ORIGIN, MINERALOGY, NOMENCLATURE AND PROVENANCE OF SILICA AND SIO_2 ROCKS

A KOVAKŐZETEK EREDETE, TERMINOLÓGIÁJA ÉS SZÁRMAZÁSI HELYE

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Abstract

The various modifications of silica, especially quartz, play a central role in the composition of geological materials. Owing to their abundance and properties, SiO_2 minerals and rocks have been used since the beginning of human being in different applications such as tools, weaponries, jewelleries or building materials. The occurrence of different silica minerals within SiO_2 rocks and the similarity in mineral composition of those stones require a clear terminology and nomenclature of both the silica polymorphs and varieties as well as the different types of SiO_2 rocks and their genesis. Because of the often monotonous composition of these rocks, they only differ in texture, grain size, kind and content of binding agents and thus, are hardly to be classified in a hand specimen or by routine polarizing microscopy. Therefore, an integrated mineralogical and geochemical analysis is necessary for a detailed characterization. The present review gives an overview concerning the state of the art of the mineralogical and petrographical nomenclature of silica and SiO_2 rocks and the analytical approach for the identification and classification of these materials.

Kivonat

Az uralkodóan kovasavból (SiO_2) álló ásványok, elsősorban a kvarc, központi szerepet játszik a kőzetek felépítésében. Gyakoriságuknak és tulajdonságaiknak köszönhetően a SiO_2 ásványokat és kőzeteket az emberi fejlődés kezdetétől gyakran felhasználták, eszközként, fegyverként, ékszerként vagy építőanyag formájában. A kovakőzeteken belül a különféle SiO_2 ásványok előfordulása és ezeknek a kőzeteknek az ásványi összetételének ismeretéhez világos és egyértelmű terminológiára és pontos kőzetgenetikai ismeretekre van szükség mind a SiO_2 ásvány módosulatok, mind a kovakőzetek tekintetében. Ezek a kőzetek, gyakran monomineralikus felépítésük következtében, szinte csak szövetben, szemcseméretben illetve az esetleges kötőanyag jellegében és minőségében különböznek, ezért nagyon nehéz őket makroszkóposan vagy polarizációs mikroszkóppal elkülöníteni és osztályozni. A részletes jellemzésükre mindenképpen integrált ásványtani és geokémiai elemzésre van szükség. Az alábbi összefoglaló az ásványtani és kőzettani nevezéktan aktuális állásáról ad áttekintést a SiO_2 ásványok és a kovakőzetek tekintetében és bemutatja az azonosításukra és rendszerezésükre alkalmazható vizsgálati módszereket.

KEYWORDS: QUARTZ, SIO_2, SILICEOUS ROCKS, SILICICLASTIC ROCKS, PROVENANCE

KULCSSZAVAK: KVARC, SIO_2 KOVAKŐZETEK, HOMOKKÖVEK, SZÁRMAZÁSI HELY MEGHATÁROZÁS

Introduction

The various modifications of silica (SiO_2) play an important role in geological as well as industrial processes. Quartz is with more than 12 weight-% one of the most abundant minerals in the Earth crust and the most important silica mineral, occurring in large amounts in igneous, metamorphic and sedimentary rocks. Due to its highly stable nature, quartz is especially enriched in all siliciclastic sediments and rocks, which may consist of up to $\geq$99% quartz and other silica minerals (Götze, 2009).

In addition, silica can be enriched and siliceous rocks formed during diagenesis, metamorphosis and magmatism, such as in the case of chert, flint, quartzite or obsidian. The alteration and diagenesis of organic silica materials (e.g., diatoms, radiolaria, siliceous sponges) result in the formation of porcellanites, diatomites or radiolarites (Füchtbauer, 1988).

Owing to their abundance and properties, SiO_2 minerals and rocks have been used in different applications (e.g. tools, weaponries, jewellery, etc.) since early human being and as traditional building materials (e.g. sandstones) worldwide for centuries. A lot of ancient buildings as well as sculptures and tombstones are made of different types of local siliceous stones. The provenance determination of this stone material and its assignment to certain deposits or quarry regions has become an important scientific tool in answering cultural and historical questions (Götze & Zimmerle, 2000). It aims at the reconstruction of political and trade relations, the

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understanding of the management of historic building sites, technical development of quarrying and transport, etc. In addition, the knowledge about the provenance of siliceous rocks on buildings is also important for the assessment of their weathering behaviour and for practical restoration activities.

Because of their widespread occurrence, sedimentary SiO_2 rocks play the most important role. Their composition is often monotonous. In most cases, quartz is the dominant mineral, and only low contents of other silica polymorphs, feldspar and a few other minerals (e.g. detrital mica, clay minerals or heavy minerals) may occur. Depending on their geological formation, these SiO_2 rocks only differ in texture, grain size, kind and content of binding agents and thus, are hardly to be classified in a hand specimen or by routine polarizing microscopy. Up to now, the nomenclatures are not always sharp with partly overlapping terms. In addition, the situation is hindered due to the use of regional names for several SiO_2 rocks. The occurrence of different silica minerals within siliceous rocks and the similarity in mineral composition of those stones require a clear terminology and nomenclature of both silica polymorphs and different types of siliceous rocks and their genesis.

The SiO_2 system

Silica (SiO_2) makes up 12.6 weight% of the Earth's crust as crystalline and amorphous silica in at least 15 ***modifications*** (**Table 1**), i.e. mineral phases with the formula SiO_2 but a different crystal structure. In respect to the occurrence in nature and the amount of technical material used, quartz is the most important silica modification. At 573°C the trigonal alpha quartz transforms reversible into the hexagonal high-temperature quartz.

The crystal structure of alpha quartz is composed exclusively of $[SiO_4]^{4-}$ tetrahedra with all oxygen joined together in a three-dimensional network. Thus, the formula is SiO_2 and the atoms are arranged in a trigonal symmetry. The properties of quartz are determined by its real structure. The type and frequency of lattice defects are influenced by the thermodynamic conditions during mineralization or subsequent processes during metamorphism or natural irradiation. These defects can be classified according to their structure and size as point defects (zerodimensional, < 10...30 Å), dislocations (linear defects), subgrain or twin boundaries (two-dimensional), and three-dimensional defects due to microinclusions of minerals and fluids.

Table 1.: The SiO_2 system (modified after Strunz & Tennyson, 1982)

1. táblázat: SiO_2 ásványok rendszere (Strunz & Tennyson, 1982 nyomán)

Quartz-tridymite-cristobalite group (atmospheric and low pressure)	
Quartz	trigonal
High-quartz	hexagonal
Tridymite	monoclinic
High-tridymite	hexagonal
Cristobalite	tetragonal
High-cristobalite	cubic
Melanophlogite	cubic
Fibrous SiO_2 (syn.)	orthorhombic
Moganite	monoclinic
Keatite-coesite-stishovite group (high and ultra-high pressure)	
Keatite (syn.)	tetragonal
Coesite	monoclinic
Stishovite	tetragonal
Seifertite	orthorhombic
Lechatelierite-opal group (amorphous phases)	
Lechatelierite	natural silica glass
Opal	water bearing, solid SiO_2 gel

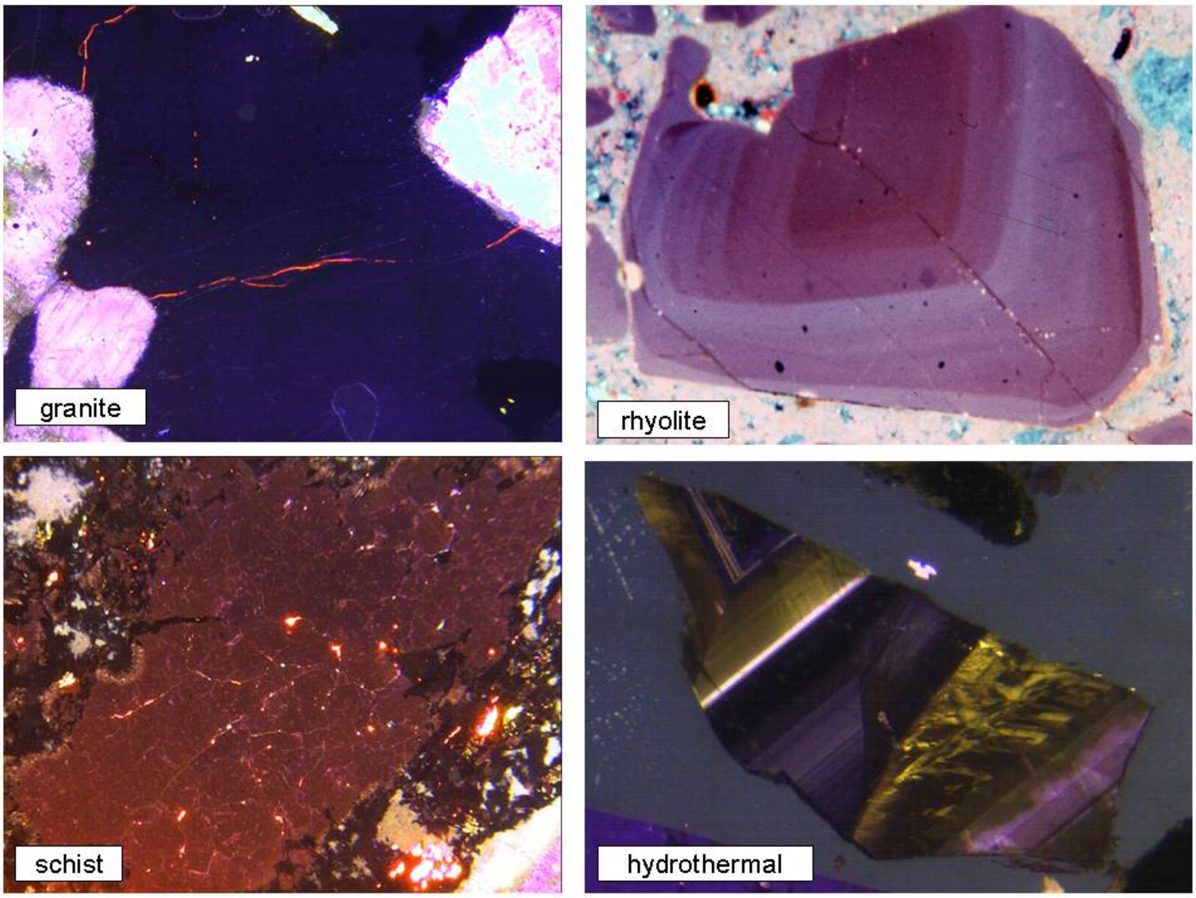

Fig. 1.: Diversity of cathodoluminescence (CL) colours of quartz from different parent rocks

1. ábra: Kvarc kristályok változó katódlumineszcens (CL) színe különböző eredetű kőzetekben

Because of the close relation between different defect types and specific genetic conditions, typomorphic properties (e.g., crystal shape, trace-element composition, luminescence properties, etc.) can be used to reconstruct geological conditions of formation. One prominent example, which is commonly used in geosciences, is the diversity in cathodoluminescence (CL) colours of quartz from different host rocks (**Fig. 1**). For instance, these properties provide the basis for provenance analyses of clastic sediments, where the detrital quartz grains can be related to possible parent source rocks.

The varying properties of quartz and other silica minerals result in the existence of numerous ***varieties***, i.e. mineral phases with the same chemical composition of SiO_2 and the same crystal structure, but different appearance in shape, colour or other physical properties (**Fig. 2**). These varieties are sometimes used as material such as in the case of rock quartz, milky quartz (vein quartz), agate or jasper and, therefore, can be used for the identification and classification of several frequent silica minerals.

On the other hand, certain non- and microcrystalline silica polymorphs and varieties, respectively exist (**Table 2**). These mineral phases play an important role as constituents of preferentially sedimentary rocks and, therefore, have to be considered for the characterisation and nomenclature of SiO_2-bearing rocks.

Origin and nomenclature of SiO_2 rocks

Despite the simple chemical formula SiO_2 of quartz, the system of silica and SiO_2 rocks is very complex. This is on one hand due to the various silica modifications and quartz/silica varieties and on the other hand the various SiO_2 rocks with partially unclear nomenclature. The basis for a useful classification is probably given by the petrological classification into magmatic, metamorphic and sedimentary rocks.

Since siliceous rocks are especially enriched at the Earth's surface, the present topic has to be dealt comprehensively under the aspect of mineralogy and sedimentary petrology. From the group of magmatic and metamorphic rocks, only fine-grained, SiO_2-rich rocks have to be taken into account such as rhyolite (20-60% quartz) and volcanic glasses (obsidian, perlite) as well as metamorphic quartzite.

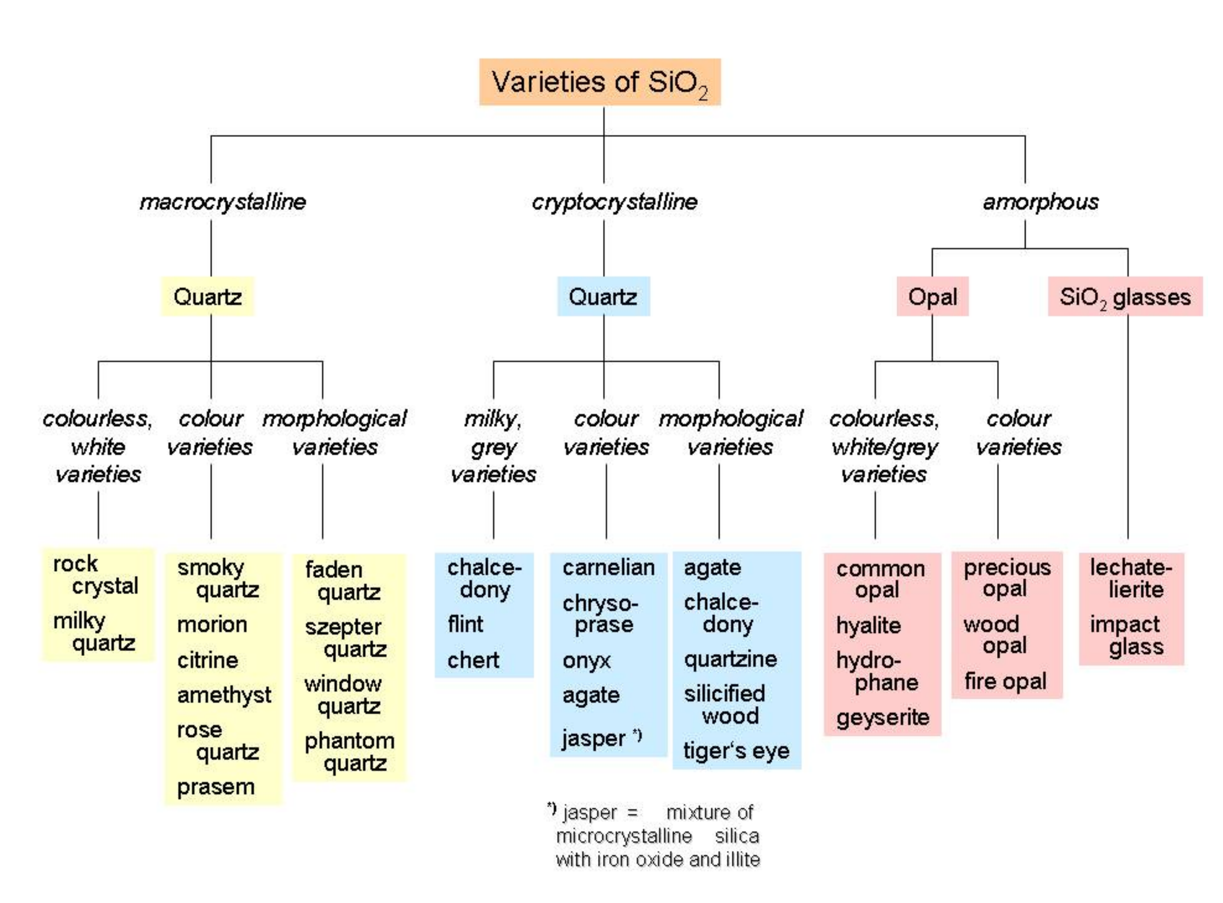

Fig. 2.: The system of different varieties of quartz and other silica phases

2. ábra: Kvarc változatok és egyéb SiO_2 ásványok rendszere

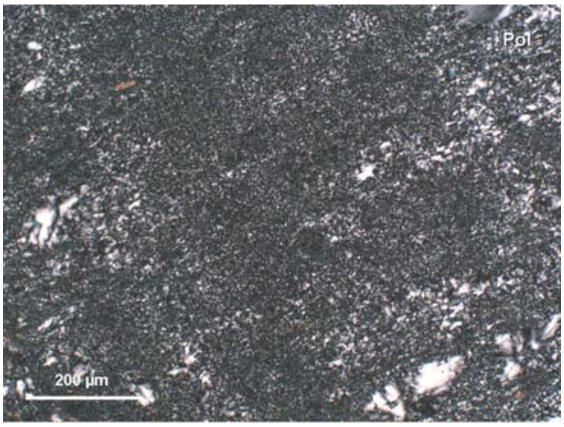

Fig. 3.: Micrograph in polarized light of massive chert with fine-grained granular quartz and chalcedony

3. ábra: Tömeges kovakőzet (s.l. tűzkő) mikroszkópos képe polarizált fényben

To cover the whole group of sedimentary SiO_2 rocks, the term ***silicite*** could probably be used without overlapping with more detailed nomenclatures. Taking into account the genetic aspect of classification, the groups of siliceous rocks and siliciclastic rocks should be distinguished.

Siliceous rocks are rocks with >50% non-detrital silica minerals such as opal-A, opal-CT, chalcedony, quartzin and/or (micro-)quartz (Füchtbauer, 1988).

In contrast, the group of ***siliciclastic rocks*** includes rocks with preferentially detrital quartz from previously existing rocks, accumulated and compacted during weathering, transport, sedimentation and diagenesis.

Siliceous rocks

A further differentiation and nomenclature within the group of siliceous rocks is possible due to aspects of formation, mineral composition and texture.

Siliceous rocks consisting almost completely of opal-CT are called ***porcellanite***, whereas those with (micro-)quartz and chalcedony belong to the group of chert. According to Knauth (1994), the term ***chert*** (= ***hornstone***, in German ***Hornstein***) is used for rocks with interlocking grains of complexly twinned, hydrous, granular microcrystalline quartz that has replaced pre-existing sediments such as opal, carbonate, or evaporate minerals (**Fig. 3**).

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Table 2.: Classification of non- and microcrystalline silica phases (modified after Graetsch, 1994)

2. táblázat: Kristályos és amorf SiO_2 fázisok osztályozása (Graetsch, 1994 nyomán)

Crystal structure or phase	Variety	Subvariety/ synonymous name	Microstructure	Optical character	Water content (weight-%)
quartz	microquartz		granular	positive	< 0.4
disordered quartz	chalcedony		fibrous [11 $\bar{2}$ 0]	length-fast	0.5 - 2
(often with moganite)	quartzine		fibrous [0001]	length-slow	0.5 - 1
moganite			platy (110), lepidospheric	length-slow	1.5 - 3
disordered cristobalite	opal-C	lussatine	platy (111)*	length-fast	1 - 3
cristobalite/tridymite	opal-CT	lussatite	fibrous [110]*	length-slow	3 - 8
		common massy opal	platy, lepidospheric	nearly isotropic	3 - 10
non-crystalline	opal-AG	precious opal	close packing of homometric spheres	play of colour, anomalous birefringence	4 - 8
		potch opal	heterometric spheres	isotropic	4 - 8
	opal-AN	hyalite	botryoidal crusts and masses	strain birefringence	3 - 7
	lechatelierite	fulgurites	vitrified tubes	isotropic	< 0.3
		impact glass	meteoritic silica glass	isotropic	< 0.3

C – cristobalite, T – tridymite, A – amorphous, G – gel-like, N – network (glass)-like

* indices refer to cubic setting of cristobalite

The formation of chert can occur by:

a) diagenetic transformation sequence from siliceous oozes (SiO_2 from diatoms, radiolarian or sponges and also volcanic glass): opal-A→ opal-CT→ microquartz or

b) direct diagenetic precipitation of microquartz (replacement of carbonate).

According to the siliceous precursors, radiolarite, diatomite or spiculite are formed. Synonymous for radiolarite the terms ribbon chert, novaculite and lydite (in German = Kieselschiefer) are used (compare **Fig. 4**).

Among the massive cherts, Precambrian cherts are sometimes named due to their origin as stromatolithic chert, which often occurs together with iron oxides in deposits of banded iron ore formations (BIF). It is recently assumed that silica-producing microorganisms play an important role in the formation of these siliceous rocks.

Nodular chert is formed during the diagenesis of carbonaceous muds by the dissolution and replacement of nodular carbonate in shallow coastal environment (**Fig. 5**). The term ***Flint*** (French: silex; German: Feuerstein) refers to nodular chert concretions in carbonate rocks, which are of preferentially Cretaceous and Jurassic age (Füchtbauer, 1988).

Another type of siliceous rocks is ***siliceous sinter***. This is a porous, layered and fine-grained siliceous rock, which originates from the evaporation of silica in hot springs (**Fig. 6**).

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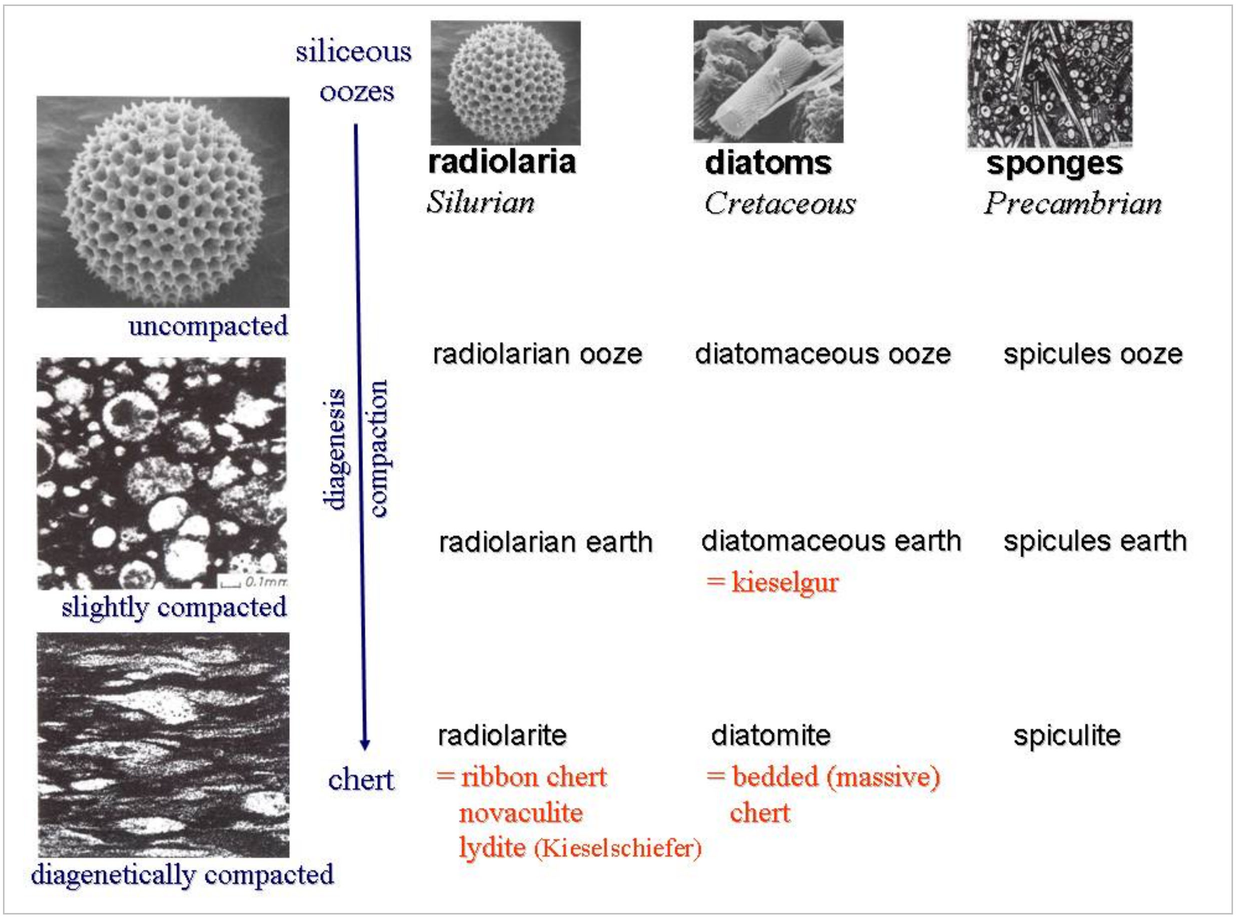

Fig. 4.: Formation of different types of chert by the diagenesis of opal-A precursors (siliceous oozes) during burial and solution-reprecipitation steps via opal-A→opal-CT →microquartz.

4. ábra: Különböző kovakőzetek képződése opal-A (kovaiszap) előzményekből (Knauth, 1994 nyomán).

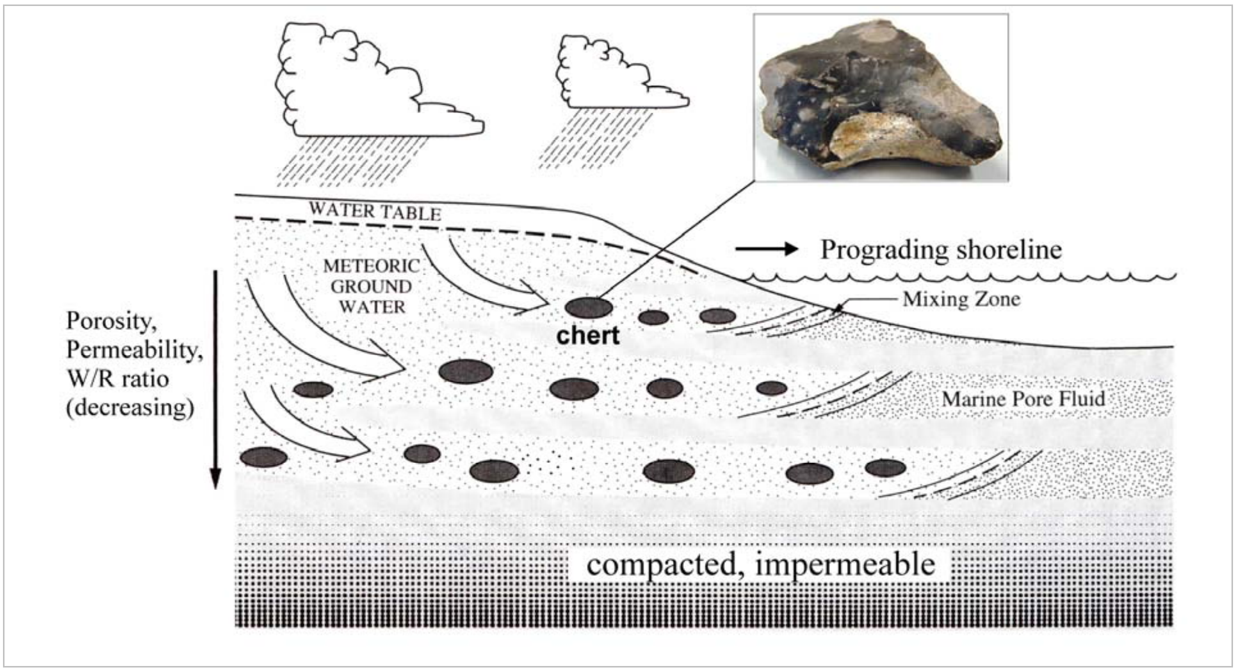

Fig. 5.: Scheme of the formation of nodular chert by dissolution and replacement of nodular carbonate in shallow sediments (modified after Knauth, 1994)

5. ábra: Gumós tűzkő képződése karbonátok helyettesítésével sekélytengeri üledékekben (Knauth, 1994 nyomán)

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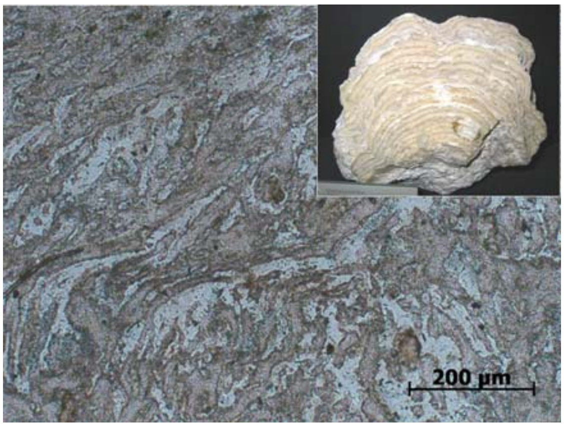

Fig. 6.: Hand specimen (upper right) and transmitted light micrograph of a typically layered siliceous sinter showing the typical microstructure

6. ábra: Kézipéldány (jobb felső sarok) és áteső fényben készült mikroszkópos felvétel egy tipikus kovás bekérgeződésből

In contrast, ***tripoli*** (or ***polishing slate***, German: Polierschiefer) is a fine-grained siliceous rock with inorganic silica source and high porosity.

A special group of siliceous rocks is represented by ***silcretes***. This group of terrestrial siliceous rocks is especially reported from Australia (silcrete) and Europe, where the rocks are called ***Tertiary quartzite*** (because of the preferred occurrence in Tertiary sediments) or ***cement quartzite*** (in contrast to metamorphic quartzite). This discrimination is necessary, since the general term "quartzite" is used for all very hard, resistant rocks with quartz contents >90%, independent on their geological formation.

These rocks originate from the silicification of pre-existing surface rocks (mostly sediments) by silica rich weathering solutions and may cover large areas (**Fig. 7**). Because of the intergrowth of both detrital and secondary quartz and silica material, these rocks represent more or less the interface between siliceous and siliciclastic rocks. The texture and appearance of the silcretes can drastically vary due to the amount of detrital material and the kind of cementing matrix material (**Fig. 7**). Probably the term ***limnoquartzite*** (or opalite) also describes this type of rocks considering that a significant amount of silica may originate from volcanic and/or hydrothermal activities.

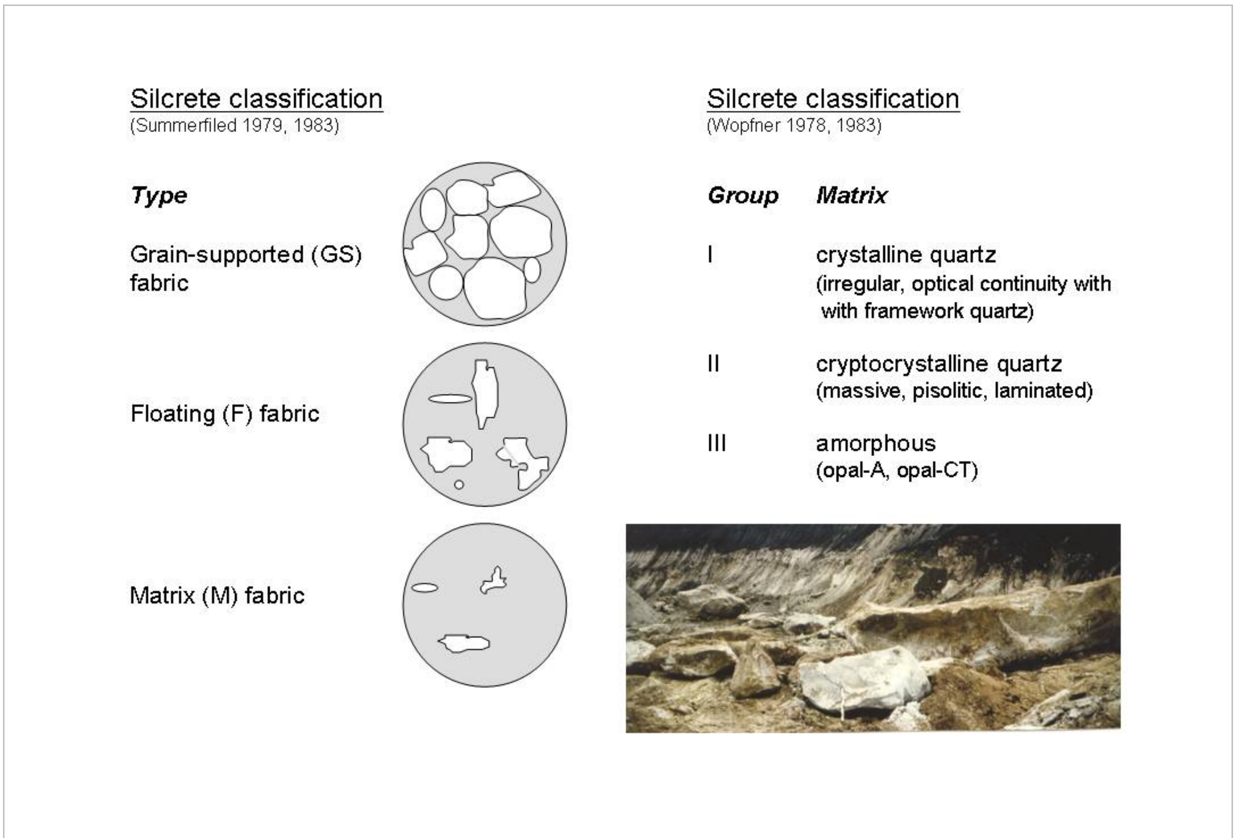

Fig. 7.: Classification criteria of silcretes based on textural features (left) and the kind of cementing material (right) and example of a dense Tertiary quartzites in the lignite open pit mine of Zwenkau, Germany.

7. ábra: Kvarchomokkövek osztályozása a szöveti bélyegek szerint (bal oldalon) és a kötőanyag szerint (jobb oldalon) Zwenkau harmadidőszaki lignitbánya feltárás példáján.

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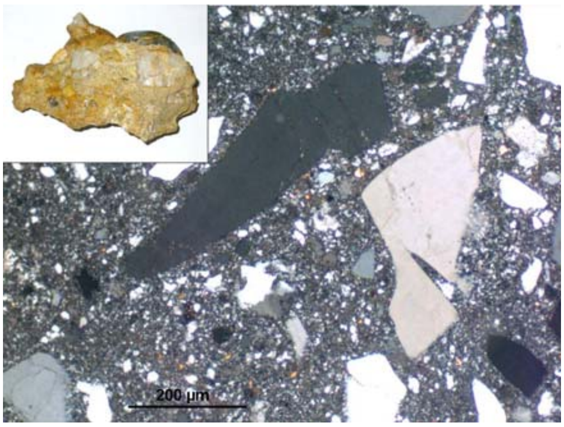

Fig. 8.: Tertiary quartzite with fine-grained siliceous matrix and large detrital quartz grains in a hand specimen (upper left) and micrograph in polarized light

8. ábra: Harmadidőszaki kvarcit finom szemű kovás alapanyaggal és nagyméretű kvarc-szemcsékkel, kézipéldány (bal felső sarok) és polarizációs mikroszkópos felvétel

These mineralogical and textural differences between different types of silcretes are clearly detectable in the hand specimen and under the microscope (**Figs. 8, 9**).

3.2. Siliciclastic rocks

Siliciclastic rocks have a different origin compared to siliceous rocks. They especially form due to the accumulation of physically and chemically resistant quartz during weathering, transport, sedimentation and diagenesis (metamorphosis). Siliciclastic rocks preferentially consist of detrital quartz from previously existing rocks. The general mineral composition and textural characteristics depend on the properties of the primary host rocks and on the sedimentary/diagenetic conditions during rock formation. Pettijohn et al. (1987) summarized main factors of this sedimentary cycle in a general scheme (**Fig. 10**).

Starting with a distinct source rock, the changes in mineral composition are mainly determined by morphological and climatic conditions. Rapid erosion as well as cold and dry climate cause a rapid mechanical destruction of the host rocks and minor chemical alteration with slow decomposition of unstable minerals. In result, the mineral composition is complex and reflects at least partially the primary composition of the host rocks (e.g. **Fig. 17**). In contrast, relatively slow erosion in the lowland together with warm and wet climatic conditions cause a rapid decomposition of unstable minerals and result in a sedimentary rock with high amounts of detrital quartz.

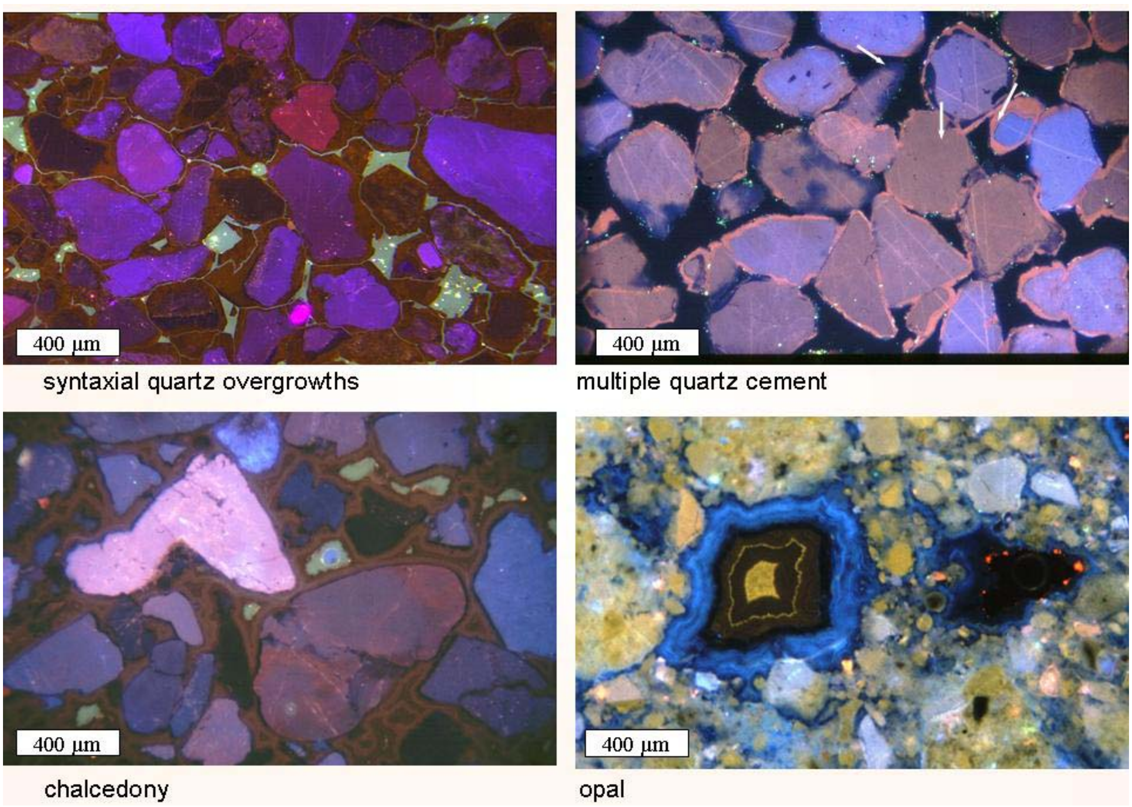

Fig. 9.: Cathodoluminescence (CL) micrographs of different types of diagenetic silica cements in silcretes/Tertiary quartzites.

9. ábra: Katódlumineszcens felvétel (CL) különféle képződésű diagenetikus kvarchomokkövekben

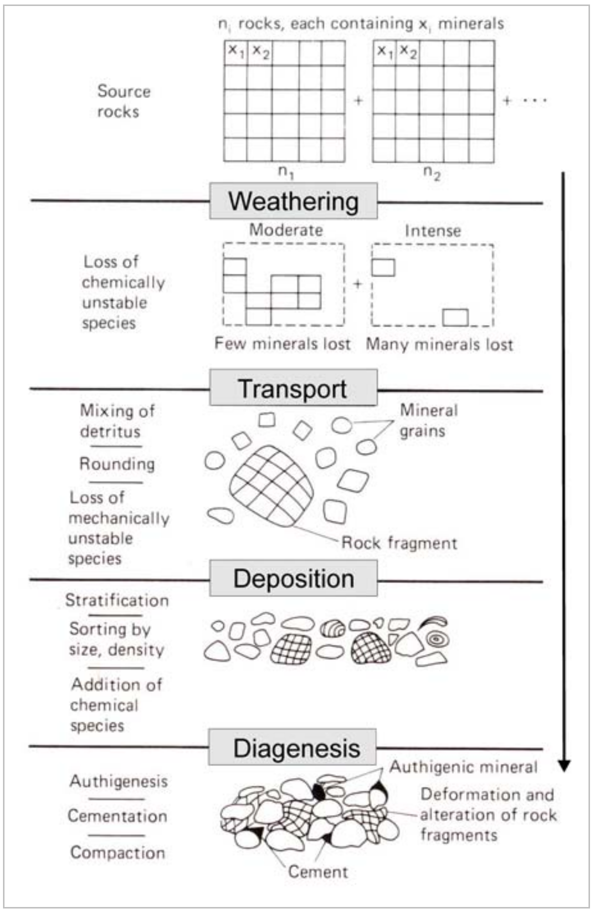

Fig. 10.: Scheme of geological processes in the sedimentary cycle (modified after Pettijohn et al., 1987).

10. ábra: Az üledékes ciklus folyamatainak vázlata (Pettijohn et al., 1987 nyomán).

The primary information of the host rock(s) is more or less lost. In these cases, the typomorphic properties of quartz may inherit important information about the origin of the material. In addition, the granumlometric properties of the sedimentary rocks are especially influenced by the distance and intensity of the transport conditions and can, therefore, provide information concerning the geological environment during rock formation. During diagenesis, compaction / cementation as well as alteration and neoformation of minerals can significantly change the properties of the rocks. According to these facts, the classification of siliciclastic rocks is mainly based on the two parameters mineral composition and grain size (**Fig. 11**).

For instance, sandstone is a sedimentary rock with quartz as main detrital mineral and an average grain size of 0.063-2.0 mm. Depending on the amount of additional mineral or rock components, we can distinguish e.g. mature quartz sandstone, feldspathic sandstone (arcose) or glauconitic sandstone (**Fig. 12-15**).

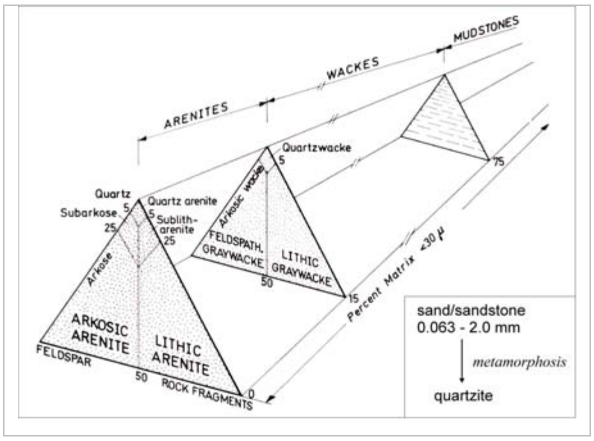

Fig. 11.: Classification of clastic sediments and sedimentary rocks based on mineral composition and grain size (modified after Pettijohn et al., 1987).

11. ábra: Klasztikus üledékek osztályozása ásványos összetétel és szemcseméret alapján (Pettijohn et al., 1987 nyomán)

During metamorphosis, sandstone can be compacted and transformed into quartzite (**Fig. 16**).

Analysis and provenance of quartz and SiO_2 rocks

The evaluation and classification of SiO_2 rocks is based on their characteristic properties. Depending on the specific direction of the investigations and the availability of analytical equipments the following properties should be analyzed:

1. Macroscopic rock properties (texture, colour, etc.)

2. Mineral composition (rock fragments, SiO_2 minerals, feldspar minerals, sheet silicates, carbonates, heavy minerals, organic compounds)

3. Granulometric properties and porosity

4. Specific properties of quartz/silica.

Therefore, a classical petrographic investigation (macroscopic appearance, thin section analysis) has to be combined with modern analytical methods. The detailed analytical scheme is mainly based on the combination of polarizing microscopy (mineral composition, texture, grain size distribution), cathodoluminescence (CL) microscopy (quartz types, feldspar, clay mineral content) coupled with image analysis, scanning electron microscopy (accessories, pore cement, diagenetic features), and analysis of pore space data (**Fig. 18**).

Several applications have shown that such an analytical procedure will provide best results.

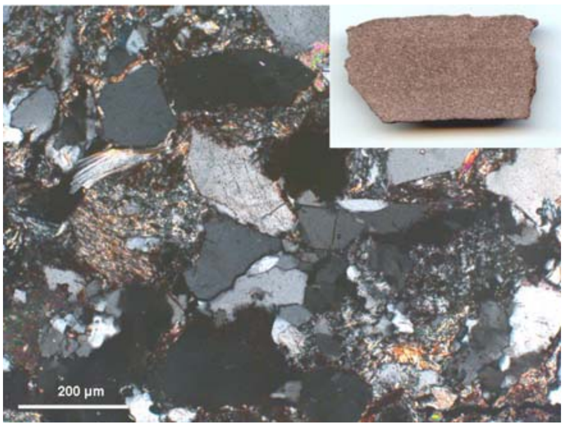

Fig. 12.: Feldspathic sandstone (arcose) in a hand specimen (upper right) and micrograph in polarized light

12. ábra: Földpátos homokkő (arkóza) kézipéldány (jobb felső sarok) és polarizációs mikroszkópos felvétele

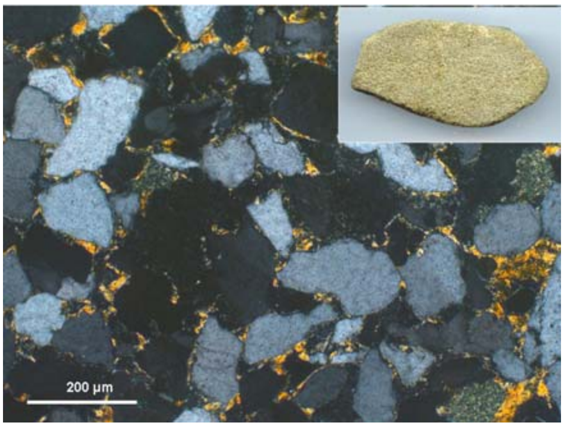

Fig. 13.: Glauconitic sandstone in a hand specimen (upper right) and micrograph in polarized light

13. ábra: Glaukonitos homokkő kézipéldány (jobb felső sarok) és polarizációs mikroszkópos felvétele

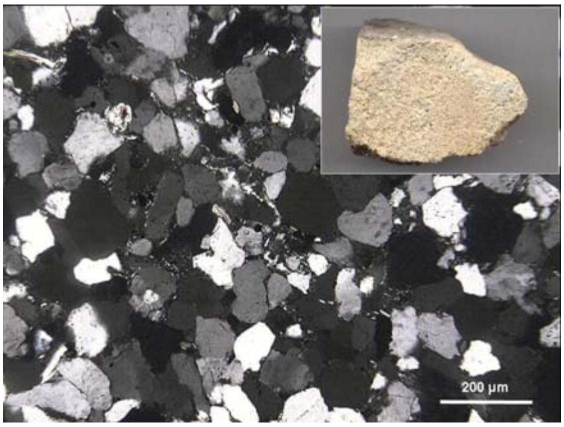

Fig. 14.: Mature, quartz rich sandstone in a hand specimen (upper right) and micrograph in polarized light

Fig. 14.: Kvarcban gazdag homokkő kézipéldány (jobb felső sarok) és polarizációs mikroszkópos felvétele

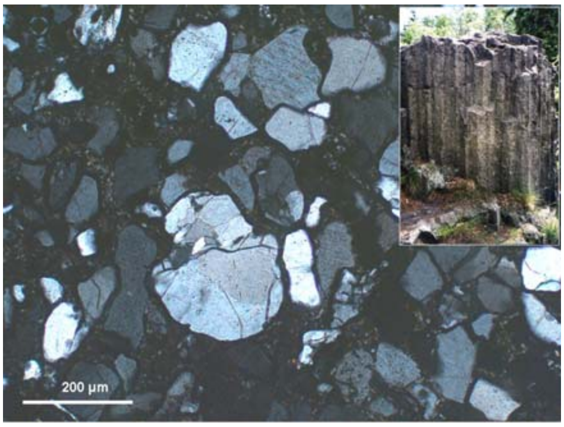

Fig. 15.: Baked (thermally overprinted sandstone) in the field (upper right) and micrograph in polarized light; note the fracturing of the detrital quartz grains due to the volume expansion during heating

15. ábra: Átsült (utólagos hőhatáson átesett) homokkő a terepen (jobb felső sarok) és polarizációs mikroszkópos felvételen. A kvarcszemcsék a hőhatás miatt töredezettek

Based on the data it was possible to distinguish and classify historical building materials (mature sandstones) from different geological provinces of Germany (e.g. Michalski et al., 2002; Götze & Siedel, 2004; Götze et al., 2007; Siedel et al., 2010 – compare **Fig. 19**).

Conclusions

SiO_2 minerals and rocks are not only important constituents in the composition of the Earth's crust, they also play an important role as usable material since the beginning of human being. Owing to their abundance and properties, SiO_2 minerals and rocks have been used in different applications such as tools, weaponries, jewelleries or building materials. The identification and differentiation of these SiO_2 materials require both a valuable analytical approach and a clear nomenclature.

In general, the characterization and classification of silica minerals and rocks could be based on the mineralogical and petrographical nomenclatures. Accordingly, we have to differentiate between SiO_2 minerals (including different varieties) and SiO_2 rocks. Among the SiO_2 rocks, in particular sedimentary rocks have to be considered. Exceptions are given by volcanic rocks (e.g., rhyolite or volcanic glass such as obsidian) or some metamorphic rocks (e.g. quartzite), which have also been used as materials.

The sedimentary SiO_2 rocks (silicite) may be subdivided into the two groups of siliceous rocks and siliciclastic rocks. The composition of these rocks is often monotonous. In most cases, quartz is the dominant mineral, and only low contents of other silica polymorphs, feldspar and a few other minerals (e.g. detrital mica, clay minerals or heavy minerals) may occur.

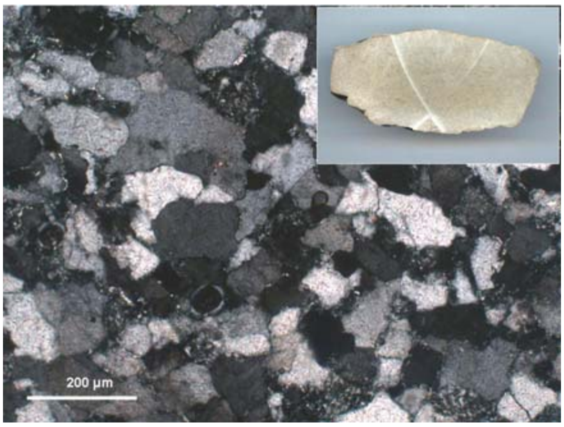

Fig. 16.: Metamorphic quartzite formed during high pressure (and temperature) from a quartz rich sediment in a hand specimen (upper right) and micrograph in polarized light; note the typical sutured grain contacts

16. ábra: Metamorf kvarcit kézipéldány (jobb felső sarok) és polarizációs mikroszkópos felvétele

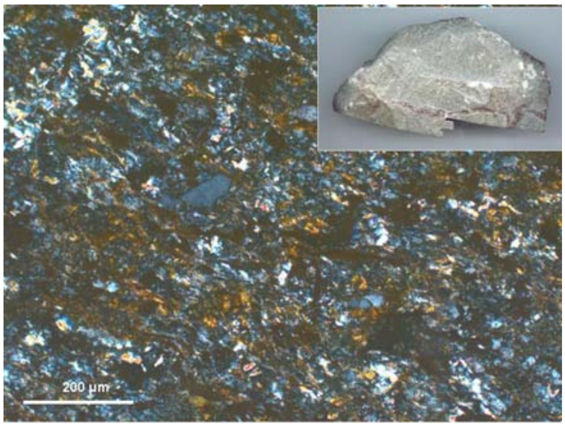

Fig. 17.: Fine-grained greywacke with complex mineral composition in a hand specimen (upper right) and micrograph in polarized light.

17. ábra: Finom szemű grauwacke kézipédány (jobb felső sarok) és polarizációs mikroszkópos felvétele

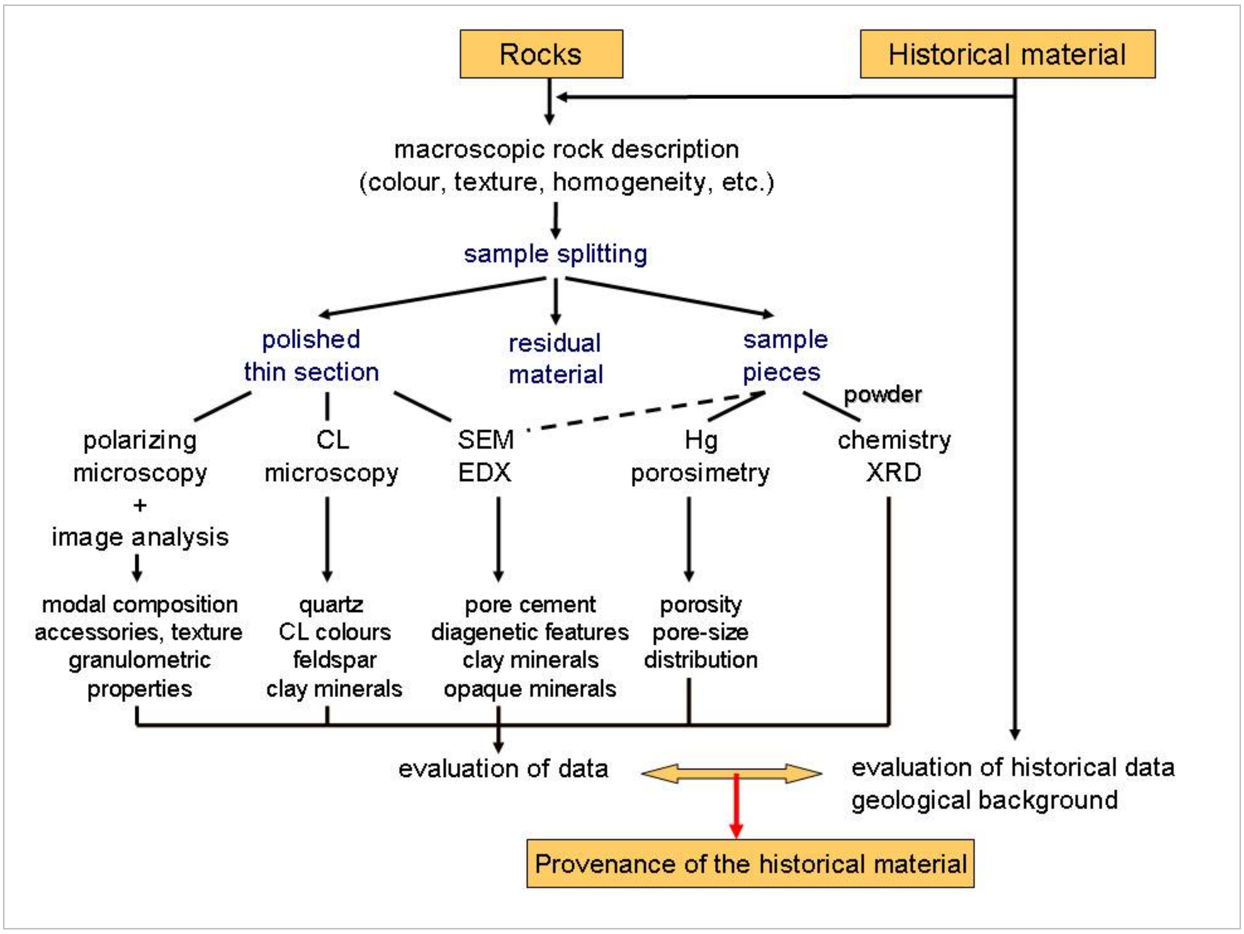

Fig. 18.: General analytical scheme for the identification and classification of SiO_2 material (modified according to Götze & Siedel, 2004)

18. ábra: A SiO_2 anyagú kőzetek azonosításának folyamatábrája (Götze & Siedel, 2004 nyomán)

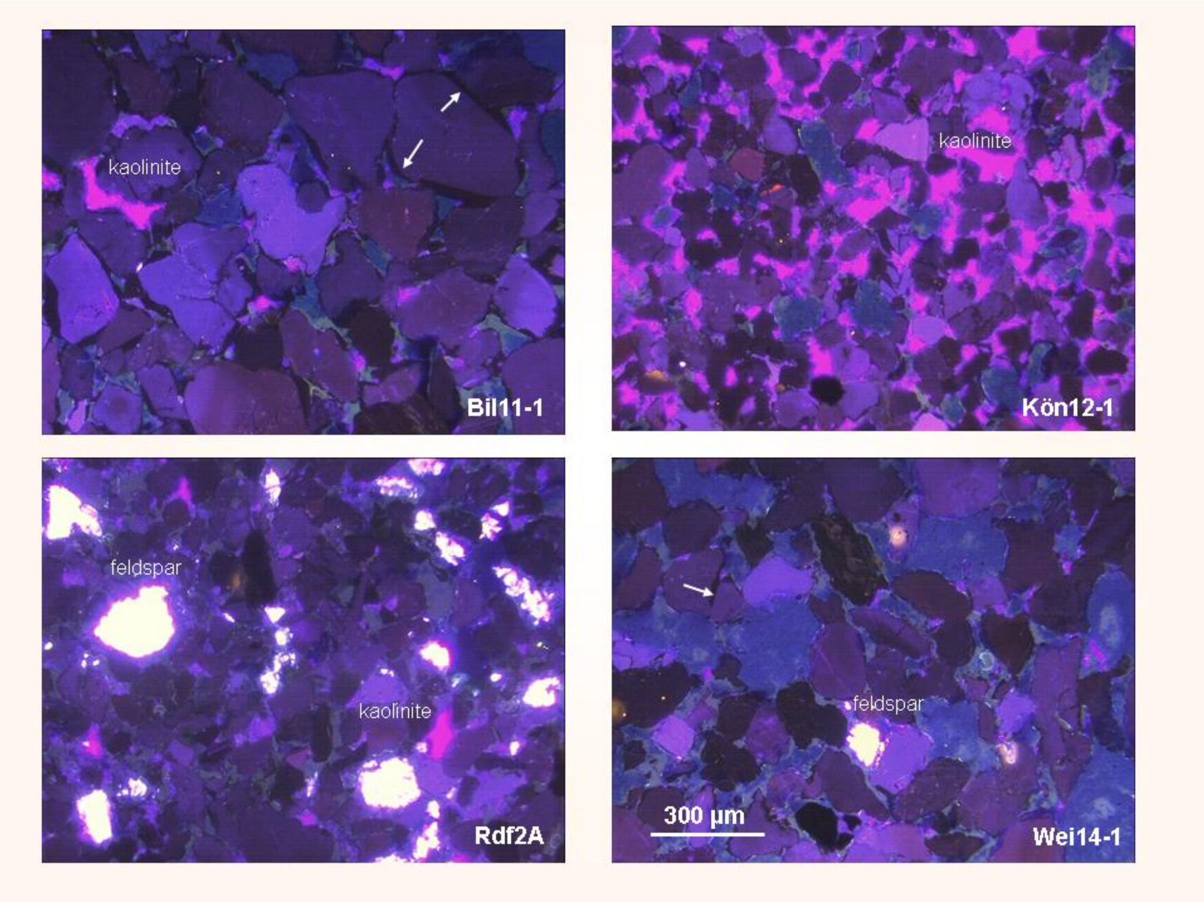

Fig. 19.: Cathodoluminescence micrographs of historical building sandstones from different quarries of the Dresden area (Saxony, Germany) illustrating the potential of advanced analytical methods to distinguish monotonous quartz-rich material

19. ábra: Történeti bányahelyek homokköveinek katódlumineszcens felvételei Drezda környékéről

Depending on their geological formation, these SiO_2 rocks only differ in texture, grain size, kind and content of binding agents and thus, are hardly to be classified in a hand specimen or by routine polarizing microscopy. Therefore, an integrated mineralogical and geochemical analysis is necessary for a detailed characterization.

However, such a detailed investigation is often not possible. Limitations in sample material or analytics (e.g. preparation) do not allow a detailed mineralogical or geochemical investigation. In such cases, the classification of the artefact should be done only as far as it is possible according to the hierarchic nomenclature and a clear identification may sometimes be impossible. Therefore, the question concerning the importance of a pure theoretical background or the practical usability of such a classification has to be answered. Another problem arises from the fact that the characterization and classification of SiO_2 rocks inherits a genetic component, which is often unknown in the case of artefacts found without geological background.

In summary the proposed classification scheme in the present study may provide a usable basis for applications, but will also be further discussed and modified in future.

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