

Thin-section petrography of pelites, a promising approach in sedimentology

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Abstract

Pelites are described mainly by their macroscopic appearance, X-ray diffraction mineralogy and chemical composition. However, these conventional methods are being increasingly supplemented by thin-section analysis. Even so-called soft-cuttings aggregates can be successfully studied in thin section after appropriate impregnation. Only by integration of the various analytical methods can pelites be fully characterized in terms of original grain size and mineralogy, present mineral composition, sedimentary fabric and history of diagenetic alteration. Thin sections of pelites from various stratigraphic levels in the FRG are briefly described: Lower Carboniferous bedded cherts, siliceous shales and tuffs; Upper Jurassic marlstones; Lower Cretaceous claystones, siliceous marlstones and tuffs; Messel oil shale (Eocene) and Eocene tuffs; Oligocene clays and tuffs. In pelites diagenetic processes such as resorption diagenesis transform the original mineral composition and alter the original sedimentary grain-size distribution. The immense diagnostic value of sedimentary as well as tectonic fabric can be exploited only by means of thin-section analysis.

Introduction

Pelites, which are thought to make up about 75 per cent of all clastic rocks, are generally characterized as clay, claystone, shale, marl, marlstone, chert etc., some of them quite old and loosely defined terms. In most cases we do not know whether clay or shale is derived from erosion of a granite, volcanite, metamorphite or from a sediment. Except for geologically very young sediments the present clay mineral composition and particle size do not necessarily reflect the original sedimentary composition and particle size. Although mineral and chemical composition of pelites are mostly well known thanks to analytical methods such as X-ray diffraction mineralogy and scanning electron microscopy, the structural and textural details on a microscopic scale are still unknown.

Repeatedly attempts have been made to demonstrate this lack of knowledge of pelites (Boswell 1961, Potter et al. 1980, Stow 1985, Schieber 1989). Ehlers & Blatt (1982, 284) even heralded 'the age of mudrocks'. Detailed microscope descriptions of shales are surprisingly rare (Schieber 1989), although since 1978 the present author and colleagues have carried out a fair number of thin-section studies of pelites such as claystones, marlstones, shales, siliceous shales, bedded cherts and tuffs in FRG (Zimmerle et al. 1980, Paproth & Zimmerle 1980, Zimmerle 1982 a, b, 1985, 1989, Zimmerle & Emeis 1983, Kubanek & Zimmerle 1986, Kubanek et al. 1988, Dehmer et al. 1989, Kuhn & Zimmerle 1989, Zimmerle et al. 1990). Since the publications mentioned above usually form part of other research projects, and since the results are commonly published in German, here a

number of annotated illustrations is presented which should communicate how the study of pelites in thin sections, enables us

1. to reconstruct the original composition of detrital components (e.g. mineralogically unstable minerals and rock fragments);
2. to observe the original particle size and particle shape. Commonly, the grain size of pelites tends to decrease during argillation;
3. to trace diagenesis. Normally pelites react chemically much faster than coarser sediments because of the larger surface area;
4. to obtain a better picture of the depositional environment of pelites.

Methods

At present pelites are described mainly by their macroscopic appearance, X-ray diffraction mineralogy and chemical composition. Improved or new analytical methods are available, but are not always fully applied. It is essential to use polished thin sections proper; this is the only type of thin section that can be examined effectively by various methods such as transmittent light microscopy, reflected light microscopy, fluorescence microscopy (FL), cathodoluminescence microscopy (CL),

scanning electron microscopy (SEM), and X-ray fluorescence spectroscopy (XRF).

The electron-optical methods are described in detail by Goldstein et al. (1981). Nöltner (1988) demonstrated their successful application for sediment petrography of rocks from Germany. The major methods and their application for the sub-microscopic range are shown in Table 1. The chief precondition for thin-section petrography of pelites is that absolutely flawless thin sections can be prepared. This is one of the weak points delaying the general acceptance and successful application of thin-section microscopy of pelites. Conventional thin-sectioning is summarized by Murphy (1986) and Miller (1988). Thin-sectioning of soft pelites, however, still seems to be a problem. By applying SEM with integrated energy-dispersive XRF analysis the resolution can be extended down to $0.1\ \mu\text{m}$, revealing submicroscopic aspects of mineral composition, texture and fabric. Soft-cuttings aggregates (SCA) are agglomerations of soft drill cuttings, consisting mainly of argillaceous material with dispersed hard components. Even these SCA can be successfully thin-sectioned after appropriate impregnation; they can then be evaluated in greater detail as is shown in a pilot study of Oligocene sediments (Zimmerle et al. 1990). Analysis of polished thin sections is best combined with X-ray diffraction analysis (XRD) and supplemented by

Table 1. Methods of determining mineral composition and microfabric of pelites (modified from Nöltner 1988, Table 1)

Methods	Grain size \AA μm					
	2000–250 m/c sand	250–62 fine sand	62–31 coarse silt	31–16 medium silt	16–4 fn/v fn silt	< 4 clay
Transmitted and reflected light microscopy (thin section, polished thin section, polished section, grain mount)	qualitative and (semi)quantitative analysis of single constituents and rock fabric					
X-ray diffraction X-ray fluorescence	qualitative and (semi)quantitative analysis, cumulative, no evaluation of rock fabric					
Electron optical methods with integrated energy-dispersive spectral analysis	qualitative and (semi)quantitative element analysis of very fine-grained single mineral and rock constituents and registration of the microfabric					

chemical analysis of major, minor and trace elements, and – if at all feasible – by autoradiographs and radiographs, differential thermal analysis (DTA), infrared absorption spectroscopy (IR) and transmission electron microscopy (TEM). Pedro (1989) summarized the present state on clay mineral studies. A scheme for thin-section petrography of shale lists the major steps and procedures (Table 2). Referring to the coarse-silt and sand components of Table 2 one should keep in mind that not only detrital quartz, feldspar and other siliciclasts can occur, but also argillaceous or thoroughly argillized rock fragments. Only under crossed nicols the amount of mineralogically instable components can be fully evaluated. One should be aware of these components.

Conventional light- and heavy-mineral analysis within the grain-size range of 63–300 μm is not adequate for the study of pelites. Further grain-size differentiation of light and/or heavy minerals is recommended, either by means of polished thin section down to 1 μm (see Nöltner 1988) or by time-consuming separation procedures, e.g. centrifuge or flotation. The approach using polished thin sections aided by the SEM is much more practicable. Certain heavy minerals such as brown spinel occur primarily as accessory constituents in the extremely fine grain fraction (Kubanek et al. 1988). Moreover, in the Pleistocene diatomites from Neuoh (Lower Saxony) volcanic glass particles are found preferentially in the grain-size fractions smaller than 53 μm (Riezebos & Zimmerle 1988,

Table 2. Scheme for thin-section petrography of shales

Colour		Macro Polished surface	Thin section	
			Analyser out	Analyser in
Shale fabric	Polarizing microscope ($> 10 \mu\text{m}$)		Primary sedimentary structures may be recognized by differential pigmentation and mineral composition	Diagenetic alteration prominent, especially through argillation!
	REM ($> 1 \mu\text{m}$)		Diagenetic fabrics predominate with secondary particle outlines mainly diagenetic	
Coarse silt/sand components	Inorganic	Shape and mineral/rock composition	Both quartz/feldspar and siliciclastics, but also argillaceous rock fragments	
	Biogenic	Shape and composition	Check for 'unwashable' microfossils; i.e. dissolved foraminifers, diatoms, radiolarians, and sponge and other remnants!	
Fine silt/clay matrix		No observation possible	As in shale fabric, but check for fecal pellets and floccules. Grain sizes generally decrease with diagenesis of clay to claystone but may increase again with deep burial (shales/slates)	As in shale fabric
If schistosity is present			Distinguish primary (relic) fabrics, primary component composition and shapes in comparison with neomineralizations induced by schistosity such as rutile needles	
Inorganic geochemistry	Major elements	Chemical bulk analyses	Areal distribution pattern of Si, Al, K, Na, Ca, Mg, Fe and relationship to components in thin section simultaneously furnishing size and shape of components	
	Trace elements		Areal distribution pattern of Ti, P, Zr, REE, Mn, Cr, Ni, Th, U and relation to components in thin section. Additional elements analyzed as necessary	

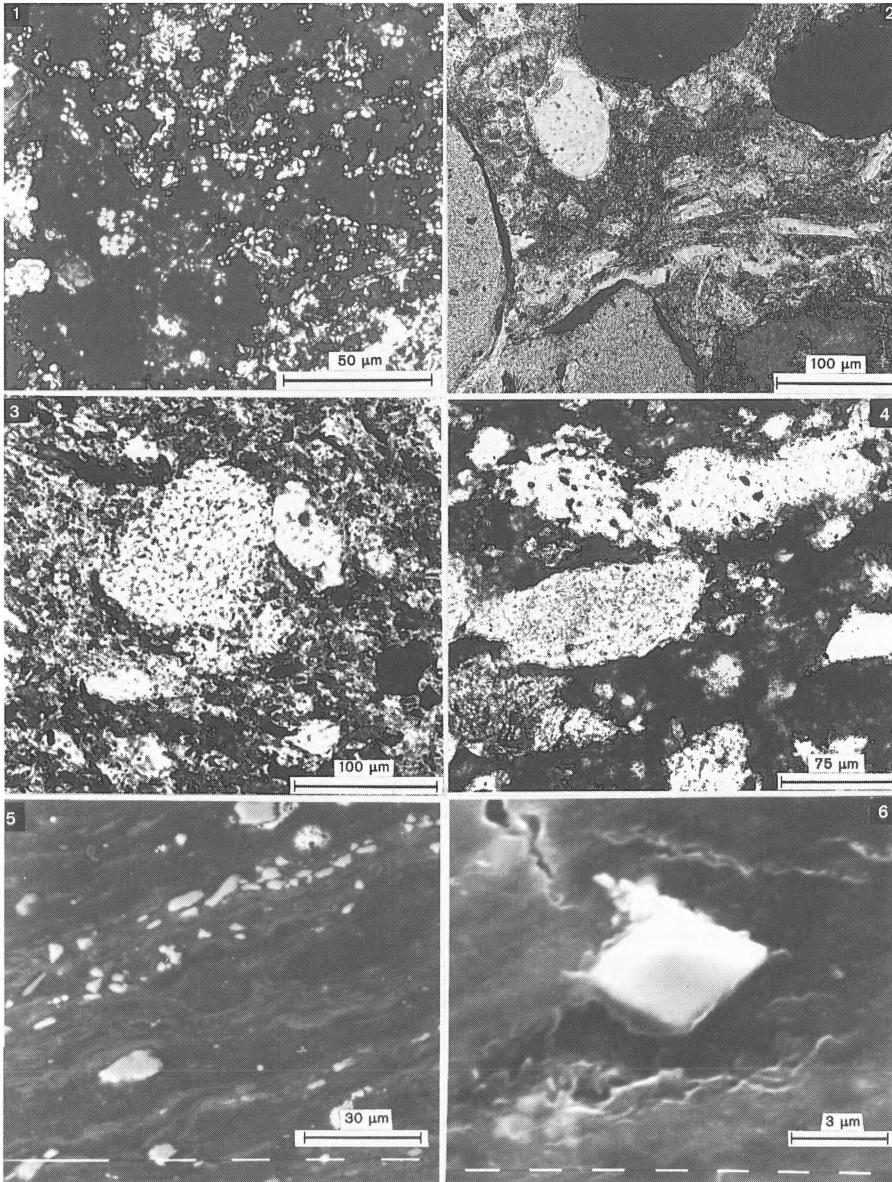


Plate 1. Thin-section photomicrographs of argillaceous pelites. *Fig. 1.* Coccolithic marlstone. Top Ornatenton, Upper Jurassic (Malm alpha 1). Sengenthal quarry, Franconia, 38 km SE of Nürnberg. *Fig. 2.* Argillaceous matrix of fine sandstone. Note elongate splintery quartz in the matrix. Base basal glauconite bed, Upper Jurassic (Malm alpha 2). Sengenthal quarry, Franconia, 38 km SE of Nürnberg. *Fig. 3.* Soft calcareous claystone with light-coloured, partly resorbed, thoroughly argillized volcanoclast. Lower Cretaceous (Upper Aptian). Mittellandkanal, between Mehrum and Schwicheldt. // Nicols. *Fig. 4.* Soft, slightly calcareous claystone with oval, thoroughly argillized sand-size volcanoclasts in an opaque matrix. Untere Flammenmergel-Folge, Lower Cretaceous (Middle Albian), Alfeld (Leine). // Nicols. *Fig. 5.* Middle Eocene smectitic Messel oil shale with oval phosphatic micronodules (40–60 µm) and siderite-pyrite layers (light coloured) parallel to bedding. Opaline components absent. SEM-BSE. Messel opencast mine, 21 km SSE of Frankfurt/M. *Fig. 6.* Minute octahedron of Cr-spinel (picotite) in Middle Eocene Messel oil shale (close-up view). SEM-BSE. Messel opencast mine, 21 km SSE of Frankfurt/M. (Dashed white lines in Figs. 5 and 6 are scale bars.)

115). Remnants of volcanic material were previously overlooked for that simple reason.

Examples of pelites in thin section

The samples selected are macroscopically characterized by their 'aphanitic' cryptocrystalline appearance, many of the younger ones simply appeared to be rather soft, often smeary clays or claystones. The samples selected are grouped into four categories according to their lithology: (1) argillaceous pelites, (2) tuffaceous pelites, (3) siliceous pelites, and (4) single components in pelites and soft-cuttings aggregates. These will be described in order from older to younger (Plates 1–4).

Argillaceous pelites

Throughout Europe argillaceous sediments at the Dogger/Malm boundary are characterized by a break in sedimentation, which is normally marked by allochthonous phosphorite accumulations and by an elevated glauconite content. At the Sengenthal clay pit, SE of Nürnberg, FRG, a coccolithic marlstone occurs underneath the disconformity (Plate 1, Fig. 1); the coccolithic components can be easily discerned in thin section. They represent the remains of a coccolithic bloom. Comparable sediments of spectacular appearance in thin section have been observed in the Lower Cretaceous (Zimmerle 1982 a) and in the Lower Tertiary (Zimmerle et al. 1990). The argillaceous matrix of the basal fine glauconitic sandstone is characterized by a marked content of tiny elongate grains of splintery quartz (Plate 1, Fig. 2). Such thorn-shaped quartz splinters often represent volcanogenic input in a sediment.

Mid-Cretaceous claystones and marlstones (Aptian/Albian) in northern Germany are widely characterized by a considerable content of volcanoclasts rendered almost unrecognizable by thorough argillation (Plate 1, Figs. 3 and 4). These sediments can be considered as a characteristic sediment type in the argillaceous sediment sequences of the mid-Cretaceous (Zimmerle 1982 a, 1989). They repre-

sent a transition between tuffs and ordinary claystones. This example demonstrates the additional information gained by proper thin-section evaluation of argillaceous rock sequences. The lack of thin-section evaluation is a serious shortcoming of the majority of sedimentological studies of the mid-Cretaceous, worldwide.

The recent petrographic study by Kubanek et al. (1988) of the Eocene Messel oil shale (northern Rhine Graben) exemplifies a successful evaluation by means of integrated clay analysis. Shale texture and spinel as diagnostic constituent, both as seen in polished thin section under the SEM, are shown in Plate 1, Figs. 5 and 6. The oil shale which is composed mainly of smectitic clays, is characterized by numerous inclusions of minute spinel octahedra ($< 10 \mu\text{m}$), which only can have been derived from basic igneous rocks (basalts). Conventional microscopy with the polarizing microscope did not reveal this feature. These particles can, however, be resolved by submicroscopic methods (SEM-SED and SEM-SSD). Several features including the high smectite content, occasional thin intercalations of tuff, high TiO_2 content ($> 2\%$), a characteristic TiO_2/Zr vs Nb/Y ratio, an elevated PE content, a surprisingly low quartz content, and the disperse spinel suggest that this pyroclastic material was derived from nearby basalts (basanites and nephelinites), which are in fact coeval with the sediments. Paleontological considerations (Rietchel 1988) also led to the conclusion that the Messel lake was a maar-type lake. This Messel oil shale story was one of the first case histories demonstrating the provenance of a bituminous pelite from nearby basic volcanic rock sources.

Tuffaceous pelites

The volcano-siliceous rock association of the Lower Carboniferous in the Harz Mts. and Kellerwald, FRG, has been studied by Kubanek & Zimmerle (1986), Nöltner (1988), Dehmer et al. (1989) and Kuhn & Zimmerle (1989). The thin tuff layers in this association, quartz keratophytic and keratophytic in composition, are thoroughly altered, either silicified or silicified and albitized. The vit-

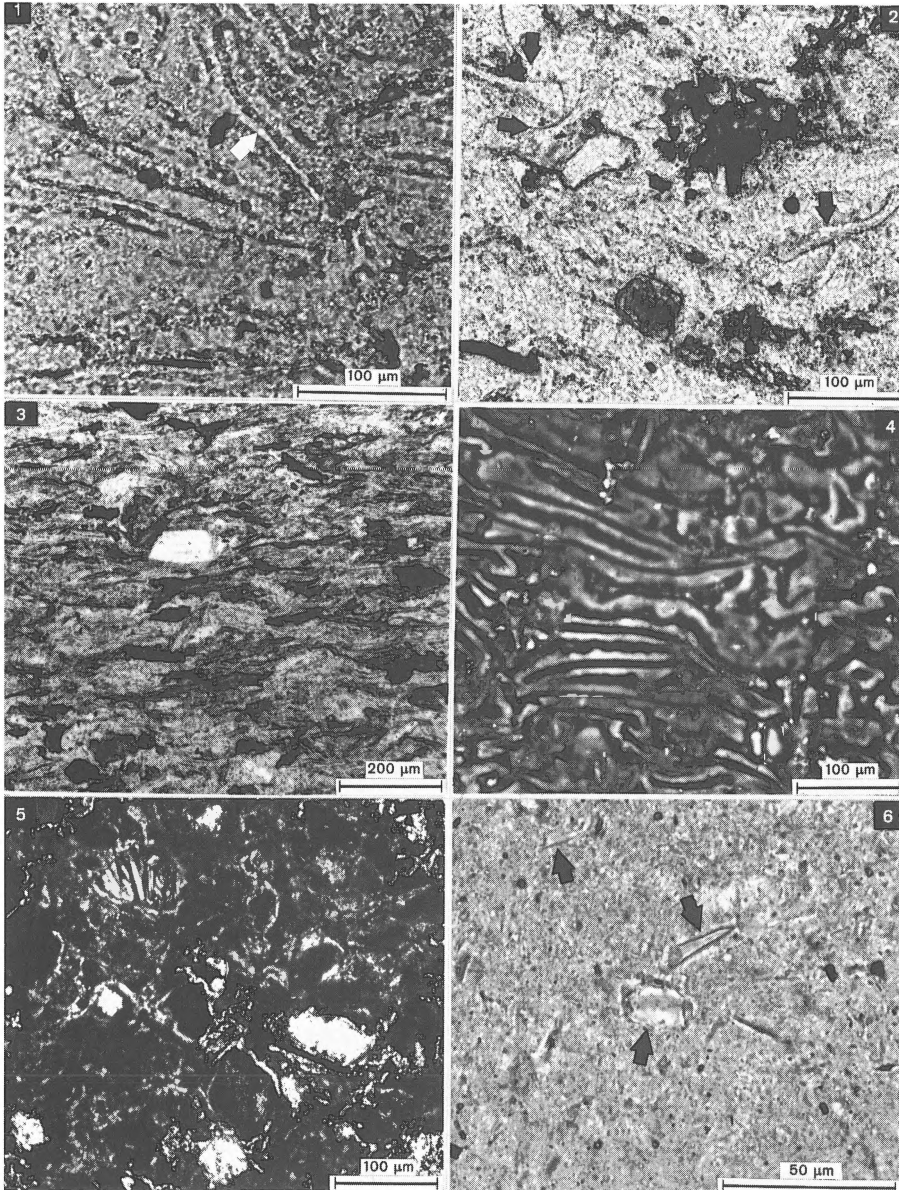


Plate 2. Thin-section photomicrographs of tuffaceous pelites. *Fig. 1.* Silicified tuff with vitroclastic texture. Lower Carboniferous (cu III ∞). Heimbergskuppe, NE of Lautenthal, Harz Mts. // Nicols. *Fig. 2.* Silicified tuff with vitroclastic texture. Lower Carboniferous (cu III ∞). Adlersberg borehole (330.20 m), Harz Mts. // Nicols. *Fig. 3.* Soft claystone (tuff) with volcanoclastic texture. Upper Aptian, Lower Cretaceous. Sarstedt clay pit, 21 km SE of Hannover. // Nicols. *Fig. 4.* Soft claystone (tuff) with vitroclastic texture. Aptian/Albian boundary, Lower Cretaceous. Vöhrum clay pit, 30 km E of Hannover. Phase-contrast microscopy (courtesy H.-J. Altemüller). *Fig. 5.* Pelite (= well sorted, fine-grained lithic tuff of basic composition) which is thoroughly argillized. B1 KKE Lingen well. Lower Tertiary, Lower Eocene. X Nicols. *Fig. 6.* Soft claystone (highly argillized dust tuff) with minute mineral fragments. Lower Tertiary, Oligocene, Rupelian 4. UWO 105 Teufelsmoor well, near Bremen. // Nicols.

roclastic texture, however, is well preserved but can only be detected in thin section (Plate 2, Figs. 1 + 2).

The mid-Cretaceous tuffs in northern Germany have generally the appearance of soft claystones; the colour does not always contrast strongly with

the enclosing argillaceous sediments. Therefore, they are difficult to recognize in the field. In thin section the vitroclastic texture is the best criterion for their tuffaceous nature (Plate 2, Figs. 3 + 4). Phase-contrast microscopy reveals the vitroclastic texture even better than conventional thin-section microscopy under transmitted light. This somewhat forgotten method even enables one to reconstruct several stages of alteration of the volcanic glass particles into clay minerals. Clay mineral composition alone, as determined by X-ray diffractometer analysis, is often inconclusive. Moreover, in tuffs the discrepancy between the original sedimentary particle size as seen or reconstructed under the microscope and the present clay mineral size determined by sedimentation techniques (Atterberg method) is tremendous (100 μm vs. 2 μm). Thus, the Atterberg particle-size determination furnishes only the particle size of the final stage of diagenetic argillation, not the original grain-size distribution of the freshly deposited tuff. In the Tertiary of Europe two main periods of volcanic activity are known; one climaxing in the Eocene and the second in the Oligocene/Miocene. The older cycle seems to be better represented in sediments, e.g. in the Moler Formation of Denmark, than the younger cycle. Thorough alteration of these fine-grained tuffs, mainly by argillation (Plate 2, Fig. 5) and/or alteration to carbonate minerals and the often extremely fine particle size (Plate 2, Fig. 6) make identification of these sediments as volcanogenic troublesome.

Siliceous pelites

The other member of the volcano-siliceous rock association in the Lower Carboniferous which was briefly mentioned above (previous section) is represented by the various kinds of siliceous pelites: bedded chert, siliceous shales and jasper. The bedded cherts (Plate 3, Fig. 1) are considered to be polygenetic, i.e. formed by several diagenetic processes (Dehmer et al. 1989). The mainly diagenetic silica matrix of the chert has a particle size of less than 5 μm , very much in contrast to the larger particle size and poorer sorting of the original vol-

canogenic sediment. Elongated, meandering micro-pore systems, partly sealed by cryptocrystalline silica, follow the bedding. Occasional large calcitic fossil fragments are characteristic of the specific chemical environment of this bedded chert and are encrusted and partly replaced by penecontemporaneous to early diagenetic silica overgrowths and occasionally by thin siderite overgrowths.

Siliceous shales containing radiolarians are transitional sediments (70–90% SiO_2) between chert (> 90% SiO_2) and ordinary shales (< 70% SiO_2). The background sediment is shaly, in part volcanogenic (Plate 3, Fig. 2). The jasper (Plate 3, Fig. 3), which in the Harz Mts. is always associated with pillow diabase of Lower Carboniferous age, does not exhibit sedimentary features in the field nor in handspecimen. It is characterized by its red colour and conchoidal fracture. The sample in Fig. 3 shows surprisingly numerous radiolarians and a large oncolid (up to 500 μm in size) 'floating' in a fine-crystalline silica matrix. The jasper depicted is a product of local diagenetic alteration of a black radiolarian chert by hydrothermal infiltration of siliceous solutions derived from the diabase below. Noteworthy is the joint occurrence of radiolarians and oncoids, a feature not previously observed in bedded cherts; it corroborates the shallow-water character of the much reduced stratigraphic profile (open 'carbonate' platform facies).

Silica was presumably derived from complex, partly hydrothermal reactions near and on the seafloor as described by Dehmer et al. (1989) and Fyfe (1989, 72). The contrast between the syndimentary fabric and the diagenetic silicification is best seen under the microscope by comparing the rock texture under plane polarized light and under crossed polarizers, or by studying the element distribution from microprobe analysis (Si versus Al, Na, K, and P) (Kuhn & Zimmerle 1989).

Minor intercalations and siliceous concretions occur in the argillaceous and marly mid-Cretaceous and Upper Cretaceous sediments of northern Germany. They are characterized by the presence of siliceous sponge spicules and radiolarians and associated with glauconite, phosphorite nodules, smectitic clays, and tuffaceous material.

The opaline radiolarians in radiolarian clays-

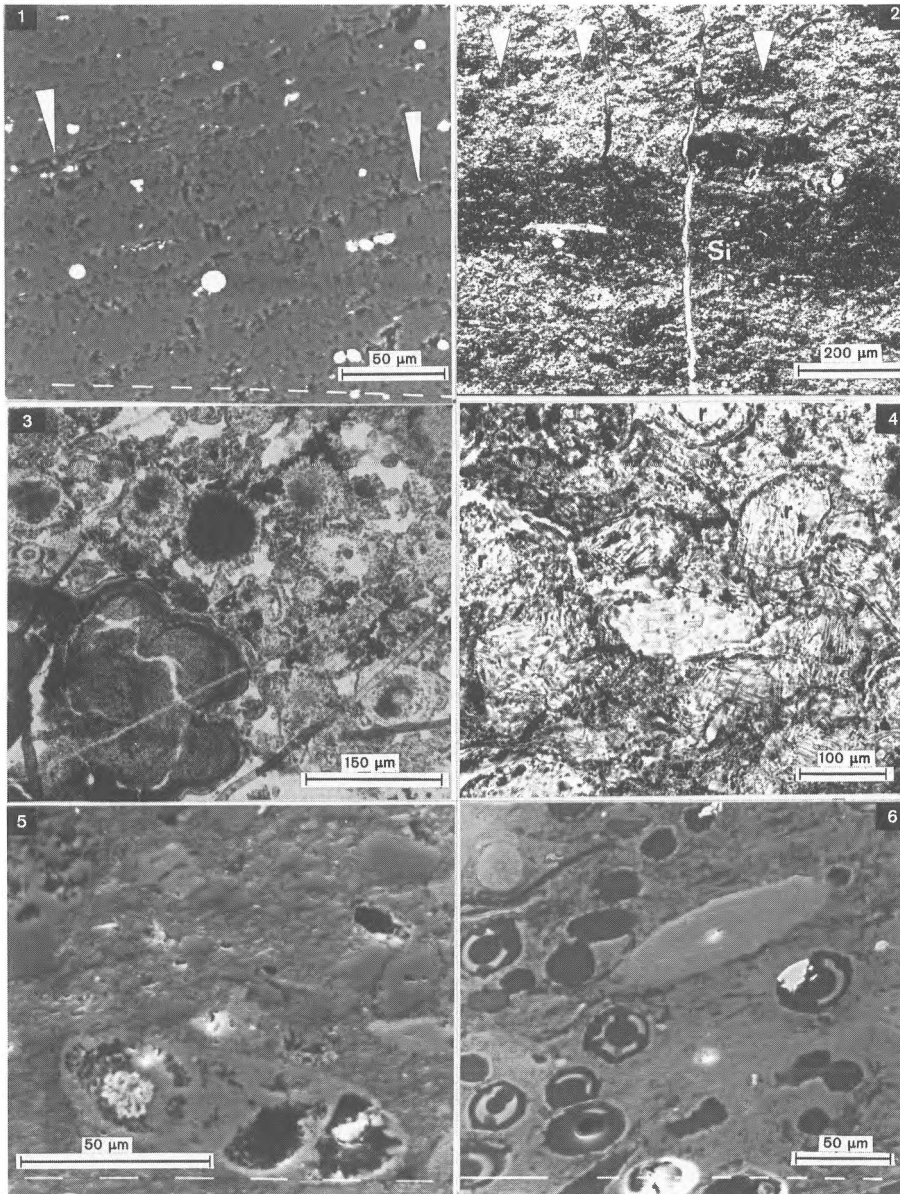


Plate 3. Thin-section photomicrographs of siliceous pelites. *Fig. 1.* Typical bedded chert with minute framboidal pyrite (light-coloured). Microporosity marks the bedding (arrows). Kieselige Übergangs-Schichten, Lower Carboniferous (cu III ∞). Adlersberg borehole (324.6–325.4 m), Harz Mts. SEM-SED. (Dashed white lines are scale bars.) *Fig. 2.* Siliceous shale with lenticular radiolarians (arrows) showing varying degrees of deformation and minute siliceous sponge spicules in the siliceous layer (Si) which appears dark under X nicols. Kulm-Kieselschiefer, Lower Carboniferous (cu III ∞). Adlersberg borehole (331.70 m), Harz Mts. X Nicols. *Fig. 3.* Jasper (Eisenkiesel) = secondarily silicified chert with numerous radiolarians and a solitary large oncolite (lower left). Lower Carboniferous (cu II ∞). Neue Harzstraße, Lerbach, Harz Mts. // Nicols. *Fig. 4.* Soft radiolarian claystone with radiolarians (r) replaced by clinoptilolite (about 40%). Lower Cretaceous (Upper Aptian). Sarstedt clay pit, 21 km SE of Hannover. // Nicols. *Fig. 5.* Foraminifer (bottom), partially dissolved quartz grains and siliceous sponge spicules (round or oval) in siliceous matrix. Flammenmergel (= bioturbated silicified marlstone), Lower Cretaceous (Middle Albian). Alfeld (Leine). SEM-SED. *Fig. 6.* Siliceous freshwater sponge spicules – partly dissolved – in an opaline matrix (spongolite). Messel oil shale, Middle Eocene. Messel opencast mine, 21 km SSE of Frankfurt/M. SEM-SED.

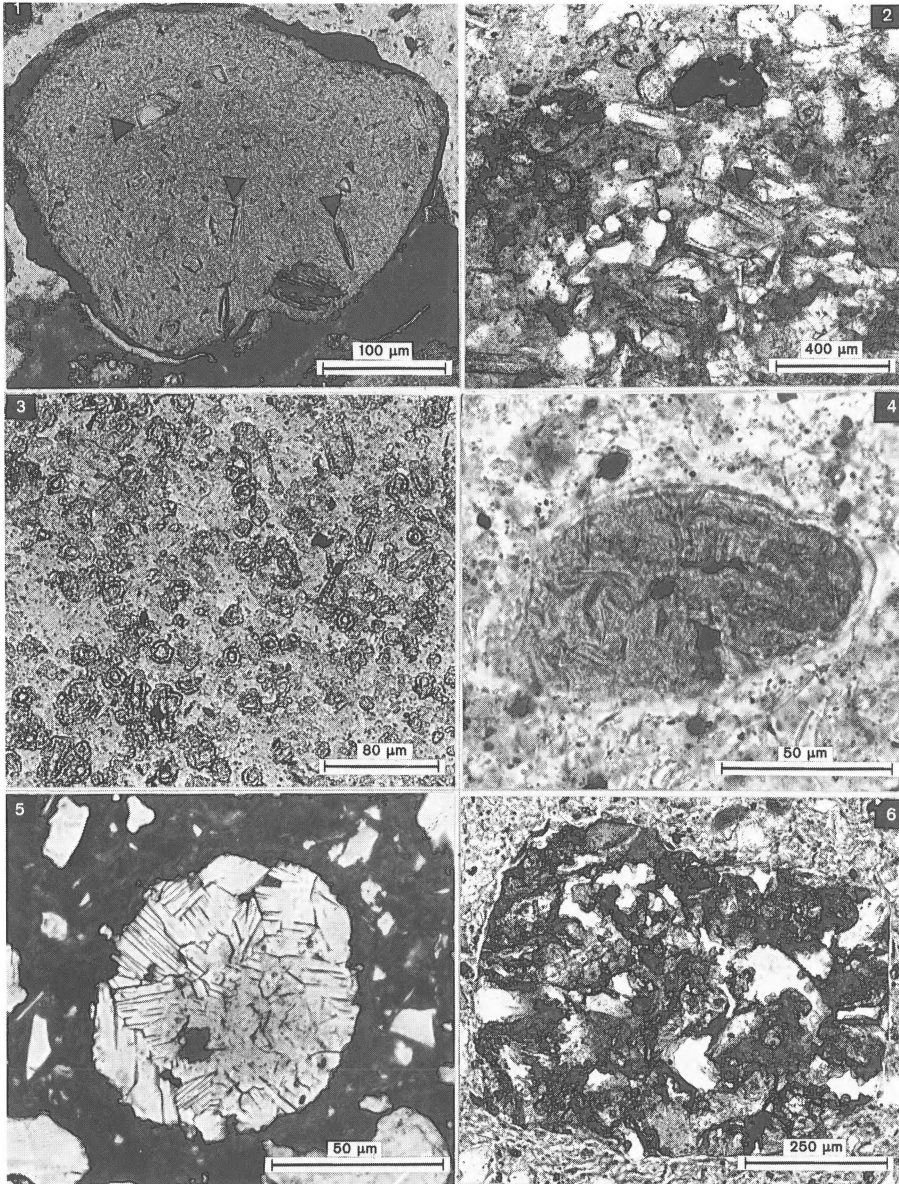


Plate 4. Thin-section photomicrographs of single components in pelites and soft-cuttings aggregates. *Fig. 1.* Rounded glauconite grain enclosing minute splinters of quartz, feldspar, and mica, marked by arrows from left to right respectively. Base basal glauconite bed, Upper Jurassic (Malm alpha 2). Sengenthal quarry, Franconia, 38 km SE of Nürnberg. // Nicols. *Fig. 2.* Opaline sponge spicules in cryptocrystalline phosphate matrix of a phosphorite nodule. Lower Cretaceous (Upper Aptian). Sarstedt clay pit, 21 km SE of Hannover. // Nicols. *Fig. 3.* Sideritized bacteria (= doughnut-shaped siderite spherules) in carbonate-phosphorite concretion). Lower Cretaceous (Lower Albian). Vöhrum clay pit, 30 km E of Hannover. // Nicols. *Fig. 4.* Schlieren-textured glauconite grain in soft clay matrix resembling deformed vitroclastic texture of some tuffs. // Nicols. *Fig. 5.* Single radiolarian in soft clay matrix diagenetically replaced by blocky clinoptilolite. // Nicols. *Fig. 6.* Opal- and chalcedony-cemented fine sandstone fragment in soft clay matrix. // Nicols. Figs. 4–6 are photomicrographs of hard-component inclusions in soft-cuttings aggregates from the Upper Oligocene/lowermost Miocene interval of shallow boreholes in the Weser, Aller and Elbe rivers area (Zimmerle et al. 1990).

tones have been diagenetically altered to clinoptilolite (Plate 3, Fig. 4), a widespread process in opaline biogenic rocks of Cretaceous to Recent age (compare also Plate 4, Fig. 5). The thoroughly bioturbated siliceous marlstone, e.g. Flammenmergel, which marks a littoral to shallow-marine facies belt that stretched in mid-Cretaceous times from France to the USSR along the southern coast of the boreal Cretaceous ocean, is another type of the volcano-siliceous rock association with distinctive petrographic properties. Fragments of siliceous sponges are commonly dissolved in the weathering crust (Plate 3, Fig. 5); secondary porosity and reprecipitation of silica are the consequence of this action.

Thin opaline spongolites are even found in the mainly smectitic Messel oil shale (Plate 3, Fig. 6).

Single components in pelites and soft-cuttings aggregates

Hard components, such as glauconite, contained in soft clays and in aggregates of soft cuttings may also be diagnostic of provenance and sedimentary environment. Numerous publications describe the X-ray mineralogy and chemistry of glauconite in detail, but few publications deal with the fabric and internal structure of glauconite. Thus, the geological significance of glauconite occurrences and glauconite fabric is not evaluated to its optimum. Jeans et al. (1982) have shown convincingly that thin-section evaluation has some unused potential. Relict structures of preexisting sediments are commonly observed in some grains of a glauconite crop such as in some of the glauconite grains from the basal Glauconite Bed of Sengenthal (Plate 4, Fig. 1). The tiny mineral fragments (10–50 μm in size) of quartz, feldspar, and mica give the glauconite grain the textural appearance of a glauconitized dust tuff. Tuffaceous material in the mid-Cretaceous, for instance, is preferentially glauconitized (Jeans et al. 1982). Zimmerle et al. (1990) also postulate glauconitization of Oligocene tuffs (compare also Plate 4, Fig. 4).

Concretions, although receiving insufficient attention, are an indispensable tool for reliably re-

constructing the early stages of sediment diagenesis. In concretions soft sediments are indurated penecontemporaneously or during early diagenesis; thus, structures are preserved undeformed and mineral components remain unaltered. One type of concretion especially common in the Lower Carboniferous and mid-Cretaceous is the phosphorite nodule (Paproth & Zimmerle 1980, Zimmerle et al. 1980, Zimmerle 1982 b, Zimmerle & Emeis 1983). An Upper Aptian phosphorite nodule enclosing numerous siliceous sponge spicules – preserved either as opal or partially as clinoptilolite (Plate 4, Fig. 2) – comes from a claystone interval which has been characterized by geochemical and petrographic means as tuffaceous. Indirect volcanic influence in phosphorite formation has already been postulated (Paproth & Zimmerle 1980, 92; Zimmerle 1982 b, 198, Table 4.7.–8).

Concretionary siderite-phosphorite burrows a few millimetres to several centimetres in diameter transect the argillaceous Lower Albian near Vöhrum; they are part of a Thalassinoides-type of burrow system. Sideritic spherites (5–25 μm in diameter) are enriched in the phosphate-rich crust of the concretionary burrows (Plate 4, Fig. 3). The spherites in their present form represent diagenetic post-mortem siderite incrustations of bacteria that have been concentrated in the original wall and mucous coating of the burrows.

Soft-cuttings aggregates as described in section 2 can reveal, if properly thin-sectioned, a wealth of additional information about constituent minerals, diagenesis, and the depositional environment. The following examples are taken from a pilot study of Upper Oligocene/lowermost Miocene sediments in northwestern Germany which were only available as soft cuttings. The schlieren-textured glauconite grain (Plate 4, Fig. 4), the single radiolarian completely replaced by clinoptilolite (Plate 4, Fig. 5) and the opal- and chalcedony-cemented, fine sandstone fragment (Plate 4, Fig. 6) reflect the wide spectrum of additional information that can be obtained. Opal- and chalcedony-cemented sandstones of Tertiary age have not been recorded before in Germany in contrast to occurrences in Belgium and France.

Review and outlook

In thin-section petrography of pelites, conventional procedures should be modified and new ones introduced e.g. the use of polished thin sections, the application of ultra-thin sections, if necessary, and the examination of heavy minerals in thin section. The provenance of pelites can often be determined successfully by sub-microscopic thin-section analysis ($< 20 \mu\text{m}$) supplemented by microprobe, X-ray diffraction, X-ray fluorescence, scanning electron microscope, and ICP-MS analysis (Kubaneck et al. 1988, Nöltner & Zimmerle, in press).

The diagenetic history of pelites which is normally only based on indirect interpretation of bulk mineralogical and chemical analyses, can be much better disentangled by submicroscopic analysis of polished thin sections (Primmer & Shaw 1985, Nöltner 1988, Huggett 1989).

The sedimentological evaluation of the usually soft sediment cores from ODP and from other sea bottom samples would greatly benefit from thin-section petrography, which would supplement smear-slide and X-ray diffraction evaluation. The 'age of mudrock petrography' sensu lato has really begun. The immense diagnostic value of sedimentary as well as tectonic fabric, can only be exploited fully by means of thin-section analysis.

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