S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
Vol. L, 2016: 105–122 PL ISSN 0081-6434

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CHEMICAL WEATHERING OF TALUS SLOPES: THE EXAMPLE OF SLOPES IN THE BRATTEGG VALLEY, SW SPITSBERGEN

Abstract. This paper presents the results of hydrogeochemical surveys carried out in the non-glaciated part of the Brattegg Valley near Hornsund Fjord (SW Spitsbergen). The aim of the study was to indicate places in periglacial zone with the greatest intensity of chemical weathering. The valley was divided into five zones where 11 observation sites were selected. The physico-chemical parameters of water were measured in situ. Water chemical composition was defined using ion chromatograph and mineral composition was obtained based on X-ray diffraction analysis. The results of the study show that in the studied valley, talus slopes are the most dynamic environment of the periglacial zone and are typified by the greatest intensity of chemical weathering.

Keywords: talus slopes, chemical weathering, periglacial zone, Svalbard, XRD analysis

INTRODUCTION

The problem of chemical weathering in the periglacial zone (or sub-polar climate zone) has been of scientific interest since the 1960s, however, first studies were carried out occasionally, and the field observations were typically short. Initially, the role of chemical weathering in the polar environment was considered marginal (e.g. Rapp 1960; Cailleux 1962; Washburn 1969). Since 1980s studies in the Arctic have developed with more focus on the relationship between the intensity of chemical weathering and bedrock lithology (Åkerman 1983; Pulina et al. 1984; Richards 1984; Kostrzewski et al. 1989). Crucial research on chemical weathering in the Arctic environments were conducted in Swedish Lapland (Allen et al. 2001; Thorn et al. 2001; Dixon, Thorn 2005; Darmody et al. 2005), in Alaska (e.g. Anderson et al. 2003; Anderson 2005) and Spitsbergen (e.g. Rachlewicz 2009; Rachlewicz et al. 2016).

Chemical weathering refers to the breakdown of rocks and minerals with accompanying mineralogical and chemical changes, and, if water is present, affecting every kind of lithology. In general, hydrogeochemical processes are dependent on the presence of CO_2, pH of the environment and water temperature, but chemical weathering is driven mainly by hydrogen ion concentration (Anderson et al. 1997, 2000). In the polar climate, frigid winter season lasts

9–10 months, whereas summer season is extremely short with temperature rarely exceeding 5°C (Marsz 2013a). Low temperatures characteristic for polar regions are the main factor of change in the morphogenetic environments of the periglacial zone (Cooper et al. 2002; Hodkins et al. 2003). These conditions severely restrict the phenomena of hydration or hydrolysis, but predispose to increased activity of physical weathering. The common sediment covers, including the talus slopes, patterned ground and also solifluction lobes, are a product of mechanical weathering of rocks in the Arctic (Åkerman 1984; Ballantyne 2002). Depending on characteristics of a hydrological system, the water leaches bedrock or/and regolith. In the study area, water mineralization is dependent on the interaction of water and bedrock in the short-time. Additionally, impact on the chemical weathering is the distance from the glaciers around, because activity of the glacier is not limited to the place of glaciation, but to the entire hydrological system of the valley, even after the withdrawal of the glacier (Gurnell et al. 1996).

The aim of this study was to indicate places in the periglacial zone in the Brattegg Valley, southwest Spitsbergen, which are influenced by chemical weathering. Hydrogeological mapping of lakes, rivers, streams and outflows of water was conducted to determine the hydrological system of the studied area. Based on in situ measurements and the analysis of chemical composition of water, five zones differing in the intensity of the weathering processes were selected. Additionally, X-Ray diffraction analysis for suspended load was performed to identify supply areas of the transported material.

STUDY AREA

The study area is located in Hornsund Fjord in the southwest part of Spitsbergen island, 10 km from the Polish Polar Station (Fig. 1). The surveys were carried out in the Brattegg Valley (nor. Bratteggdalen) in the foreland of the Brattegg Glacier (nor. Bratteggbreen). There are three proglacial lakes in the studied area: upper, central (both unnamed) and lower – Lake Myrkt (nor. Myrktjørna). The lakes are located at 234 m, 139 m and 72 m asl respectively (Górniak et al. 2016). The eastern slopes of the valley are gentle, comparing to the steep western slopes.

From the west, the valley is limited by a mountain range which culminates at the top of Gullichsenfjellet (583 m asl) and where a system of eight talus cones is present. These talus cones are characterized by a steep proximal part (up to 50° inclination), an average apex elevation of 230 m asl, and a distal part which flows directly into the proglacial Lake Myrkt. Some of the fans, distant from the lake coastline, turn into alluvial fans (with an inclination up to 2–10°).

The studied area is underlain by Caledonian metamorphic rocks of the Hecla Hoek succession (Harland 1997). There are two formations in the Brattegg

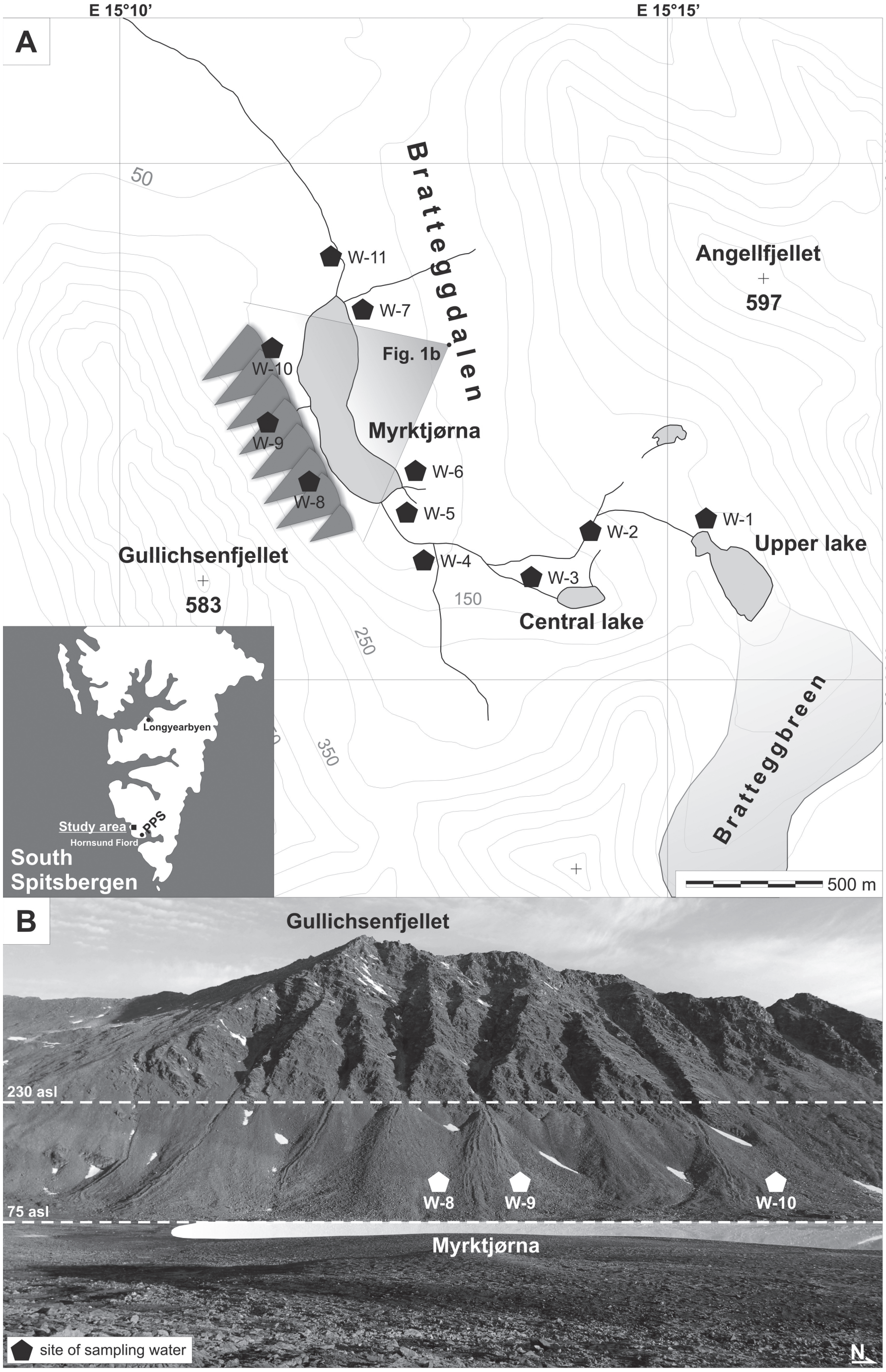

Fig. 1. Study area: A) Location of the water sampling sites in the Brattegg Valley (based on: J a n i a et al. 2002; K a r c z e w s k i et al. 1984), B) the eastern slopes of the Gullichsenfjellet. Symbols: W – number of water samples, PPS – Polish Polar Station

Valley: the Brattegdalen and the Gullichsenfjellet. The former is represented by the series of volcanites overlying the Skälfjellet metabasites. The lithology consists of amphibolites, metarhyolites and rhyolite metatuffs (i.e. muscovite and biotite schists). The Gullichsenfjellet Formation includes a complex of quartzites overlying metavolcanites of the Bratteggdalen and Skälfjellet formations. Quartzites are dominant, whereas amphibolites and mica schists are subordinate (Czerny et al. 1993).

Mean annual temperature in the vicinity of the Polish Polar Station for the period 1979–2009 was –4.3°C. The coldest month was January (–10.9°C) and the warmest was July (+4.4°C) (Marsz 2013a). The mean annual air humidity was close to 79% (Marsz 2013b), and mean annual precipitation amounted to 434,4 mm. The highest precipitation is recorded in the summer season, especially in August (Łupikasza 2013). The study area is under the influence of marine aerosols from the coastal zone of the Greenland Sea transported from the west over the Gullichsenfjellet. The non-glaciated surface is typified by the presence of permafrost and tundra plants (Humlum et al. 2003).

METHODS

At the first stage of the analysis, hydrogeological mapping of the Brattegg Valley was carried out in July and August 2012. The mapping included places particularly sensitive to chemical weathering. The study area was divided into five research areas (zones), including three sites representing typical depositional environment in the periglacial zone (talus cones, solifluction lobes, covers of weathered material). Two additional sites included the beginning and the end of the valley's hydrological system. The measurements were carried out at a total of 11 observation sites (Fig. 1; Tab. 1).

The physico-chemical parameters of water were measured at each observation site using multiparameter meter HI9828 (Hanna Instruments). Measurements in situ included temperature, pH, redox potential (pH Mv), conductivity and resistivity, amount of solids (TDS), dissolved oxygen (DO) and salinity. These parameters were measured twice, on 24 and 29 July, and the results were averaged. The water was sampled twice at all 11 sites and the samples were filtered (0.25 dm^3, Whatman GF/F 0.45 μm). Chemical composition of 22 water samples was determined using ion chromatograph (Metrohm at Polish Polar Station of the Institute of Geophysics Polish Academy of Sciences) and averaged.

The filters, used for the filtration of water samples, were dried at 105°C and weighed to determine the amount of suspended load. The successive analysis was performed only on the samples from talus cones (W-8, W-9, W-10) as the remaining samples contained insufficient amount of suspended load. In laboratory conditions, material from three filters was dissected using small amount of distilled water. The samples of suspended load were placed on a microscope

Table 1

General characteristic of 11 observation sites

Site symbol	Elevation (m asl)	Site characteristics	Zone
W-1	234	The upper lake under the influence of the Brattegg Glacier.	I
W-2	175	The sites located below the upper lake and above Lake Myrkt where water flows through crystalline bedrock and a thin cover of weathered material (sand, debris and boulder-size).	II
W-3	135		
W-4	115		
W-5	72		
W-6	80	Sites located in the eastern part of the Brattegg Valley with water flowing through the fields of solifluction lobes.	III
W-7	80		
W-8	85	Outflows from the talus cones in the western part of the Brattegg Valley.	IV
W-9	85		
W-10	85		
W-11	72	A site located under Lake Myrkt representing the whole hydrological system of the Brattegg Valley	V

slide and dried again. Then the preparations were analyzed microscopically to define the textural properties of suspended load. Photographs were taken in transmitted light at one lens and in reflected light. Since the prepared samples were in the form of powder, the obtained microscopic images revealed the shape of the grains but did not allow for clear identification of mineral composition of the suspended load. Determination of the mineral composition thus required the use of X-ray diffraction analysis. This analysis was performed using X-ray diffractometer Siemens D5005 at the Institute of Geological Sciences, University of Wroclaw. The samples were ground in an agate mortar and then subjected to X-ray analysis in the range of 4° to 75° 2Θ.

RESULTS AND INTERPRETATION

PHYSICO-CHEMICAL PARAMETERS AND CHEMICAL COMPOSITION OF WATER

Data on the physico-chemical parameters and chemical composition of the water were compared to characterize the intensity of chemical weathering in the valley's hydrological system. The beginning of the system is indicated by site W-1 (zone I). Water parameters and composition of the upper lake are influenced mainly by the Brattegg Glacier. This site has the lowest measured water temperature (0.33°C) and also the lowest mineralization (11.11 mg/dm^3). The W-1 site is a reference for other areas in the valley where chemical weathering intensity is considerably higher. The end of the hydrological system in the valley is the site

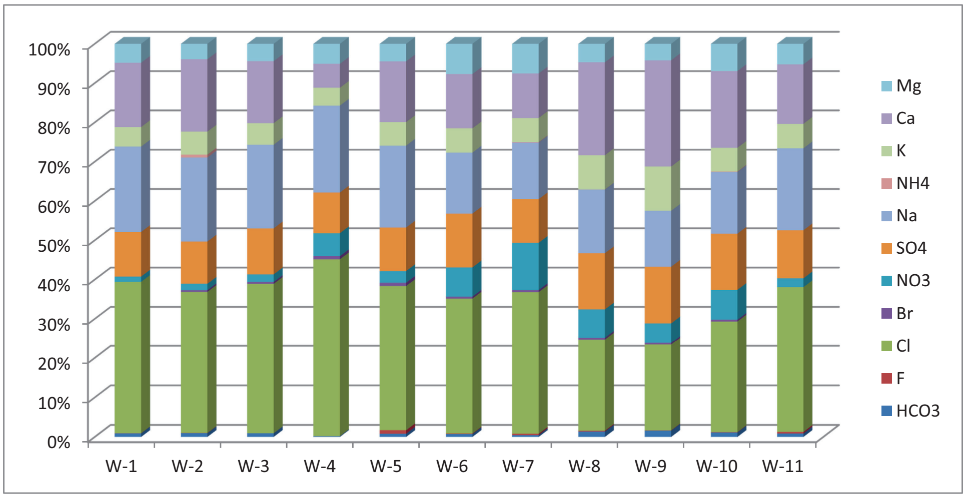

Fig. 2. Average chemical composition of water in the Brattegg Valley in the I–V zones (in %)

W-11 (zone V), with the highest measured water temperature (4.12°C) and not very high mineralization (13.16 mg/dm³).

Zone II covers the area where water flows through crystalline bedrock and a thin cover of weathered material with sand, gravel and rock boulders. Short transport from the Brattegg Glacier and the resistance of the weathered material limit the rate of chemical weathering which is very slow in this zone. This is confirmed by water mineralization values below 15 mg/dm³. Zone III includes the area with the greatest amount of fine material. Apart from sand and debris, the fields of solifluction lobes consist of silty and clay material. Water mineralization exceeding 21 mg/dm³ suggests long-term deposition and water infiltration in the weakly permeable material. The last zone (IV) represents the environment of talus cones on the eastern slopes of Gullichsenfjellet. The dominant slope material is debris and rock boulders. The water flowing out of these features has the highest mineralization (over 30 mg/dm³) and the largest amount of solids (50 ppm). The water runs on a short distance but influences the high dynamics of mechanical weathering. This directly contributes to the intensity of rock dissolution in the chemical weathering processes. The parameter of solids content (TDS ppm) corresponds to differences in chemical composition between individual sites.

The detailed analysis of chemical composition indicates a considerable difference in the contents of the selected ions between zone IV (talus cones) and other zones. The major difference concerns chloride (Cl^-) and sodium (Na^+) ions. These ions are the main components of sea water which is transported into the Brattegg Valley in the form of marine aerosol. In all areas the content of these ions is in the range of 35–70%. The water flowing out from talus cones has the highest concentrations of Cl^- and Na^+ among all sites in the valley but these ions constitute only about 35% of each sample. Other components are calcium (Ca^{2+}), sulfate (SO_4^{2-}) and potassium (K^+). Only in this zone these components are present in such amount. For example, the content of these three elements at site W-9 amounts to 52%, what is more than the two basic components of the aerosols: Cl^- and Na^+ (36%). In addition, the water flowing out from talus cones brings the largest amount of suspended load, as shown in the photos of drains after filtration (Fig. 3) and the weight of the load (Tab. 2).

Field observations indicate that water outflows from talus cones are irregular. The springs disappeared completely after 12 days (13–24 August, 2012) with precipitation of 0 to 1.6 mm per day (B e n e d y k, S z u m n y 2012). Moreover, the

Fig. 3. Drains after filtration; W-1 – upper lake, small amount of suspended load, W-8 – talus cone, fine sand fraction, W-9 – talus cone, mud fraction

Table 2

Selected physico-chemical parameters of water measured using multiparameter meter and amount of suspended load

Site	°C	pH	Redox potential (pHmV)	Conductivity (μS/cm)	Resistivity (MΩ*cm)	Solids (TDS ppm)	Dissolved oxygen (mg/l)	Salinity	Suspended load (g/dm^3)
W-1	0.33	8.9	–140.22	30.40	0.0329	15	13.72	0.01	–
W-2	1.83	8.04	–98.58	31.18	0.0325	15.71	13.28	0.01	0.0386
W-3	2.49	7.82	–87.71	25.36	0.0393	12.56	13.25	0.01	0.0164
W-4	1.96	7.59	–76.51	34.07	0.0303	16.93	13.37	0.02	0.0188
W-5	2.71	8.09	–101.33	32.73	0.0311	16.39	13.14	0.01	0.0368
W-6	3.81	7.63	–78.45	50.33	0.0201	25.28	12.17	0.02	0.0132
W-7	3.19	7.86	–89.62	58.31	0.0174	29.07	12.32	0.03	0.0194
W-8	**1.87**	**8.74**	**–132.77**	**85.73**	**0.0117**	**42.82**	**13.02**	**0.04**	**0.0896**
W-9	**2.82**	**8.37**	**–114.78**	**100.40**	**0.0101**	**50**	**13.24**	**0.05**	**0.0516**
W-10	**3.06**	**8.28**	**–110.36**	**82.82**	**0.0695**	**41.35**	**12.91**	**0.04**	**0.0340**
W-11	4.12	8.09	–101.26	33.74	0.0307	16.85	12.92	0.02	0.0240

cones are powered by infiltration of precipitation and water from the melting snow patches in the niches between the cones and the upper parts of slopes. The water coming from the surface flows on the rock walls and slopes, infiltrates into the cone at the apex, flows through the material of cone, flows out in distal part and finally reaches lower lake.

XRD ANALYSIS OF SUSPENDED LOAD

The analysis of suspended load was possible only for the water samples from talus cones. The microscopic analysis and the use of X-ray diffraction (XRD) were used to identify mineral composition of suspended load and supply areas of individual components. Both similarities and differences were observed in analyzed preparations. The main similarities referred to the maturity of mineral composition as well as texture of individual grains.

The minerals with platy habit were found at sites W-8 and W-9. Under the microscope, these elements are the largest part of suspended load (Fig. 4). Among these minerals, most elements identified with XRD analysis were from the chlorite group (Fig. 5 and 6) present in the quartzites of Gullichsenfjellet Formation (Czerny et al. 1993). In addition, the minerals of amphibolites were observed in this sample. The material from the site W-8 contained richterite, whereas the one from site W-9 contained ferro-actinolite. Some amphiboles are characterized by fibrous or acicular habit, and therefore can easily be subject to movement in suspension. Their source are the amphibolites of Bratteggdalen Formation occurring in the proximal parts of the cones. The water flowing on the surface or inside the cones does not have sufficient energy to transport heavy minerals.

Other minerals with platy habit were also found in the minerals composition of sites W-8 and W-9. The XRD analysis confirmed the presence of muscovite. This mineral is very mobile in the periglacial environment and resistant to chemical weathering processes. The occurrence of muscovite at sites W-8 and W-9 is interesting for two reasons. Firstly, it is present in the rock material of the cones or mica schist coexisting with amphibolites of Bratteggdalen Formation. The amphibolites occur on the boundary with the quartzite rocks of Gullichsenfjellet Formation (Czerny et al. 1993). Secondly, the presence of muscovite within the cones can indicate that this mineral was transported by wind. In summary, two kinds of muscovite were found in the suspended load: muscovite from Gullichsenfjellet Formation (in situ) and plates of muscovite which could be transported due to storms of sand and silt in the foreland of the surrounding glaciers.

Small grains of quartz were found in all of the three samples (W-8, W-9 and W-10) . The diffractogram clearly indicated the reflection values of d = 3.34 which is diagnostic for quartz. The quartz has the form of dust and its origin, as in the case of muscovite, is associated with wind transport.

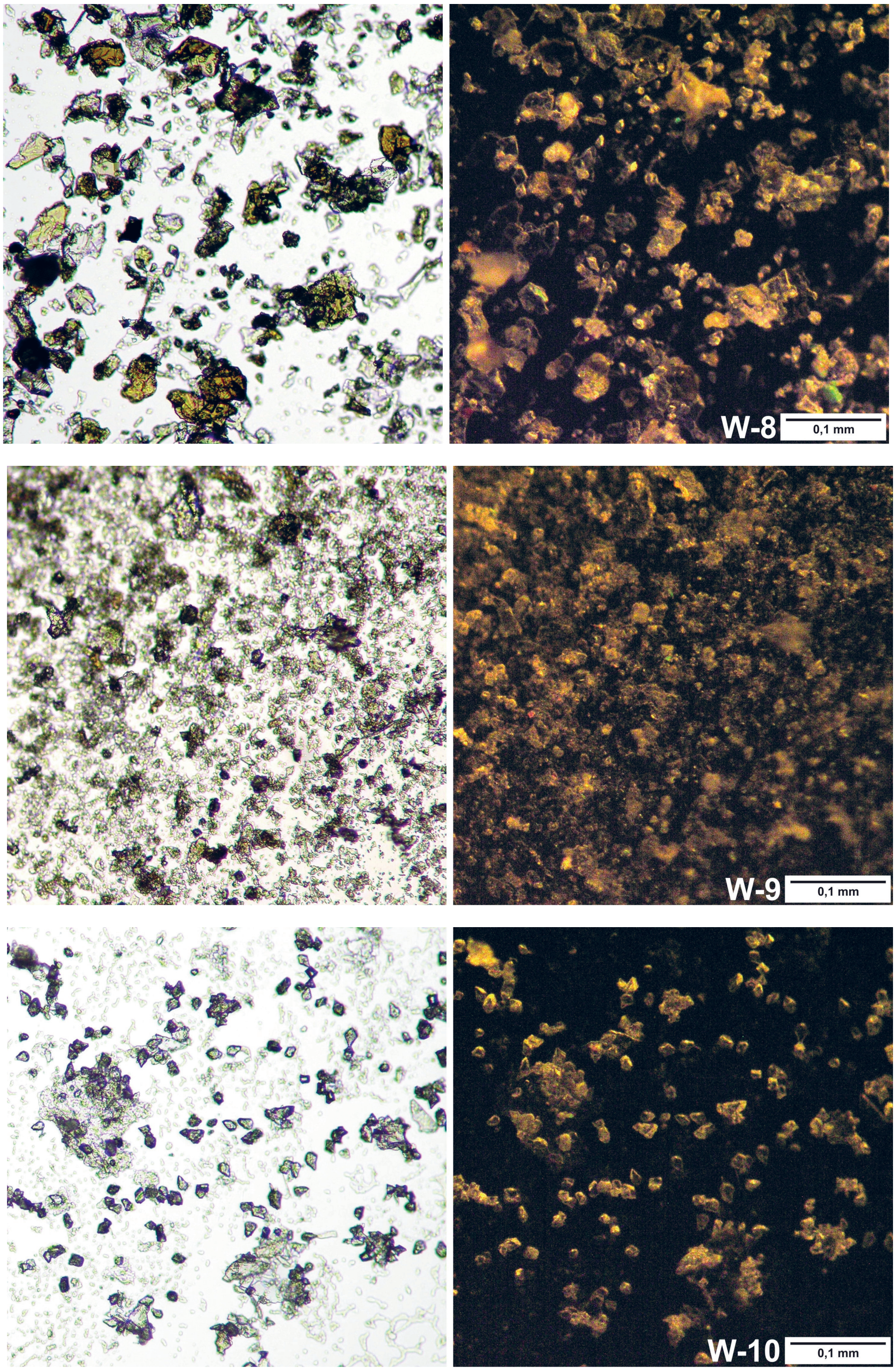

Fig. 4. Sample W-8 under microscope: the dominant minerals with platy habit, light muscovite and darker chlorite. W-9: larger minerals with platy habit within fine material. W-10: evaporites and quartz dust within fine material

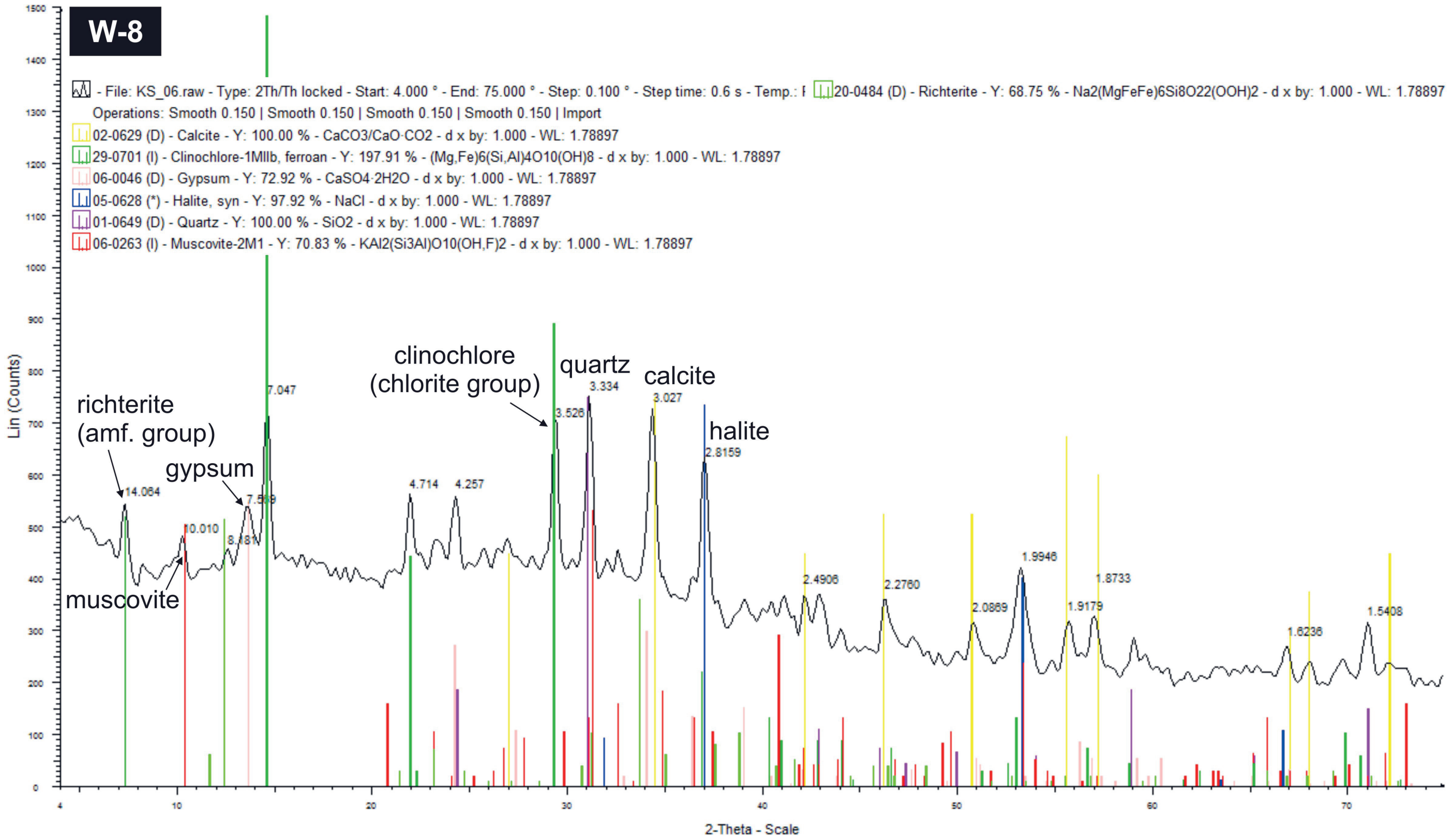

Fig. 5. Diffractogram of a sample W-8

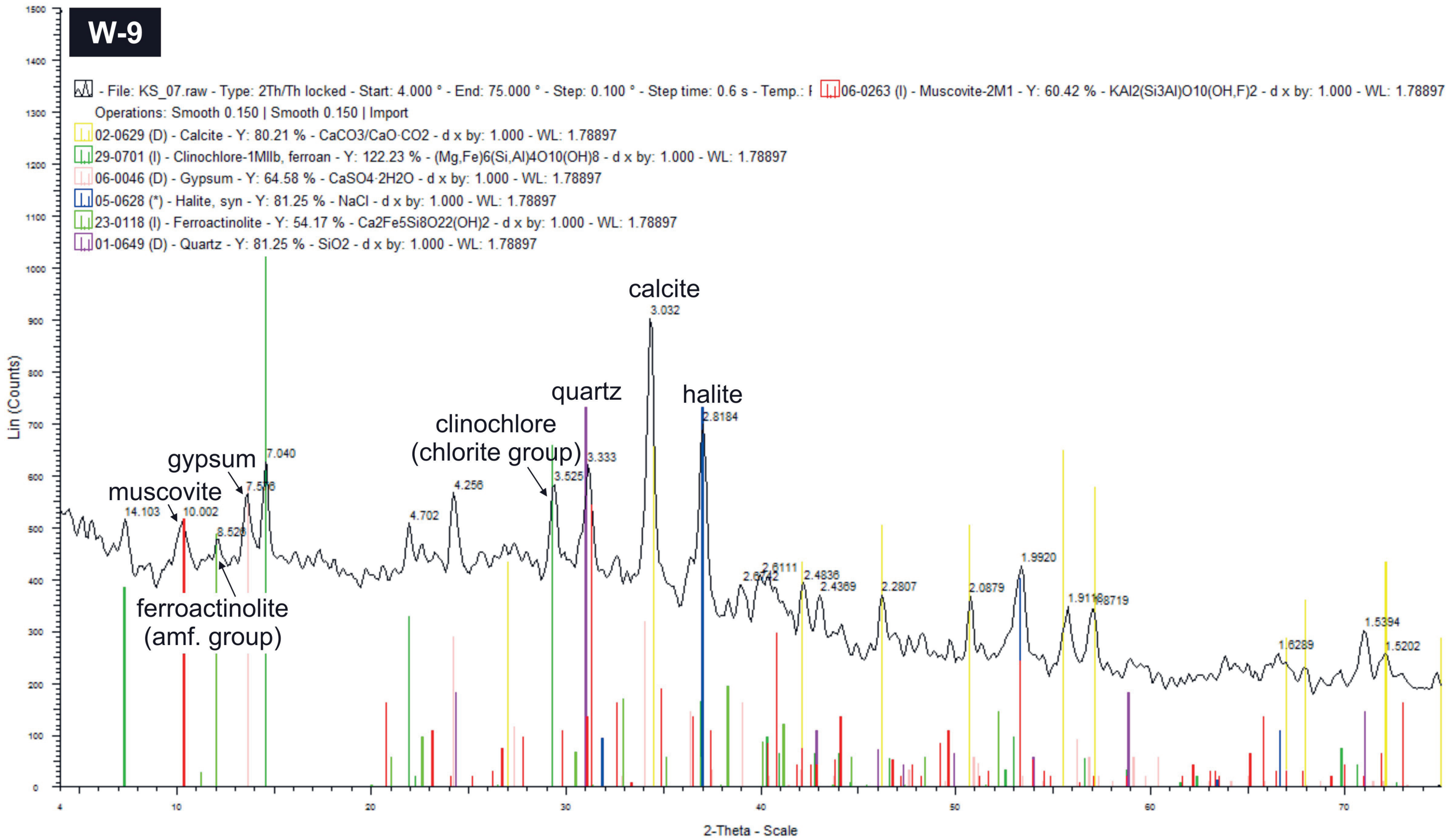

Fig. 6. Diffractogram of a sample W-9

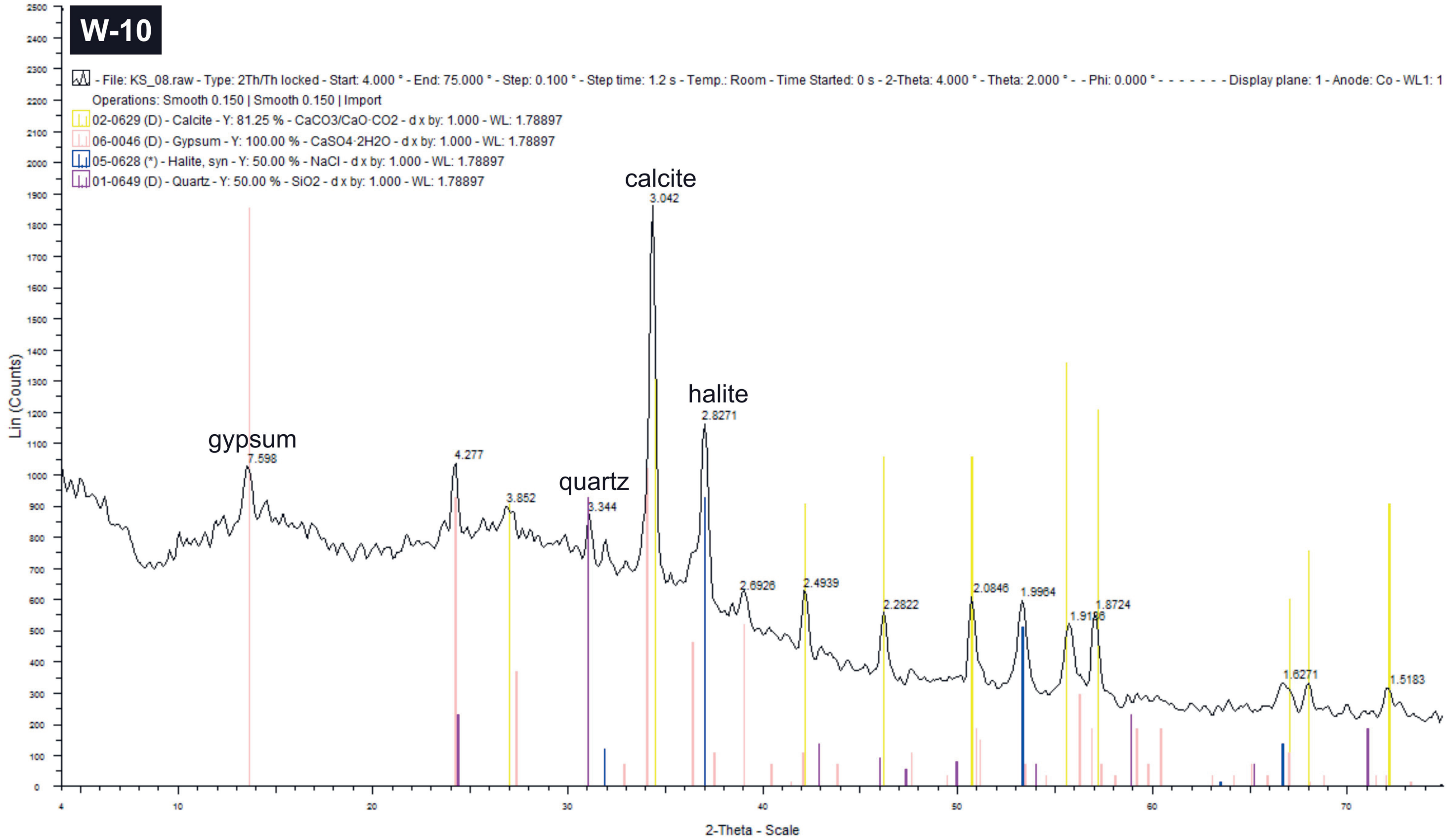

Fig. 7. Diffractogram of a sample W-10

The last group of minerals observed in the mineral composition of all three sites includes calcite, gypsum and halite. Their origin is directly linked to the short distance between water sampling sites and the Greenland Sea and to the occurrence of marine aerosols. Chemical composition of water is dominated by Cl^-, Na^+, SO_4^{2-} and Ca^{2+} ions, which started to crystallize after evaporation of water from the drains. It should be emphasized that the occurrence of these three minerals in a sample does not necessitate their presence in the suspended load. Precipitation of evaporite minerals in the periglacial zone will not be possible due to low temperature. The presence of these minerals in the preparations confirms the occurrence and impact of marine aerosols on the environment of the Brattegg Valley. Salt chlorides (mainly NaCl) can be entrained by wind in the form of marine aerosol and this process is especially intense during storms. For example in the Netherlands "salty rain" may occur as far as 50 km inland (Macioszczyk, Dobrzyński 2007).

All of the mentioned minerals were found at sites W-8 and W-9. The samples contained minerals derived from weathering of crystalline rocks forming talus cones (chlorite and amphibole). There were also minerals transported by wind (muscovite, quartz) as well as the synthetic evaporites, which had precipitated from marine aerosols during drying of the drains (calcite, gypsum, halite). The sample from site W-10 contains very little of the material transported in suspended load. Minerals with platy or needle habit, which could come from the rocks of Gullichsenfjellet, were lacking. The microscopic and XRD analyses of suspended load from site W-10 indicated the presence of quartz and evaporite minerals. The lack of minerals from chlorite and amphibole group and also of muscovite does not influence the precipitation of calcite, gypsum and halite in this site. The analysis confirms that the evaporites come from the marine aerosol. On the basis of the sites W-8 and W-9 it can be assumed that the origin of evaporites is also linked to dissolution of rocks occurring in situ.

DISCUSSION

This study identified locations within a periglacial area with different dynamics of chemical weathering processes. The small study area, small differences of relative height, lack of differentiation in the amount of precipitation, domination of weakly reductive environment, and similarities in bedrock lithology indicate that the differences in the rate and intensity of chemical weathering processes depend on the fragmentation of rocks and duration of water contact with rock mass in the leek-slit circulation system. The work of R.G. Darmody et al. (2005) from Swedish Lapland showed increased weathering at lower elevation and farther down the valley, which might be caused by an older age of debris and slightly warmer climate at the lower part of slopes.

The talus cones in non-glaciated part of Brattegg Valley are the example of an environment with the most dynamic weathering processes, including chemical weathering as confirmed by the results of the water analysis. In the polar

Table 3

Chemical composition of water (in mg/dm^3)

Site	Anions						Kations					Mineralization
	HCO_3^-	F^-	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Na^+	NH_4^+	K^+	Ca^{2+}	Mg^{2+}	
W-1	0.10	0.00	4.24	0.00	0.15	1.25	2.39	0.00	0.55	1.80	0.53	11.11
W-2	0.12	0.01	4.53	0.06	0.20	1.36	2.70	0.09	0.74	2.33	0.50	12.75
W-3	0.11	0.00	4.49	0.06	0.23	1.38	2.52	0.00	0.65	1.87	0.52	11.94
W-4	0.03	0.00	6.19	0.11	0.81	1.42	3.05	0.00	0.62	0.84	0.70	13.80
W-5	0.11	0.12	4.93	0.11	0.40	1.49	2.80	0.00	0.81	2.08	0.60	13.55
W-6	0.16	0.03	7.27	0.11	1.58	2.91	3.29	0.00	1.31	2.93	1.63	21.37
W-7	0.11	0.07	8.01	0.12	2.67	2.47	3.21	0.03	1.36	2.53	1.68	22.37
W-8	**0.40**	**0.06**	**6.69**	**0.14**	**2.09**	**4.15**	**4.69**	**0.01**	**2.52**	**6.84**	**1.36**	**29.35**
W-9	**0.56**	**0.03**	**7.57**	**0.15**	**1.75**	**5.03**	**4.96**	**0.00**	**3.93**	**9.43**	**1.47**	**35.44**
W-10	**0.35**	**0.03**	**8.55**	**0.14**	**2.32**	**4.36**	**4.78**	**0.04**	**1.84**	**5.95**	**2.11**	**30.79**
W-11	0.12	0.05	4.80	0.00	0.30	1.60	2.72	0.00	0.81	1.98	0.68	13.16

environment the changes of air temperature and the fluctuations of the kind and intensity of precipitation are responsible for the weathering of rocks (Anderson et al. 2003). Those weathering processes are typical in periglacial zone and cause intensive interaction between lithology and hydrosphere. This relationship results in physical (or mechanical) weathering, which destroys rocks and unconsolidated sediments and, simultaneously, accelerates chemical weathering of modern sediments (Åkerman 1983; Anderson 2005). M.W. Williams et al. (2006) also indicated that mechanical weathering may lead to enhanced chemical weathering. It is strictly associated with freshly weathered organic and inorganic rock rinds. The processes of dissolution, hydrolysis and hydration occur at all observation sites in the valley, however outside the zone of talus cones (zone IV), most environments have a low rate of chemical weathering.

The amount of suspended load in the five selected zones is different, but most of it is transported by water flowing out of the talus cones. In the polar environment chemical weathering does not influence development of talus cones (Åkerman 1984). The evolution of these forms is largely associated with mechanical weathering and mass movements (Nitychoruk, Dzierżek 1988; André 1996; De Haas et al. 2015). In the case of slope system in Brattegg Valley, the transport of suspended load affects only the distal part of cones during periodic water outflows. The exact area of impact of this process are the places of periodic outflows of water, which determine also the transition from talus cone in the form of alluvial fan. The development of hydrogeochemical conditions is similar to source water of rock glacier outflows from alpine areas (Williams et al. 2006). The study from Colorado Front Range (USA) showed analogous scheme of water infiltration and outflow at the lower part of slopes.

Analysis of the suspended load allowed to specify the mineral composition and sediment supply area for individual grains. Based on analysis using microscopic and X-ray diffraction identified three source material transported in suspension. C.E. Allen et al. (2001) conducted the similar analysis using XRD to material from Swedish Lapland, where their research allowed to determine landscape evolution. Minerals from the group of chlorites, amphibolites and muscovite are derived directly from rocks forming talus cones (quartzites, amphibolites). Quartz in the form of dust and again muscovite was relocated to the talus cones by aeolian transport as a result of sand-dust storms which are typical for the periglacial zone. The last group in the suspended load are the evaporite minerals (calcite, gypsum and halite) which were precipitated after evaporation of water in the preparations. Their presence is associated with the proximity to the coast of the Greenland Sea and the influence of marine aerosols on the chemical composition of water (Małecka 1991; Małecki 1998; Petelski, Chomka 2000). It needs to be highlighted that the minerals associated with marine salts (e.g. S and Cl) are not uncommon in the alpine and polar weathering environments, where they might be associated with the presence of pyrite in the bedrock (Anderson 2005; Dixon, Thorn 2005; Williams et al. 2006).

CONCLUSIONS

The results of this study indicate that talus slopes show greatest intensity of chemical weathering and are the most dynamic environment of the periglacial zone in the analyzed valley. It was confirmed by the highest total mineralization of water and the amount of suspended load. The other two environments: the fields of solifluction lobes and bedrock with thin cover of deposit are less active in terms of chemical weathering.

Water from the outflows within talus cones in the Brattegg Valley does not take part in the main transport mechanisms of slope material directly, but it is a factor responsible for all kinds of weathering in this environment. The activity of different morphogenetic processes on the slopes increases rates of chemical weathering in comparison with the other zones in the valley. Suspended load has two different supply areas: minerals of quartzites and amphibolites of Gullichsenfjellet (minerals of the amphibole and chlorite group) and quartz dust transported by wind from the foreland of the surrounding glaciers.

The samples of suspended load contained evaporite minerals derived from marine aerosols of the Greenland Sea. Chemical composition of water at all observations sites consisted primarily of chlorine (Cl^-) and sodium (Na^+) ions. Concentration of these ions depends on the distance from the coast, but also on wind velocity and direction, especially in the case of the Brattegg Valley.

ACKNOWLEDGMENTS

Participation of Krzysztof Senderak in field expedition has been financed from the funds of the Faculty of Earth Sciences and Environmental Management at the University of Wroclaw. Cooperation in the analysis of the chemical composition of water: Arctic Field Grant 2012, Norwegian Research Council, No. 1885. Krzysztof Senderak is grateful to A. Krzywicka and P. Modzel for practical advice, S. Madej for help with XRD analysis, E. Łepkowska and M. Laska for assistance in lab, and Ł. Stachnik for help with ion chromatography. We are also grateful for two anonymous and helpful reviews.

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