

Mineral composition of sediments underlying the Velenje lignite seam in the P-9k/92 borehole (Slovenia)

Mineralna sestava talninskih plasti velenjskega lignitnega sloja v vrtini P-9k/92

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Abstract

The paper presents the results of granulometrical, geochemical and mineralogical characterisation of sediments underlying the Velenje lignite seam as drilled through the P-9k/92 borehole in the central part of the Pliocene intermontane Velenje Basin. This study of differently lithified sediments/sedimentary rocks is based on analyses of 32 samples from 21 core intervals at the depth of 562.6–580.0 m (end of the borehole). Grain size was analysed on 12 samples, 24 samples were investigated geochemically, while mineral composition was obtained with X-ray diffraction (XRD) on 23 samples, and optical microscopy was performed on 7 samples. Granulometry of very low lithified samples revealed that they are mostly clayey silts (>85 % of the silt fraction), only two are silty sands and one is pebbly/rubbly sandstone. Well-lithified clastics are all sandstones cemented by calcite, siderite and/or marcasite. Geochemical analysis indicated that most samples are $\text{SiO}_2 + \text{Al}_2\text{O}_3$ rich (>60–80 %). Some sediments, mostly at the base of the profile, are enriched in Fe_2O_3 and inorganic C both indicating the presence of siderite. At the top of the profile, thin limestone and gravelly sandstone beds contain a high CaO content and have high loss on ignition (LOI). Qualitative XRD analysis and microscopy showed that all clastic sediments consist of quartz, kaolinite and muscovite/illite. Feldspars occur sporadically, mainly in sands and sandstones. Gypsum was found in some samples of siltstones. Pyrite occurs only in a sample of limestone at the top of the profile. Also marcasite was found only in one sample.

Izvleček

V članku predstavljamo rezultate granulometrične, geokemične in mineraloške opredelitve talninskih plasti lignitnega sloja, prevrtanega z vrtino P-9k/92, v osrednjem delu pliocenskega intermontanega (medgorskega) Velenjskega bazena. Raziskava različno litificiranih sedimentov oziroma sedimentnih kamnin obravnava 32 vzorcev iz 21-ih jedrnih odsekov v globini 562,6–580,0 m, to je do končne globine omenjene vrtine. Granulometrično je bilo analiziranih 12 vzorcev, geokemično 24, mineraloško z rentgensko difrakcijo (XRD) 23 vzorcev in mikroskopsko 7 vzorcev. Granulometrična analiza je pokazala, da so zelo slabo litificirani različni večinoma glinasti melji (>85 % frakcije melja), le dva sta bila meljasta peska in eden prodnati do gruščnati pesek. Mikroskopsko preiskani dobro litificirani klastiti so vsi peščenjaki, cementirani s kalcitom, sideritom ali markazitom. Geokemična analiza je pokazala za večino vzorcev prevladujočo $\text{SiO}_2 + \text{Al}_2\text{O}_3$ (60–80 %) sestavo. Zlasti v spodnjem delu profila je izstopajoča vsebnost Fe_2O_3 in anorganskega C, kar nakazuje prisotnost siderita. V zgornjem delu profila se pojavljata plasti apnenca in prodnato gruščnatega peščenjaka, ki sta nosilki visoke vsebnosti CaO in imata znatno žaroizgubo (LOI). Kvalitativna XRD analiza je pokazala, da vse preiskane vzorce sestavljajo kremen, kaolinit in muskovit/illit. Glinenci nastopajo večinoma v peskih in peščenjakih. V nekaj vzorcih meljev in meljevecev je bila določena sadra. Pirit je bil določen le v plasti apnenca v zgornjem delu profila, v najgloblej v zornem vzorcu peščenjaka pa je bil določen markazit.

Introduction

The Velenje lignite seam is up to 100 m, extremely even up to 165 m thick. It occurs approximately in the middle of the Pliocene to Pleistocene intermontane Velenje Basin (Fig. 1) which is filled with lacustrine, marshy and fluvial clastic sediments in a thickness of more than 1000 m (Fig. 2). The lignite is an ortho-lignite by rank,

mostly xylite-rich, and of medium to low grade by its ash (mineral matter) content. The Velenje Basin and the lignite seam – its geometry, tectonics, petrology, inorganic and organic geochemistry, paleofloristic assemblages, genesis, quality, and reserves – have been thoroughly described and discussed in the following key works from the 1960s onwards: DROBNE (1967), ŠERCELJ (1968, 1987), BREZIGAR (1987), BREZIGAR et al. (1987, 1988),

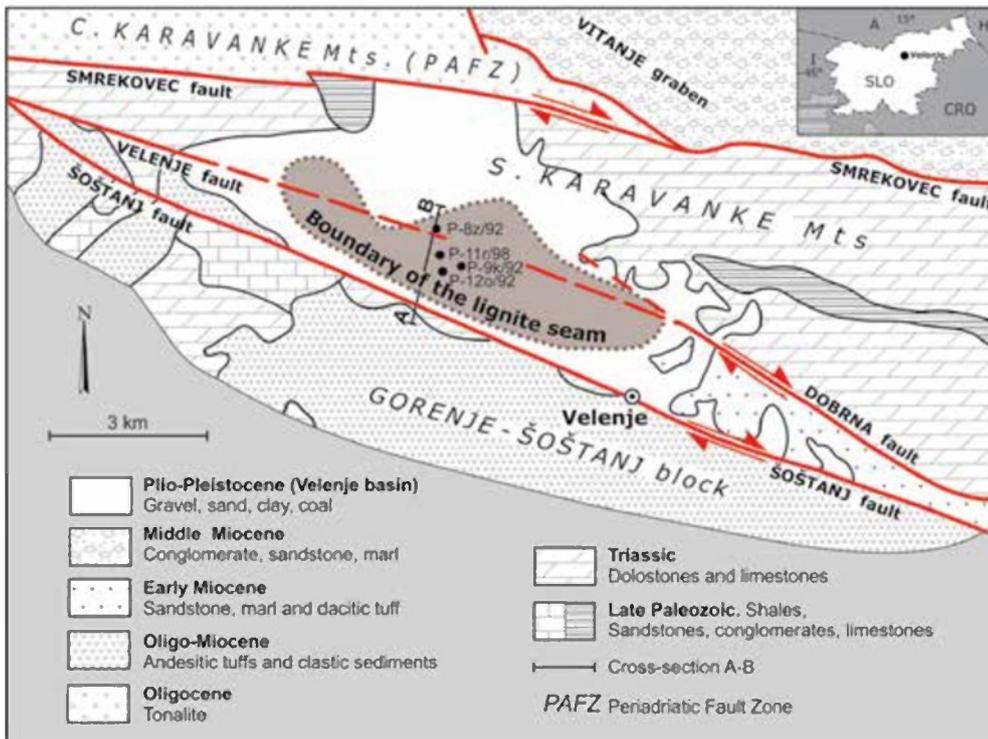
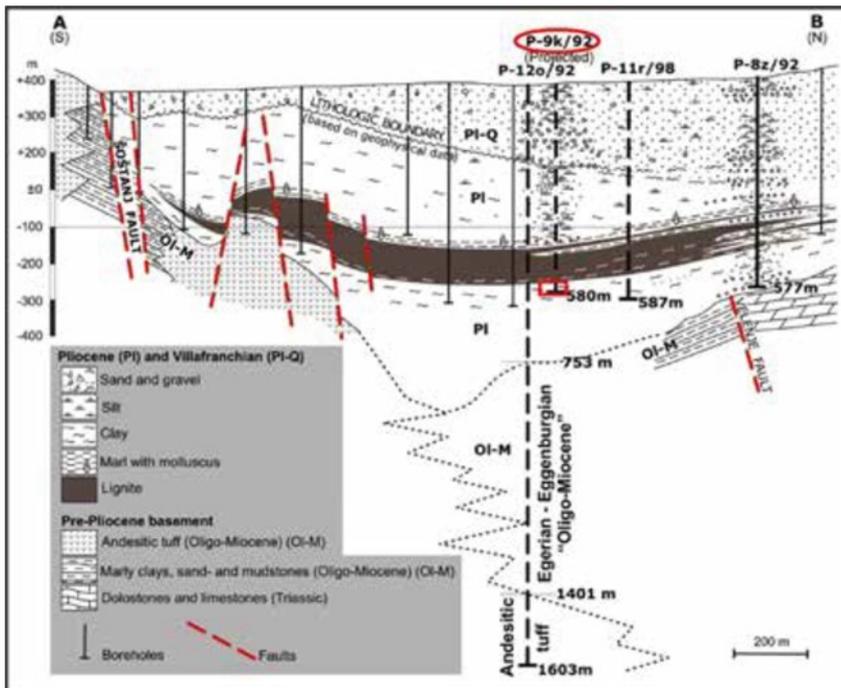


Fig. 1. Geological map of the lignite-bearing Velenje Basin (simplified after BREZIGAR, 1987, and BREZIGAR et al., 1987). Note the position of the P-9k/92 borehole and A-B cross-section shown in Fig. 2.

Sl. 1. Geološka karta Velenjskega bazena (poenostavljeno po BREZIGAR-ju, 1987 in BREZIGAR-ju et al., 1987). Prikazan je položaj vrtnice P-9k/92 in prereza A-B na Sl. 2.



LITH. UNITS	Lithologic description	UNIT	Thickness (m)	Lithology	Age	Depositional environment	Pollen
EARLY QUATERNARY	Silt and gravel	G	5		HOLOCENE	terrestrial	
	Green and yellow sandy silts, thin lignite bed	C	40				
		F	50				
Pliocene hanging wall	Silt and sands	E	100		UPPER Pliocene	marshy terrestrial	"Pappus flora"
	Massive clay-stone and sands	D	100				
	Massive and laminated claystones and sands	C	120				
	Claystone	B	30				
		A	5				
COAL HORIZON	Main lignite seam	O	160		Pliocene	marshy	"Eggenburgian"
	Clay, lignite, coaly clay	III	50				
BASEL BEDS FOOT WALL	Green sandy silts	II	250		Pre-Pliocene basement	terrestrial	
	Silty sediments with coarse clastics	I	150				

Fig. 2. Left: Geological cross-section A-B – adapted after BREZIGAR's (1987) profile 3-3'. Basic geological facts along the P-120/92 are summarised from VESELIĆ et al. (1993). Note the position of the lignite underlying sediments in the studied P-9k/92 borehole. Right: Representative litho-stratigraphic column of the Pliocene and post-Pliocene sedimentary fill of the Velenje Basin (after BREZIGAR, 1987).

Sl. 2. Levo: Geološki prerez A-B – prirejen po BREZIGAR-jevem (1987) profilu 3-3'. Podatki za globoko vrtnico P-120/92 so povzeti po VESELIĆ-u et al. (1993). Prikazan je položaj talninskih sedimentov pod lignitnim slojem v vrtnici P-9k/92. Desno: Značilni stratigrafski stolpec pliocenske in postpliocenske sedimentne zapolnitve Velenjskega bazena (po BREZIGAR-ju, 1987).

PEZDIČ et al. (1998), VEBER (1999), VRABEC (1999), VRABEC et al. (1999), BRUCH (in HEMLEBEN, 2000), MARKIČ et al. (2001), BECHTEL et al. (2003), VEBER & DERVARIČ (2004), MARKIČ (2006), and MARKIČ & SACHSENHOFER (1997, 2010). Rock-mechanical methods of measurements, properties and modelling were introduced and studied by RIBIČIČ

(1985, 1987), ŽORŽ et al. (1984), KOČAR et al. (1988, 1989), LIKAR (1995), PSAKHIE et al. (2000, 2001), and ZAVŠEK (2004). Basic questions concerning dewatering of different aquifers above and within the lignite seam have been mostly solved in the 1970s and 1980s (VESELIĆ, 1985; VESELIĆ et al., 1993). Hydrogeochemistry and the origin of

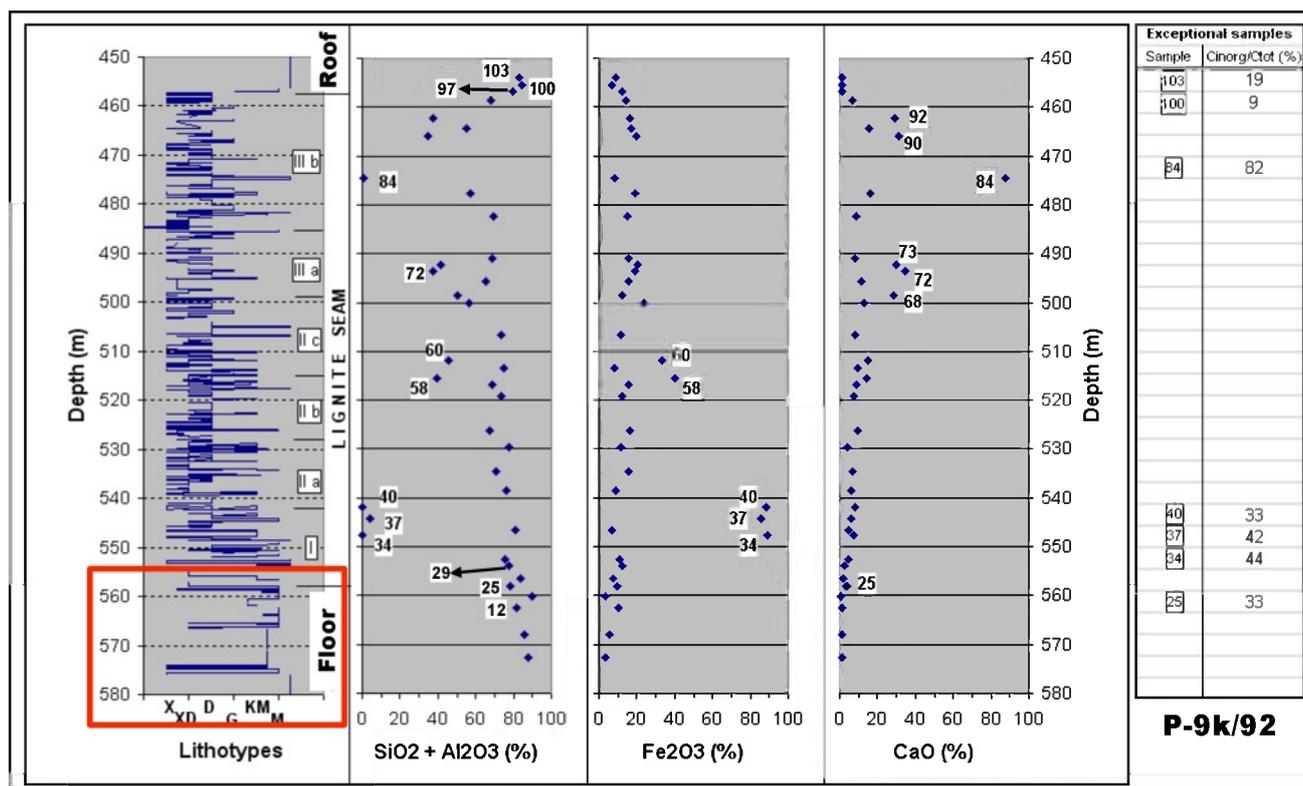


Fig. 3. Lithotype log of the lignite seam and contents of the main element oxides in the P-9k/92 borehole (MARKIČ, 2006). The studied lignite underlying sediments at the depth of 560–580 m are marked as “floor”.

Sl. 3. Litotipnost velenjskega lignitnega sloja in vsebnosti oksidov glavnih prvin v vrtni P-9k/92 (MARKIČ, 2006). Talninski sedimenti, obravnavani v tem prispevku, so označeni kot “floor”.

groundwaters were studied by MALI & VESELIČ (1989), while the monitoring of water drainage was summarised by FLJAVŽ (2002). ZAPUŠEK & HOČEVAR (1998), PEZDIČ et al. (1999), ŽULA et al. (2011), LIKAR et al. (2008), LIKAR & TAJNIK (2013) studied gas (mostly CO₂) adsorption/desorption properties of different lignite lithotypes, whereas the chemical composition of the lignite gasses (sampled in the mine), their origin and dynamics were thoroughly analysed, described and interpreted (especially using stable isotopes) by KANDUČ & PEZDIČ (2005), KANDUČ et al. (2003, 2011), LAZAR et al. (2014). Even though it has been carried out for a long time already, a systematic study in how to degasify the lignite seam more successfully has been intensified in the recent years (JAMNIKAR et al., 2015). Most recently, monitoring and modelling of gas dynamics during exploitation in the Velenje lignite seam has been studied and published by SI et al. (2015a, 2015b). In their study, the Velenje lignite served as a general case for monitoring and modelling gas dynamics within ultra-thick coal seams during the mining process of multi-level longwall top caving. The most recent hydrogeological study was about groundwater/surface-water interaction based on geochemical and stable isotopic investigations (KANDUČ et al., 2014).

The aim of this paper is to present the results of petrological and mineralogical investigations of sediments that underlie the Velenje lignite seam in the P-9k/92 borehole (Fig. 3) located in the

centre of the Velenje lignite-bearing Basin. This borehole was chosen because it is a key borehole in which the lignite has been thoroughly studied petrologically (MARKIČ & SACHSENHOFER, 1997, 2010), geochemically (BECHTEL et al., 2003; MARKIČ, 2006), and in the very close vicinity (in P-11r/98 – see Figs. 1 and 2) also paleobotanically (BRUCH – in HEMLEBEN, 2000).

Lithological, mineralogical, and geochemical investigations presented in this paper have been carried out by the first author of this paper in the frame of her B.Sc. Thesis work at the University of Ljubljana – Department of Geology (ČERU, 2013). Before that, petrological characterisation of the lignite underlying sediments had not attracted any special interest. The reason was probably that the lignite underlying sediments (also termed “footwall” or “floor” sediments) were not problematic from the coal-mining point of view. It was only BREZIGAR (1987) who published that the footwall sediments consist of clays/claystones, coaly clays, silts/siltstones, sands/sandstones, and also of gravels at the base. The thickness of the entire sedimentary fill between the pre-Pliocene sediments and the lignite seam is from a couple of metres to 450 m, depending on the position within the basin and the tectonic displacement of the pre-Pliocene basement, respectively. The pre-Pliocene basement is composed of a wide spectrum of carbonate, siliciclastic, volcanoclastic and magmatic rocks, from Paleozoic to Miocene in age (MIOČ & ŽNIDARČIČ, 1976; MIOČ, 1978; BREZIGAR

et al., 1988) (Figs. 1 and 2). These rocks gave the sedimentary material that filled the basin. The southern hinterland of the Velenje Basin is mostly built up of volcanoclastic deposits of prevalingly andesitic and subordinately dacitic composition (also known as the Oligocene andesitic tuff) of the Smrekovec Volcanic Complex (KRALJ, 2013). Areas to the north of the basin are composed of Triassic limestones and dolostones (MIOČ & ŽNIDARČIČ, 1976), and further to the north of the Oligocene tonalite of the Central Karavanke Mountains (FANINGER, 1976).

The bottom part of the sedimentary fill is characterised by coarse clastics, which grade upwards into finer clastics, and finally to clayey silts/siltstones, organic matter-rich and coaly mudstones, mineral-rich lignite and lignite.

Published information about mineralogical composition of the Velenje lignite underlying sediments is very scarce. In the overview study of non-metallic raw materials in the Šalek Valley only ŠTERN et al. (1988) described the so-called “white footwall clay”. It occurs in the northern periphery of the Velenje Basin above the “dolomite (Triassic) threshold”, where the lignite seam lies close to the carbonate basement. The clay – in fact silty clay – is of the illite-kaolinite type, composed mainly of quartz, muscovite/illite, kaolinite, and feldspars. The thickness of the “white footwall clay” is variable, 12.7 m at most. According to ŠTERN et al. (1988) it could be used as a ball clay but it lies too deep underground to be economically exploitable.

The “white clay” is not present in our studied profile because it is situated in the centre of the basin, quite far from the dolomite threshold.

Studying coal's underlying sediments in coal mines is in most cases primarily important from the rock-mechanical point of view because mine workings often run at least partially in such “coal's footwall” strata. Among the rock-mechanical parameters, load capacity, strength, and possibility of swelling are the most crucial ones. They are primarily dependent on the degree of lithification, tectonic deformations, water content, and mineral composition. Montmorillonite- (Na, Ca, Mg clay-mineral) bearing clays are especially undesirable due to their expanding behaviour in the presence of water. In many cases of coal deposits, mudrocks are the predominant lithology of strata just below a coal seam. They most often represent a final stage of the fining upwards sequences which preceded the development of peat-forming environments. In the time of biomass deposition, coal underlying sediments influenced the geochemistry of the standing waters. The type and abundance of dissolved chemical elements, salinity, acidity (pH), the redox potential (Eh), and the activity of bio-organisms governed processes of either precipitation or leaching of special chemical elements or minerals as well as processes of

biochemical transformations of the organic matter during the early peatification/coalification process, known as the biochemical stage of coalification (STACH et al., 1982; DIESSEL, 1992; TAYLOR et al., 1998). The topography just before the development of a peat-forming environment probably also governed the distribution of different types of biomass, e.g. wet versus dry forest swamps, bush moors, fens, moss and grass lands.

The authors are aware that the extent of the studied sediments in the P-9k/92 borehole is quite small in relation to the whole complex of the lignite underlying sediments. However, number of archived samples (25) and the interval studied (the depth of 560–580 m), were the most optimal in relation to available samples from some other wells (P-12o/92, P-8z/92, and P-11r/98).

Sampling and analytical methods

Our study of the lignite underlying sediments from the Velenje P-9k/92 borehole is based on collection, macroscopic description, granulometry, optical microscopy of standard thin sections, X-ray diffraction (XRD) and geochemical analysis of 32 samples. They were collected from 21 core-samples, representing 0.2–2.0 m long intervals (Fig. 4, Tab. 1). Prior to the beginning of this research, the samples were archived for almost 20 years in PVC bags in the rock samples depository of the Geological Survey of Slovenia. Core samples 1–21 were treated as whole samples (if homogeneous), or divided into two or three sub-samples (if heterogeneous) and marked with “a”, “b”, and “c”. The types of analyses are given in Tab. 1.

The chosen samples were macroscopically described and photographed (see results and Fig. 5).

The 12 compact but not lithified samples which were easily split into smaller fragments by hand, then gently crushed in an agate mortar and/or disintegrated by drowning into water for 48 hours, were granulometrically analysed with the laser diffraction particle size analyser Analysette 22. The following groups of fractions were separated: <0.002 mm (clay), 0.002–0.063 mm (silt), 0.063–2 mm (sand), and >2 mm (gravel). Three of the 12 samples, which were coarse grained, were also manually dry sieved and separated into the following fractions: <0.125 mm, 0.125–0.25 mm, 0.25–0.5 mm, 0.5–1 mm, 1–2 mm, 2–4 mm, and > 4 mm.

Well-lithified 7 samples were saw-cut (if visible, perpendicular to bedding) and prepared as thin sections for optic microscopy in transmitted light. Each sample was carefully petrographically described (ČERU, 2013), while its mineral composition was defined semi-quantitatively. In this paper, specific lithologic types are outlined and presented as groups of samples. Representative mineral compositions are described in detail and presented as microphotos in Plates 1–5.

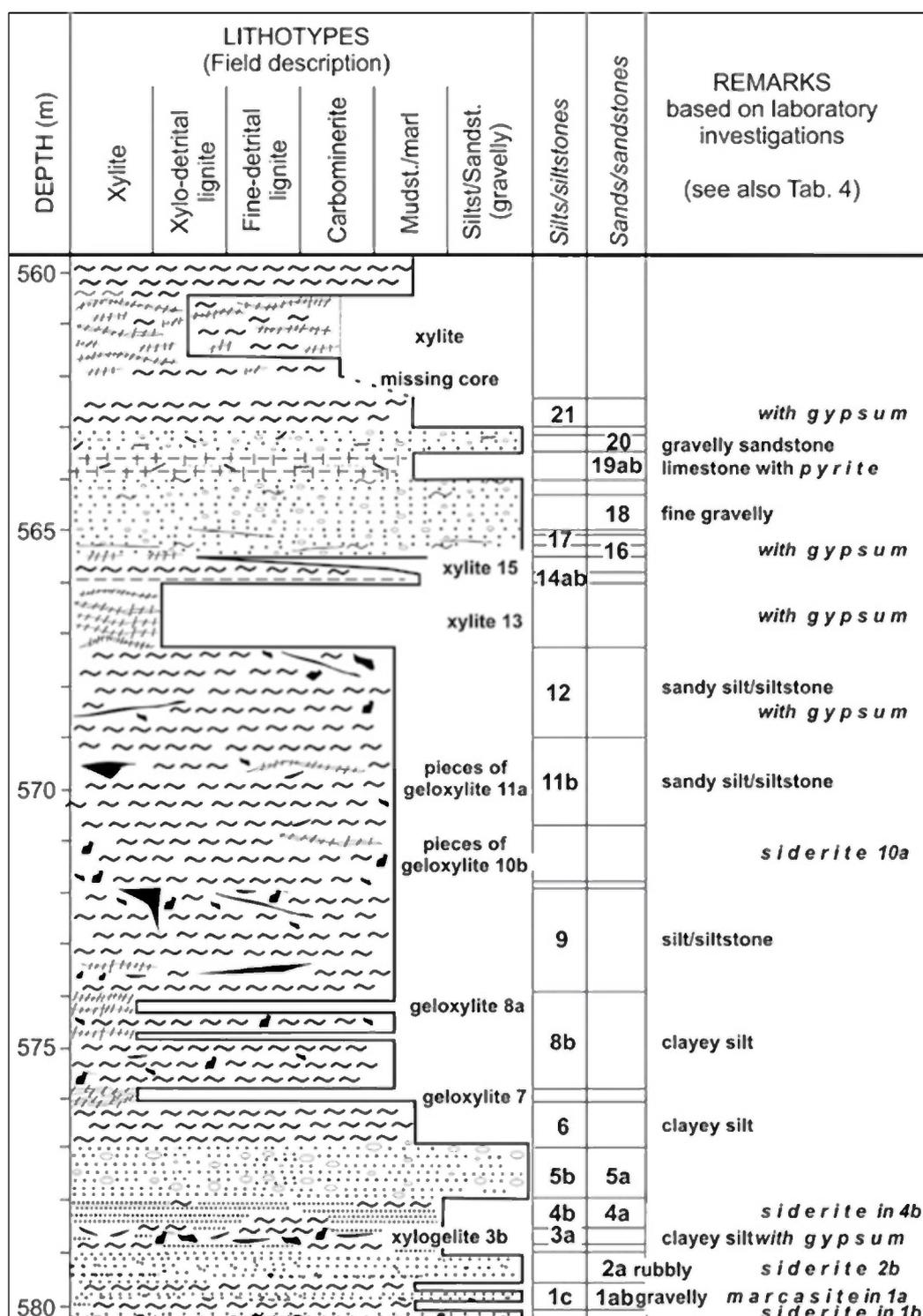


Fig. 4. Lithotype log and sampling of the lignite underlying sediments in the P-9k/92 borehole.

Sl. 4. Litotipnost in vzorčenje talninskih sedimentov v vrtni P-9k/92.

For the XRD analysis, 23 samples were pulverised. Each sample weighted ca. 50 g. Pulverizing was done by milling in a Co/W ring mill. The XRD was carried out at the Department of Geology – University of Ljubljana on the PHILIPS PW3710 Diffractometer at the voltage of 40 kV, electric current of 30 mA, and the CuK α wavelength of 1.54060 Å. The X'Pert HighScore Plus programme and the PAN-ICSD data basis were used for the XRD qualitative estimation of the mineral composition. Identification of minerals was done according to BRINDLEY & BROWN (1980) and MOORE & REYNOLDS (1997).

The same samples as for the XRD and one additional sample, all weighting ca. 10 g, were prepared also for geochemical analysis. Inductively coupled plasma/atomic emission spectrometry (ICP/AES) was used to determine the main oxides, whereas ICP/MS (mass spectrometry) was applied to determine trace elements. The total sulphur (Stot.) and the total and organic carbon (Ctot., Corg.) were determined with Leco. The difference between Ctot. and Corg. is considered as the inorganic carbon (Cinorg.). The loss on ignition (LOI) was determined on the basis of the weight loss

Table 1. Types of analyses of 32 samples from the lignite underlying sediments in the P-9k/92 borehole. Samples are from 21 depth intervals, which are 0.2 to 2.0 m long. Shaded are lignite samples, which were described only macroscopically.

Tabela 1. Vrste analiz 32-ih vzorcev iz 21 globinskih intervalov talninskih sedimentov v vrtini P-9k/92. Dolžina intervalov 0,2–2,0 m. Osenčeni so vzorci lignita, opisani le makroskopsko.

Sample	Depth (m)	Macroscopic description	Granulometry	Optical microscopy	Geochemical analysis	XRD analysis
21	563.00 - 562.60	x			x	x
20	563.50 - 563.15	x		x	x	x
19b	564.00 - 563.60	x			x	x
19a	564.00 - 563.60	x		x	x	x
18	565.00 - 564.35	x	x		x	x
17	565.30 - 565.10	x	x		x	x
16	565.50 - 565.30	x	x		x	x
15	565.80 - 565.50	x				
14b	566.00 - 565.80	x	x		x	x
14a	566.00 - 565.80	x	x			
13	567.35 - 566.00	x			x	x
12	569.00 - 567.35	x			x	x
11b	570.75 - 569.00	x			x	x
11a	570.75 - 569.00	x				
10b	571.75 - 570.75	x				
10a	571.75 - 570.75	x		x	x	x
9	573.95 - 571.95	x			x	x
8b	575.85 - 573.95	x	x		x	x
8a	575.85 - 573.95	x				
7	576.05 - 575.85	x				
6	577.00 - 576.05	x	x		x	x
5b	577.95 - 577.00	x	x		x	x
5a	577.95 - 577.00	x	x		x	x
4b	578.55 - 577.95	x	x		x	x
4a	578.55 - 577.95	x		x		
3b	578.85 - 578.65	x				
3a	578.85 - 578.65	x	x		x	x
2b	579.50 - 578.90	x		x	x	x
2a	579.50 - 578.90	x			x	
1c	580.00 - 579.50	x	x		x	x
1b	580.00 - 579.50	x		x	x	x
1a	580.00 - 579.50	x		x	x	x

on heating at 1000 °C for 1 hour. Geochemical analysis was done in the ACME Laboratories in Vancouver (Canada) according to their well-established procedures (Acme Labs Schedule & Fees, 2012 – Groups 4A and 4B, and 2A for Leco).

Results and discussion

Macroscopic description

The macroscopic appearance of the main lithologic varieties from the lignite underlying sediments in the Velenje P-9k/92 borehole is presented with photographs in Fig. 5.

Photos 1–4 (samples 1c, 6, 9, 17 – see Fig. 4 for position) represent compact clayey silts. The most compacted is sample 9 (photo 3), but we did not succeed in preparing a thin section of it. However, it was also too lithified to be disintegrated for granulometric measurements, as we did with the other three samples (1c, 6, 17).

Photo 5 (sample 10a) shows siderite (cut view at the bottom) covered with goxolite (surface view), and photo 6 (sample 2b) is siderite concretion within sandstone. Very similar to sample 2b is sample 4a.

Photo 7 (sample 1a) is a gravelly sandstone. It was sawn through and a thin section was prepared.

Photos 8, 9 and 10 (samples 5a, 18 and 16) show compact silty sands (samples 5a and 16) and a gravelly sand (sample 18). All three samples were disintegrated in water and granulometrically analysed both by dry sieving and the laser analyser.

Photos 11 and 12 (samples 19b and 20) both show lithified slightly gravelly sandstone composed of quartz, feldspars and clay (kaolinite). The sandstone is calcite-cemented. It reacts with diluted HCl.

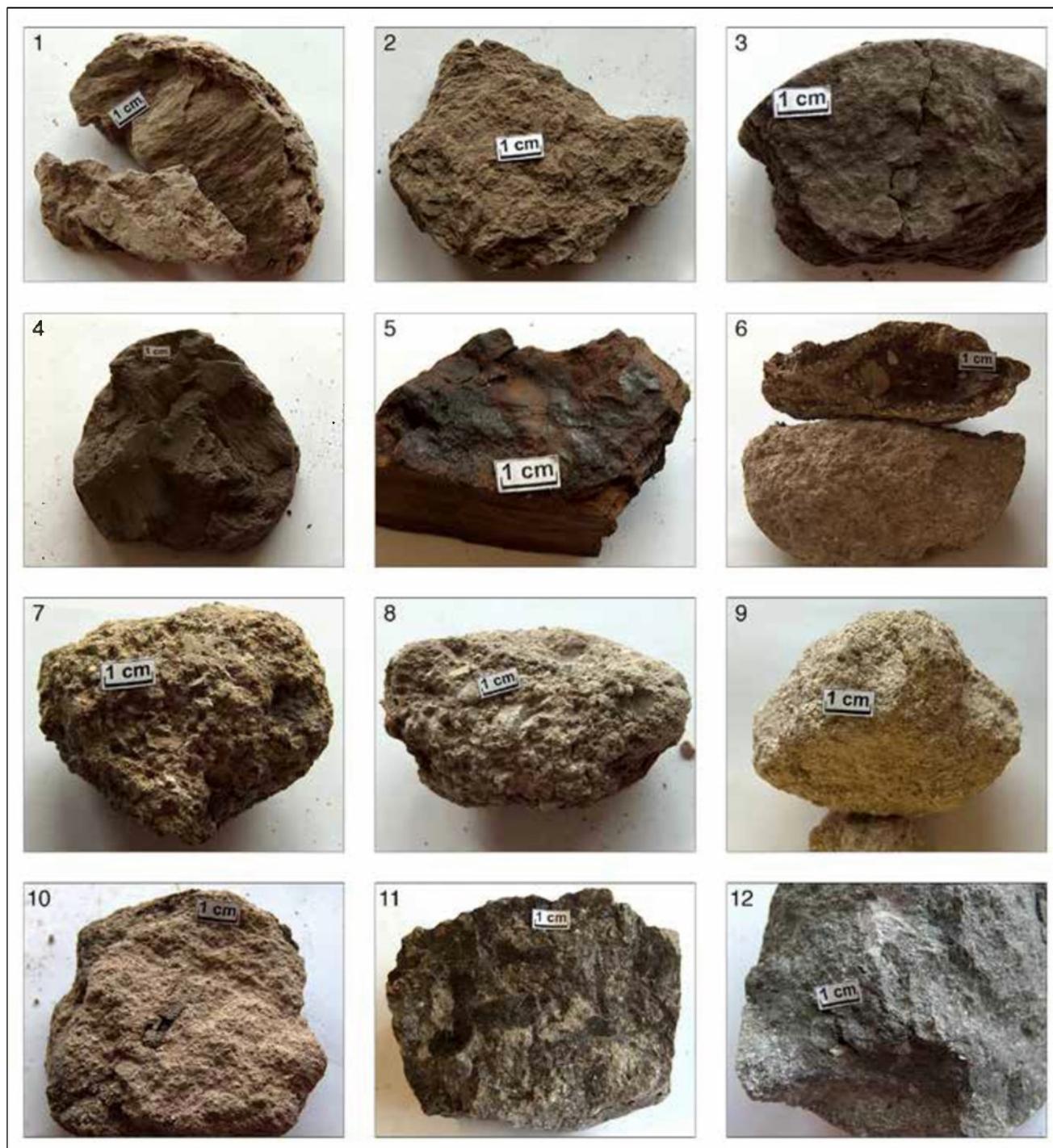


Fig. 5. Photographs of characteristic lithologic varieties: Photos 1–4 (samples 1c, 6, 9, 17): compact clayey silts; Photo 5 (sample 10a): siderite coated with geloxylite; Photo 6 (sample 2b): siderite concretion within sandstone; Photo 7 (sample 1a): gravelly sandstone; Photos 8, 9, 10 (samples 5a, 18 and 16): compact silty sands (photos 8 and 10) and a gravelly sand (photo 9); Photos 11 and 12 (samples 19b and 20): lithified slightly gravelly calcite-cemented quartz sandstones.

Sl. 5. Fotografije značilnih litoloških različkov: Foto 1–4 (vzorci 1c, 6, 9, 17): kompaktni glinasti melji; Foto 5 (vzorec 10a): siderit, obdan z geloksilitom; Foto 6 (vzorec 2b): sideritna konkrecija v peščenjaku; Foto 7 (vzorec 1a): prodnato-gruščnati peščenjak; Foto 8, 9, 10 (vzorci 5a, 18, 16): kompaktni meljasti pesek (foto 8 in 10) in prodnato-gruščnati pesek (foto 9); Foto 11 in 12 (vzorca 19b in 20): litificiran prodnato-gruščnati kremenov peščenjak s kalcitnim vezivom.

Concerning the term “sediments” as used in this paper for the “lignite underlying sediments” we suggest to the reader to keep in mind that we are discussing about Neogene lithology, which is mostly considered to be composed of sediments, not sedimentary rocks. In the broad literature, as well as colloquially, we normally encounter to terms such as “Tertiary sediments”, “Neogene

sediments”, “sediments of the Pannonian Basin” etc. The reason for the term “sediments” in these cases is the fact that the Neogene lithologies are generally not yet “totally” cemented and lithified as are “true sedimentary rocks” from Mesozoic and older geological formations, for example. Strictly speaking, the term “sediment” is restricted only to designation of a loose material, e.g. clay, silt, sand,

Table 2. Granulometric composition of samples which were easily disintegrated. Siltstone samples 1c-17 are listed from the lower to the upper part of the lithologic column in Fig. 4.

Tabela 2. Granulometrična sestava kompaktnih vzorcev, ki jih je bilo mogoče z lahkoto dezintegrirati. Vzorci meljevcev 1c-17 so navedeni po litološkem stolpcu (sl. 4) od spodaj navzgor.

Sample	CLAY	SILT	SAND	GRAVEL	Particle size distribution classification	Sedi- ment name
	<2 μm (%)	2-63 μm (%)	63 μm -2 mm (%)	>2 mm (%)		
17	13.82	85.53	0.65	0	slightly clayey silt	Clayey SILTS
14b	6.57	92.09	1.34	0	very slightly sandy slightly clayey silt	
14a	18.42	81.41	0.17	0	slightly clayey silt	
8b	14.76	85.24	0	0	slightly clayey silt	
6	14.36	84.52	1.12	0	very slightly sandy slightly clayey silt	
5b	12.63	85.97	1.40	0	very slightly sandy slightly clayey silt	
4b	14.84	84.64	0.52	0	slightly clayey silt	
3a	16.22	83.78	0	0	slightly clayey silt	
1c	27.20	71.21	1.59	0	very slightly sandy clayey silt	
18	1.86	23.79	51.69	22.66	gravelly silty sand	Silty/ grav. SANDS
16	1.82	28.11	69.40	0.67	very slightly clayey silty sand	
5a	5.09	36.32	57.79	0.80	slightly clayey silty sand	

or gravel. When loaded under succeeding sediments, losing air and water, and becoming less porous, "sediment" transforms to a "compact material". If such "compact materials" can still be disintegrated in a laboratory by hand, by gentle crushing (with no fracturing of mineral grains), and/or finally by drowning in water for some tens of hours, we can still call such materials "sediments". Therefore, we apply the term "sediments" to all materials which were granulometrically investigated by dry sieving or by the laser diffraction method, whereas we use "-stones" for materials from which we were able to prepare thin sections. The materials in between, which could neither be sieved nor thinly sliced, we arbitrarily designate as a "sediment/-stone", e.g. silt/siltstone etc.

Granulometry

As already mentioned, granulometry was carried out on samples of compact but not yet cemented and well-lithified sedimentary materials. Results are given in Tab. 2. In the set of samples 1c to 17, the silty fraction highly predominates with a share of more than 80 %. The sandy fraction is negligible, it is below 2 %. The clayey fraction is below 20 %. The only exception is sample 1c with 27 % of the clay fraction. In general, all samples from 1 to 17 in Tab. 2 are clayey silts.

Samples 5a and 16 are silty sands with negligible (<5 %) clay and gravel fractions.

Sample 18 contains a considerable gravel fraction (23 %). It was not the only gravelly sample in the whole suite, but other gravelly samples were

more lithified, thus not suitable for the sieving analysis, but for preparing thin sections.

In the gravelly fraction, rounded and angular grains are distinguished, the first termed as "pebbles" and the second as "rubbles". If only grain size is discussed, both extreme grain shapes are unified under the term "gravel".

Granulometric composition of the sediments in Tab. 2 is additionally presented in triangular diagrams in Figs. 6 and 7.

A large proportion of silt, clay and organic matter indicates a dominantly low-energy depositional environment. Furthermore, on the basis of low sorting and asymmetric grain-size distributions (ČERU, 2013, p. 83) a short transport of these sediments can be presumed. On the other hand, coarse-grained sedimentary rocks reflect intense events and increased fluvial input of terrigenous material from the south and also from the north into the sedimentary basin.

Geochemistry

In this paper we take into consideration only the bulk geochemical analysis, which includes the determination of oxides of the main rock-forming elements such as Si, Al, Fe, Mg, Ca, Na, and K, plus Loss on Ignition (LOI), Ctot. and Corg. The results of the geochemical analysis are presented in Tab. 3 in which samples are grouped according to their main outstanding geochemical characteristics, that is: samples with increased Fe_2O_3 contents, increased CaO contents, increased $\text{SiO}_2 + \text{Al}_2\text{O}_3$ contents, and samples with outstanding organic matter content.

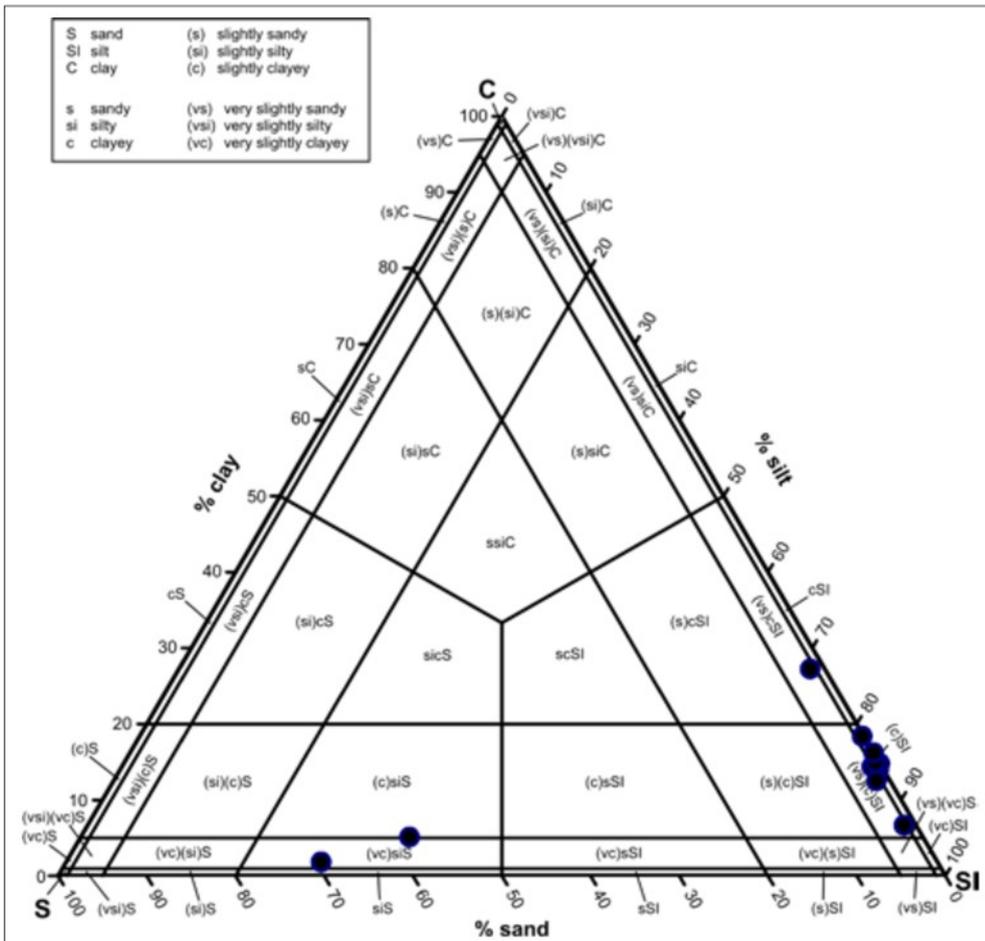


Fig. 6. Triangular diagram Sand-Silt-Clay (after BLOTT & PYE, 2012) showing a predominance of the clayey silt composition of the granulometrically investigated samples. Two samples are silty sand.

Sl. 6. Trikotni diagram pesek-melj-glina (po BLOTT & PYE, 2012) za granulometrično preiskane vzorce. Večina vzorcev je glinasti melj, dva pa sta meljasti pesek.

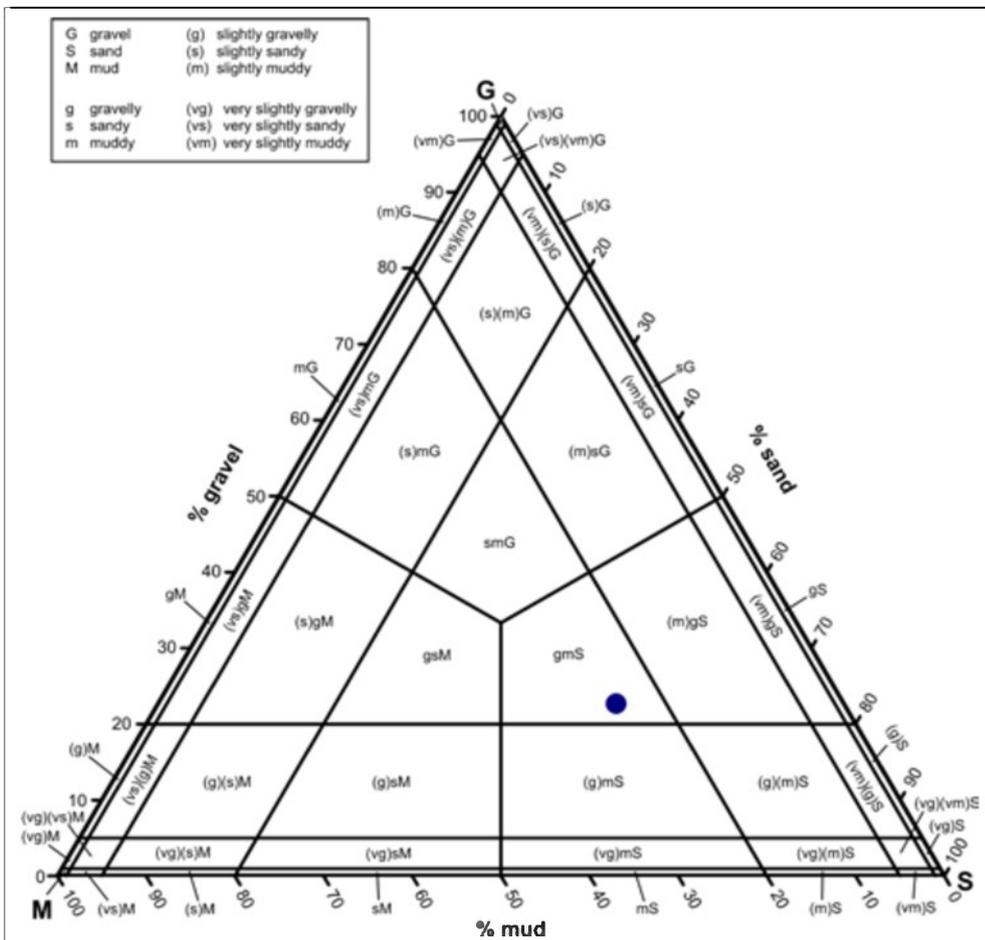


Fig. 7. Triangular diagram Mud-Sand-Gravel (after BLOTT & PYE, 2012) showing the granulometric composition of sample 18, which is gravelly muddy sand.

Sl. 7. Trikotni diagram mulj-pesek-prod prikazuje (po BLOTT & PYE, 2012) sestavo vzorca 18, ki je prodnato muljasti pesek.

Table 3. Basic (main elements) geochemical analysis of investigated sediments in the lignite underlying sediments of the P-9k/92 borehole, and geochemically distinguished groups of samples.

Tabela 3. Osnovna geokemična analiza preiskanih vzorcev talninskih sedimentov pod lignitnim slojem v vrtini P-9k/92 in geokemično ločljive skupine vzorcev.

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	LOI	Ctot	Corg	Groups of samples
	%	%	%	%	%	%	%	%	%	%	
1a	49.2	8.6	19.3	0.3	0.6	1.4	1.3	18.8	0.2		High Fe₂O₃
1b	52.8	10.4	15.6	1.1	1.8	1.2	1.6	14.6	3.8	1.4	
2b	11.7	3.2	48.7	0.7	3.6	0.3	0.4	29.2	9.3		
4b	35.8	12.2	20.3	2.0	3.3	0.4	1.5	23.6	7.1	3.7	
10a	4.9	2.8	49.2	1.4	4.3	0.1	0.4	35.5	12.1	5.6	
19a	15.0	5.4	6.5	0.8	35.7	0.1	0.7	34.6	11.1		High CaO
19b	51.4	9.3	0.8	0.5	17.6	1.2	1.9	16.7	4.1		
20	52.1	9.3	0.7	0.5	17.1	1.2	1.9	16.6	4.1		
1c	56.8	22.3	1.9	1.3	0.3	0.5	3.0	12.8	1.9		Prevailing SiO₂ + Al₂O₃
3a	50.1	22.4	2.5	1.4	0.4	0.5	2.9	18.8	4.5	4.4	
5a	61.6	17.7	2.6	1.0	0.5	0.8	2.1	12.5	2.3		
5b	71.4	14.6	1.7	0.5	0.3	1.3	1.9	7.3	0.6		
6	56.6	21.8	2.1	1.1	0.4	0.5	2.5	13.9	2.5		
8b	57.7	20.7	1.8	1.0	0.9	0.4	2.6	13.8	2.8		
9	46.2	21.6	1.7	1.2	0.5	0.4	3.1	24.2	9.2	9.2	
14b	50.3	23.2	1.7	1.2	0.4	0.3	3.0	18.7	4.9		
16	66.8	14.8	1.9	0.2	0.1	0.3	3.6	11.5	1.4		
17	50.4	20.6	2.8	1.0	0.4	0.3	2.6	20.7	5.2		
18	71.3	15.4	1.1	0.3	0.4	1.5	3.3	6.0	0.2		
21	38.1	14.7	3.9	0.9	0.7	0.4	2.0	38.5	14.1	14.1	High LOI and C Corg = Ctot
11b	32.8	16.7	5.1	1.1	1.1	0.3	2.2	39.4	17.9	17.9	
12	17.9	8.5	2.7	0.7	0.9	0.3	1.0	64.0	30.3	30.3	
13	21.3	11.3	1.5	0.9	1.0	0.3	1.3	58.1	29.1	29.0	

It is evident from the data in Tab. 3 that most samples (1c–18) belong to SiO₂ + Al₂O₃ rich sediments, composed mainly of quartz and kaolinite.

The composition of organic matter-rich sediments with outstanding LOI (~ 40–65 %) and Corg. (~ 15–30 %) can be considered as a normally expected composition of sediments under a lignite (or coal) accumulation. In coal-bearing sequences, the content of organic matter often starts to increase already in the under-coal strata. It correlates more or less tightly with fining upwards trend in the grain size of the clastic sediments.

The intervals (samples) with increased Fe₂O₃ content, remarkable C_{inorg.} content and low S content indicate siderite. Siderite (FeCO₃) forms in more oxidative conditions than pyrite or marcasite (FeS₂). It is highly probable that environmental conditions were more oxidative in pre-peat (lignite) forming environments than later in the true swamp environment. More oxidative conditions in presence of siderite have also been confirmed with the cerium (Ce) anomaly (ČERU, 2013).

CaO-rich samples are typically from the upper-most part of the investigated profile. CaO enrichment shows an influence of carbonate-

enriched inflowing waters. The carbonate influence was also one of the key factors during the peat-to-lignite diagenesis of the Velenje lignite (MARKIČ, 2006; MARKIČ & SACHSENHOFER, 2010).

Mineral composition as studied with XRD analysis of powdered samples

The qualitative mineral composition of the majority of samples (23; without lignite) was interpreted using the XRD method on pulverised samples. The mineral composition and textures were studied supplementary with conventional optical microscopy, the results of which are presented in a separate chapter. The collected diffractograms of the XRD analysis are given in Fig. 8. The obtained mineral composition of samples is presented in Tab. 4. The interpreted diffractograms revealed the presence of the following 9 minerals: quartz (Qz), feldspars (Fsp), kaolinite (Kln), gypsum (Gp), siderite (Sd), muscovite/illite (Ms/Ilt), marcasite (Mrc), calcite (Cal), pyrite (Py).

Quartz is present in all samples with the most characteristic diffraction pattern at the d-spacing value of 3.34 Å (MOORE & REYNOLDS, 1997). In general, quartz is mostly of terrigenous origin and is brought by a river or wind transport

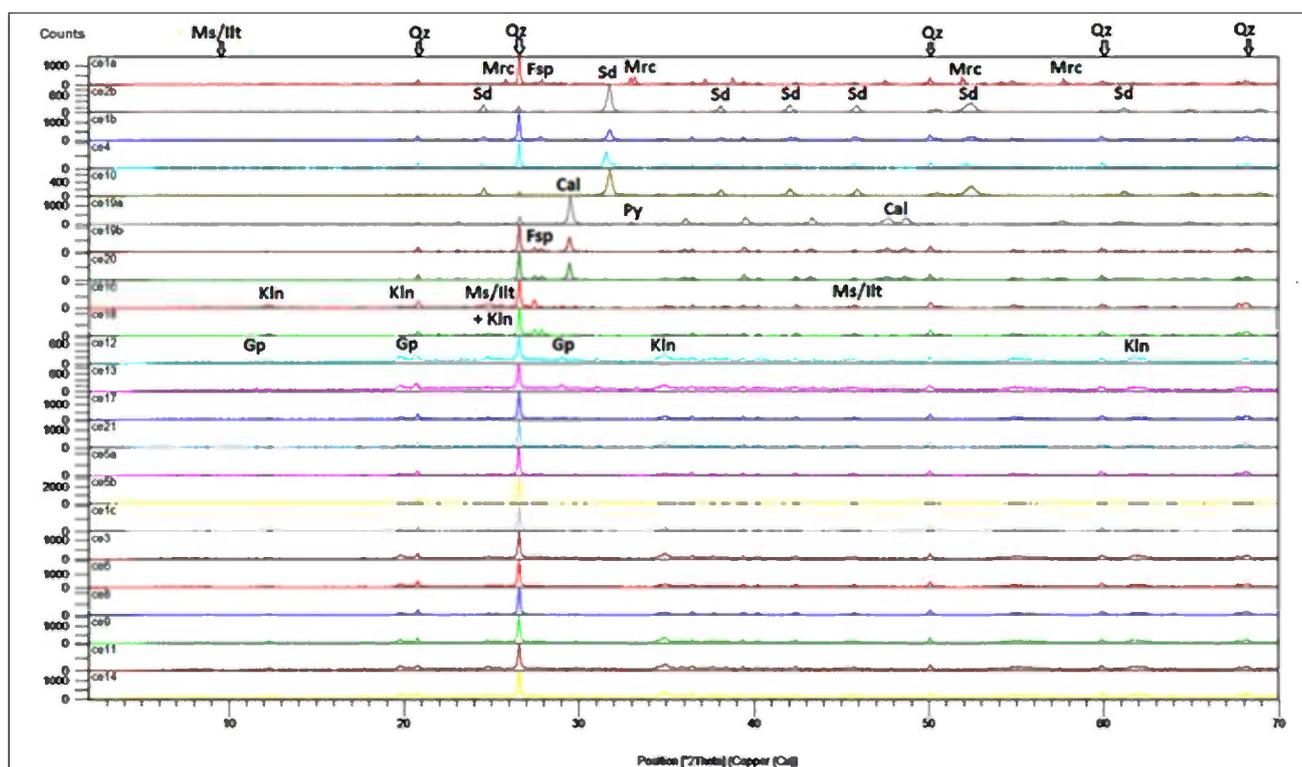


Fig. 8. X-Ray powder diffraction patterns for all analysed samples. Marked are characteristic peaks of determined minerals (Qz-quartz, Ms/Ilt- muscovite/illite, Mrc-marcasite, Fsp-feldspars, Kln-kaolinite, Gp-gypsum, Cal-calcite, Py-pyrite). Interpretation was made for each sample separately on its own diffractogram.

Sl. 8. Rentgenogrami rentgenske praškovne difrakcije vseh analiziranih vzorcev z označenimi značilnimi ukloni določenih mineralov (Qz-kremen, Ms/Ilt- muskovit/illit, Mrc-markazit, Fsp-glinenci, Kln-kaolinit, Gp-sadra, Cal-kalcit, Py-pirit). Interpretacija je bila izvedena za rentgenogram vsakega vzorca posebej.

into a depositional basin (TAYLOR et al., 1998; RENTON, 1982).

Feldspars, predominantly occurring in coarse-grained sediments, are also of terrigenous origin. Their presence is the result of occurrences of lithic grains. Microscopic observations confirmed the presence of both plagioclases and K-feldspars.

Clay minerals also represent a terrigenous material as a result of weathering of silicates such as feldspars and mica and as a result of alteration of volcanic rocks, respectively. On the other hand, they could also have been formed authigenically, i.e. chemically within a sedimentary basin (WARD, 1989; TAYLOR et al., 1998). In most coals, for instance, clay minerals form the most common constituents of the mineral matter (GLUSKOTER et al., 1981; TAYLOR et al., 1998; VELDE, 1995; WARD, 2002), among which kaolinite and illite are the most abundant (RENTON, 1982; WARD, 2002). Only these two clay minerals were determined by the XRD analysis in our study in almost all samples.

Muscovite/illite was determined by the most characteristic diffraction peak at the d-spacing values of 9.9–10.1 Å (BRINDLEY & BROWN, 1980). Muscovite/Illite was recognised in most of the samples, except in coarse-grained sediments, siderite concretions and sedimentary rocks with

calcite. Muscovite and illite were not distinguished by the XRD, so the tag muscovite/illite is used in the results. Only small amounts of muscovite mineral within coarse-grained sediments were recognised under optical microscope; therefore we assume that almost all samples contain higher amounts of illite, especially fine-grained samples.

Kaolinite was determined on the basis of the characteristic diffraction from the basal plane (001) at 7.15 Å (BRINDLEY & BROWN, 1980). Kaolinite occurs in significant amounts in all samples, except in the siderite concretions and limestone.

Fine-grained clastics are made up of quartz, kaolinite and muscovite/illite. A few samples also contain small amounts of gypsum. Marcasite was determined only in a sample 1a (gravelly sandstone) by the XRD and microscope, where it represents an authigenic mineral. A small amount of pyrite was recognised only in sample 19a (limestone). Thin section petrography showed that sample 20 (lithic feldspar quartz sandstone) also includes small amounts of framboidal pyrite, which is partly replaced by Fe-hydroxides. Calcite was determined only in three samples in the upper part of the profile (limestone and gravelly sandstones). Siderite and calcite were determined by the XRD and also by optical microscopy. Siderite occurs in sandstones (three samples) and in a clayey silt (one sample). It can only be formed if the activity

of the sulphide ion is low. Siderite indicates the freshwater environment (RENTON, 1982).

On the basis of the XRD analysis, 23 samples were divided into 8 groups with similar mineral composition (Tab. 5). The mineral composition of fine-grained clastics significantly differs from coarse-grained clastics. Silts and siltstones are composed essentially of quartz and clay minerals. Only a small number of samples contains a small amount of gypsum, while the coarse-grained clastics also contain feldspars (lithic grains) and cementitious minerals belonging to calcite, siderite and marcasite. Carbonate minerals (calcite, siderite) and marcasite are authigenic in origin. Siderite concretions within coarse-grained clastics are made up of quartz and siderite.

Petrographic composition and texture of the well-lithified samples

Samples of well-lithified (cemented) sediments representing rocks were investigated using optical microscopy of thin sections to get more detailed insight into their mineral composition and texture. Only 7 samples were suitable for this kind of study. Three groups of lithologic varieties were distinguished: 1) well-lithified coarse-grained sandstones, 2) calcite-rich sedimentary rocks, and 3) siderite-rich concretions. Mineral contents were estimated semi-quantitatively in plan-view percentages.

Well-lithified slightly gravelly sandstones (samples 1a, 1b)

According to the mineral composition sample 1a was determined as feldspar quartz lithic sandstone and sample 1b as quartz lithic sandstone. Both of them are slightly pebbly to rubbly, exhibiting homogeneous clastic texture with similar mineral assemblages but different degree of cementation, either with marcasite (1a) or siderite (1b). They occur in the lowest part of the analysed profile (Fig. 4).

Sample 1a is composed of minerals and lithic grains (65 %), marcasite cement (15 %) and pores (20 %). Sandstone is poorly-to-moderately

sorted, containing detrital grains of various sizes (0.1–2.8 mm), which are mainly subangular-to-subrounded. Lithic grains, quartz, feldspars, clay minerals and some opaque minerals were identified. The most common are various lithic grains, among which dominate rock fragments of volcanic origin with phenocrysts in microcrystalline to cryptocrystalline matrix (Pl. 2, fig. 3). The intersertal texture with plagioclase laths is visible (Pl. 1, fig. 2; Pl. 2, fig. 2) and also hyalophitic and trachytic texture (Pl. 1, figs. 6a, 6b) occur in some volcanic lithic grains. Grains of metamorphic and sedimentary origin (0.8–1.4 mm in size) are rarer and are represented by low-grade metamorphic rocks (Pl. 1, fig. 1; Pl. 2, figs. 6a, 6b), cherts (Pl. 1, fig. 5) and quartz sandstones (Pl. 1, fig. 4). Quartz is second to lithic grains in abundance. It occurs both as monocrystalline and polycrystalline grains with mean size of 1 mm (Pl. 1, figs. 3a, 3b). Feldspars represent a very low content of all detrital components and are mainly sericitised or/and kaolinised. Grains of K-feldspars (Pl. 1, fig. 3a) are more common than plagioclase.

Pore spaces of the sample 1a sandstone are filled almost entirely by marcasite cement, in some places also by chlorite and brown-coloured Fe-oxy-hydroxides (Pl. 2, figs. 1a, 1b). An interstitial clayey matrix can be either detrital or authigenic –the determination of their origin is unreliable. Euhedral grains of marcasite are concentrated in some places (Pl. 2, fig. 4). Marcasite also occurs as a corrosive cement in lithic grains (Pl. 1, fig. 6a; Pl. 2, fig. 6a). Pl. 2, fig. 5 shows chalcedony with radially oriented quartz fibers.

Sample 1b consists of 40 % minerals and lithic grains, 50 % siderite cement and 10 % pores. The sandstone is moderately sorted and the grain size of detrital grains is in the range of 0.02–3 mm, mainly 0.1–0.2 mm. Subangular quartz grains are smaller than rounded rock fragments (Pl. 3, figs. 1a, 1b). Monocrystalline quartz with grain size varying from 0.02 to 1.6 mm is a major component of terrigenous grains. A small amount of quartz belongs to the polycrystalline grains with mainly straight and infrequently sutured grain boundaries. Feldspars are sparse and represent less than 5 % of all terrigenous components.

Table 5. XRD mineral composition of lithologically grouped samples – summarized from Tab. 4.

Tabela 5. Rentgensko določena mineralna sestava litološko združenih vzorcev – povzeto iz Tab. 4.

Samples and lithology		XRD mineral composition
1c, 4b*, 6, 8b, 9, 11b, 14b	SILTS and SILTSTONES	quartz, kaolinite, muscovite/illite, siderite*
3a, 12, 13, 17, 21	SILTS and SILTSTONES with gypsum	quartz, kaolinite, muscovite/illite, gypsum
5a, 5b, 16, 18	SILT (5b) and SANDS	quartz, kaolinite, feldspars, muscovite/illite
19a	LIMESTONE	calcite, quartz, pyrite
19b, 20	SANDSTONES with calcite cement	quartz, kaolinite, feldspars, calcite
1a	SANDSTONE with marcasite cement	quartz, kaolinite, feldspars, muscovite/illite, marcasite
1b	SANDSTONE with siderite cement	quartz, kaolinite, feldspars, muscovite/illite, siderite
2b, 10a	SIDERITE CONCRETIONS	quartz, siderite

Table 4. Qualitative mineral composition of 23 samples determined by the XRD and lithologic names defined by macroscopic observation, granulometry and optical microscopy. At the sample numbers, abbreviation "Mic" means that the sample was also investigated microscopically, and "Gr" means that it was also analysed granulometrically. All samples were analysed geochemically.

Tabela 4. Kvalitativna mineralna sestava 23 vzorcev, določena z rentgensko praškovno difrakcijo ter litološka imena, določena makroskopsko ter na podlagi granulometrične analize in optične mikroskopije. Kratica »Mic« pomeni, da je bil vzorec preiskan tudi mikroskopsko, kratica »Gr« pa da tudi granulometrično. Vsi vzorci so bili preiskani geokemično.

Sample	Depth (m)	Lithologic name	MINERAL COMPOSITION DETERMINED BY XRD ANALYSIS								
			quartz (Qz)	feldspar (Fsp)	kaolinite (Kln)	gypsum (Gp)	siderite (Sd)	muscovite/illite (Ms/Ilt)	marcasite (Mrc)	calcite (Cal)	pyrite (Py)
21	563.00 - 562.60	silt/siltstone	x	x	x	x		x			
20 (Mic)	563.50 - 563.15	slightly gravelly sandstone	x	x	x					x	
19b	564.00 - 563.60	slightly gravelly sandstone	x	x	x					x	
19a (Mic)	564.00 - 563.60	limestone	x							x	x
18 (Gr)	565.00 - 564.35	gravelly muddy sand	x	x	x			x			
17 (Gr)	565.30 - 565.10	slightly clayey silt	x		x	x		x			
16 (Gr)	565.50 - 565.30	very slightly clayey silty sand	x	x	x			x			
14b (Gr)	566.00 - 565.80	very slightly sandy slightly clayey silt	x		x			x			
13	567.35 - 566.00	xylite	x		x	x		x			
12	569.00 - 567.35	slightly sandy silt/siltstone	x		x	x		x			
11b	570.75 - 569.00	slightly sandy silt/siltstone	x		x			x			
10a (Mic)	571.75 - 570.75	siderite concretion	x				x				
9	573.95 - 571.95	silt/siltstone	x		x			x			
8b (Gr)	575.85 - 573.95	slightly clayey silt	x		x			x			
6 (Gr)	577.00 - 576.05	very slightly sandy slightly clayey silt	x		x			x			
5b (Gr)	577.95 - 577.00	very slightly sandy slightly clayey silt	x	x	x			x			
5a (Gr)	577.95 - 577.00	slightly clayey silty sand	x	x	x			x			
4b (Gr)	578.55 - 577.95	slightly clayey silt	x		x		x	x			
3a (Gr)	578.85 - 578.65	slightly clayey silt	x		x	x		x			
2b (Mic)	579.50 - 578.90	siderite concretion within sandstone	x				x				
1c (Gr)	580.00 - 579.50	very slightly sandy clayey silt	x		x			x			
1b (Mic)	580.00 - 579.50	slightly gravelly muddy sandstone	x	x	x		x				
1a (Mic)	580.00 - 579.50	slightly gravelly sandstone	x	x	x				x		

Twinned plagioclase and K-feldspar were determined, which are strongly sericitised. As in sample 1a, volcanic rock fragments (Pl. 3, fig. 4) prevail over plutonic ones also in sample 1b. Low-grade metamorphic rock fragments occur sparsely (Pl. 3, figs. 3a, 3b). Chert fragments are infrequent. Some grains of amphiboles (Pl. 3, figs. 2a, 2b) and biotite are replaced by chlorite as an alteration product. Very small amounts of calcite grains are also present. Brownish-coloured areas with high birefringence are mostly authigenic interstitial and also corrosive siderite cement, which is partly limonitised.

Calcite-rich sedimentary rocks (samples 19a and 20)

Calcite-rich rocks, reacting with a diluted HCl, appear only in the upper part of the observed profile (Fig. 4).

Sample 19a represents a limestone with fragments of carbonised plant remains. Pore spaces are filled with sparite cement. Subrounded monocrystalline quartz grains with mean grain size 0.06–0.1 mm dominate, while lithic grains of igneous origin are sparser (Pl. 4, fig. 6).

Sample 20 was determined as a slightly pebbly to rubbly lithic feldspar quartz sandstone. It has a clastic texture (Pl. 5, figs. 1a, 1b) and consists of about 50 % terrigenous grains of various sizes (0.02–3 mm). The most common are monocrystalline quartz grains of 0.02–0.2 mm in size, grains of polycrystalline quartz also occur (Pl. 5, fig. 3). Feldspars belong to plagioclase and K-feldspar. Most of them are generally sericitised or/and kaolinised and 0.035–1.4 mm in size. Lithic grains are the least abundant; fragments of igneous rocks dominate among them. The Altered volcanic lithic grains with phenocrysts of plagioclase laths in microcrystalline matrix are the most common (Pl. 5, figs. 4, 7). Felsic plutonic rock fragments with holocrystalline texture (Pl. 5, fig. 5) and aplite with granophyric texture also occur (Pl. 5, fig. 6). In addition to igneous lithic grains the sandstone also contains rock fragments of metamorphic and sedimentary origin. Grains of cherts and quartz sandstones (Pl. 5, fig. 2) 0.4–1.3 mm were determined. Flakes of muscovite and grains of framboidal pyrite are very rare. The cement is sparry calcite, which occurs mainly as interstitial and in some places as corrosive and radial fibrous cement. Some grains contain micro-cracks filled with sparry calcite cement.

Siderite-rich concretions (samples 2b, 4a, 10a)

Siderite also occurs in the investigated samples in the form of siderite-rich concretions. Its origin is well known as authigenic, formed in low oxidative environments, but still somewhat higher in oxygen supply than in the case of pyrite formation. A slightly higher (oxygen providing) energy level of the environment is mostly interpreted when

siderite occurs in the sediment instead of pyrite/marcasite, for example. Organic matter can also be well preserved in the Eh conditions of the siderite formation. In our case concentrations of siderite still contain small amounts of quartz (samples 2b and 4a) or they are almost clean siderite (sample 10a).

The most pure siderite sample 10a contains only very few quartz and lithic grains. It is covered by geloxylite (Fig. 5/5). A microscopic view of the siderite-geloxylite contact is shown in Pl. 4, fig. 5.

A thin section of sample 2b was made from a siderite concretion within a slightly pebbly to rubbly sandstone. Quartz grains of two size classes (0.06–0.1 mm and 0.14–0.2 mm) predominate over lithic grains among terrigenous components (Pl. 4, figs. 1a, 1b). Lithic grains (mean grain size 2–3 mm) of volcanic and plutonic igneous rocks prevail over chert and metamorphic lithic grains (Pl. 4, fig. 2). Flakes of muscovite are very rare and their sizes reach up to 0.1 mm.

Sample 4a contains 10 % terrigenous component, 85 % siderite and 5 % pores. The terrigenous component in the siderite concretion is mainly composed of monocrystalline quartz grains (Pl. 4, figs. 4a, 4b) in addition to minor amounts of lithic grains. Rock fragments of volcanic origin with porphyritic texture predominate, while grains of cherts (Pl. 4, fig. 3) are very rare. Lithic grains are commonly altered and partly replaced by siderite and Fe-hydroxides, which also occur as interstitial minerals. Rare small grains of framboidal pyrite were also recognised.

Conclusions

Granulometrical, geochemical and mineralogical characterisation of sediments that underlie the Velenje lignite seam in the locality of the P-9k/92 borehole (central part of the Velenje Basin) has been carried out on a suite of 32 samples from 21 depth intervals. In spite of a relatively restricted extent of the investigated strata (only 20 m) we suppose that the study answered several questions and represents a good guide for eventual further investigations. Our work can be summarised in conclusions as follows:

The Velenje lignite underlying strata of the Pliocene age are heterogeneous by their granulometrical, chemical and mineral composition. Clastic grains vary from well-rounded to angular. The sedimentary material as a whole varies from almost non-lithified (easy to be disintegrated) material, termed "sediment" (e.g. silt), to well-lithified (cemented) material termed with the ending "-stone" – e.g. "siltstone". Non-lithified sediments were easily disintegrated and sieved for the grain size analysis, whereas lithified "stones" were suitable for preparation of thin sections. Clayey silts and siltstones predominate in the

investigated profile. They indicate a prevailing low energy level of the depositional environment. Sands and sandstones with admixtures of the gravelly fraction occur subordinately. They indicate sporadic water influxes of a higher energy level. Low roundness and angularity of terrigenous lithic grains, low sorting and asymmetric grain-size distributions show that the transport distances of deposited materials were short.

Both the XRD analysis and the optical microscopy have shown that the mineral composition of fine-grained clastics is different from the mineral composition of coarse-grained clastics. It is also different in the lower part of the profile in comparison to the upper part. Fine-grained clastics are mainly composed of quartz grains bound by kaolinite matrix, whereas coarse-grained clastics also contain lithic grains, which are mostly angular. They indicate a relatively short distance from the erosion site to the depositional basin.

Cementitious minerals in well-lithified lithologic varieties are calcite, siderite and marcasite.

The composition of the lower investigated strata with abundant lithic grains of andesitic volcanic rocks indicates an inflow of eroded sedimentary material mainly from the south. At the same time lithic grains of magmatic and metamorphic rocks indicate inflow of eroded material from the Železna Kapla (Eisen Kappel) – the Karavanke magmatic zone, i.e. from the north.

The increased Ca-content in the upper part of the sedimentary succession indicates the influence of carbonate-rich waters inflowing from the northern terrains composed of Triassic limestones and dolostones. Carbonate waters from the north therefore became geochemically decisive toward the end of the pre-peat forming clastic infilling of the Velenje intermontane basin.

Ca-HCO₃ type of water and consequential alkalinity governed the diagenetic processes throughout the development of the peat-lignite formation.

Well-lithified clastic samples are sandstones, whereas poorly lithified clastics are mostly clayey silts with a negligible sandy fraction. This indicates that cementation was stronger in the case of coarse clastics than in the case of fine-grained clastics.

Siderite forms cement and concretions. Pyrite/marcasite occurs more rarely than siderite. Siderite indicates somewhat more oxidative conditions than pyrite. Both siderite and pyrite indicate low Eh environments caused by the presence of a considerable amount of decaying organic matter. The observed incrustations of geloxylite (coalified wood) over siderite and xylitic remnants in siderite concretions support this statement.

Gypsum was detected in some samples. It is most possibly a result of the oxidation of pyrite/marcasite in the presence of Ca and organic matter.

A detailed provenance of the sedimentary material that filled up the Velenje Basin prior to the establishment of the peat-forming environment still remains quite an open question and challenge for further research. A profound knowledge of geology and petrology of the wider area (the Savinja Alps, Smrekovec, Karavanke and Pohorje Mts) is necessary to solve such questions. Considerable knowledge already exists from the past and recent times. Our will is that it will be continued with further investigations. Referring to our study, the questions that remain especially interesting touch upon temporal dynamics and influx directions of the sedimentary material, as well as the roles of tectonics and climate as initial and controlling factors of sedimentary processes in the broader realm of the Velenje Basin.

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PLATE 1 - TABLA 1

All thin sections viewed under plane polarised light.

Vsi zbruski opazovani v presevni polarizirani svetlobi.

Sample 1a (Feldspar quartz lithic sandstone with marcasite cement)

Vzorec 1a (glinenčevo-kremenov litični peščenjak z markazitnim cementom)

Fig. 1. Lithic grain of low-grade metamorphic rock with mica flakes and quartz grains. The opaque mineral, filling the space between grains, is authigenic marcasite cement. Crossed polars, scale bar 500 μm .

Sl. 1. Litično zrno nizko metamorfne kamnine z zrni sljude in kremenca. Nepreseven mineral, ki zapolnjuje medzrnski prostor, je avtigeno izločen markazitni cement. Navzkrižni nikoli, merilo 500 μm .

Fig. 2. Lithic grain of altered volcanic rock. Small laths of plagioclase in microcrystalline matrix on the right part of the lithic grain show intersertal texture. The left side of the black line separates the quartz vein which is visible within the lithic grain. Crossed polars, scale bar 100 μm .

Sl. 2. Spremenjeno litično zrno predornine. Podolgovati preseki plagioklazov v drobno kristaljeni do steklasti kažejo značilno intersertalno strukturo. Leva stran črne črte loči kremenovo žilico znotraj litičnega zrna. Navzkrižni nikoli, merilo 100 μm .

Fig. 3a. Polycrystalline quartz grain (Qz) and altered orthoclase grain (Or). Parallel polars, scale bar 500 μm .

Sl. 3a. Zrno polikristalnega kremenca (Qz) in spremenjeno zrno ortoklaza (Or). Vzporedni nikoli, merilo 500 μm .

Fig. 3b. The same as fig. 3a. Polycrystalline quartz grain. Crossed polars, scale bar 500 μm .

Sl. 3b. Isto kot sl. 3a. Zrno polikristalnega kremenca. Navzkrižni nikoli, merilo 500 μm .

Fig. 4. Weathered lithic grain of quartz sandstone. Crossed polars, scale bar 500 μm .

Sl. 4. Preperelo litično zrno kremenovega peščenjaka. Navzkrižni nikoli, merilo 500 μm .

Fig. 5. Lithic grains (Lg1 and Lg2). Lg1 belongs to the chert. Crossed polars, scale bar 500 μm .

Sl. 5. Litični zrna (Lg1 in Lg2). Litično zrno Lg1 pripada rožencu. Navzkrižni nikoli, merilo 500 μm .

Fig 6a. Altered volcanic rock fragment. Matrix is partly replaced by corrosive marcasite cement. Parallel polars, scale bar 100 μm .

Sl. 6a. Spremenjeno litično zrno predornine. Korozivni markazitni cement mestoma nadomešča osnovo litičnega zrna. Vzporedni nikoli, merilo 100 μm .

Fig. 6b. Hyalophitic texture is visible on the left part of the lithic grain and oriented plagioclase laths on the right show trachytic texture in altered volcanic (intermediate-mafic) rock. Crossed polars, scale bar 100 μm .

Sl. 6b. Na levi strani litičnega zrna je vidna hialofitska struktura, ki prehaja v trahitsko z usmerjenimi paličastimi plagioklazmi v spremenjeni predornini (srednje do bazični sestave). Navzkrižni nikoli, merilo 100 μm .

PLATE 1 - TABLA 1

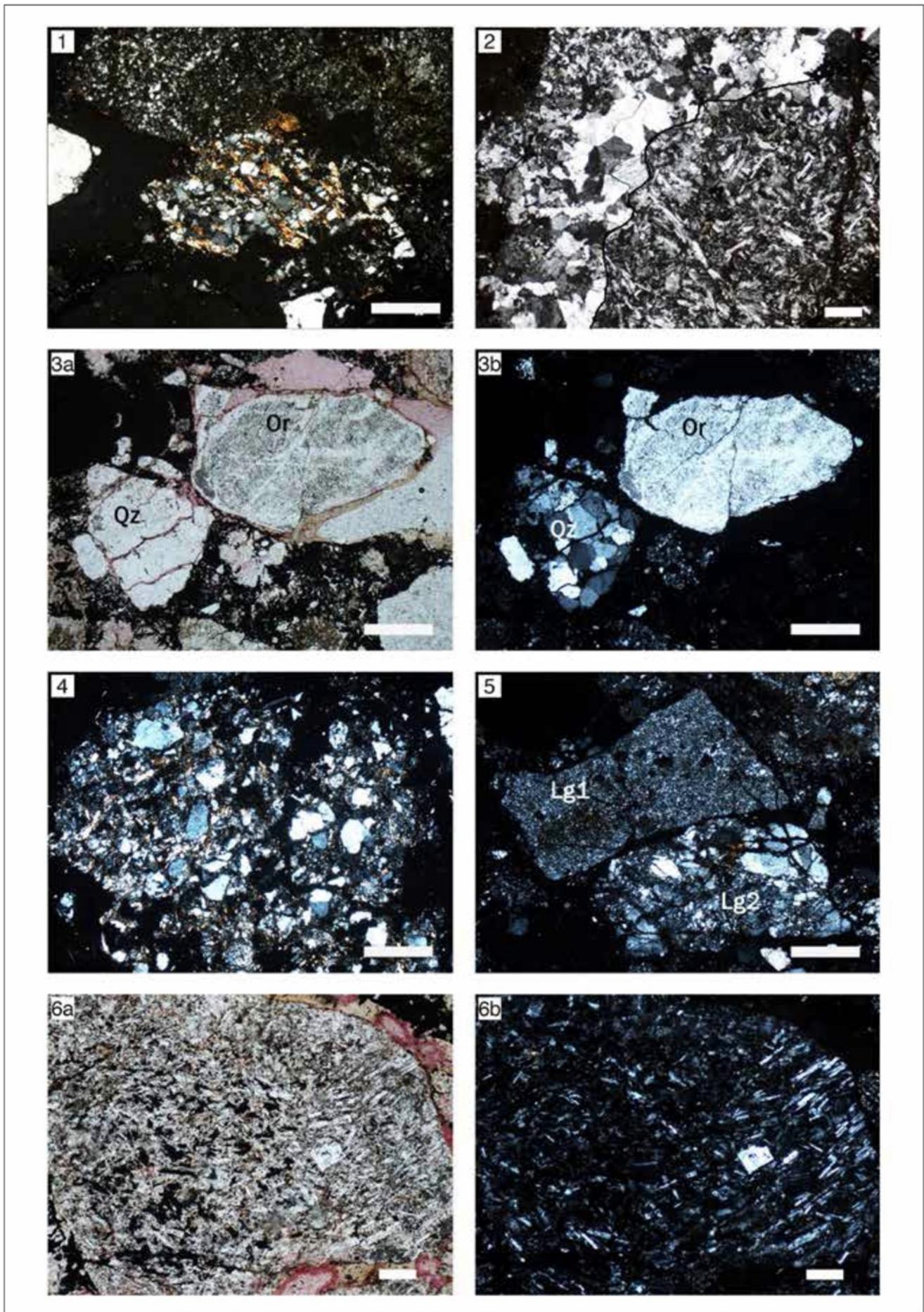


PLATE 2 - TABLA 2

Fig. 1a. Pores filled by marcasite (Mrc) and chlorite group mineral, and brown-colored Fe-oxy-hydroxides (Fe-hy). Parallel polars, scale bar 100 μm .

Sl. 1a. Z markazitom (Mrc) in mineralom iz kloritne skupine zapolnjene pore ter rjavo obarvani minerali Fe-oksidi in hidroksidi (Fe-hy). Vzporedni nikoli, merilo 100 μm .

Fig. 1b. The same motif as in Fig. 1a. Interference colours of chlorite group mineral (Chl), which occur together with marcasite as interstitial cement. Crossed polars, scale bar 100 μm .

Sl. 1b. Isti motiv kot na sl. 1a. Interferenčne barve minerala kloritove skupine (Chl), ki skupaj z markazitom nastopa kot porna cementna zapolnitev med zrn. Navzkrižni nikoli, merilo 100 μm .

Fig. 2. Lithic grain of volcanic rock with visible contact (white line) between the different granularities plagioclase phenocrysts. The bigger twinned grain may belong to sanidine (Sa?). Crossed polars, scale bar 500 μm .

Sl. 2. Litično zrno z vidnim prehodom (bela linija) različne velikosti vtrošnikov plagioklazov. Večje dvojlično zrno lahko pripada sanidinu (Sa?). Navzkrižni nikoli, merilo 500 μm .

Fig. 3. Lithic grain of probably felsic volcanic rock with plagioclase phenocrysts in microcrystalline-cryptocrystalline matrix. Crossed polars, scale bar 1mm.

Sl. 3. Litično zrno najverjetneje kisle predornine z vtrošniki plagioklazov v mikrokristalni-kriptokristalni osnovi. Navzkrižni nikoli, merilo 1mm.

Fig. 4. Nests of opaque mineral marcasite. Parallel polars, scale bar 100 μm .

Sl. 4. Gnezda markazita. Vzporedni nikoli, merilo 100 μm .

Fig. 5. Chalcedony with radially oriented quartz fibers. Crossed polars, scale bar 100 μm .

Sl. 5. Kalcedon z radialno žarkovito strukturo. Navzkrižni nikoli, merilo 100 μm .

Fig. 6a. Lithic grain (Lg) of low-grade metamorphic rock. Marcasite cement forms the interstitial and also the corrosive cement (visible in the frame). Grain of plagioclase (Pl) occurs at the lower margin. Parallel polars, scale bar 500 μm .

Sl. 6a. Litično zrno nizko metamorfne kamnine. Markazitni cement se pojavlja v dveh oblikah, kot porni in korozivni cement (viden v označenem kvadratu). Manjše zrno plagioklaza na spodnjem robu slike (Pl). Vzporedni nikoli, merilo 500 μm .

Fig. 6b. The same as Fig. 6a. Sericite, chlorite and a plagioclase grain (Pl) can be seen. Crossed polars, scale bar 500 μm .

Sl. 6b. Isto kot sl. 6a. Vidni so listki sljude, klorit in zrno plagioklaza (Pl). Navzkrižni nikoli, merilo 500 μm .

PLATE 2 - TABLA 2

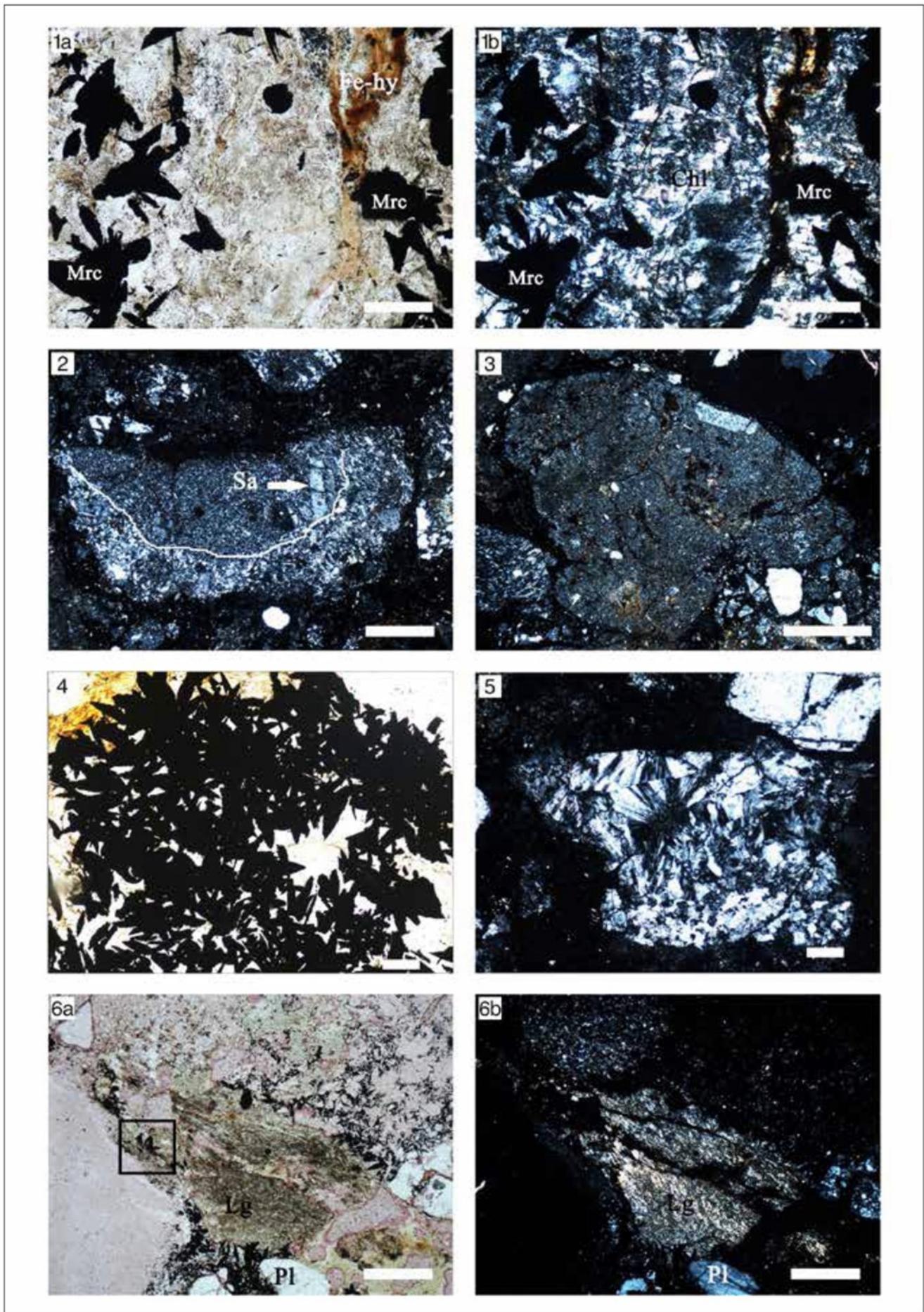


PLATE 3 - TABLA 3

Sample 1b (Quartz lithic sandstone with siderite cement)

Vzorec 1b (kremenovo-litični peščenjak s sideritnim cementom)

Fig. 1a. Grains of subangular quartz (Qz), rounded lithic grains (Lg) and fragments of carbonised plant residues in sandstone. Parallel polars, scale bar 1 mm.

Sl. 1a. Peščenjak z zrnji kremenca (Qz) in drobci različnih kamnin (Lg) ter fragmenti pooglenelih rastlinskih ostankov. Zrna kremenca so pologlasta, medtem ko so drobci kamnin zaobljeni. Vzoredni nikoli, merilo 1mm.

Fig. 1b. Most of the lithic grains in sandstone with authigenic siderite cement belongs to both, volcanic and plutonic rocks. Crossed polars, scale bar 1 mm.

Sl. 1b. Večina litičnih zrn v peščenjaku z avtigenim sideritnim cementom pripada magmatskim kamninam, tako predorninam kot globočinam. Navzkrižni nikoli, merilo 1mm.

Fig. 2a. Grain of some altered (chloritized) mafic mineral, most probably belonging to the amphibole group (Chl-Amp) and a smaller grain of quartz (Qz). Parallel polars, scale bar 100 μ m.

Sl. 2a. Zrno spremenjenega (kloritiziranega) mafičnega minerala, ki verjetno pripada skupini amfibolov (Chl-Amp) in manjše zrno kremenca (Qz). Vzoredni nikoli, merilo 100 μ m.

Fig. 2b. The same as Fig. 3. Crossed polars, scale bar 100 μ m.

Sl. 2b. Isto kot sl. 3. Navzkrižni nikoli, merilo 100 μ m.

Fig. 3a. Lithic grain of metamorphic rock (Lg1), quartz grains (Qz) and rock fragments (Lg2) in limonitised siderite cemented sandstone. Parallel polars, scale bar 500 μ m.

Sl. 3a. Litično zrno metamorfne kamnine (Lg1), zrna kremenca (Qz) in ostali drobci kamnin (Lg2) v sideritnem cementu peščenjaka. Vzoredni nikoli, merilo 500 μ m.

Fig. 3b. The same as Fig. 3a. Lithic grain of metamorphic origin consists of quartz and muscovite (Lg1). Lithic grain of volcanic origin (Lg2) is visible on the left edge of the photo. Small quartz grains (Qz) occur over the entire surface of the thin section. Crossed polars, scale bar 500 μ m.

Sl. 3b. Isto kot sl. 3a. Kremen in muskovit v sestavi litičnega zrna metamorfne kamnine (Lg1). Na levem robu slike je vidno zrno predornine (Lg2) in posamična manjša kremenova zrna (Qz), ki se pojavljajo po celotni površini zbruska. Navzkrižni nikoli, merilo 500 μ m.

Fig. 4. Lithic grain of volcanic rock with phenocrysts of plagioclase in microcrystalline matrix. Crossed polars, scale bar 500 μ m.

Sl. 4. Litično zrno predornine z vtrošniki plagioklazov v mikrokristalni osnovi. Navzkrižni nikoli, merilo 500 μ m.

PLATE 3 - TABLA 3

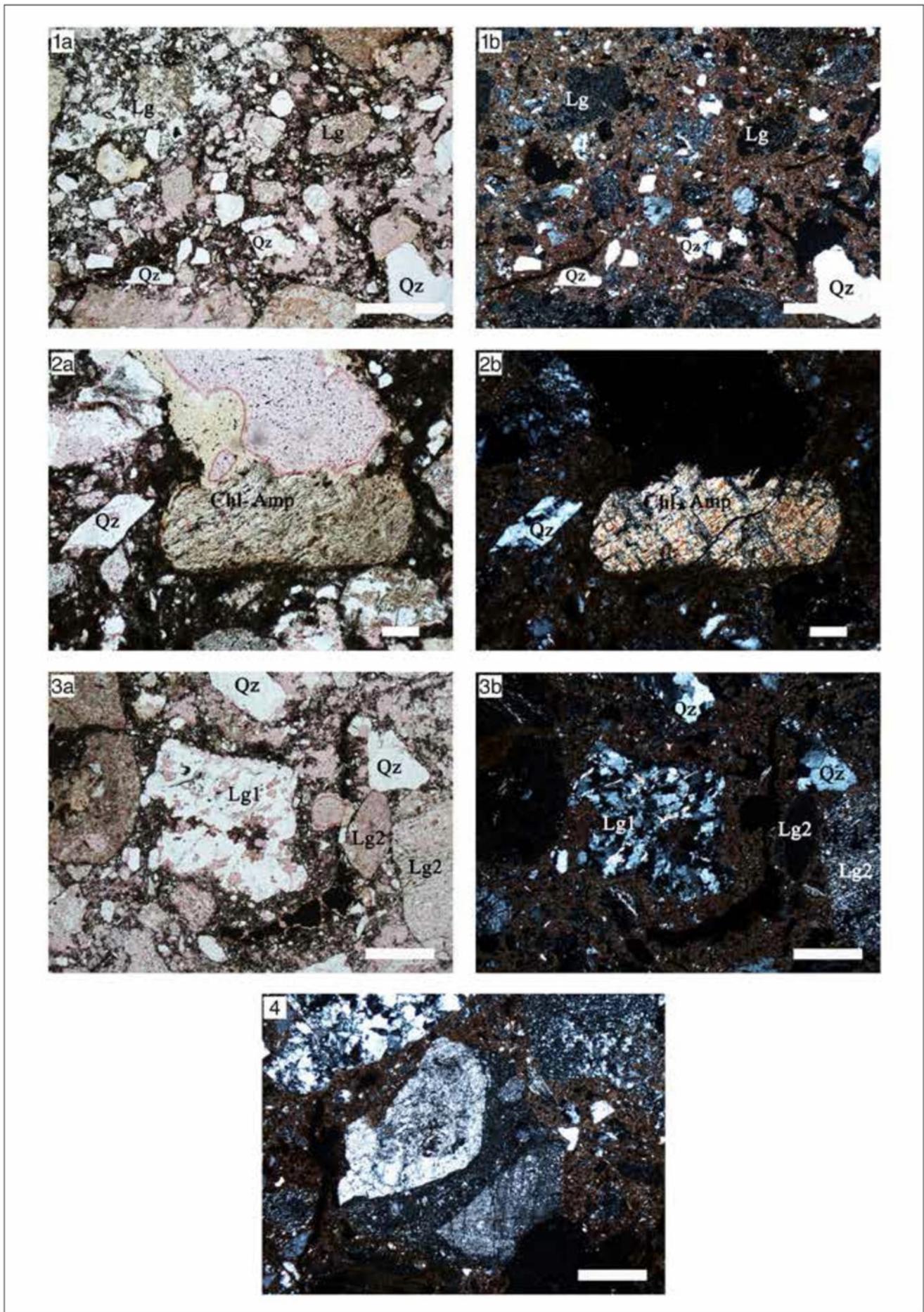


PLATE 4 - TABLA 4**Sample 2b (Siderite concretion within sandstone)****Vzorec 2b (sideritna konkrecija znotraj peščenjaka)**

Fig. 1a. Small terrigenous quartz grains (Qz) and bigger lithic grains (Lg) in limonitised siderite cemented sandstone. Parallel polars, scale bar 1 mm.

Sl. 1a. Manjša terigena kremenova zrna (Qz) in večja zrna različnih drobcev kamnin (Lg) v peščenjaku z limonitiziranim sideritnim cementom. Vzporedni nikoli, merilo 1mm.

Fig. 1b. The same as Fig. 1a. Sandstone consists of crystals of quartz (Qz), lithic grains (Lg) and fragments of carbonised plant residues (black). Crossed polars, scale bar 1 mm.

Sl. 1b. Isto kot sl. 1a: Peščenjak z zrnji kremenova (Qz), drobci kamnin (Lg) in fragmenti pooglenelih rastlinskih ostankov (črni). Navzkrižni nikoli, merilo 1mm.

Fig. 2. Two lithic grains of igneous origin with holocrystalline texture (Lg1). Two grains of chert (Lg2) and volcanic rock fragment (Lg3) are visible. Crossed polars, scale bar 1 mm.

Sl. 2. Dve litični zrnji kisle globočnine s holokristalno strukturo (Lg1), dve zrnji roženca (Lg2) in zrno predornine (Lg3). Navzkrižni nikoli, merilo 1mm.

Sample 4a (Siderite concretion with quartz and lithic grains)**Vzorec 4a (sideritna konkrecija s kremenovimi in litičnimi zrnji)**

Fig. 3. Lithic grain of chert is visible in the middle of the microphotograph (Lg). Small grains of quartz and fragments of carbonised plant residues (black) occur within siderite concretion. Crossed polars, scale bar 500 µm.

Sl. 3. Na sredini slike je večje zrno najverjetneje roženca. Po celotni površini so manjša zrna kremenova ter premoški fragmenti rastlinskih ostankov (črni). Navzkrižni nikoli, merilo 500 µm.

Fig. 4a. Small grains of quartz in siderite cement. Parallel polars, scale bar 500 µm.

Sl. 4a. Majhna zrna kremenova v sideritnem cementu. Vzporedni nikoli, merilo 500 µm.

Fig. 4b. The same as Fig. 4a. Crossed polars, scale bar 500 µm.

Sl. 4b. Isto kot sl. 4a. Navzkrižni nikoli, merilo 500 µm.

Sample 10a (Siderite concretion)**Vzorec 10a (sideritna konkrecija)**

Fig. 5. Limonitised siderite concretion with several grains of quartz (white) and fragments of carbonised plant residues. Parallel polars, scale bar 1mm.

Sl. 5. Limonitizirana sideritna konkrecija s posameznimi zrnji kremenova (bela) in fragmenti pooglenelih rastlinskih ostankov. Vzporedni nikoli, merilo 1mm.

Sample 19a (Limestone)**Vzorec 19a (apnenec)**

Fig. 6. Rare small quartz grains (white and gray) and fragments of carbonised plant residues (black) in calcite cement. Crossed polars, scale bar 500 µm.

Sl. 6. Posamezna majhna zrna kremenova (bela in siva) in premoški fragmenti rastlinskih ostankov (črni) v kalcitnem cementu. Navzkrižni nikoli, merilo 500 µm.

PLATE 4 - TABLA 4

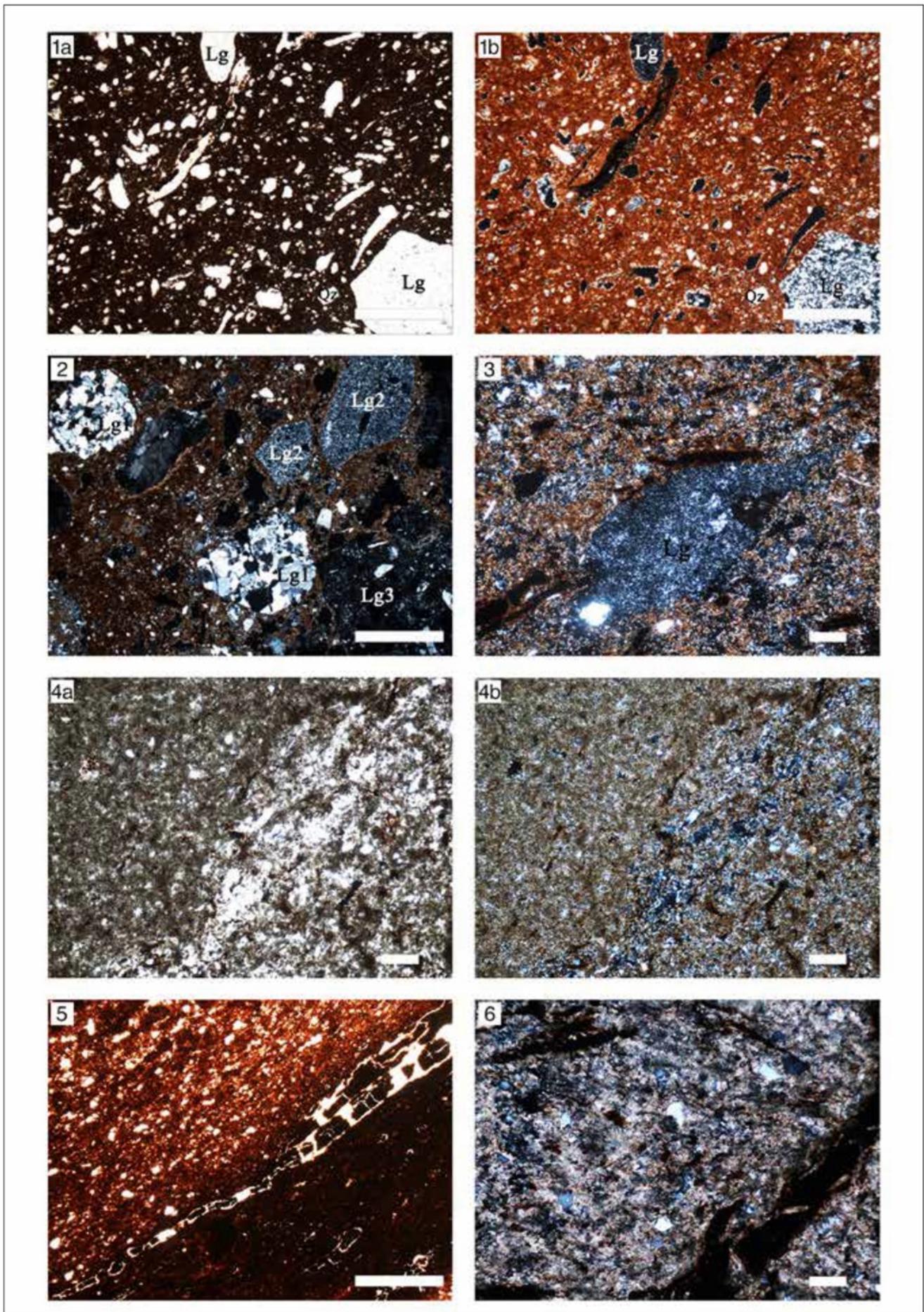


TABLA 5 - PLATE 5**Sample 20 (Lithic feldspar quartz sandstone with sparry calcite cement)****Vzorec 20 (litično-glinenčev kremenov peščenjak s sparitnim kalcitnim cementom)**

Fig. 1a. Several monocrystalline quartz grains (Qz) and lithic grains (Lg) in sandstone with sparry calcite cement (stained red). Parallel polars, scale bar 1 mm.

Zrna monokristalnega kremenca (Qz) in litičnih zrn (Lg) v peščenjaku s kalcitnim cementom (rdeče obarvan). Vzporedni nikoli, merilo 1 mm.

Fig. 1b. The same as Fig. 1. Crossed polars, scale bar 1 mm.

Sl. 1. Isto kot sl. 1. Navzkrižni nikoli, merilo 1 mm.

Fig. 2. Quartz sandstone lithic grain at the centre of photo and grains of quartz (Qz). Crossed polars, scale bar 100 μ m.

Sl. 2. Litično zrno kremenovega peščenjaka na sredini slike in zrna kremenca (Qz). Navzkrižni nikoli, merilo 100 μ m.

Fig. 3. Grain of recrystallized polycrystalline quartz with undulose extinction. Crossed polars, scale bar 500 μ m.

Sl. 3. Zrno rekristaliziranega polikristalnega kremenca z valovito potemnitvijo. Navzkrižni nikoli, merilo 500 μ m.

Fig. 4. Strongly altered volcanic rock fragment. Crossed polars, scale bar 500 μ m.

Sl. 4. Zelo spremenjeno litično zrno predornine. Navzkrižni nikoli, povečava 500 μ m.

Fig. 5. Lithic grain of felsic plutonic rock. Micro-cracks within the feldspar grain are filled with sparry calcite. Crossed polars, scale bar 100 μ m.

Sl. 5. Litično zrno kisle globočnine. Razpoke v zrnju glinenca so zapolnjene s sparitnim kalcitom. Navzkrižni nikoli, merilo 100 μ m.

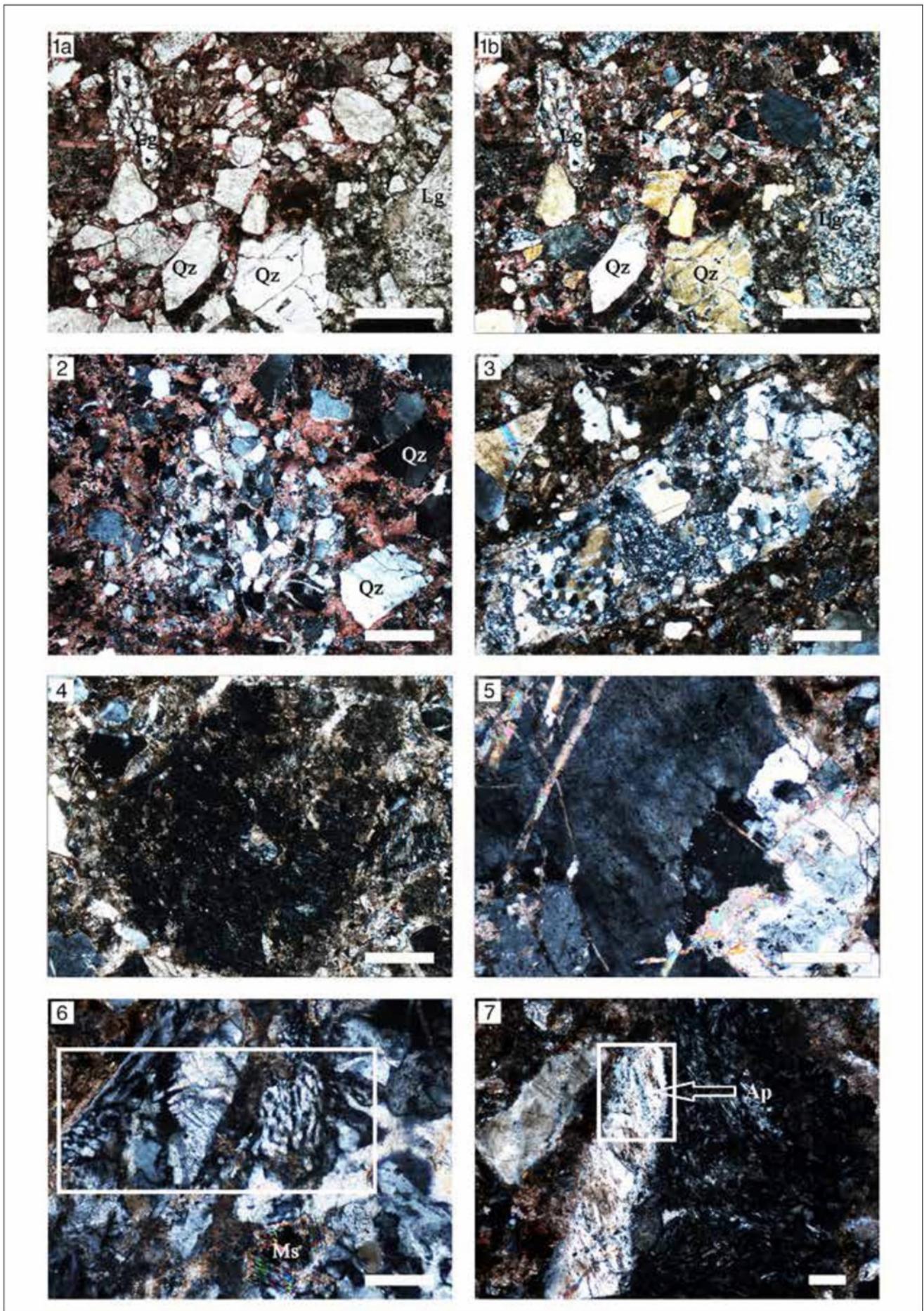
Fig. 6. Lithic grain of some igneous rock, most probably belonging to aplite with granophyric texture. Detail in rectangle shows an intergrowth of quartz and K-feldspar. Muscovite flake (Ms) is visible at the lower margin. Crossed polars, scale bar 100 μ m.

Sl. 6. Litično zrno magmatske žilnine z granofirsko strukturo, najverjetneje aplita. V okvirju je vidno preraščanje kalijevih glinenecv in kremenca. Na spodnjem robu se pojavlja muskovit (Ms). Navzkrižni nikoli, merilo 100 μ m.

Fig. 7. Volcanic rock fragment with phenocrysts of plagioclase. Grains of elongated apatite mineral (Ap) are visible in the frame. Crossed polars, scale bar 100 μ m.

Sl. 7. Litično zrno predornine z vtrošniki plagioklazov. V okvirju so vidna podolgovata zrna apatita (Ap). Navzkrižni nikoli, 100 μ m.

PLATE 5 - TABLA 5



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