type of fabric support	
	Clast-supported	Matrix-supported
>90	Quartzose conglomerate	Quartzose diamictite
<90	Petromict conglomerate	Petromict diamictite

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5.4 Shales (Mudrocks)

Shales are fine-grained, siliciclastic sedimentary rocks, that contain more than 50% siliciclastic grain less than 0.062 (1/16) mm. They are made up dominantly of silt-sized (1/16~1/265 mm) and clay-size (<1/256 mm) particles.

Makes up about 50% of all sedimentary rocks

Shale (or mudrock) is used as a class name for all fine-grained siliciclastic rocks, regardless if the rocks develop fissility (the ability to split easily into thin layers) or not.

Blatt et al. (1980) used shales to indicate laminated (or fissile) rocks and mudstones to indicate non-laminated rocks.

Boggs (2006), p.140

Shale

Mudstone

Boggs (2006), p.141

Figure 5.11
Backscattered scanning electron microscope (BSE) photograph of a laminated shale. The elongated, platy, or flaky minerals are clay minerals (illite) and fine micas. Other coarser minerals are quartz (Q), feldspar (F), calcite (C), mica (M), and pyrite (very bright mineral). Note that orientation of clay minerals and fine micas creates the lamination. Whitby Mudstone (Jurassic), Yorkshire, England. Scale bar = 50 μm. Photograph courtesy of David Krinsley.
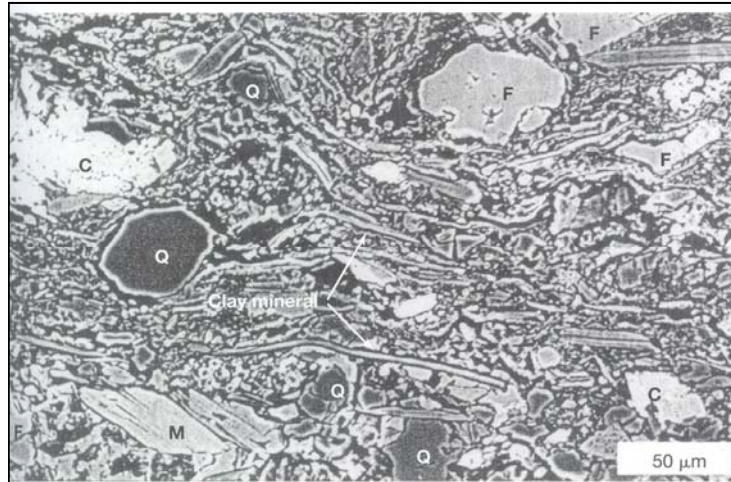
Clay minerals (arrows)
Q (quartz)
F (Feldspar)
C (Calcite)
M (Mica)

Figure 5.10
A. Laminated (red) shale (pre-Mississippian), Arctic National Wildlife Refuge, Alaska. Note binoculars for scale. B. Lacustrine mudstones (nonlaminated), Furnace Creek Formation (Miocene/Pliocene), Death Valley, California. Photograph by James Stovall.

1. Mineralogy

Table 5.5 Average percent mineral composition of shales of different ages

Age	Number of analyses	Clay minerals	Quartz	Potassium feldspar	Plagioclase feldspar	Calcite	Dolomite	Siderite	Pyrite	Other minerals	Organic carbon
Quaternary	5	29.9	42.3	12.4	—	6.6	2.4	—	5.6	—	0.9
Pliocene	4	56.5	14.6	5.7	11.9	3.2	—	2.9	1.8	<1.0	2.6
Miocene	9	25.3	34.1	7.4	11.7	14.6	1.2	—	1.9	2.4	1.4
Oligocene	4	33.7	53.5	3.0	—	5.5	—	—	—	4.0	0.4
Eocene	11	40.2	34.6	2.0	8.1	3.8	4.6	1.7	1.6	—	3.5
Cretaceous	9	27.4	52.9	3.6	1.6	2.9	7.9	0.1	1.6	—	2.0
Jurassic	10	34.7	21.9	0.6	4.4	14.6	1.6	0.4	10.9	—	10.9
Triassic	9	29.4	45.9	10.7	0.7	3.7	4.1	5.1	—	—	0.3
Permian	1	17.0	28.0	4.0	8.0	—	1.0	—	—	42.0	0.2
Pennsylvanian	7	48.9	32.6	0.8	6.2	1.4	2.1	3.4	3.5	—	1.0
Mississippian	3	57.2	29.1	0.4	2.9	—	—	0.6	5.1	—	4.7
Devonian	22	41.8	47.1	0.6	—	2.0	1.3	0.3	3.3	—	3.7
Ordovician	2	44.9	32.2	<1.0	6.3	9.8	0.5	0.5	3.4	—	1.5
Misc. ages	29	47.8	33.1	<1.0	5.5	5.2	2.3	0.8	3.1	—	4.5

Source: O'Brien, N. R., and R. M. Slatt, 1990, *Argillaceous rock atlas*, Springer-Verlag, New York, Table 1, p. 124–125.

Note: Values adjusted to 100% for shales of each age.

Boggs (2006), p.141

Dominant minerals:
• Clay minerals
• Quartz (fine-grained)
• Feldspar (fine-grained)

Accessory minerals:
• Carbonate minerals (calcite, dolomite, siderite)
• Sulfides (pyrite, marcasite)
• Iron oxides (goethite)
• Heavy minerals
• Organic carbon

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Origins of minerals in shale:

Clay, quartz, and feldspar minerals are mainly detrital (terrigenous) mineral, although some fraction of these minerals may also form during burial diagenesis.

Carbonate minerals, sulfides mainly formed during burial as cements or replacement minerals.

Factors that affect the composition of shales:
Tectonic setting, provenance (source), depositional environments, grain size, and burial diagenesis.

Kaolinite and smectite change to illite and chlorite during burial diagenesis. →

Figure 5.12
Systematic changes in relative abundance of major clay minerals as a function of geologic age. [After Singer, A., and G. Müller, 1983, Diagenesis in argillaceous sediments, *in* Larson, G., and Chilingarian, G. V. (eds.), Diagenesis in sediments and sedimentary rocks, v. 2, Fig. 3.28, p. 176, reproduced by permission of Elsevier Science Publishers, New York.]

Boggs (2006), p.142

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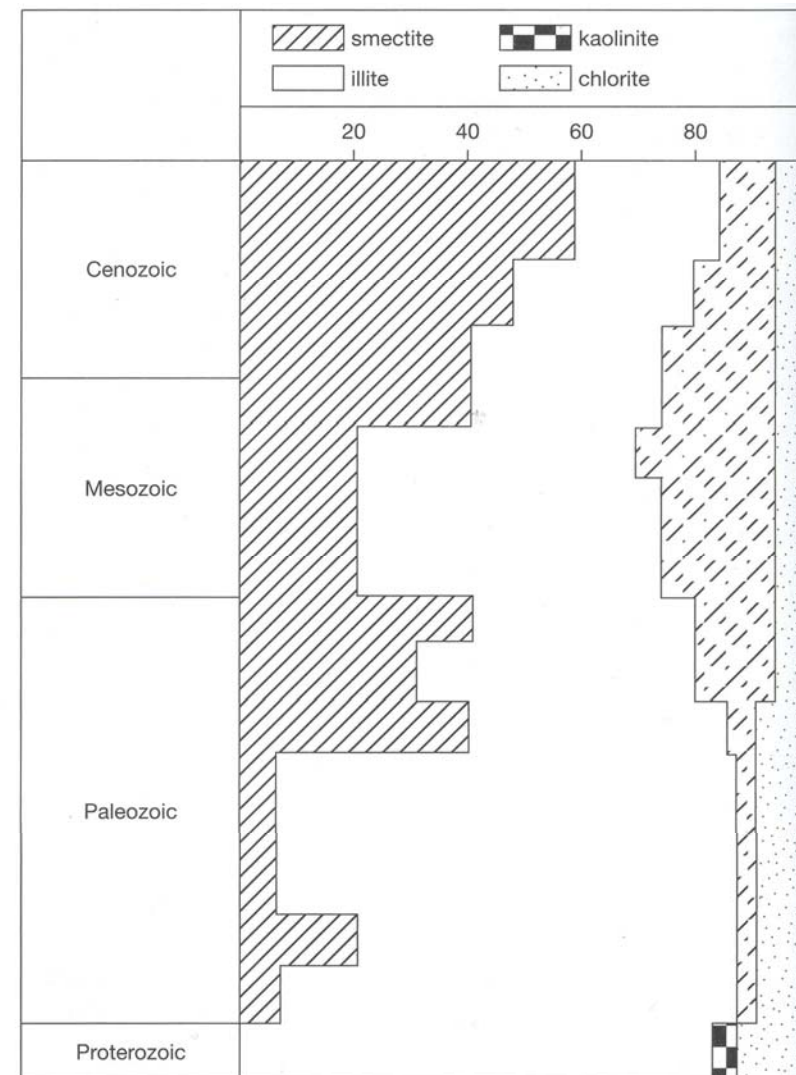
2. Chemical Composition

Table 5.6 Average chemical composition of selected shales reported in the literature

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	60.65	64.80	59.75	56.78	67.78	64.09	66.90	63.04	62.13	65.47	64.21	64.10	63.31
Al_2O_3	17.53	16.90	17.79	16.89	16.59	16.65	16.67	18.63	18.11	16.11	17.02	17.70	17.22
Fe_2O_3	7.11	—	—	—	—	—	—	—	—	—	—	2.70	0.82
FeO	—	5.66	5.59	6.56	4.11	6.03	5.87	7.66	7.33	5.85	6.71	4.05	5.45
MgO	2.04	2.86	4.02	4.56	3.38	2.54	2.59	2.60	3.57	2.50	2.70	2.65	3.00
CaO	0.52	3.63	6.10	8.91	3.91	5.65	0.53	1.31	2.22	4.10	3.44	1.88	3.52
Na_2O	1.47	1.14	0.72	0.77	0.98	1.27	1.50	1.02	2.68	2.80	1.44	1.91	1.48
K_2O	3.28	3.97	4.82	4.38	2.44	2.73	4.97	4.57	2.92	2.37	3.58	3.60	3.64
TiO_2	0.97	0.70	0.98	0.92	0.70	0.82	0.78	0.94	0.78	0.49	0.72	0.86	0.81
P_2O_5	0.13	0.13	0.12	0.13	0.10	0.12	0.14	0.10	0.17	—	—	—	0.10
MnO	0.10	0.06		0.08		0.07	0.06	0.12	1.10	0.07	0.05	—	0.06

Source:
(1) Moore, 1978 (Pennsylvanian shale, Illinois Basin)
(2) Gromet et al., 1984 (North American shale composite)
(3) Ronov and Migdisov, 1971 (average North American Paleozoic shale)
(4) Ronov and Migdisov, 1971 (average Russian Paleozoic shale)
(5) Ronov and Migdisov, 1971 (average North American Mesozoic shale)
(6) Ronov and Migdisov, 1971 (average Russian Mesozoic shale)
(7) Cameron and Garrels, 1980 (average Canadian Proterozoic shale)
(8) Ronov and Migdisov, 1971 (average Russian Proterozoic shale)
(9) Cameron and Garrels, 1980 (average Canadian Archean shale)
(10) Ronov and Migdisov, 1971 (average Archean shale)
(11) Clarke, 1924 (average shale)
(12) Shaw, 1956 (compilation of 155 analyses of shale)
(13) Average of values in columns 1 through 12

Boggs (2006), p.143

SiO_2 (57~68%): quartz and other silicate minerals
Al_2O_3 (16~19%): clay minerals, feldspars.
Fe: iron oxide minerals (hematite, goethite), biotite, siderite etc.

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5.4.2 Classification

There is no widely accepted shale classification.

Potter, Maynard, and Pryor (1980)'s classification based on grain size, lamination, and degree of induration.

Siltstone: < 33% clay-size particles
Mudstone: 33-65% clay-size particles
Claystone: 66-100 clay-size particles

5.4.3 Origin and Occurrence of Shales

Shales form under any environment conditions in which fine sediment is abundant and water energy is sufficiently low to allow settling of suspended fine silt and clay. Shales are particularly characteristic of marine environments adjacent to major continents where the seafloor lies below the storm wave base, but they can form also in lakes and quiet-water parts of rivers, and in lagoonal, tidal-flat, and deltaic environments.

Table 5.7 Classification of shales and siltstone (>50% grains <0.062 mm)

	Percentage clay-size constituents		0–32	33–65	66–100
	Field adjective		Gritty	Loamy	Fat or slick
NONINDURATED	Beds >10 mm		Bedded silt	Bedded mud	Bedded claymud
NONINDURATED	Laminae <10 mm		Laminated silt	Laminated mud	Laminated claymud
INDURATED	Beds >10 mm		Bedded siltstone	Mudstone	Claystone
INDURATED	Laminae <10 mm		Laminated siltstone	Mudshale	Clayshale
METAMORPHOSED	Degree of metamorphism Low → High	Low	Quartz Argillite	Argillite	
METAMORPHOSED			Quartz Slate	Slate	
METAMORPHOSED		High	Phyllite and/or Mica Schist		

Source: Potter, P. E., J. B. Maynard, and W. A. Pryor, 1980, Sedimentology of shales: Springer-Verlag, New York, Table 1.2, p. 14.

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5.5.1 Stages and realms of diagenesis

Newly deposited sediments are characterised by:

• loosely packed, uncemented fabrics;
• high porosities
• high interstitial water content

Diagenesis is all the changes that take place in sediments at low temperature (<250 degree) and pressure after deposition.

During sediment burial, temperature and pressure increase and pore-water chemistry changes. This leads to diagenetic processes such as compaction, dissolution, cementation, replacement, and recrystallization. These processes are the means by which unconsolidated, loose sediments are turned into sedimentary rocks.

Figure 5.13
Pressure-temperature diagram relating diagenesis to metamorphic regimes and typical pressure-temperature, geostatic, and hydrostatic gradients in Earth's crust. The 10°C/km geothermal gradient is typical of stable cratons; the 30°C/km gradient is typical of rifted sedimentary basins. [Modified from Worden, R. H., and S. D. Burley, Sandstone diagenesis: The evolution of sand to stone, in Burley, S. D., and R. H. Worden, 2003, Sandstone diagenesis: Recent and ancient: Blackwell Pub., Malden, Mass. Fig. 1, p. 3. Reproduced by permission.]

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Fabrics in Sandstone created by diagenetic processes

Porosities decrease with increasing burial depth by burial compaction and cementation

Boggs (2006), p.149
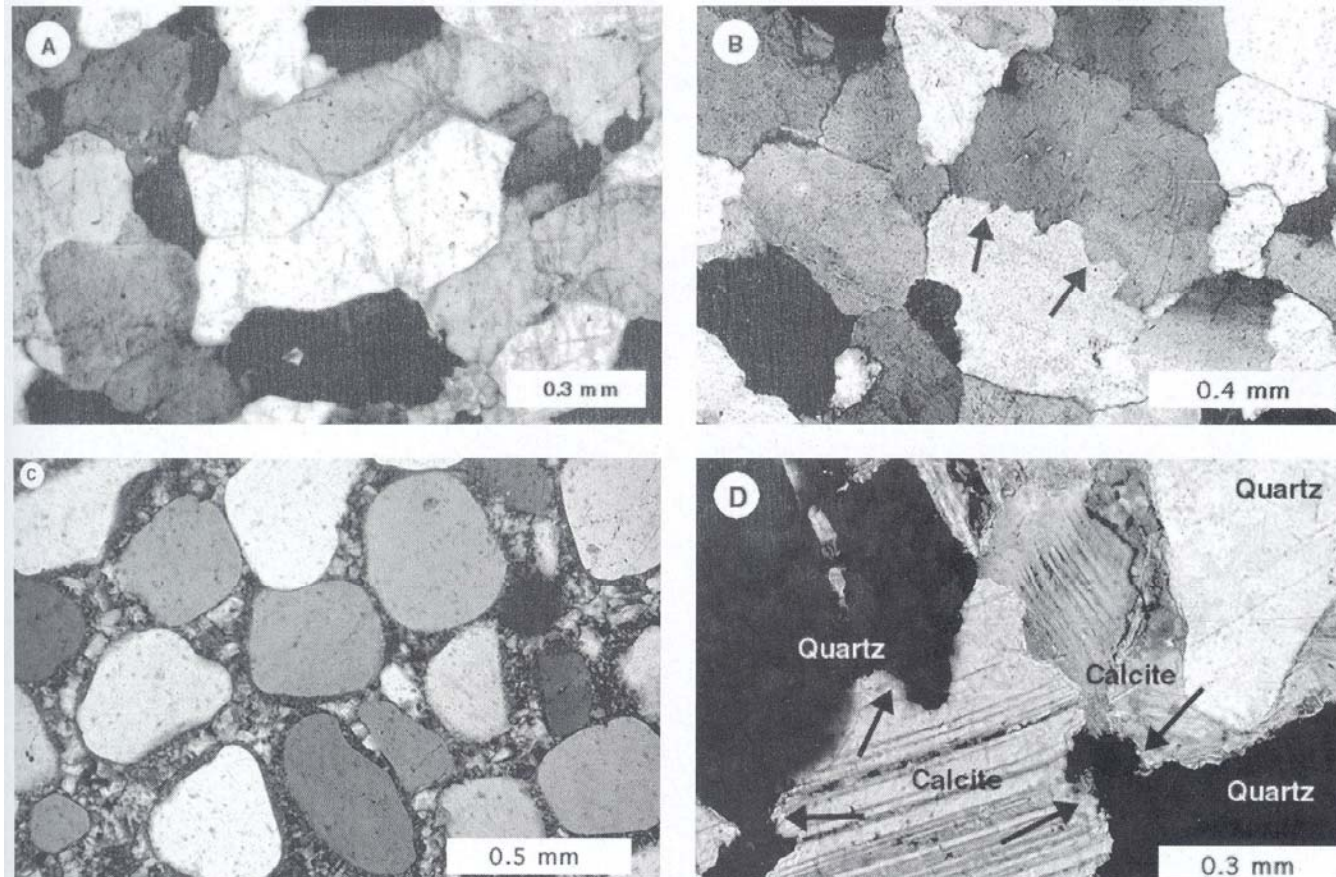
Figure 5.15
Fabrics in sandstones created by diagenetic processes: A. Physical compaction (note prevalence of concavo-convex and long contacts), Tuscarora Sandstone (Silurian), Pennsylvania. B. Chemical compaction owing to pressure solution (note irregular sutured contact indicated by arrows), Oriskany Quartzite (Devonian), Pennsylvania. C. Cementation by microquartz (chert), Jefferson City Fm. (Ordovician), Missouri. D. Replacement of quartz by calcite, creating "nibbled" contacts (arrows), Mauch Chunk Group (Mississippian), Pennsylvania. Crossed nicol photomicrographs.

Figure 5.16
Approximate best-fit curves showing changes in porosity of sediments related to burial compaction and cementation in some California (sandstone) and Louisiana (shale) basins. [Sandstone curve based on Wilson, J. C., and E. F. McBride, 1988, Compaction and porosity evolution of Pliocene sandstones, Ventura Basin, California: Am. Assoc. Petroleum Geologists Bull., v. 72, Fig. 4, p. 669; shale curve based on Dzevanshir, R. D., et al., 1986, Sed. Geology, v. 46, Fig. 1, p. 170.]
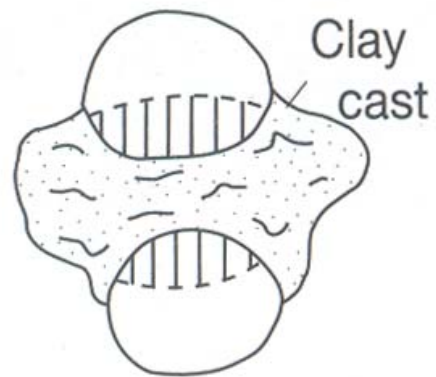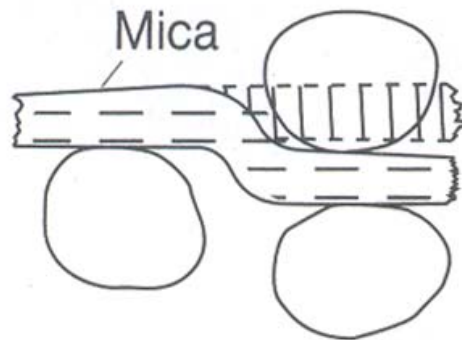
A: Physical compaction   B: Chemical compaction (pressure solution)
C: Cementation   D: Replacement

Boggs (2006), p.150
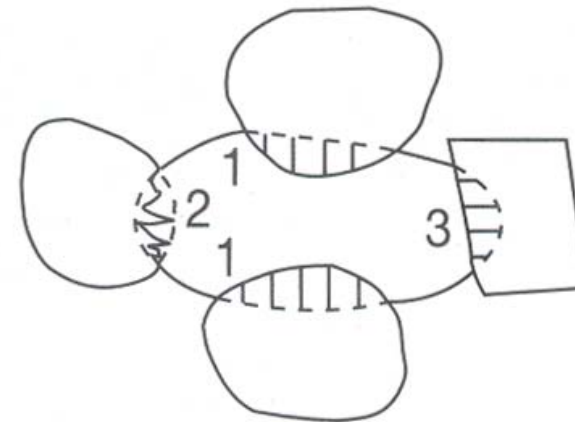
Fig. 5.17 Schematic representation of textural criteria used to estimate volume loss in sandstones owing to compaction. The hachured areas indicate rock volume lost by grain deformation and pressure solution.

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5.5.2 Major Diagenetic Processes and Effects
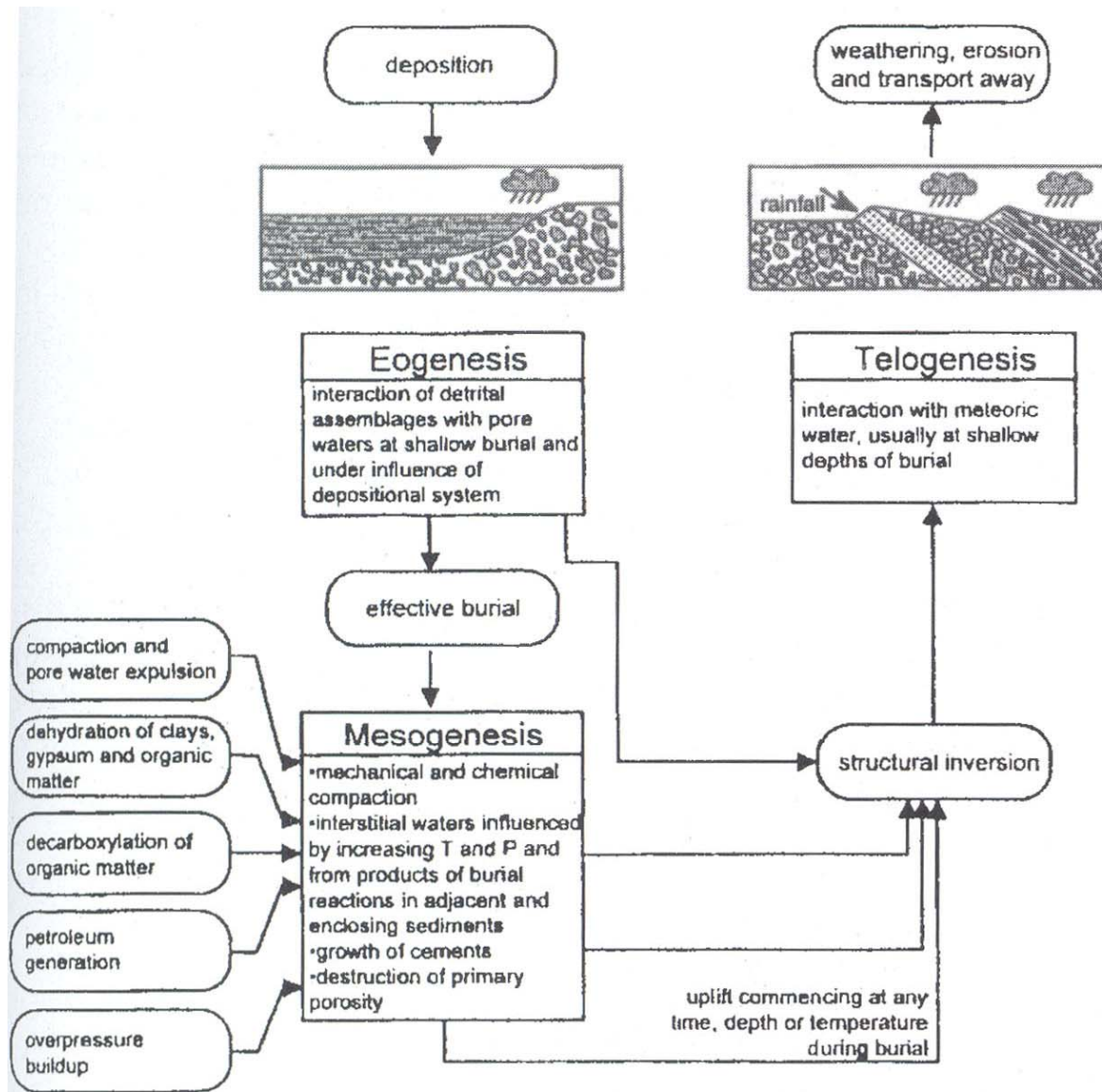
Eodiagenesis (eogenesis): 早期成岩作用
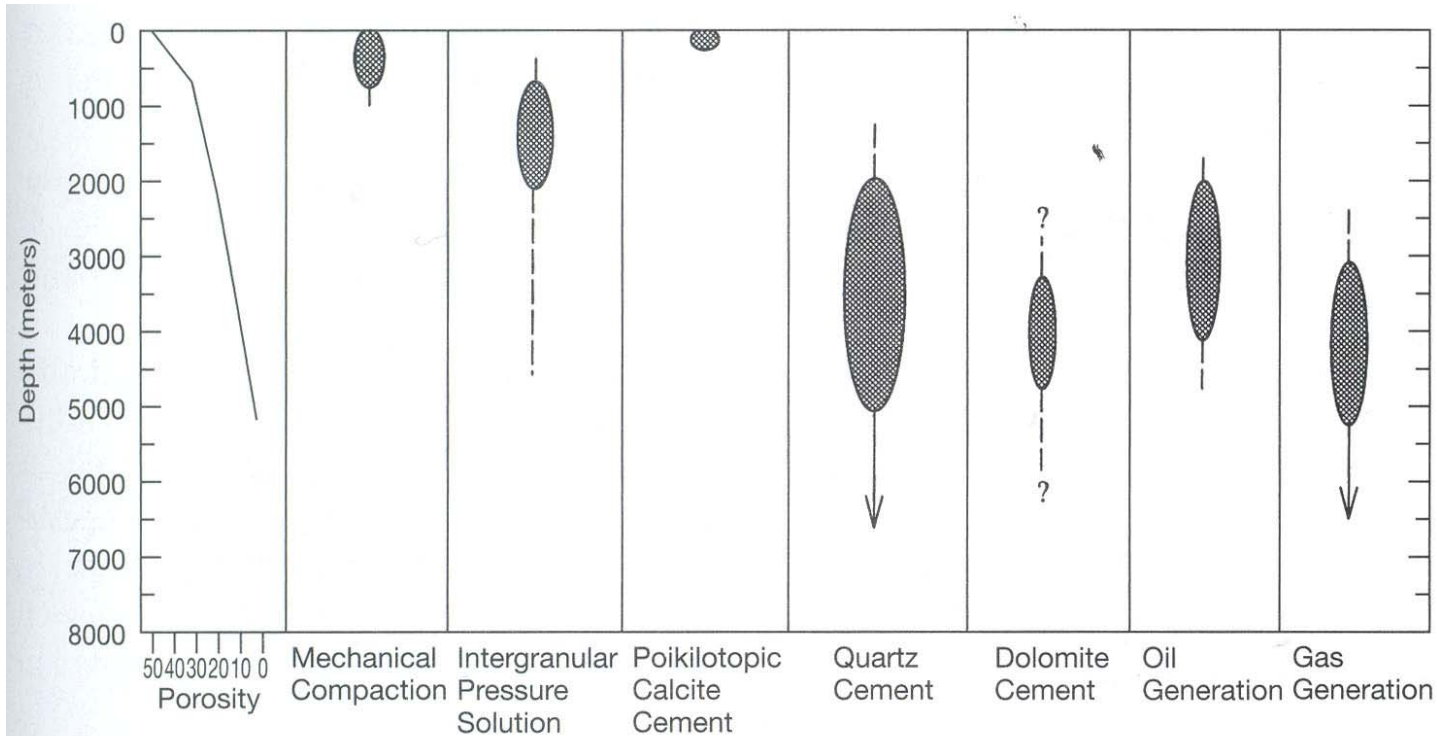Mesodiagenesis (mesogenesis): 中期成岩作用
Telodiagenesis (telogenesis): 晚期成岩作用

Figure 5.14
Flow chart illustrating the links between the regimes of diagenesis. Structural inversion refers to uplift. [From Worden, R. H., and S. D. Burley, Sandstone diagenesis: The evolution of sand to stone, *in* Burley, S. D., and R. H. Worden, 2003, Sandstone diagenesis: Recent and ancient: Blackwell Pub., Malden, Mass. Fig. 4, p. 7. Reproduced by permission.]

Boggs (2006), p.147

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Table 5.8 Principal diagenetic processes and changes that occur in siliciclastic sedimentary rocks during burial

	Diagenetic stage	Diagenetic process	Result
Burial	Eogenesis	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
	Mesogenesis	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	Telogenesis	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)

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Boggs (2006), p.148

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Depths vs. diagenetic processes

Cementation (膠結作用): Precipitation of minerals into the pore space of sediment, thereby reducing porosity and bringing about lithification of the sediments. Carbonate and silica cements are most common.

Figure 5.18
Summary diagram showing depth ranges at which mechanical compaction, pressure solution, and cementation reduce porosity in quartzose sandstones. Note that porosity is reduced from approximately 50 percent at the surface to virtually zero at a burial depth of about 5000 m. This diagram also shows the approximate depths at which oil and gas are generated in the subsurface (Chapter 7). [From Stone, W. N., and R. Siever, 1996, Quantifying compaction, pressure solution and quartz cementation in moderately- and deeply-buried quartzose sandstones from the greater Green River Basin, Wyoming, *in* Crossey, L. J., R. Loucks, and M. W. Totten, eds., 1996, Siliciclastic diagenesis and fluid flow: SEPM Special Publication No. 55, Fig. 5, p. 134.]

Boggs (2006), p.151

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Fig. 5.19 Large concretions weathering out on the surface of a laminated sandstone bed, Coaledo Formation (Eocene), southern Oregon coast. Calcite, precipitated around some kind of nucleus, filled pore spaces in the sandstone, gradually building up the globular masses. Note the sandstone lamination preserved in the concretions.

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The kinds of siliciclastic minerals and rock fragments preserved in sedimentary rocks provide evidence of the lithology of the source rocks.

A. Rock fragments provide the most direct lithologic evidence: volcanic rock fragments, metamorphic rock fragments etc.

B. Potassium feldspars often suggest sources of alkaline plutonic igneous or metamorphic rocks.

C. Sodic (Na-) plagioclases often suggest alkaline volcanic rocks.

D. Calcic (Ca-) plagioclase often comes from basic volcanic rocks.

E. Quartz: (1) Low-grade metamorphic source rocks: high percentage of quartz grains with undulose extinction greater than 5° combined with a high percentage of polycrystalline grains containing more than three crystal units per grain.

(2) High-grade metamorphic or plutonic igneous source rocks: Nonundulose quartz and polycrystalline quartz containing less than three crystal units per grain.

F. Heavy minerals suites as source-rock indicators

Source rocks

Apatite, biotite, hornblende, monazite, rutile, titanite, pink tourmaline, and zircon	→ Igneous rocks
Augite, chromite, diopside, hyperthene, ilmenite, magnetite, and olivine	→ Basic igneous rocks
Andalusite, garnet, staurolite, topaz, kyanite, sillimanite, and staurolite	→ Metamorphic rocks
Barite, iron ores, leucoxene, rounded tourmaline, rounded zircon	→ Recycled sedimentary rocks

Relative chemical stabilities and the degree of weathering and alteration of certain minerals can be sued as a tool for interpreting the climate and relief of source areas.

Source rocks

Large, fresh, angular feldspars ⟶ High-relief source areas or derived from a very arid or extremely cold climate that retarded chemical weathering.

Small, rounded, highly weathered feldspar ⟶ Low-relief source areas and/or a warm, humid climate where chemical weathering was moderately intense.

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Tectonic settings of sediment source areas
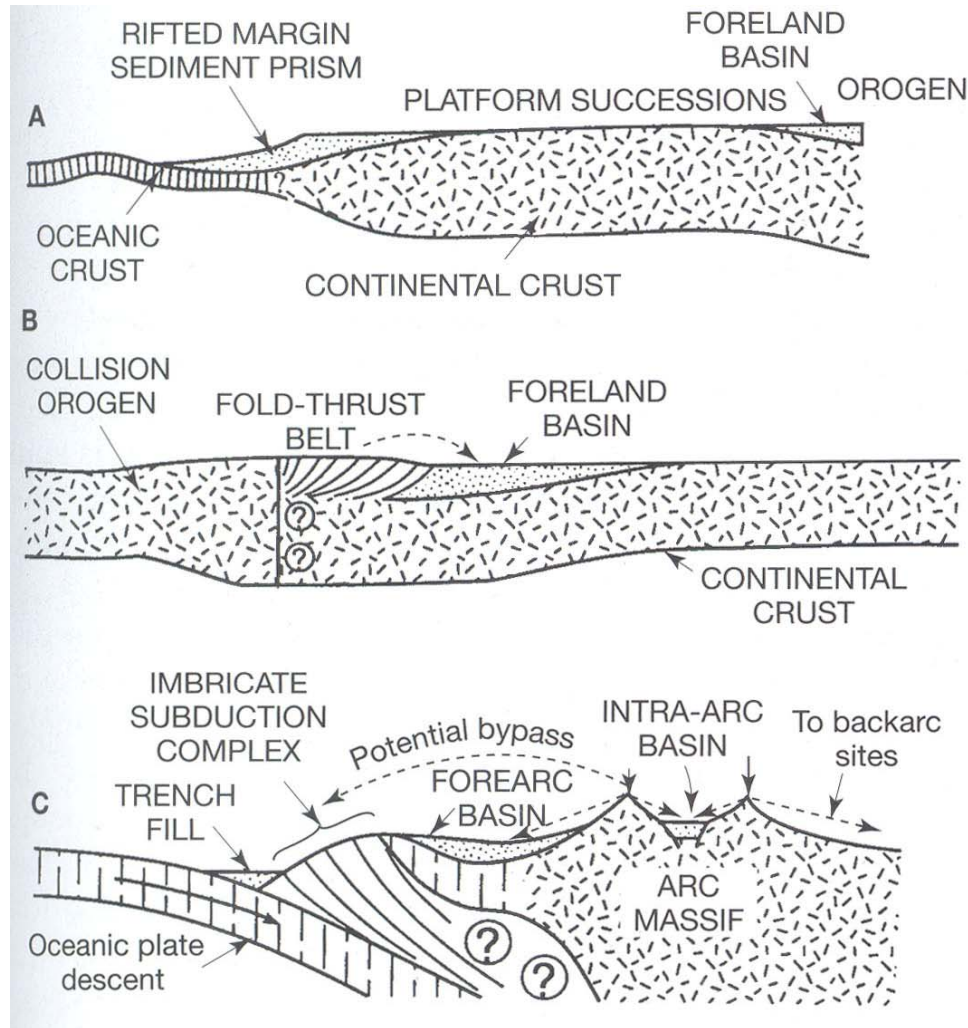
A. Continental block
B. Recycled orogen
C. Magmatic arcs

Figure 5.21
Schematic representation of the principal tectonic settings of sediment source areas. A. Continental block provenances. B. Recycled orogen provenances. C. Magmatic arcs. The dashed lines with arrows indicate sediment transport paths. (After Dickinson, W. R., and C. A. Suczek, 1979, Plate tectonics and sandstone composition: American Association Petroleum Geologists Bull., v. 63, Fig. 5, p. 2174, Fig. 6. p. 2175, Fig. 7, p. 2177, reprinted by permission of AAPG, Tulsa, Okla.).

Boggs (2006), p.155

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Relationship between framework composition of sandstones and tectonic setting
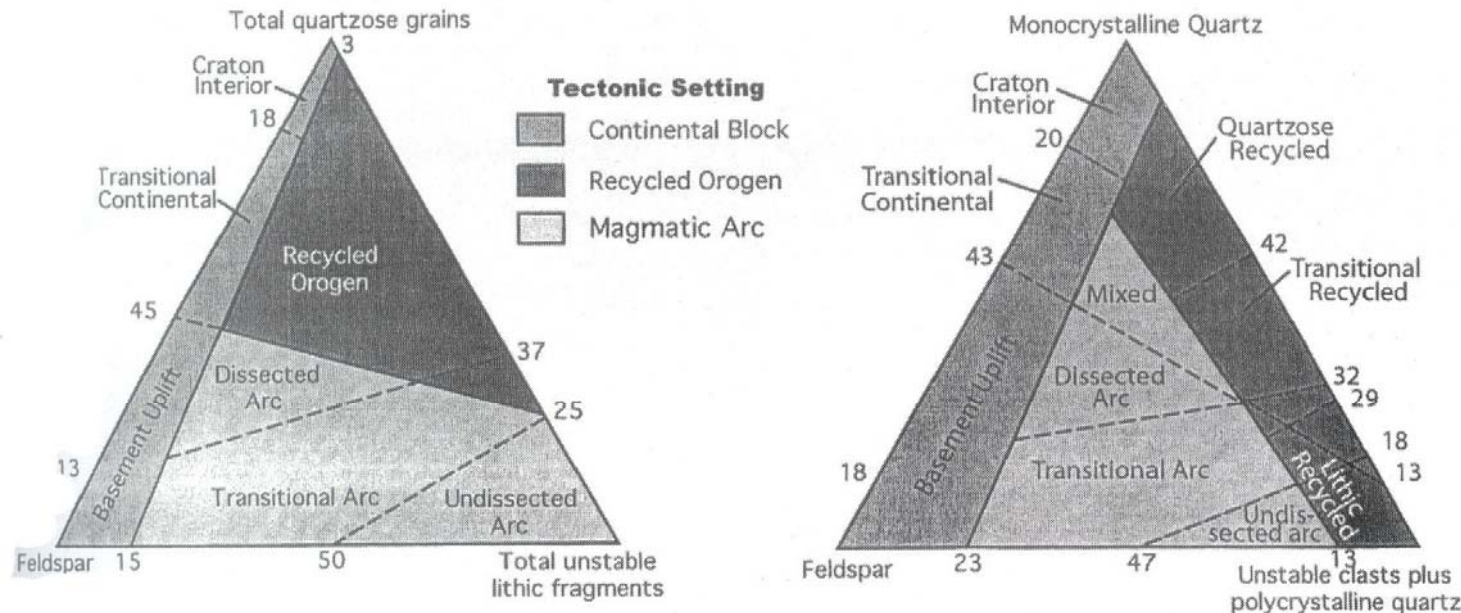
Figure 5.22
Relationship between framework composition of sandstones and tectonic setting. [After Dickinson, R. W., et al., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geol. Soc. America Bull., v. 94, Fig. 1, p. 223.]

Boggs (2006), p.157

A. Continental block provenances: quartzose sand, feldspars with high ratios of potassium feldspar to plagioclase feldspar, and metamrophic and sedimentary rock fragments.

B. Recycled orogen provenances: (1) continent-continent collision: abundant sedimentary, metamorphic rock fragments, moderate quartz, and a high ratio of quartz to feldspars.
(2) arc-continent collision: Many types of rock fragments (e.g., rock fragments of sedimentary, metamorphic, metamorphic basic igneous rocks), quartz, feldspars, and chert.

C. Magmatic arc provenances: volcanic lithic fragments, plagioclase feldspars. Quartz and potassium feldspars are commonly very sparse except where the volcanic cover is dissected by erosion to expose underlying plutonic rocks (dissected arcs).

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Possible sediment Provenances:
A._____
B._____
C._____

B. 太麻里海灘

A. 四稜砂岩(龍洞)

C. 都巒山層(烏石鼻)

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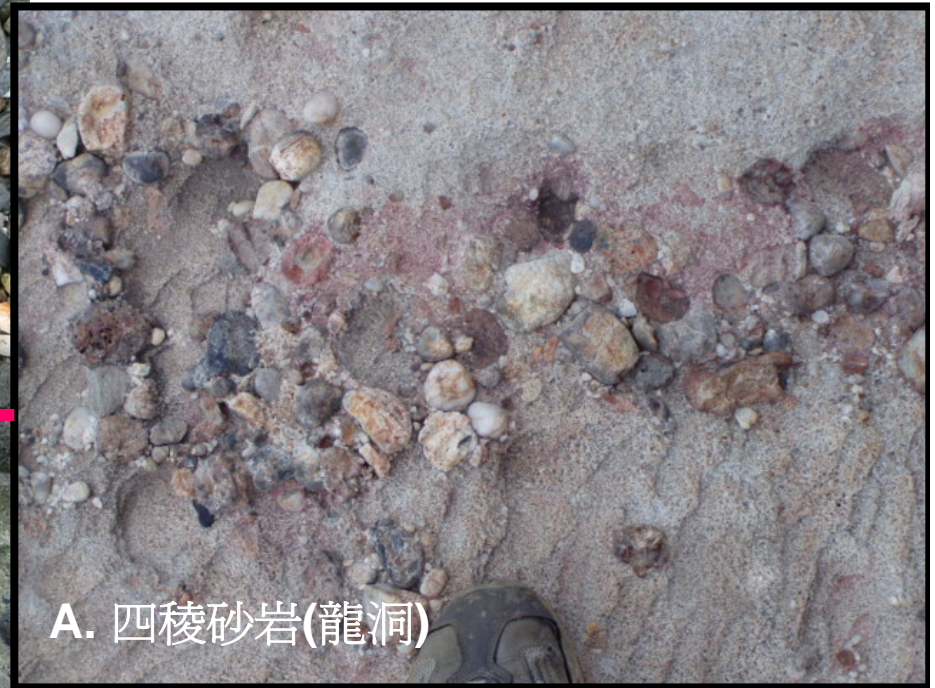
a: sedimentary rock fragments; b: volcanic rock fragments, c: quartz grains: monocrystalline and polycrystalline quartz grains with poikilotopic calcite; d: feldspar and quartz grains.

Plate 1

(a) Lithic grains of sedimentary origin — laminated and silty shale, also angular quartz grains. Plane-polarized light. Carboniferous fluvial sandstone. Cantabrians, Spain. Field of view 3×2 mm.

(b) Lithic grains of volcanic origin. The two dark grains consist of mafic phenocrysts in a very altered, originally glassy, dark groundmass. The other grains consist of minute feldspar laths in a glassy groundmass, and have numerous small dark iron-rich spots. The cement is calcite. Plane-polarized light. Triassic shallow-marine sandstone. The Dolomites, Italy. Field of view 3×2 mm.

(c) Quartz grains: several monocrystalline quartz grains showing both uniform and unit extinction; polycrystalline quartz grains with several and many subcrystals, some of the latter with sutured contacts. The cement is poikilotopic calcite. Crossed polars. Permian aeolian sandstone. Durham, England. Field of view 3×2 mm.

(d) Feldspar grains: microcline on left with grid-iron twinning and orthoclase on right with bright specks of alteration material (sericite). Quartz grains also present (mostly monocrystalline with unit extinction), the one in lower centre with overgrowth. Muscovite flake extreme right showing blue colour. Grains are coated with hematite, giving red/brown rim. Crossed polars. Precambrian fluvial sandstone. Torridon, Scotland. Field of view 1.2×0.8 mm.
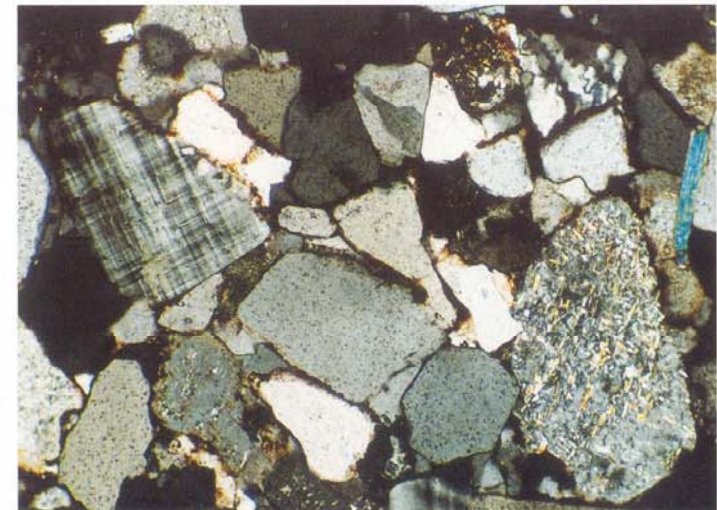

(a)

(b)

(c)

(d)

Tucker (2001)

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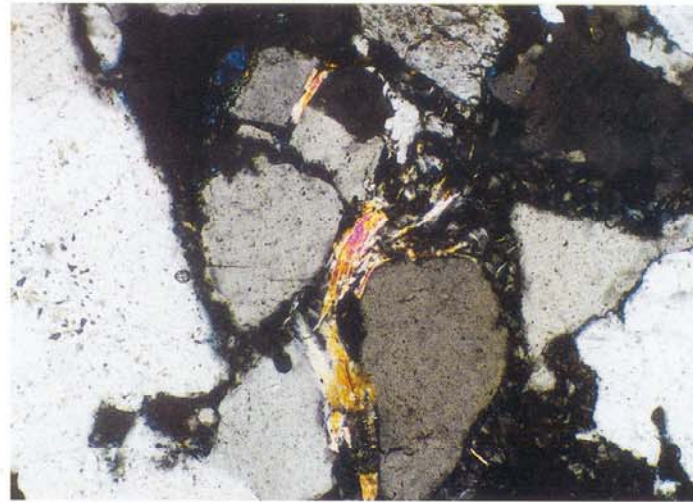National Central U. Taiwan
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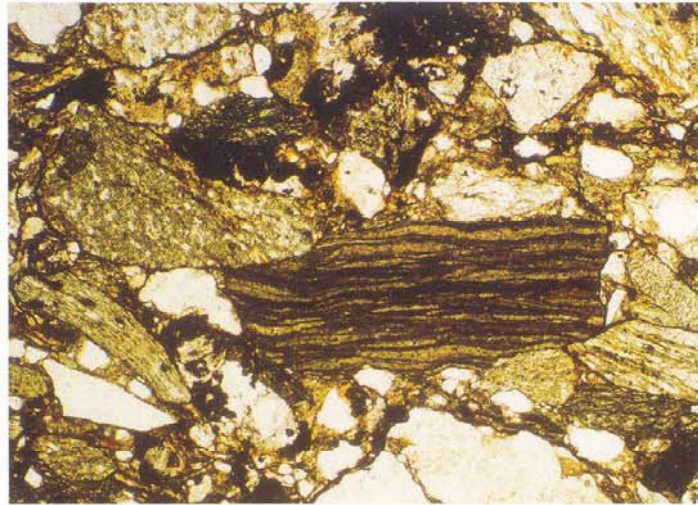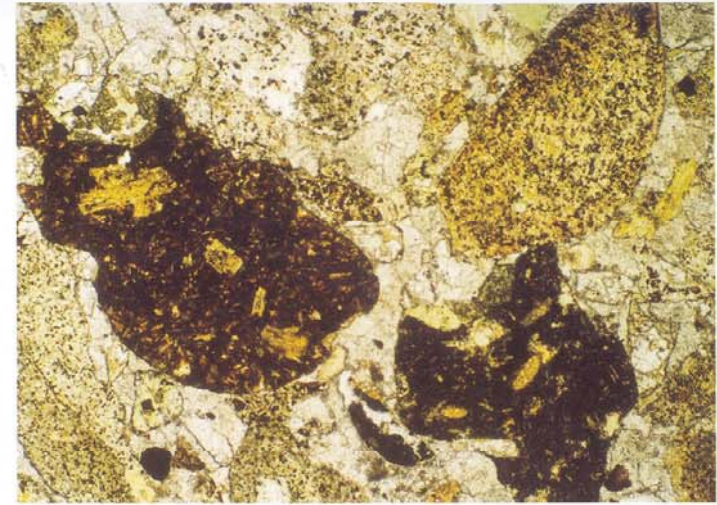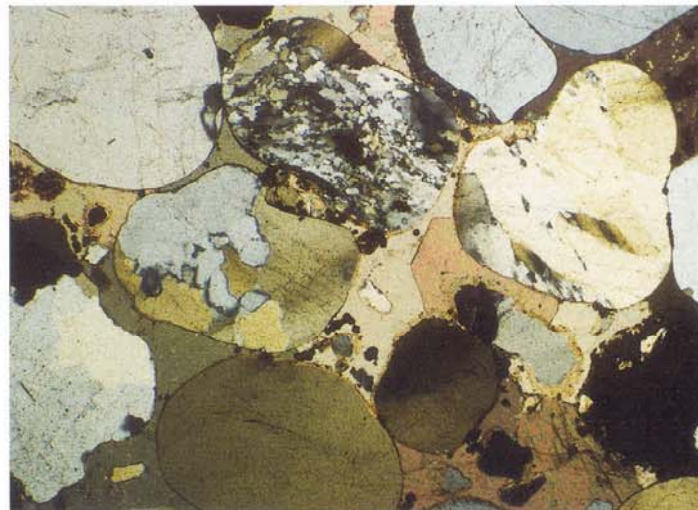
a: Muscovite and kaolinite in quartz arenite; b: biotite mica, matrix consisting of clay minerals, quartz grains; c, d: quartz arenite with overgrowths.
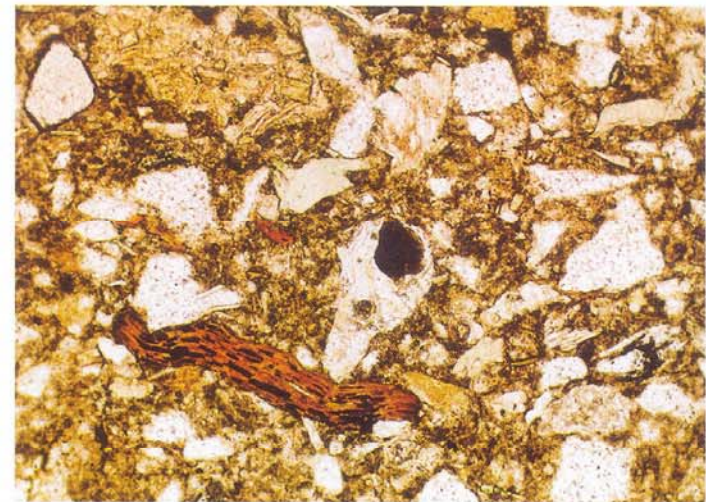
Plate 2

(a) Muscovite and kaolinite in quartz arenite. Muscovite shows orange colour. Kaolinite forms the small dark crystals between the quartz grains, which are mostly monocrystalline with unit extinction; the one on the left has minute fluid and mineral inclusions. Crossed polars. Carboniferous fluvial sandstone. Northumberland, England. Field of view 1.2×0.8 mm.

(b) Biotite mica (brown) showing effects of compaction, and light brown matrix consisting of minute, unresolvable clay minerals, iron minerals (dark brown/black), and silt-grade quartz. Also present are many angular quartz grains (white), and feldspar and lithic grains. Plane-polarized light. Silurian turbidite greywacke. Scotland. Field of view 1.2× 0.8 mm.

(c, d) Quartz arenite with well-developed overgrowths on quartz grains, which are mostly monocrystalline with unit extinction. Dusty looking quartz grain on left is of hydrothermal origin and is full of fluid inclusions. Note clear overgrowth. Red hematite coating around grains. Two feldspar grains show effects of dissolution. Rock impregnated with blue resin to show porosity (reduced intergranular and dissolutional intragranular). **(c)** Plane-polarized light; **(d)** crossed polars. Permian aeolian sandstone. Cumbria, England. Field of view 3×2 mm.

(a)

(b)

(c)

(d)

Tucker (2001)

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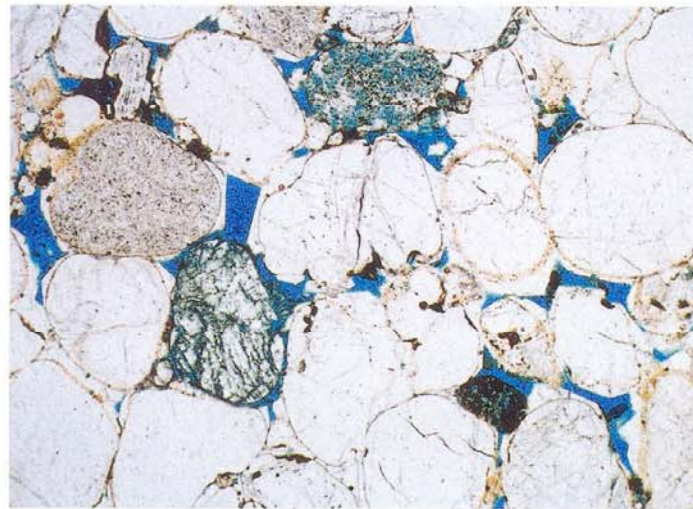
a: Quartz arenite, zircon; b: litharenite with sedimentary rock fragments; c: arkose with many feldspar grains; d: arkose.
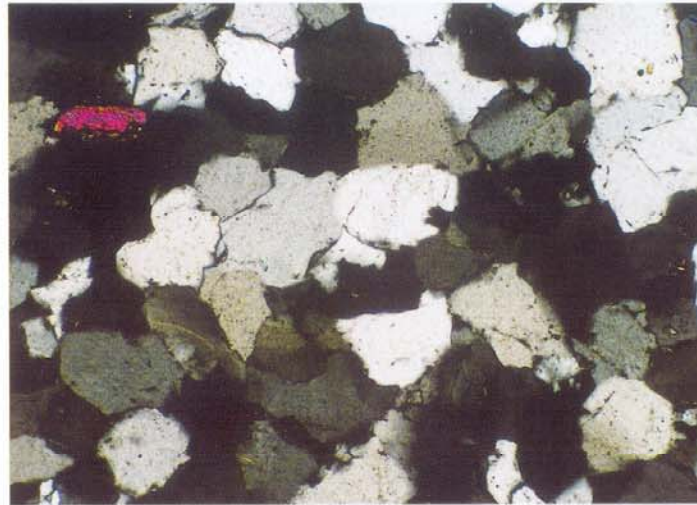
Plate 3

(a) Quartz arenite with angular looking quartz grains from overgrowth cement. Dust-line around grains visible in some cases. Supermature sandstone consisting of monocrystalline, unit-extinguishing quartz grains. Zircon, a heavy mineral, upper left (red). Crossed polars. Carboniferous marine sandstone. Durham, England. Field of view 1.2×0.8 mm.
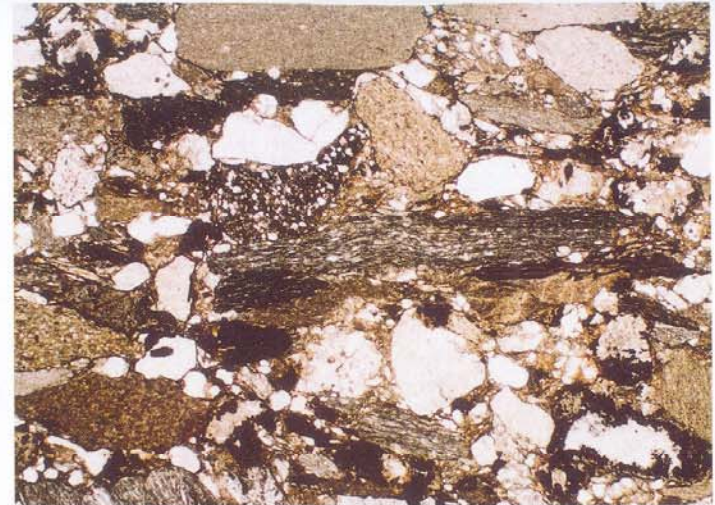
(b) Litharenite with sedimentary rock fragments of fine sandstone and mudrock (some showing lamination). Quartz grains also present (clear). Note the effects of compaction: a tight-fitting arrangement of grains, and some interpenetration and squashing of grains too. Plane-polarized light. Carboniferous fluvial sandstone. Cantabrians, Spain. Field of view 6×4 mm.

(c) Arkose with many feldspar grains (dusty/dirty looking compared with clearer quartz grains), and hematite coatings around sand grains; note that hematite is absent where grains are in contact. Plane-polarized light. Precambrian fluvial sandstone. Torridon, Scotland. Field of view 1.2×0.8 mm.
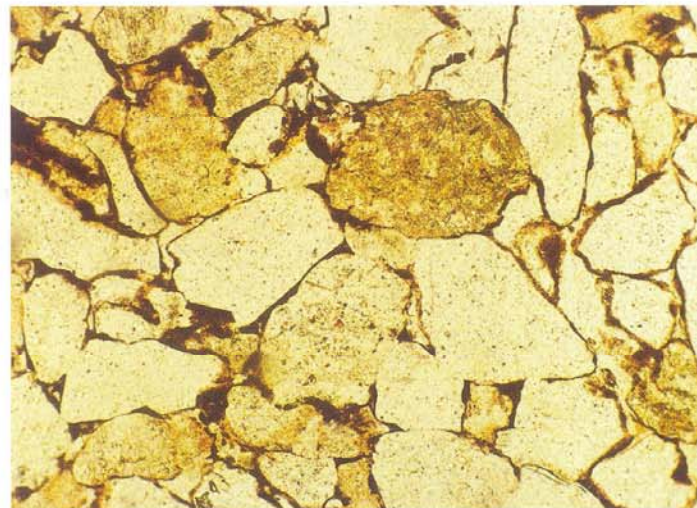
(d) Arkose with feldspar grains (orthoclase, microcline) showing incipient replacement by sericite (minute bright crystals). Crossed polars. Precambrian fluvial sandstone. Torridon, Scotland. Field of view 1.2×0.8 mm.
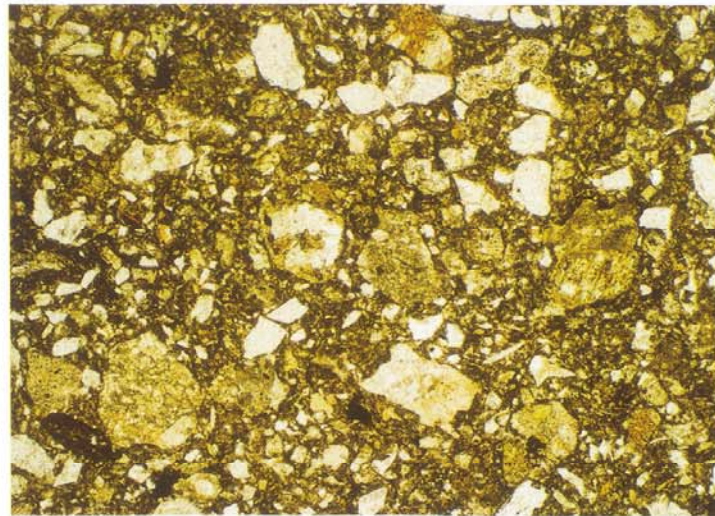

(a)

(b)

(c)

(d)

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a, b: greywacke; c, d: quartz overgrowths.

Plate 4

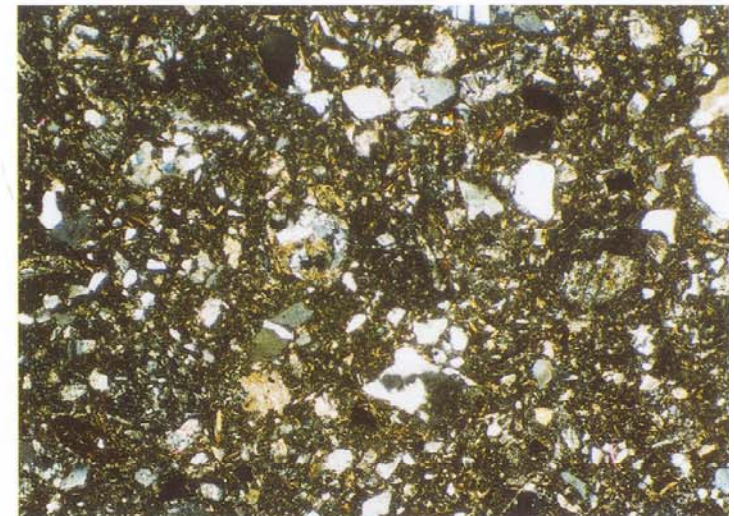**(a, b)** Greywacke. Quartz, feldspar and lithic grains are contained in a fine-grained matrix of chlorite and silt-grade quartz: **(a)** plane-polarized light; **(b)** crossed polars. Silurian turbidite greywacke. Southern Uplands, Scotland. Field of view 3×2 mm.
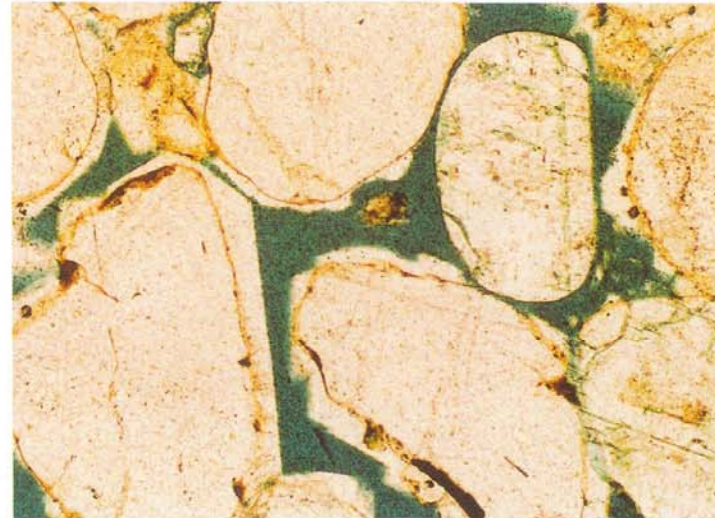
(c, d) Quartz overgrowths on quartz grains. The grain surface is shown by the red hematite coating. Better overgrowths on monocrystalline quartz than polycrystalline quartz grains. Feldspar grain upper right has no overgrowth and shows some effects of dissolution. Rock impregnated with blue resin to show porosity (reduced intergranular): **(c)** plane-polarized light; **(d)** crossed polars. Permian aeolian sandstone. Cumbria, England. Field of view 1.2×0.8 mm.
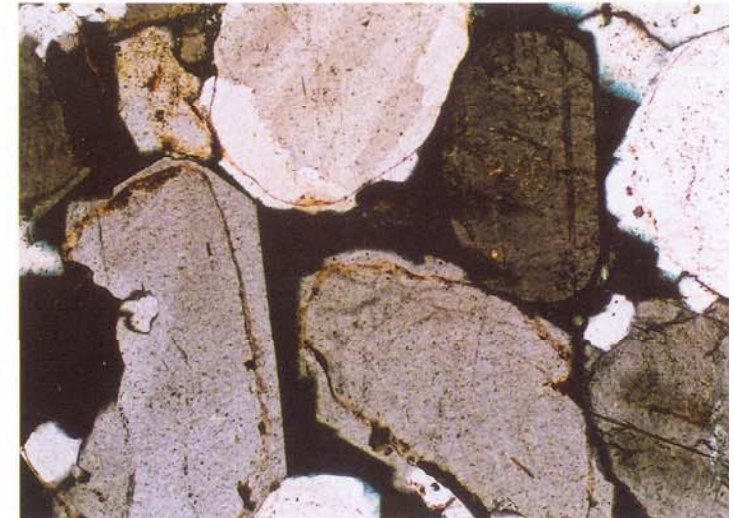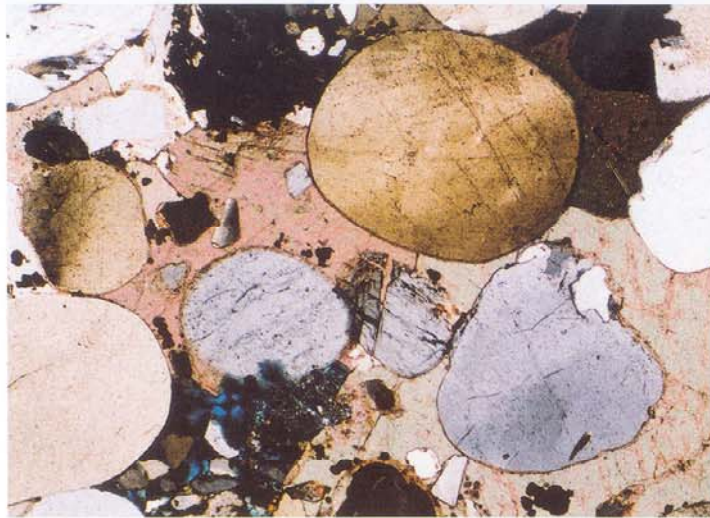

(a)

(b)

(c)

(d)

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a, b: calcite cement in quartz arenite; c: kaolinite between quartz grains; d: mudrock.
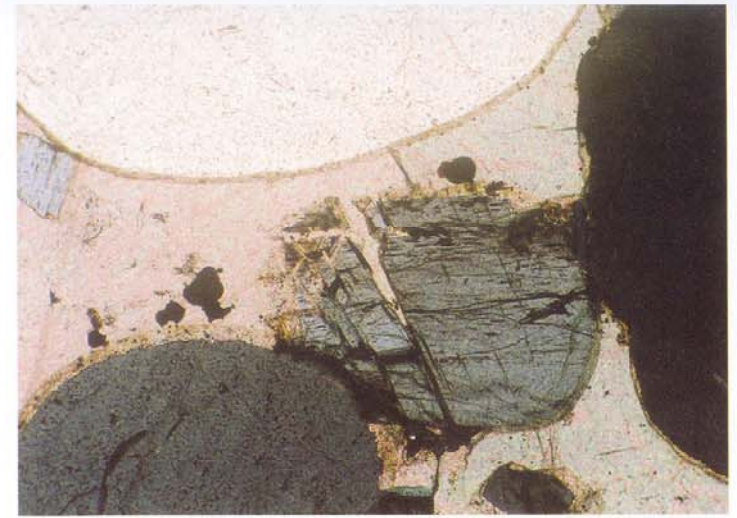

Plate 5

(a, b) Calcite cement in quartz arenite. Large poikilotopic calcite crystals enclosing several grains. Quartz grains are well-rounded monocrystalline, with unit and undulose extinction, and polycrystalline. Feldspar grain showing splitting by calcite crystal; detail in (b). Crossed polars. Permian aeolian sandstone. Durham, England: **(a)** field of view 3×2 mm; **(b)** field of view 1.2×0.8 mm.

(c) Kaolinite (small black and white crystallites) between quartz grains (mono- and polycrystalline), probably replacing a feldspar grain. Distorted muscovite flake (showing blue colour) between quartz grains. Crossed polars. Carboniferous fluvial sandstone. Northumberland, England. Field of view 1.2×0.8 mm.

(d) Mudrock showing effects of compaction with fracture of shells (thin brachiopods), folding of laminae around shells and flattening of burrows (upper left). Minute silt-grade quartz and shell debris disseminated throughout mud; round white grain (centre left) is crinoid ossicle. Carboniferous marine mudrock. Northumberland, England. Field of view 6×4 mm.
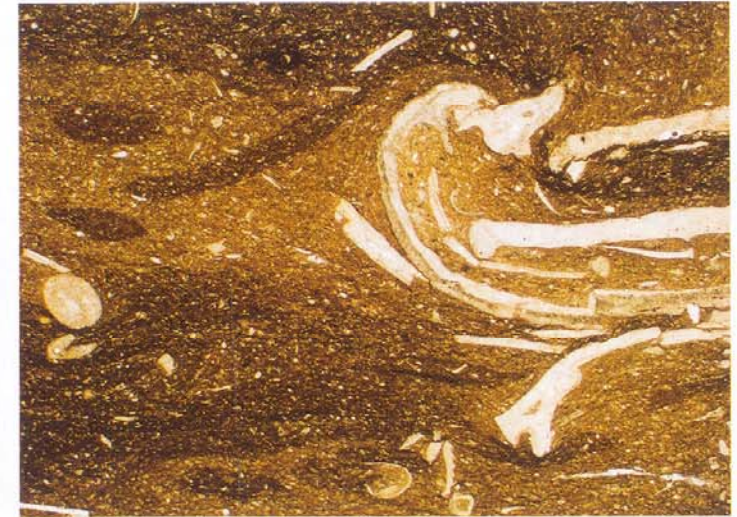
(a)　(b)　(c)　(d)

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