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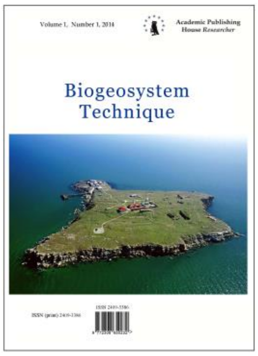

Silica Microphorms in Soils Affected by Hydrothermal Activity on the Yellowstone Volcanic Plateau, USA

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Abstract

Many prominent ecological characteristics of Yellowstone derive from its hotspot-induced uplift, including the moderate- to high-elevation terrain, the cool climate and deep snowfall. Heat from the hotspot rises upward and drives Yellowstone's famed geysers, hot springs and mud pots. The major soil-forming factors in the area are volcanic parent rocks – rhyolite and andesite – and lake sediments overlying rhyolite, cold temperatures, and deep snow in winter and low precipitation in summer. The purpose of the work was to study the effect of hydrothermal activity – geysers, hot springs and mud pots on the Yellowstone Plateau post-volcanic soils, developed on rhyolite, lake sediments and andesite. The sampling sites were chosen in areas both affected by hydrothermal activity – by mud pots, active geysers and the field of thermal waters and off the direct hydrothermal effect – Hayden Valley and the Lamar River Valley. Chemical weathering was a major feature of the affected soils. Near active mud pots, at pH 5.1–5.6, active rhyolite weathering resulted in abundant amorphous silica production and sequential thriving of diverse diatom algae. In soils on the lake sediments and close to the geysers, at low pH values (< 4), weathering was moderate and biogenic silica was presented mostly by shells of testate amoebae. The content of diatoms in these soils corresponded with that in the parent lake sediments. Similar conditions were observed for the soils on andesite in the Lamar River Valley. Biogenic silica was also found in the form of phytoliths, well-preserved in the productive grassland of the Hayden Valley, but significantly affected in the soils near active hydrotherms. Hydrothermal activity was a driving force of silicate mineral weathering and resulted in the thriving of diatoms on the plateau.

Keywords: soils, hydrothermal weathering, opal-A, diatoms, testate amoebae, phytoliths, Yellowstone.

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1. Introduction

Investigations of relatively simple natural systems may contribute significantly to our understanding of more complex phenomena. In soil science, an example of such systems can be a soil developed in extreme environments such as cold ultra-arid oases of Antarctica, hot ultra-arid deserts – Atacama, soils on recent volcanic rocks – Hawaii, Kamchatka (Karpachevskiy, 1965; Amundson et al., 2008; Mergelov et al., 2012; Targulian et al., 2017) and specific post-volcanic soils of the Yellowstone Plateau, affected by hydrothermal activity (Pierce et al., 2007).

At an elevation of about 2,500 m, the Yellowstone Plateau forms the core area of the Yellowstone National Park. The area is one of the last remaining large, nearly intact ecosystems in the northern temperate zone of the Earth and one of the world's foremost natural laboratories in landscape ecology and Holocene geology (Schullery, 2004; Hansen, 2006; Pierce et al., 2007).

The plateau was built up by extrusion of volcanic rocks – siliceous rhyolitic lavas and caldera-forming rhyolite tuffs produced by hotspot volcanism (Fournier, 1989; Christiansen, 2001). In contrast to the rhyolite plateau, which extends over much of Yellowstone, the northeastern part and the Absaroka Range are characterised by steep topography and high relief, primarily on friable Eocene volcanic clastic andesitic rocks (Prostka et al., 1975; Meyer, 2001).

Heat from the hotspot rises upward and drives Yellowstone's famed geysers, hot springs and mud pots. The thermal waters are specialised, primitive ecosystems, rich in algae and bacteria (Pierce et al., 2007). Neutral to alkaline, the thermal waters are mostly chloride- and silica-rich (300–500 and 230–676 mg L^{-1}, correspondingly). Acid-sulphate (-Fe-rich) boiling pools and mud pots occur in some of the geyser basins.

Many prominent ecological characteristics of Yellowstone derive from its hotspot-induced uplift, including the moderate- to high-elevation terrain and the associated cool climate and deep snowfall. The rhyolite plateau is remarkably gently sloping.

Climate

The region is characterised by cold continental climate, although influenced by elevation, latitude and broad-scale air masses. The two main features of the weather in Yellowstone are low temperatures and heavy snowfall. The nearest reporting station is at West Yellowstone, and this is usually the coldest place in the USA for several days every month of the year. Spatial extrapolations from meteorological stations indicate annual average temperatures from 6 to 7°C, a growing season longer than 5 months and average annual precipitation from 240 to 480 mm. Solar radiation is relatively high due to lower cloud cover, while the vapour pressure deficit is high due to low humidity and high temperatures. In the summer days, daytime temperatures range between +21 and +27°C, while night-time temperatures often fall below +4°C. Spring and autumn are transitional seasons between the long, cold winter and the short, mild summer. Winter air masses from the northern Pacific Ocean traverse the topographic low of the Snake River Plain to where orographic rise onto the Yellowstone Plateau and adjacent mountains produce deep snow (Hansen, 2006; Pierce et al., 2007).

Soils

The major soil-forming factors in the area are volcanic parent rocks – rhyolite and andesite – and lake sediments overlying rhyolite, cold temperatures, deep snow in winter and low precipitation in summer. Rhyolite is rich in silica (typically > 69%) and poor in plant nutrients and forms sandy, well-drained soils that support the monotonous, fire-adapted lodgepole pine (*Pinus contorta*) forests of the Yellowstone Plateau. As the summer progresses, the upland rhyolite areas and their lodgepole forests generally become dry earlier than the adjacent areas on non-rhyolite substrates. During the Pleistocene, glaciers sculpted the bedrock and produced glacial moraines that are both forested and woodless, sand and gravel of ice-marginal streams that are commonly covered with sagebrush-grassland as well as silty lake sediments that are commonly covered by lush, highly productive grassland, such as the Hayden Valley in the northwest (Marcus et al., 2012).

Most of the plateau soils fall into three orders, of which we sampled two: (1) Inceptisols (Cryepts, the cold Inceptisols of high mountains or high latitudes, corresponding approximately to Entisols) and (2) Mollisols (Cryols). Inceptisols are the most common soil order in Yellowstone and dominate the central and southwestern parts of the National Park. They have a poorly developed soil profile. Cryepts, representing the most common suborder, are formed under extremely cold conditions. Mollisols have relatively thick, dark surface horizons rich in organic matter and are usually associated with grassland in Yellowstone. The suborder Cryols is the most common type here.

One can presume that the soils in Yellowstone are subject to impacts from salt aerosols generated by hot geysers, geothermal springs and basins as well as mud pots. Hot-water systems are characterised by the dominance of a liquid-phase flow and carry solutes that stay in solution during boiling, such as Cl^-, SiO_2 and major cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+), sometimes enriched with Fe. Vapour-dominated systems may contain H_2S (Nordstrom et al., 2005; Lowenstern and Hurwitz, 2008). Klages and Hsieh (1975) found that in the suspended matter of streams draining the area, quartz gave the dominant diffraction peak in the silt fraction.

The purpose of the present work was to study the effect of hydrothermal activity – geysers, hot springs and mud pots on the development of the post-volcanic soils of the Yellowstone Plateau.

2. Materials and Methods

Study area and soils

The study was focused on soils of the Yellowstone Plateau within the Yellowstone National Park. The soil samples were taken from the soil surface (0-10 cm layer) in August 2017. Sampling sites no. 1–5 were located on Inceptisols, the most common soils on the Yellowstone Plateau. Sampling sites no. 6, 7 were on grassland Mollisols with a relatively thick, dark surface horizon rich in organic matter. The sampling sites are briefly characterised in Table 1 and are shown on a schematic chart (Fig. 1).

Table 1. Brief characteristics of the sampled sites in Yellowstone National Park

No.	Site	Description	Soil, parent rocks
		Near sites of active hydrothermal activity	
1	Biscuit Basin East	Several tens of m from bubbling thermal springs	Inceptisol on rhyolite
2	Ibid	About 50 m from site 1	
3	Fountain Flat Drive	100-200 m from thermal waters, Celestine Pool, and about 400 m from an erupting geyser	
4	By Old Faithfull geyser	A forested spot, about 1 km from Old Faithfull geyser and acid-sulphate (-Fe) boiling pools and mud pots	Inceptisol on lake sediments
		Far from sites of hydrothermal activity	
5	Haiden Valley	A grassland enclave on fine-grained lake sediments surrounded by lodgepole pine forests on rhyolite	Inceptisol on lake sediments
6	Lamar, dry spot	High bank of the Lamar River	Mollisol on andesite
7	Ibid, meadow	Low bank of the Lamar River, about 30 m to site no. 6, grassland	

Fig. 1. A schematic map showing sample site locations

The sampling sites were chosen in areas both (1) affected by hydrothermal activity – by mud pots, active geysers and the field of thermal waters and (2) off the direct hydrothermal effect – Hayden Valley and the Lamar River Valley (Fig. 2).

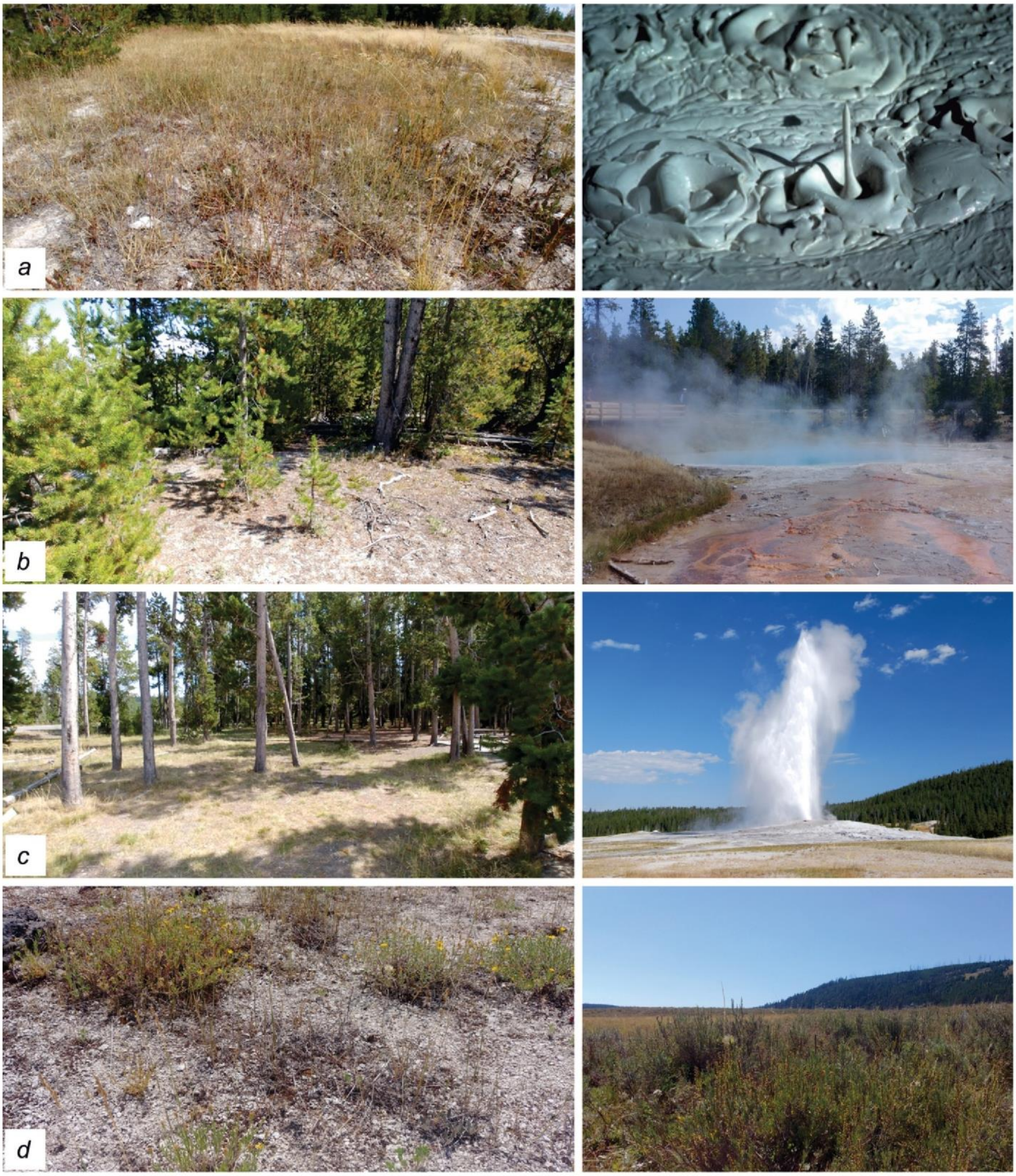

Fig. 2. Typical landscapes of the sampling site: *a* – Biscuit Basin East, mud pots, *b* – field of thermal water, Celestine Pool; *c* – forested spot near the large Old Faithfull geyser, *d* – grassland area next to the Lamar River. (Field picture *b* is from Pierce et al., 2007)

A brief description of selected physical and chemical properties of the soils is given in Table 2.

Table 2. Selected physical and chemical properties of surface soils (0–10 cm)

No.	pH	EC, mS cm^{-1}	Granulometric composition, %		Gross composition of fine earth, %						
			< 2 μm	> 50μm	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
Soils on rhyolite											
1	5.08	0.214	2.2	55.5	91.8	4.4	1.5	0.6	0.4	0.5	0.5
2	5.35	0.056	0	83.5	96.4	1.7	0.6	0.2	0.3	0.3	0.4
3	5.62	0.267	3.2	57.3	92.6	3.3	1.1	0.7	0.4	0.6	0.8
Soils on lake sediments											
4	3.86	0.170	1.0	56.4	74.3	12.2	4.6	1.1	1.0	2.4	2.9
5	5.19	0.274	1.1	56.0	74.1	11.9	3.7	1.8	1.0	3.1	3.2
Soils on andesite											
6	7.33	0.227	1.0	56.4	60.3	13.9	9.2	6.1	3.4	3.0	2.1
7	9.56	0.391	0.7	61.7	59.0	12.8	8.9	7.6	4.4	3.3	2.1

Methodology

The major methods were granulometric and gross analyses and scanning electron microscopy (SEM). The SEM analysis was carried out using VEGA 3 LMH (TESCAN, Czech Republic). For the analysis, the samples, after grinding and sieving through a 2-mm sieve, were prepared via pouring, Pt-spraying and magnification of up to 20,000. A backscattered electron detector (BSE detector) was used for the analysis of phases with a high atomic number. When images are acquired using a BSE detector, phases with a high average atomic number are reflected in contrast more vividly than those with a lower atomic number. The X-max 80 energy-dispersive spectrometer (Oxford Instruments, UK) was used to analyse the elemental composition of the most representative regions. The capture area of the microanalysis was about 1 μm in diameter. If a smaller object was scanned, the result was distorted due to the influence of the surrounding matrix or the carbon table of the device. The granulometric composition determined a particle size distribution from 0.01 to 2,000 μm with the laser diffraction method on a particle size analyser SALD-2300 (SHIMADZU, Japan) (Rawle, 2017; Wolform, 2011). The contents of selected chemical elements were determined via the X-ray fluorescence method (XRF) (Pioneer S4, Bruker AXS, Germany), using the silicate technique. The SEM and XRF analyses were carried out in the Analytical Centre at the Institute for Tectonics and Geophysics, Khabarovsk, Far East Branch of the Russian Academy of Sciences.

3. Results and Discussion

The results of the chemical analysis (Table 2) showed that the soil composition was inherited from the parent rocks. The soils on rhyolite (no. 1–3) were characterised by a high concentration of SiO_2 (92–97 %) and a weak acid reaction at pH 5.1 to 5.6. The soils on andesite (no. 6, 7) were neutral to alkaline at pH 7.3 to 9.6 due to the high content of alkali and alkaline-earth metals and the relatively low content of SiO_2 (59–60 %). The soils on lake sediments (no. 4, 5) had intermediate characteristics. Site no. 4, however, showed an acid reaction at pH 3.9, the lowest value among all the studied soils, most likely due to the impact from the waters influenced by Old Faithfull geyser. All soils had low electroconductivity, ranging from 0.056 to 0.391 mV cm^{-1}, most likely due to effective drainage patterns and intensive leaching during spring snowmelt; no salt accumulations could be detected with SEM.

Despite the difference in chemical composition, the soils, however, were similar in granulometric characteristics and all showed a medium silt-loam texture. This is a rather paradoxical fact because usually particle sizes are closely related to the chemical composition (van Genuchten et al., 1999; Buurman et al, 2001; Eshel et al., 2004; Pachepsky, Rawls, 2004). This phenomenon could be explained by similar physical weathering conditions in the soils. The main granulometric fraction ranged from 20 to 200 μм. The maximum peaks of differential curves of particle-size distribution (PSD) (Fig. 3) corresponded to the low limit of physical weathering of quartz (~100 μм). In site no. 2, the high sand content (> 80 %) could be explained by eructation of the mud pots.

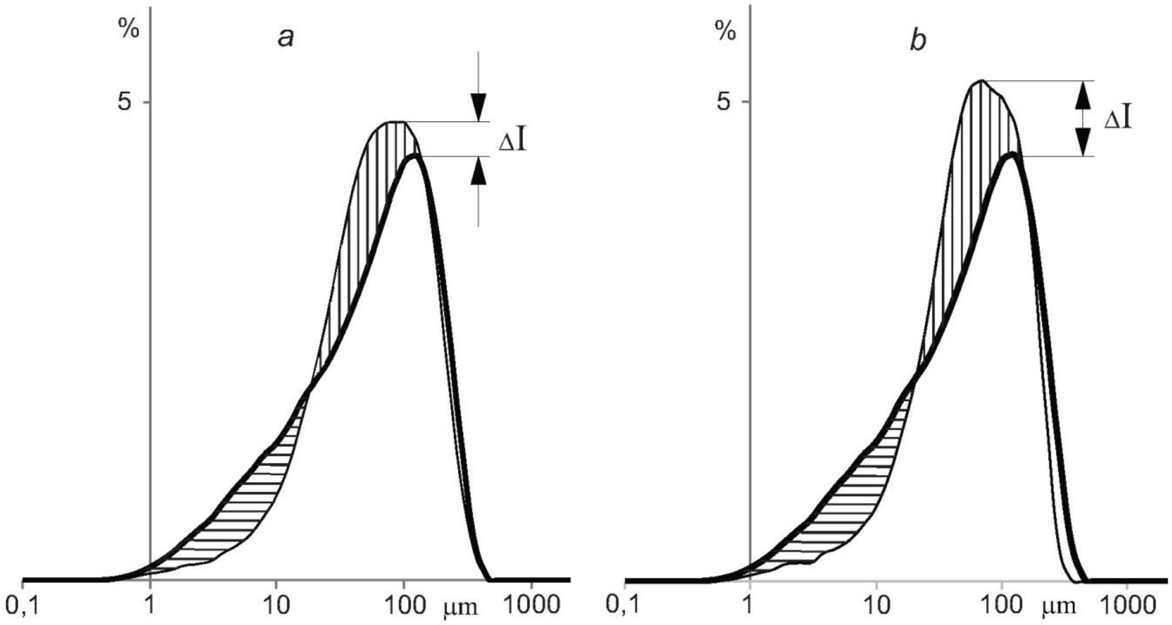

Fig. 3. Particle-size distribution in soils, differential curves: thick line – site 1(a, b), thin line – site 5(a), site 6(a), ΔI – peak intensity difference

Being similar in terms of granulometry, the soils, however, varied in particle size distribution. Mineral particles of soils on lake sediments and andesite were sorted more evenly compared to the soils on rhyolite. The former had differential PSD curves with intensive, narrow symmetrical peaks of the basic fraction compared to the soils on rhyolite. The latter had a left peak asymmetry with a long tale in the area of fine particles < 20 μм. Considering the 'more quartzite' composition of rhyolite soils, the effect of mud pots on their chemical weathering can be presumed.

According to SEM analysis, the effect of mud pots on chemical weathering of the rhyolite soils resulted in the formation of amorphous silica (Fig. 4). For example, in site no. 1, both clastic quartz (Fig. 4*a*) and 'acicular quartz' of varying degrees of amorphisation (Fig. 4*b–d*) were determined as, most probably, the result of hydrothermal weathering of feldspars. Similar acicular crystals of Na-feldspars have been found in sand granular soils in Mongolia (Shein et al., 2017). Semi-quantitative EDS-analysis of the elemental composition of 'acicular quartz' evidenced its mono-silica composition. This allows hypothesising the formation of both kinds of quartz, i.e. amorphous and acicular from clastic quartz. In site no. 2, the formation of amorphous silica (Fig. 4*e–f*) from rhyolitic tuff (together with silicified plant litter) (Fig. 4*h*) could be observed. Silicification of plant litter (Fig. 4*h*) and anomalously high concentrations of biogenic silica in the form of diatoms (Fig. 5) in the soils indicate the effective dissolution of amorphous silica.

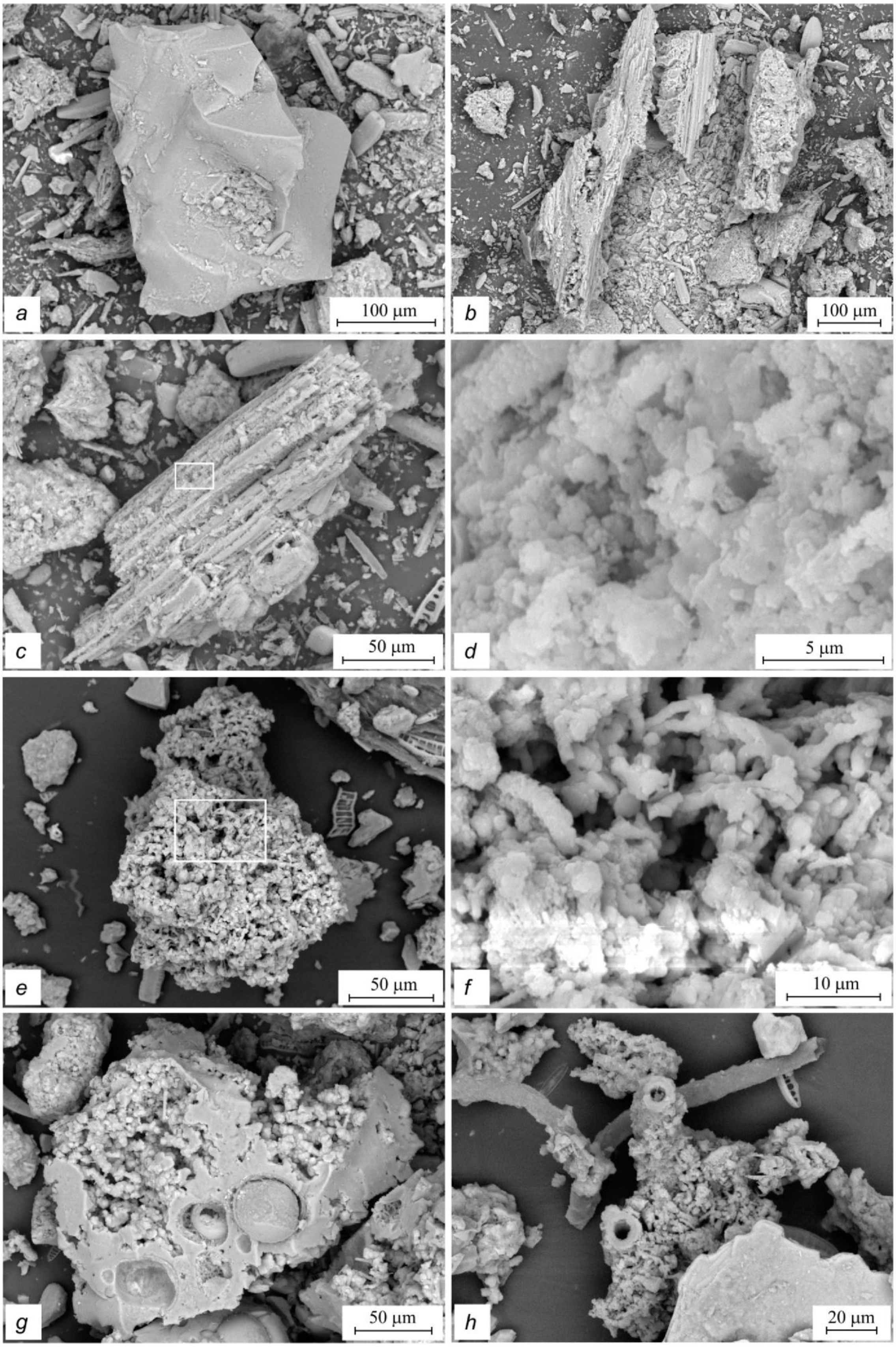

Fig. 4. Micrographs of SiO_2-formations in sampling sites no. 1 (a–d) and 2 (e–h): a – clastic quartz; b, c – 'acicular quartz'; d – bordered area in Fig. 4c is amorphous silica; e – new formations of amorphous silica, f – bordered area in Fig 4e; g – weathered rhyolitic tuff; h – silicified detritus (SEM, BSE-detector)

Biogenic opal (opal-A) in the form of diatoms can be found in small quantities in some soils (Lynn et al., 2008). Whilst aquatic diatoms have been studied extensively (Soininen, 2007), investigations of terrestrial diatom communities and diatom assemblages that can be found on the soil surface are scarce (Antonelli et al., 2017). However, special methods of maceration have been developed (Gol'yeva, 2008), and standards on diatom content have been established (European Committee for Standardization, 2003). However, for this preliminary work, we did not use special methods of diatom concentrating, mainly because the direct detection of diatoms in bulk soil samples is evidence of abnormal high contents in the soil. The commonly found diatoms (*Bacillariophyta*) are presented in Fig. 5. We found all three classes: *Fragilariophyceae* (Fig. 5*a*–*d*), *Bacillariophyceae* (Fig. 5*e*–*g*) and *Coscinophyceae* (Fig. 5*h*), showing high species variety in the soils from the mud pots, site no. 1. Diatoms were not identified to the genus and species levels.

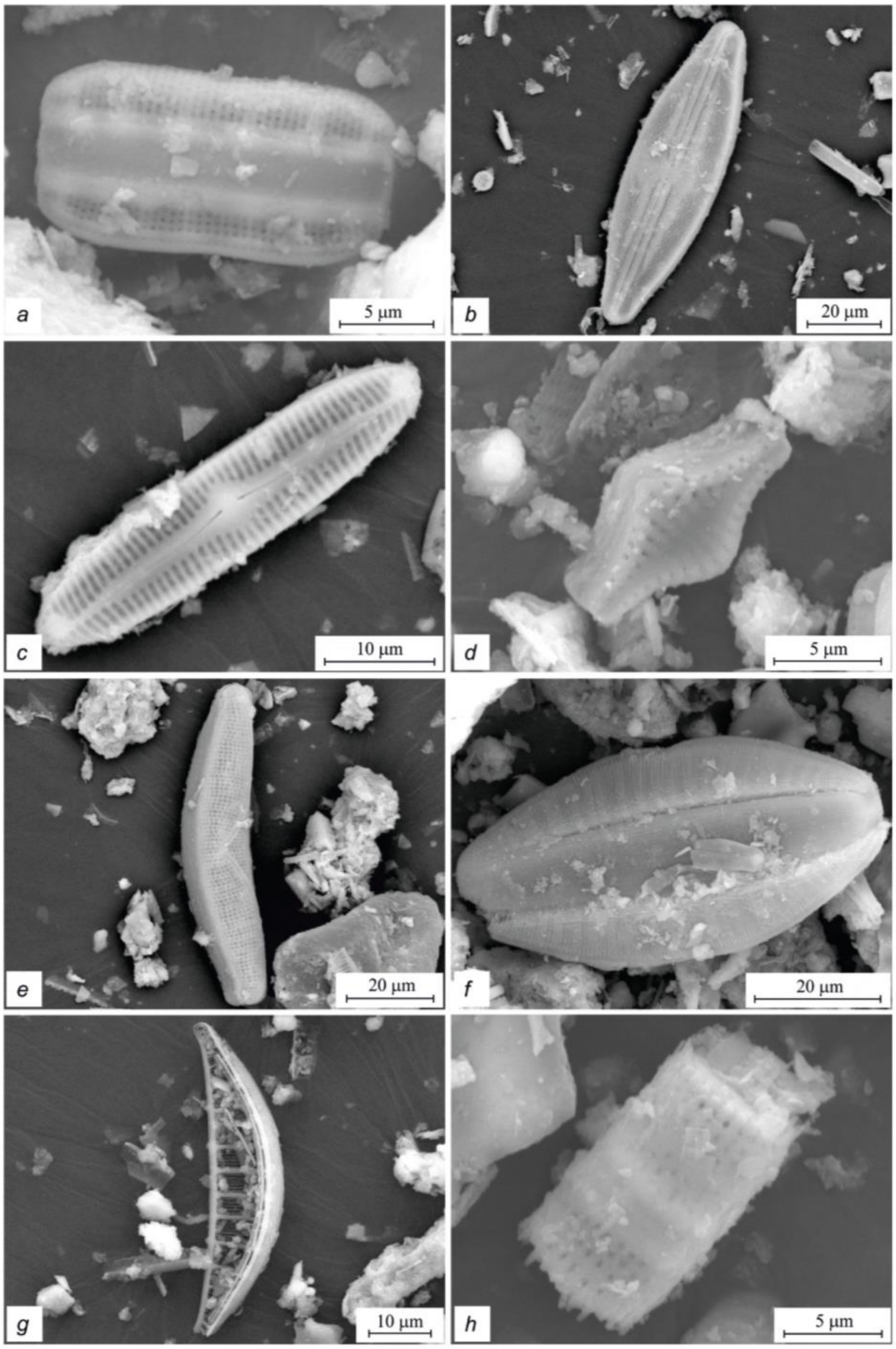

Fig. 5. Micrographs of the most representative species of diatoms, site no. 1: *a*–*d* – Class *Fragilariophyceae*; *e*–*g* – Class *Bacillariophyceae*; *h* – Class *Coscinophyceae*; SEM, BSE-detector

In site no. 3, near the field of the thermal waters and about 400 m from an erupting geyser (Fig. 6), chemical weathering was more moderate compared to site no. 1. 'Acicular silica' could not be found, and amorphous silica was only observed in small quantities of cemented and covered microaggregates of primary clastic grains (Fig. 6*a–b*). Diatoms were represented by closely related species, albeit in smaller quantities than in site no. 1 (Fig. 6*c–g*). In both cases (sites no. 1 and 3), diatoms formed microaggregates in the soils (Fig. 6*h*). Such aggregation occurs mainly through the production of muco- and polysaccharide gels (Zimmermann-Timm, 2002; Keil and Mayer, 2014). It is likely that in hydrothermally affected soils, organic matter produced by diatoms can contribute significantly to the primary soil organic matter. According to Brzezinski (2008), diatoms account for about 20 % of the carbon fixed through photosynthesis, whilst the contribution of other microbiota species is significantly lower.

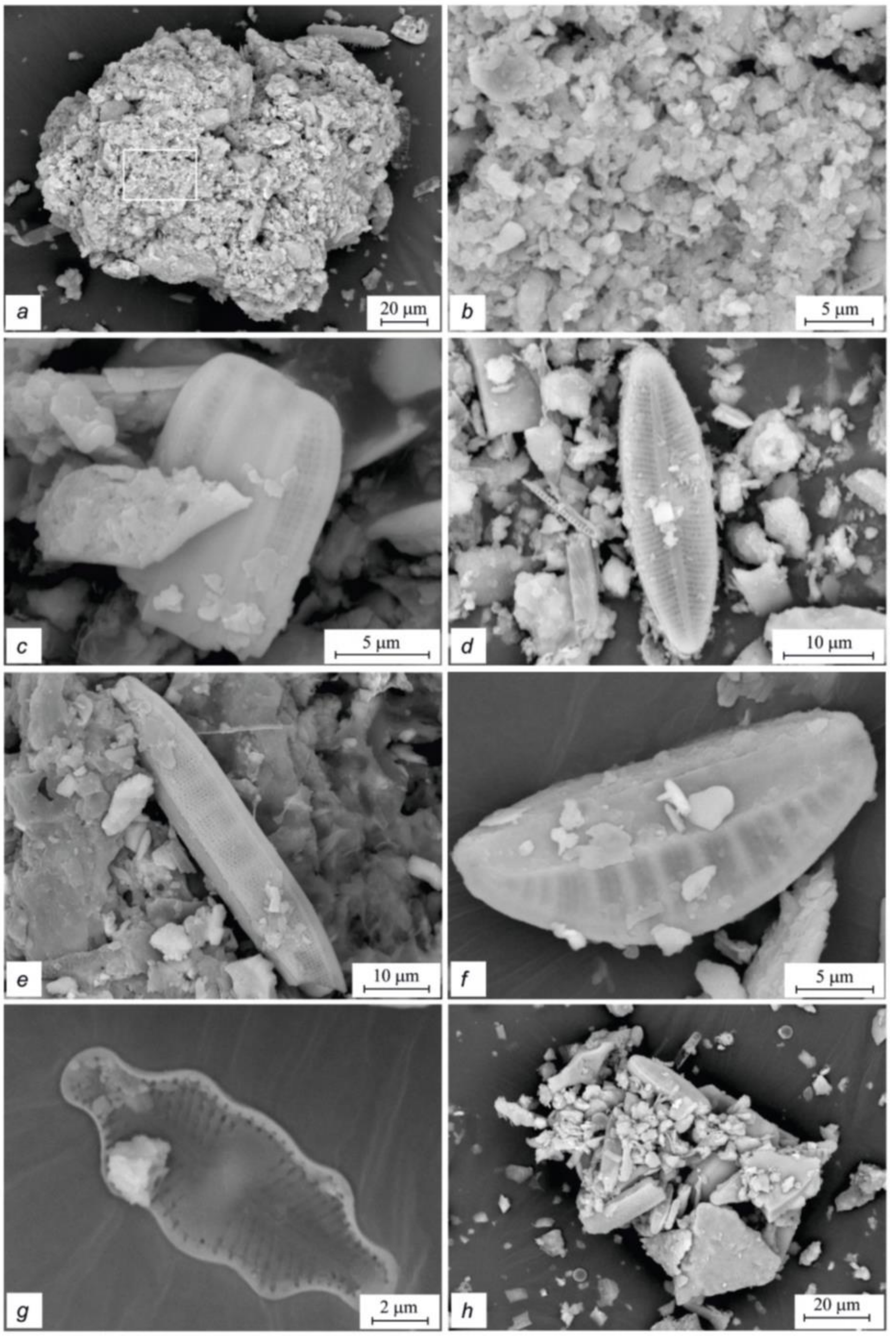

Fig. 6. Micrographs of diatoms, site no. 3: a – microaggregate with amorphous silica; b – bordered is the area (a) with amorphous silica; c–g – most representative diatom species; h – microaggregate with diatoms (SEM, BSE-detector)

In sites on lake sediments, sites no. 4 and 5, no weathered amorphous silica could be determined. Quartz was significantly less abundant than in the rhyolite sites, represented in the forms of both clastic and rounded grains; the latter can be related to glaciation. According to bulk chemical analysis, feldspar minerals dominated here. The content of diatoms was similar to that in the lake sediments (Fig. 7). It should be noted that in the acid soils of site no. 4, near Old Faithfull geyser, testate amoebae dominated over silica microbiophorms (Fig. 7*a*, *b*). Testate amoebae inhabit raw humus litter and promote the decomposition of organic matter. Their presence indicates a low rate of bioprocesses and an acid milieu (Corbet, 1973). These organisms use dissolved silica for their shell plates, fastened with protein, which disintegrate rapidly after the death of the organisms. The preservation of testate amoebae shells is lower compared to that of diatom shells, about tens and millions years, respectively (Gol'yeva, 2008). Therefore, the high amount of shells found on the sites indicates recent formation.

In the soil of site no. 5, Fe-Mn concretions were a product of diagenesis in lake sediments (Fig. 7*e*). In addition, frustules of centric diatoms were found in this site (Fig. 7*f*), presumably from *Stephanodiscus yellowstonensis*, an endemic species of Yellowstone Lake.

In the soils on andesite of the Lamar River Valley, no formation of amorphous silica could be determined, with low diatom contents.

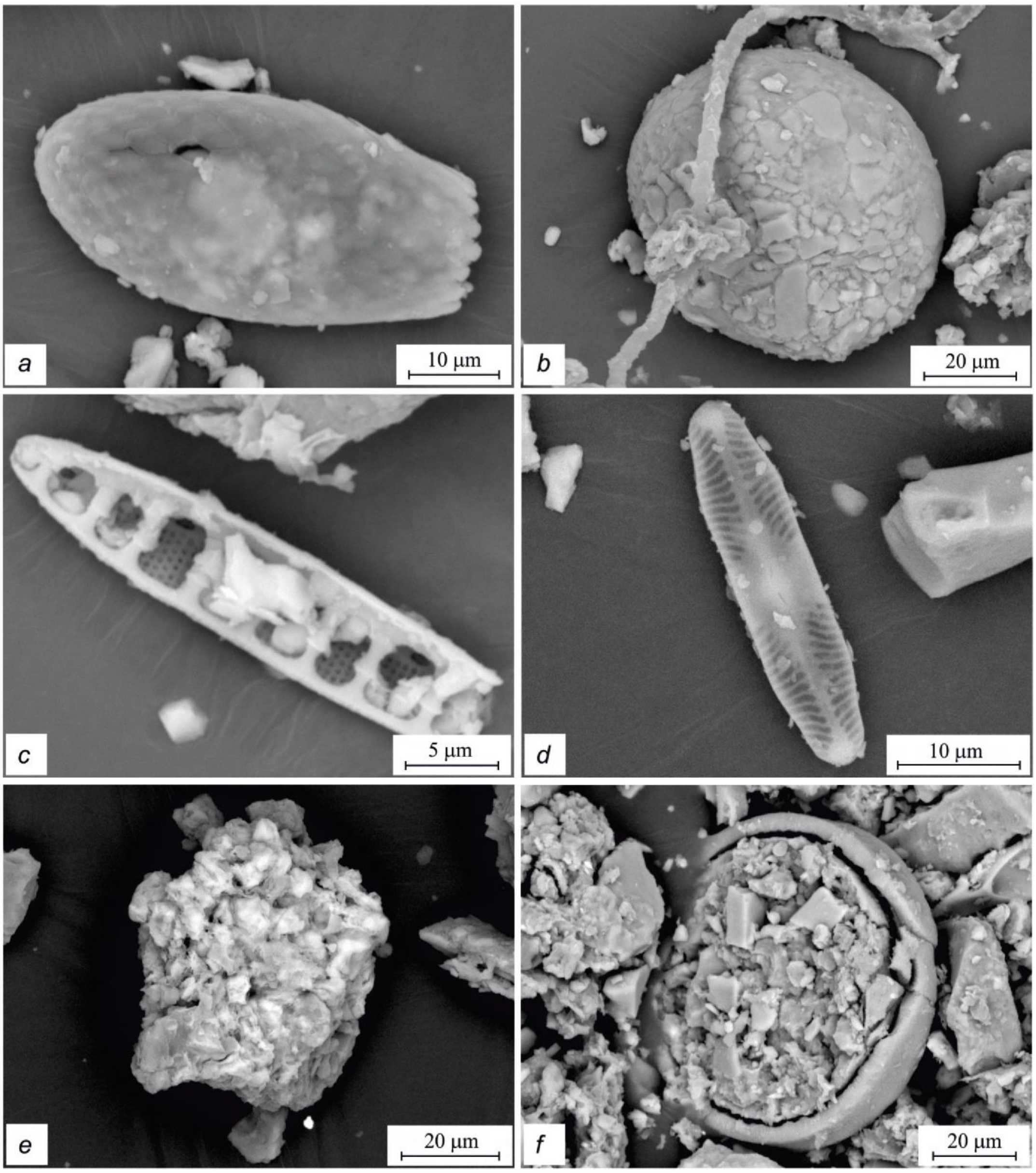

Fig. 7. Micrographs of testate amoebae (a, b), diatoms (c, d, f) and Fe-Mn concretions (e): a–c –site no. 4; d–f, site no. 5; SEM, BSE-detector

In addition to diatoms and testate amoebae, another of biogenic silica, phytoliths, could be detected (Fig. 8). They are formed during intracellular silica precipitation and follow the shape of the cell. Phytoliths are indicative of phytocenosis, a major soil formation factor (Gol'yeva, 2008). An abundance of well-preserved phytoliths was determined in the Hayden Valley (site no. 5), a highly productive grassland ecosystem (Fig. 8*a*, *b*). In the soils of the Lamar River Valley, phytoliths are represented by close associations. In less productive forest ecosystems on rhyolite, next to the field of the thermal waters of Fountain Flat Drive and about 400 m from an erupting geyser (site no. 3), grass and pine-tree phytoliths were found (Fig. 8c, *d*), although less abundant and of average preservation. Least preserved phytoliths were determined in site no. 1, Biscuit Basin East, several tens of m from the field of bubbling thermal springs (Fig. 8*e*, *f*), probably as a result of effective weathering. Similar processes have been observed, for example, in highly weathered podbel (whitened) horizons of meadow podbel soils of the middle Amur River Valley (Kharitonova et al., 2013). According to a previous study, the weathering of grass phytoliths resulted in the formation of fine spherical particles of opal silica of about 150–300 ηm (Chizhikova, 2013). No evidence of chemical weathering of the two other forms of biogenic silica, i.e. diatomic and testate amoebae skeletons, could be found in this active hydrothermal spot due to their high resistance, but we found evidence of mechanical destruction.

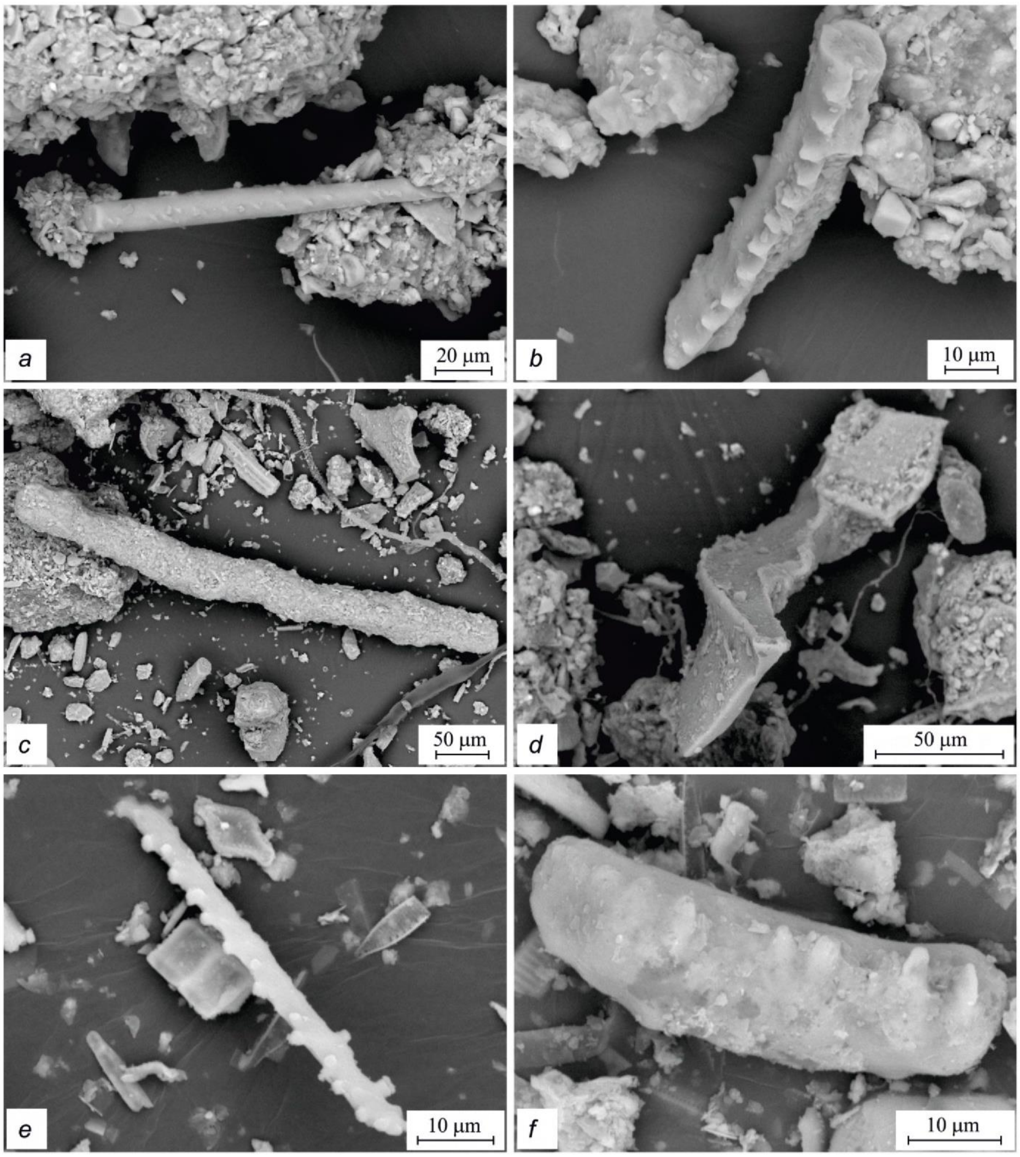

Fig. 8. Micrographs of phytoliths: a, b – site no. 5; c, d – site no. 3; e, f – site no. 1; SEM, BSE-detector

4. Conclusion

Soils of the Yellowstone volcanic plateau, developed on rhyolite, lake sediments and andesite, were investigated. The soils near and beyond hydrothermal phenomena varied significantly in their chemical, biotic and mineral patterns. In the area of mud pots, at pH values from 5.1 to 5.6, effective chemical weathering of rhyolite resulted in the formation of abundant amorphous silica and the sequential thriving of diatoms of high species diversity. In the soils on lake sediments near the active geysers and with low pH values (< 4), chemical weathering was moderate and biogenic silica was mostly represented by shells of testate amoebae. Similar contents of diatoms were found in the soils and parent lake sediments of the Lamar River Valley, not directly influenced by hydrothermal effects. Additionally, soil biogenic silica in the form of phytoliths was abundant in lake sediments of the productive grassland of the Hayden Valley. These phytoliths were more susceptible to hydrothermal weathering compared to the more stable shells and frustules of diatoms and testate amoebae.

5. Acknowledgements

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