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Petrology, provenance and shape of clasts in the glaciofluvial sediments of the Mníšek member, northern Bohemia, Czechia

Petrologie, původ a tvary klastů z mníšeckých glacifluviálních sedimentů v severních Čechách

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Abstract: Clast petrology, provenance and shape data for the Middle Pleistocene glaciofluvial sand and gravel of the Mníšek member are presented and discussed. The results are compared with those for *in situ* weathered bedrock debris and recent fluvial sediments from the same area. The most common petrological classes are local and near granitoids, and the feldspar and quartz grains that result from their breakdown. Clast form is influenced mainly by the petrological and mineralogical properties of the material; the degree of rounding is controlled by length, energy and mode of transport and, less importantly, by resistance. These findings are at variance with those proposed by others in recent studies. The covariant plot of RA index versus C_{40} index is the most appropriate tool for the graphical presentation and differentiation of glaciofluvial sediments. However, a combination of this type of plot, other covariant plots and linear diagrams yielded good results for the material investigated in this study. The appropriateness of the C_{40} index for differentiation of actively glacially transported material is illustrated by its application to nordic granitoids. The work considered here reinforces the established need, in studies of the impact of environment on clast shape, to examine resistant and isotropic materials such as quartz, quartzite and certain granitoids. Other, far-travelled, rocks investigated in this study (nordic sandstone, chert and flint) are too brittle for the successful application of these methods.

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Introduction

Bedrock geology

The study area lies within the Krkonoše-Jizera Region of northern Bohemia, at the boundary of the Variscan Jizera Massif [JM] in the east and the Early Palaeozoic Jizera Metamorphic Complex [JMC] in the west (Kozdrój et al. 2001) (Fig. 1B). The Jizera granite of the JM underlies the northeastern part of the catchment of the Jeřice River. It is a light grey to pink, almost-invariably porphyritic, medium-grained biotite monzogranite (Klomínský 1969; Kozdrój et al. 2001). The majority of the phenocrysts are of pink K-feldspar, generally 30–50 mm and exceptionally up to 70 mm long; plagioclase phenocrysts are rare (Klomínský 1969). The inequigranular groundmass is composed of plagioclase, K-feldspar, biotite, chlorite and hornblende crystals some 3–5 mm in length. The Jizera granite has been weathered, predominantly by physical processes, to form a waste mantle up to ~3 m thick, consisting of matrix of quartz grains and bleached K-feldspar fragments with relatively resistant corestones (Nývlt 2003a).

The JMC is composed by metagranitoids, granite gneisses and orthogneisses. The Jizera metagranitoids, granite gneisses and orthogneisses are thought to have resulted from metamorphism of the same medium- to coarse-grained granitoids (Domečka 1970, Kozdrój et al. 2001). The metagranitoids display only slight metamorphism and are composed predominantly of bluish quartz and light yellow-grey plagioclase; muscovite and biotite occur as accessory minerals. The JMC rocks are generally more resistant to physical weathering than is the case with the Jizera granite.

Glacial geology

Northern Bohemia was repeatedly invaded by ice sheets during the Middle Pleistocene (Macoun and Králík 1995, Nývlt 1998). The ice reached the area only at times of maximum expansion; glaciation was therefore invariably associated with the marginal zone of the ice sheets, and probably only during relatively short intervals. The extent of each glaciation was also influenced by local topography. The predominantly

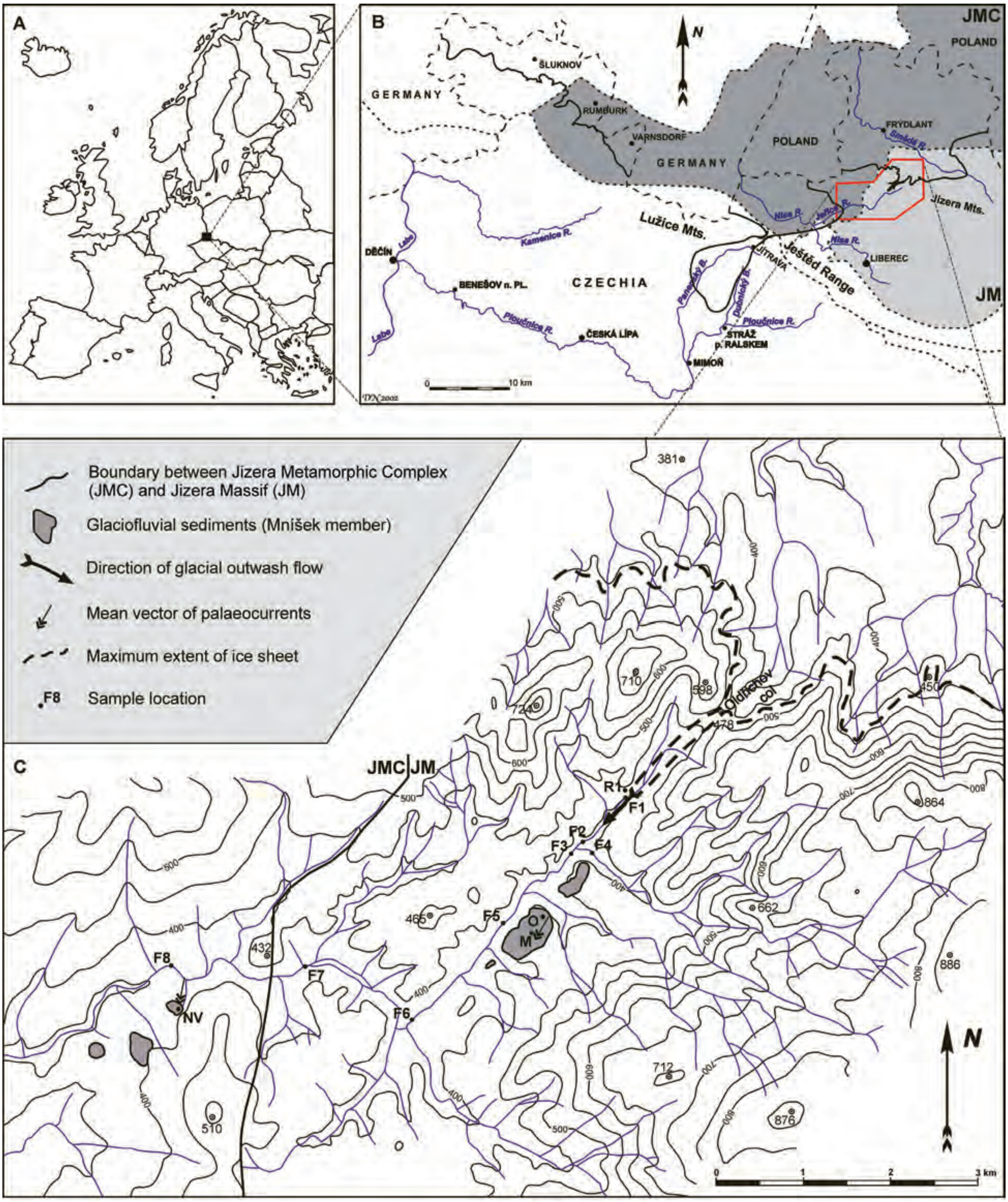


Fig. 1. Location of the studied area (1A and 1B), bedrock geology of the study area: JMC in dark grey, JM in light grey (1B), and sites mentioned in the text with the extent of the Mníšek glaciofluvial sand and gravel terrace and mean palaeocurrent vectors in the outwash sediments (1C). The boundary between the bedrock units is that determined by Kozdrój et al. (2001); the maximum extent of the glaciation is modified from Nývlt (2003a).

rolling uplands of the area culminate in the ridge of the Jizera Mountains. Ice crossed this obstruction at the Oldřichov col (478 m a.s.l.), the highest-known col in northern Bohemia to have been glaciated (Nývlt 2003a). At its maximum extent, this transfluent ice lobe advanced ~1800–2000 m to the south of the col (Figs 1C and 2, modified from Nývlt 2003a). The study area, the valley leading southwards from the Oldřichov col, is a preglacial feature which was modified during the glacial episode and, more recently, by the action of the Jeřice River and its mainly left-bank tributaries (Nývlt 2003a).

Glacial sedimentology

Outwash sediments accumulated as a valley sandur (sensu Bluck 1974) at the front of the transfluent lobe of the ice sheet. Palaeocurrent measurements within the proglacial glaciofluvial sediments, for which we propose the informal name Mníšek member, and the surface slope of the sediment body, provide confirmation of its input from the Oldřichov col (Nývlt 2003a) (Fig. 1). The sediments were subsequently eroded by the Jeřice River to form terrace relics on the southern flank of the valley (Nývlt 2003a) (Figs 1C and 2).

At Mníšek and Oldřichov (Fig. 1C) the material is poorly sorted, fine skewed, mesokurtic to platykurtic gravelly sand and sandy gravel. The most common lithofacies exposed at these two sections are massive clast-supported gravel (Gm), planar (Sp, Gp) and trough (St, Gt) cross-bedded sand and gravel; less common are subhorizontally to horizontally bedded gravel (Gh) and sand (Sh), and ripple cross-laminated sand (Sr) (facies code names are *sensu* Miall [1977] and Benn and Evans [1998]). These lithofacies are characteristic of proximal-intermediate braided stream deposition.

Moderately sorted, fine skewed mesokurtic sand and gravelly sand typifies the more distal sediment at Nová Ves (Fig. 1C). Subhorizontally to horizontally bedded sand with subordinate gravel (Sh, Gh) predominates; cross beds are rare (Nývlt 2003a). Till was not found at any exposure of the Mníšek member (Nývlt and Hoare 2000, Nývlt 2003a). Site to site variations in the petrology of the glaciofluvial sediments at Mníšek and at other exposures in northern Bohemia (Grabštejn, Václavice, Pertoltice) are principally related to the position in which debris was carried within the ice sheet, and to the relief of the area surrounding the depositional sites (Nývlt and Hoare 2000).

Åland rapakivi granitoids and Dala porphyries make up 83–88% of all Nordic indicators found at Mníšek and Nová Ves sites (Nývlt 2003b). Depletion of Nordic indicator granitoids at Nová Ves compared to Mníšek was caused by the mechanical destruction of less resistant granitoid rocks in the dynamic proglacial transport between the Mníšek and Nová Ves localities (Nývlt 2003b).

Although post-depositional periglacial processes are known to have modified Middle Pleistocene glaciofluvial sediments in northern Bohemia to a maximum depth of ~2 m (Nývlt and Hoare, unpublished data), there is no apparent physical evidence of this having occurred at the exposures described in this paper.

Materials and methods

Fine-medium pebble (4–16 mm) fractions were collected by wet sieving material from three localities of the Mníšek member. Samples were obtained at Oldřichov (sample O1), Mníšek (M1–M10) and at Nová Ves (NV1–NV3) (Fig. 1C, Tables 1 and 2). These were divided into 4–8 mm and 8–16 mm fractions by dry sieving in the laboratory for the Oldřichov and Nová Ves samples. Only the 4–8 mm fraction was sampled at the Mníšek locality, these samples were implemented by results from the 8–16 mm fraction of samples M2, M5, M6 and M10 (Nývlt and Hoare 2000). These fractions were studied because the petrology of clasts of this size is relatively easily determined macroscopically.

In situ weathered JM granite debris (sample R1), and eight modern fluvial samples (F1–F8) were sampled. To ensure that the weathered JM granite sample did not include clasts that had been transported by ice or by water, the material was taken immediately above a surface of unweathered granite on a valley sideslope ~30 m above the level of the outwash terrace (Fig. 1C). Since the weathered material consists only of granite debris and grades imperceptibly down into granite bedrock, it is most unlikely that any of it had undergone downslope movement. The recent fluvial gravel was collected from point bars within the channel of the Jeřice River and from an un-named right-bank tributary (Fig. 1C). An 8–16 mm fraction was obtained from all sites by a combination of wet (field) and dry (laboratory) sieving and all three local petrological classes (JM granite, feldspar and quartz) were measured individually. Note that fluvial sediment sample F8 alone lies within the area of JMC rocks (Fig. 1C).

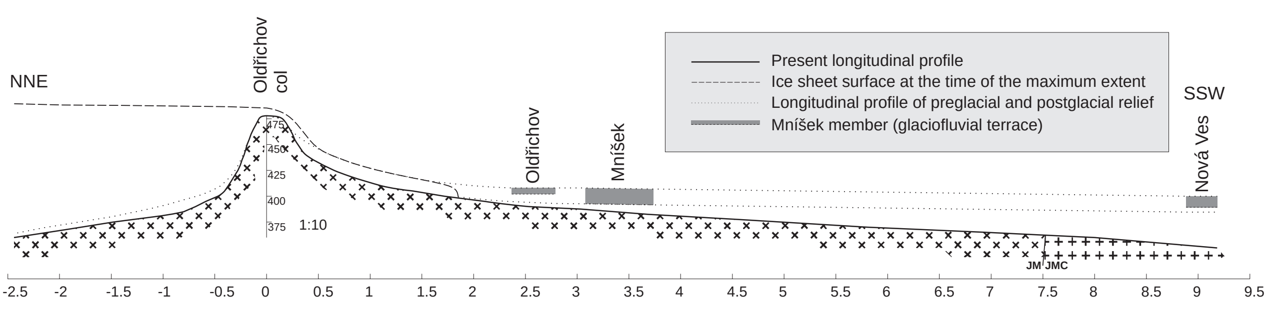


Fig. 2. Longitudinal profile of the Jeřice River valley, the maximum extent of the Middle Pleistocene ice sheet, the position of the Mníšek glaciofluvial terrace, together with longitudinal profiles of the preglacial and postglacial relief (modified after Nývlt 2003a).

Clast petrology and provenance were determined on the Mníšek member samples from Mníšek, Oldřichov and Nová Ves (Table 1 and 2), clast shape on Mníšek member material from Mníšek (sample M5) and Nová Ves (sample NV2) and on *in situ* weathered JM granite debris (R1) and modern fluvial sediments (F1–F8).

Clast petrology and provenance

Sixteen petrological classes have been identified (the term *petrological* should be read to include *mineralogical* in the following account) in the Mníšek member sediments. These are [1] quartz, [2] JM granite, [3] JM feldspar, [4] JMC metagranitoid, [5] JMC feldspar, [6] JMC gneiss, [7] JMC phyllite, [8] JMC quartzite, [9] basalt, [10] conglomerate, [11] near sandstone, [12] nordic sandstone, [13] flint, [14] chert, [15] nordic granitoid and [16] an indeterminate category. These classes are assigned to five 'provenance groups': JM – Jizera Massif includes JM granite and JM feldspar. JMC – Jizera Metamorphic Complex includes JMC metagranitoid, JMC feldspar, JMC gneiss, JMC phyllite and JMC quartzite. K-feldspars were assigned as JM feldspars, plagioclase feldspars on the other hand as JMC feldspars due to the petrological properties of the JM granites and JMC metagranitoids (see above). The group of near rocks comprises basalts (from Czechia and Poland), conglomerate and near sandstone (from Poland). The nordic group includes flint (of Baltic origin), chert, nordic granitoid and nordic sandstone (all of Fennoscandian origin).

Near rocks are derived from closest exposures 10–100 km distant in an up-ice (N) direction. Nordic rocks came from Fennoscandia, Baltic region, and/or from northern Poland and northern Germany, they must had been glacially transported >100 km, but much larger transport distances are very probable. Some of the erratic clasts in the glacial sediments of northern Bohemia have been glacially transported over distances >1000 km.

JM and JMC rock-types may be either 'local' or 'near' as they crop out in both the Jeřice river basin and to the north of Oldřichov col (Fig. 1B). The material delivered from the area to the north of the Oldřichov col examined in this study must have been transported first by ice and then by glacial streams. The 'local' material may simply have been removed from weathered bedrock and carried only by glacial meltwater.

Table 1. Petrology of the samples (% by number)

sample	**O1**		**M1**	**M2**	**M3**	**M4**	**M5**	
clast fraction (mm)	**4–8**	**8–16**	**4–8**	**8–16**	**4–8**	**4–8**	**4–8**	**8–16**
quartz	67.96	46.81	50.25	46.74	75.10	64.33	68.78	46.88
JM granite	15.24	22.05	26.46	25.01	7.58	9.14	13.26	30.47
JM feldspar	2.84	7.47	8.58	18.48	8.91	8.69	5.77	4.69
JMC metagranitoid	6.21	5.65	4.90	0.54	1.33	5.79	5.77	
JMC feldspar	1.29	1.82	3.19	0.54	2.13	4.72	1.97	
JMC gneiss	1.03	2.73	3.68	1.63	0.67	0.30	0.70	0.78
JMC phyllite						0.15	0.26	
JMC quartzite	1.03	2.00					0.09	2.34
basalt	0.26	0.91						
conglomerate					0.27			2.34
near sandstone	1.81	4.37	1.23	1.63	2.27	3.96	0.78	3.13
nordic sandstone	1.03	0.37	0.73	2.17	0.81	0.61	0.26	0.78
flint	0.52	1.46	0.25	0.54	0.13	0.46	0.52	0.78
chert	0.78	3.28	0.25	0.54	0.40	1.22	0.87	3.91
nordic granitoid		1.08	0.49	2.17	0.40	0.15	0.96	2.34
indetermined						0.46		1.56
Total	100.00	100.00	100.01	99.99	100.00	99.98	99.99	100.00

Table 2. Provenance of the clasts in the samples (% by number)

sample	**O1**		**M1**	**M2**	**M3**	**M4**	**M5**	
clast fraction (mm)	**4–8**	**8–16**	**4–8**	**8–16**	**4–8**	**4–8**	**4–8**	**8–16**
JM	18.08	29.52	35.04	43.49	16.49	17.83	19.03	35.16
JMC	9.56	12.20	11.77	2.71	4.13	10.96	8.79	3.12
near	2.07	5.28	1.23	1.63	2.54	3.96	0.78	5.47
nordic	2.33	6.19	1.72	5.42	1.74	2.44	2.61	7.81
quartz	67.96	46.81	50.25	46.74	75.10	64.33	68.78	46.88
indetermined						0.46		1.56
Total	100.00	100.00	100.01	99.99	100.00	99.98	99.99	100.00

It is not possible to establish unequivocally the provenance of hand specimens of quartz in the Mníšek member. Nearly all of the quartz clasts in the study area are likely to have been derived from JM and JMC rocks and to have been transported <30 km; extremely short transport distances are quite probable (Nývlt and Hoare 2000). However, since all the principal rivers to the north of the study area flow towards the north, clasts composed of ‘near’ rocks which have been taken by the ice sheet from older fluvial or glacial sediments may have travelled over distances >100 km. In so doing, they are likely to have acquired a succession of overprinted shapes.

Clast shape

We consider only the form, roundness and sphericity since the coarse-grained crystalline lithologies that dominate the fractions examined in this study seldom display striations, chatter/percussion marks or other micro-scale surface erosional features. Form refers to the relative dimensions of the orthogonal long (*a*), intermediate (*b*) and short (*c*) axes of a clast and is here presented in equilateral ternary clast-form diagrams (Sneed and Folk 1958, Hockey 1970, Benn and Ballantyne 1993, 1994). Roundness is the degree of curvature of a clast’s corners and edges; we used visual roundness (Krumbein 1941) in this study. The decimal values (Krumbein 1941) were transferred to the Powers (1953) scale of six roundness classes. Sphericity measures the equality of the length axes of a clast and in this study is represented by the maximum projection sphericity – MPS (Folk 1955, Sneed and Folk 1958). Form, sphericity and roundness were determined for each clast by following the procedures outlined in Gale and Hoare (1991) and Evans and Benn (2004).

Twenty clasts from the 4–8 mm and 8–16 mm fractions and from 11 petrological classes (quartz, JM granite, JM feldspar, JMC metagranitoid, JMC feldspar, JMC gneiss, near sandstone, nordic sandstone, flint, chert, nordic granitoid) were measured for the Mníšek member samples M5 and NV2. The other petrological classes were not represented in sufficient numbers in the studied samples of the Mníšek member and are not considered for clast shape study. *In situ* weathered JM granite debris (sample R1), and eight modern fluvial samples (F1–F8) were analysed in order to provide

Table 1 – continued

M6		M7	M8	M9	M10	NV1		NV2		NV3	
4–8	**8–16**	**4–8**	**4–8**	**4–8**	**8–16**	**4–8**	**8–16**	**4–8**	**8–16**	**4–8**	**8–16**
72.12	67.23	69.06	72.28	70.38	64.36	73.55	59.14	70.77	58.49	73.10	59.58
11.78	16.81	12.65	12.95	11.73	9.34	12.38	14.10	10.75	11.42	8.62	8.53
4.80	2.52	5.74	4.37	3.37	7.96	4.46	5.18	3.87	4.04	3.41	2.28
4.11		5.38	4.88	7.34		3.05	8.15	7.31	11.08	7.30	12.73
1.71		1.88	1.33	0.73		1.36	3.05	1.51	3.87	2.96	3.41
0.82	0.84	1.43	0.51	1.61	4.84	0.84	1.32	1.16	3.03	0.35	3.04
0.07		0.27		0.29	0.35		0.33				
0.34	3.36	0.09	0.51	0.73	4.84		0.49	0.43	1.01	0.18	0.76
					0.35						0.95
	0.84				0.35	0.08	0.33	0.29	0.34	0.18	0.38
1.37	0.84	1.70	0.89	0.88	0.35	1.14	3.13	0.72	1.84	1.24	3.41
0.48	4.20	0.27	0.13	0.88	1.38	0.99	0.17	0.29	0.17	0.18	2.09
0.07		0.27	0.38	0.73	0.69	0.08	1.15	0.43	0.84	0.35	0.95
1.23	0.84	0.27	1.01	0.73	1.73	1.45	0.99	1.45	2.35	1.06	0.76
1.10	2.52	0.99	0.77	0.59	2.77	0.61	2.14	1.01	1.51	1.06	1.13
					0.69		0.33				
100.00	100.00	100.00	100.01	99.99	100.00	99.99	100.00	99.99	99.99	99.99	100.00

Table 2 – continued

M6		M7	M8	M9	M10	NV1		NV2		NV3	
4–8	**8–16**	**4–8**	**4–8**	**4–8**	**8–16**	**4–8**	**8–16**	**4–8**	**8–16**	**4–8**	**8–16**
16.58	19.33	18.39	17.32	15.10	17.30	16.84	19.28	14.62	15.46	12.03	10.81
7.05	4.20	9.05	7.23	10.70	10.03	5.25	13.34	10.41	18.99	10.79	19.94
1.37	1.68	1.70	0.89	0.88	1.05	1.22	3.46	1.01	2.18	1.42	4.74
2.88	7.56	1.80	2.29	2.93	6.57	3.13	4.45	3.18	4.87	2.65	4.93
72.12	67.23	69.06	72.28	70.38	64.36	73.55	59.14	70.77	58.49	73.10	59.58
					0.69		0.33				
100.00	100.00	100.00	100.01	99.99	100.00	99.99	100.00	99.99	99.99	99.99	100.00

benchmark values against which to judge changes in clast shape brought about by ?glacial, fluvial and glaciofluvial transport. The Oldřichov col has been adopted as the ‘zero point’ from which to evaluate downstream changes in clast shape. We have made the not unreasonable assumption that the modern fluvial sediments were derived almost exclusively from the subjacent JM granite bedrock. The present valley floor of the Jeřice River is isolated from the lithologically varied glaciofluvial sediments of the Mníšek member by a bedrock ridge and the incorporation of glaciofluvial sediments to the present river is unlikely.

Equilateral ternary clast-form diagrams were constructed for petrological and provenance groups from different depositional environments (Figs 4 and 5). Clast roundness is presented as relative-proportion histograms for individual petrological classes (Figs 7 and 8). The RA index is defined as the percentage of very angular and angular clasts (Benn and Ballantyne 1994). An arbitrary threshold value for Krumbein’s visual roundness of 0.25 according to Powers (1953) has been adopted in this study. The C_{40} index gives the percentage of clasts with a *c : a* ratio of <0.4; this value was chosen by Ballantyne (1982) and has been confirmed as ‘meaningful’ on the basis of numerous empirical studies (e.g. Ballantyne 1986, Benn 1989, 1992, Vere and Benn 1989). For sphericity MPS (Folk 1955, Sneed and Folk 1958) is preferred to intercept sphericity (Krumbein 1941) as the former is widely regarded as more sensitive to clast settling velocity. The average roundness and average MPS were calculated for individual samples. The overall shape of clasts is expressed in covariant plots of (a) average roundness versus average maximum projection sphericity (MPS), and (b) C_{40} index versus RA index.

Clast petrology and provenance

The petrology of the Mníšek member is dominated by JM granites and JMC metagranitoids, together with their weathering and erosional products (feldspars and quartz) (Tables 1 and 2). These constituents make up 86–97% of the petrological counts. The proportion of ‘near’ rocks lies between 0.8 and 5.5%, and that of ‘nordic’ rocks between 1.7 and 7.8% of the stone-count fraction.

At Mníšek (located on JM bedrock) a greater amount of local JM granite and feldspar is apparent in the lower part of the exposure especially in the coarser fraction studied (Fig. 3, Table 2). The content of JM rocks diminishes up-section in both studied fractions. The content of JMC rocks varies throughout the section in the finer fraction, however there is a clear increase of JMC rocks in the 8–16 mm fraction. The trend in the increasing content of the JMC rocks up-section is true for all its petrological classes but JMC feldspar. Quartz is generally more common in the finer 4–8 mm fraction, where its content is more or less stable and lies in the range of 65–75% (if the lowermost sample M1 is omitted). Quartz is more common in the 8–16 mm fraction in the upper part of the Mníšek succession then is the case of its lower part. The ‘near’ and ‘nordic’ groups are more common in the coarser studied fraction. They are poorly represented in the lowermost beds at Mníšek, but their maximum content was found in the middle part of the succession (samples M4–M6).

Quartz is the most common petrological class in both fractions in the more distal sediments at Nová Ves, it is more common in the finer fraction (71–74%), than in the coarser fraction (58–60%). The Nová Ves sediments (on JMC bedrock) also display an up-section change in provenance from a more common JM material at the base to a greater proportion of JMC rock types in both studied fractions. The ‘near’ and ‘nordic’ groups are more common in the coarser fraction. Overall, however, there is much less vertical variation in the percentages of the various petrological classes here than at Mníšek (Fig. 3). In spite of that, we should take in mind, that we do not know which layers at the Mníšek locality are synchronous to the layers at the Nová Ves locality. Compared with the petrological composition of the sediments at Mníšek, the Nová Ves deposits show nearly similar contents of all petrological classes but JMC rocks, the content of which is significantly higher. Greater amounts of JMC rocks at Nová Ves are consistent with the position of the site on the JMC, ~1.0–1.5 km downstream from the JMC/JM boundary.

Clast shape

Clast form

The equilateral ternary clast-form diagrams for the major petrologies represented in the glaciofluvial sediments of the Mníšek member are shown in Figure 4. The form of clasts composed of local JM rocks found in the *in situ* weathered bedrock debris and in the recent fluvial sediments are compared in Figure 5.

In situ weathered bedrock debris

JM quartz clasts in the *in situ* weathered bedrock debris sample display compact, compact-bladed to compact-platy forms, with high average values of the *c:a* ratio (0.65) and low C_{40} value (5%). The JM feldspar class in the *in situ* weathered bedrock debris is principally composed of bladed and platy to compact-platy clasts with relatively low average values of the *c:a* ratio (0.54) and still low C_{40} value (15%). The JM granite class in the *in situ* weathered bedrock debris contains the highest proportion of compact-bladed, compact-elongated and bladed clasts, and displays average values for the *c:a* ratio (0.61) with the lowest possible C_{40} value (0%). Clasts of both JM quartz and JM feldspar classes tend to be more platy than clasts of the JM granite from the *in situ* weathered bedrock debris (Fig. 5).

Fluvial deposits

JM quartz clasts in recent fluvial gravel display compact, compact-bladed to compact-platy forms, with medium average values of the *c : a* ratio (0.58) with C_{40} values between 5 and 15%. The JM feldspar class is principally composed of bladed and platy to compact-platy clasts with relatively low average values of the *c : a* ratio (0.44) and nearly half of the clasts with *c : a* ratio below 0.4 – C_{40} values (20–70%). The sample F6 is exceptional as it contains a higher proportion of more compact JM feldspar clasts with lower C_{40} value (20%). The JM granite class contains the highest proportion of compact-bladed and compact-elongated clasts, and displays average values for the *c:a* ratio (0.57) with the lowest C_{40} values (<10%).

It is evident that there is a slow but progressive reduction of the average *c : a* ratio for all three petrological classes during the downvalley fluvial transport. Clasts of fluvially transported JM quartz and JM feldspar tend to be, similarly to the *in situ* weathered bedrock debris, more platy than those of the JM granite (Fig. 5).

Mníšek member

Glaciofluvially transported quartz, together with all granitoid classes, typically shows the highest average values for the *c : a* ratio (usually 0.50–0.55) and lowest

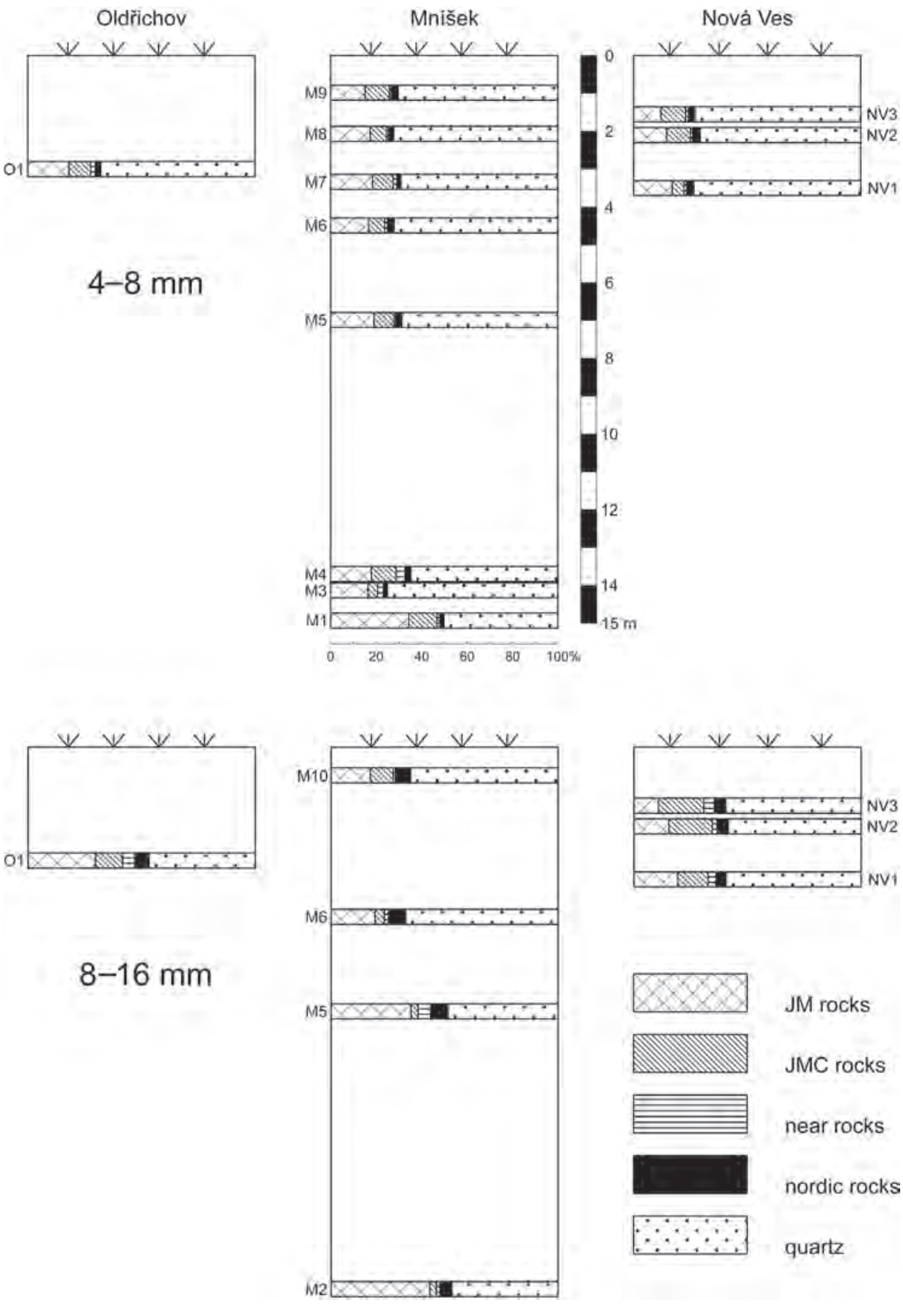


Fig. 3. Comparison of vertical and downstream clast provenance changes of the glaciofluvial samples in each clast fraction (relative depth from the undisturbed present top surface of the accumulation).

C_{40} values (mostly 5–20%) within all studied petrological classes of glaciofluvial sediments, the C_{40} values are lower for the 4–8 mm fraction. The C_{40} values for JM feldspar and JMC feldspar are moderate at ~20%, but they are generally higher in the 4–8 mm fraction. The highest C_{40} values (30–75%) with the lowest average *c : a* ratio (usually ≤0.4) are on the other hand typical for JMC gneiss, flint and both sandstone classes. A comparison in both analysed quartz fractions in the glaciofluvial material at Mníšek does not show any important differences in clast form. There is no significant change in the form of quartz clasts between Mníšek and Nová Ves (Fig. 4).

There is evidence, that glaciofluvial transport of the material from Mníšek to Nová Ves was responsible for a reduction in the number of JM granite clasts with a *c:a* ratio >0.7; a smaller range of values is therefore evident at Nová Ves (Fig. 4). The same general trends hold true for the more variable JM feldspar but, since it is a relatively less resistant material, a higher proportion of C_{40} clasts with bladed forms are produced during glaciofluvial transport.

All of the JMC clasts at Mníšek must have been glacially transported from outcrops and/or sediments located to the north of the Oldřichov col, then carried and finally deposited by glaciofluvial processes. The class of JMC metagranitoid is therefore more homogeneous in clast form than that derived from the subjacent JM granite, having fewer compact clasts and a greater number of elongated ones.

The prominent downstream change in the form of the JMC metagranitoid clasts in the 8–16 mm fraction towards more elongated forms is apparent at Nová Ves. This change is thought to be due to the entrainment of some relatively local JMC clasts with either lower *c:a* values and/or more elongated form. The JMC gneiss and feldspar classes tend to contain more platy-formed clasts in the coarser fraction at Nová Ves.

Both near and nordic sandstone classes display considerable within-sample variation in clast form, but generally exhibit high C_{40} figures (30–60%). The dimension of the within-site variation in flint clast shape at Mníšek is greatly reduced at Nová Ves, where C_{40} values are lower and there has been a significant increase in the *c:a* ratio, especially in the 8–16 mm fraction. This change appears to have been brought about by the reduction in numbers of clasts with the highest (>0.65) and lowest (<0.25) *c : a* values (Fig. 4). Glaciofluvial transport produced more elongated flint and chert clasts in the smaller fraction.

Chert shows moderate (at Mníšek) to high (Nová Ves) C_{40} values. Significant decreases in the elongation index for chert in the smaller fraction is seen as a shift from platy to predominantly elongated clasts. The more platy forms of the nordic granitoid clasts at Mníšek are changed towards more bladed or slightly elongated forms at Nová Ves.

Clast sphericity

In situ weathered bedrock debris

JM quartz clasts in the *in situ* weathered bedrock debris sample display high average values for MPS (0.79), the JM feldspar clasts has relatively high average values for MPS (0.71), the JM granite clasts display average values for MPS (0.77) which are intermediate between those for JM quartz and JM feldspar (see Fig. 6).

Fluvial deposits

The trend of change of the MPS values in the downvalley direction is very similar for the JM quartz and JM granite. The highest MPS values (0.78–0.79) are typical for the most upstream sample F1, the MPS values decrease downward being lowest at the F4–F5 samples (0.70–0.71) and then rise towards (0.75–0.76) at the F8 sample. The same trend is typical for JM feldspar, but as a less spherical petrological class its MPS values are much lower (0.67 for F1, 0.59 for F5 and 0.64 for F8); with the exception of the F6 sample (MPS = 0.71), which is clearly an outlier (see Fig. 6).

Mníšek member

Glaciofluvially transported quartz, together with all granitoid classes and JMC feldspar, shows the highest MPS values (usually >0.7) within all studied petrological classes of the glaciofluvial sediments of the Mníšek member. The lowest values are on the other hand typical for JMC gneiss, flint and both sandstone classes (mostly <0.63). Both feldspar classes and chert display intermediate MPS values of ~0.63–0.72.

There is a clearly defined decrease in the average MPS values of quartz in the 8–16 mm fraction (0.76 at Mníšek) after glaciofluvial transport of the material to Nová Ves (0.69 at Nová Ves) (Figs 4 and 9). Nevertheless, as is to be anticipated, certain individual quartz clasts display high MPS values in all environments. The provenance of quartz clasts from the glaciofluvial Mníšek member is unknown and the change in sphericity may be caused by different properties of some proportion of quartz clasts in the Mníšek member. However, typical average MPS values of quartz are highest for the *in situ* weathered JM quartz debris (0.79), somewhat lower for the JM quartz from fluvial sediments upstream (0.78–0.74), and lowest for the downstream JM quartz from fluvial sediments (0.75–0.70) and for quartz from glaciofluvial Mníšek member (0.76–0.69).

The proportion of highly spherical (MPS > 0.75) local JM granite clasts in the glaciofluvial sediments at Mníšek is similar to that in the *in situ* weathered JM granite bedrock debris and in material, which has undergone only short fluvial transport. The proportion, however, is greater than that in the Nová Ves deposit (Fig. 5). There is evidence, that further glaciofluvial transport of the material to Nová Ves was responsible for a reduction in the number of highly spherical JM granite clasts

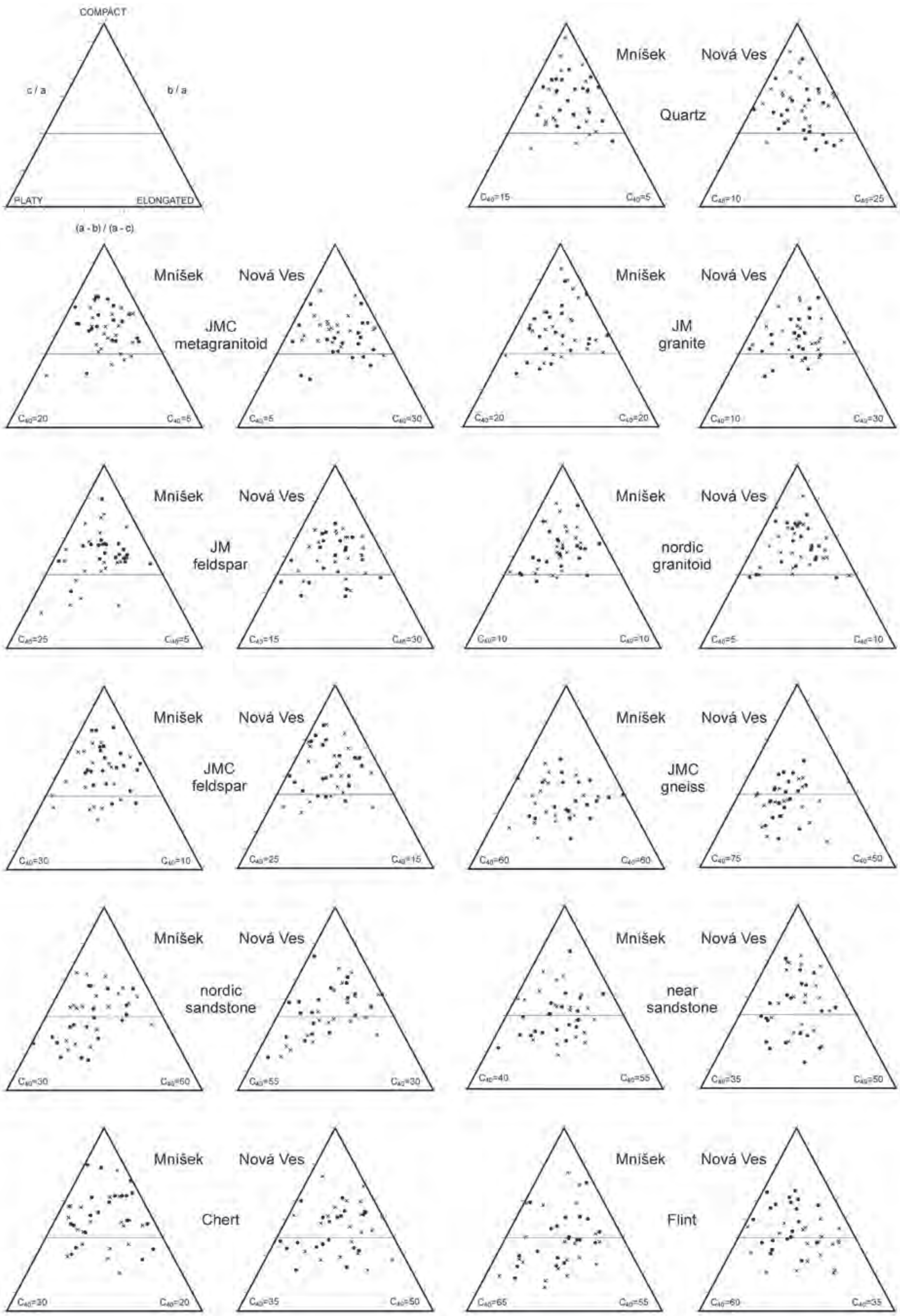


Fig. 4. Equilateral ternary clast-form diagrams for all petrological classes, Mníšek member; sample M5 for Mníšek and sample NV2 for Nová Ves. The coordinate system is based on Hockey's (1970) modification of Sneed and Folk's (1958) clast-form triangular diagram and was drawn using Graham and Midgley's (2000) spreadsheet method. Each sample contains 40 clasts, 20 from the 4–8 mm fraction with C_{40} value on the left side (crosses) and 20 from the 8–16 mm fraction with C_{40} value on the right side (circles).

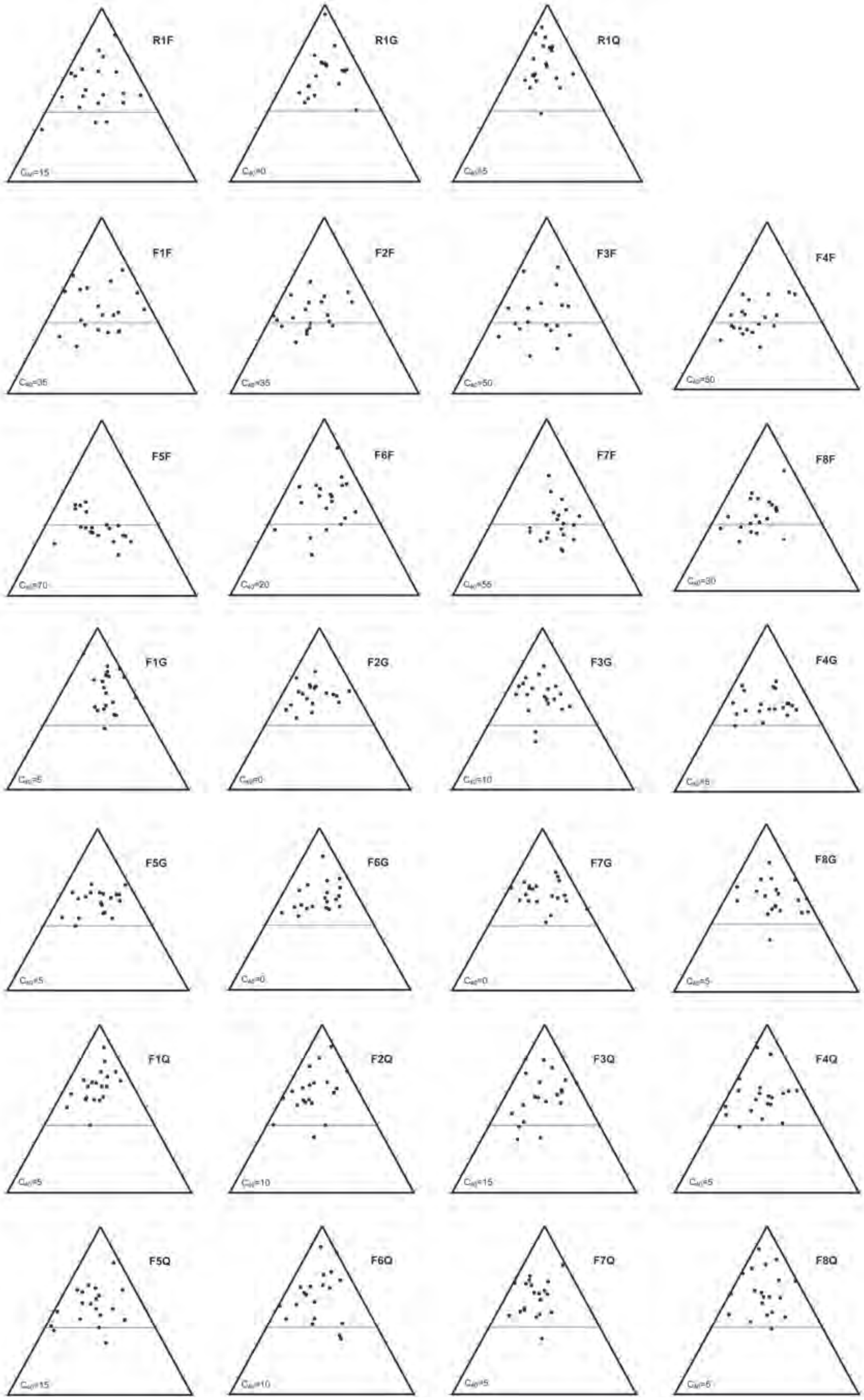


Fig. 5. Equilateral ternary clast-form diagrams for local JM rocks from *in situ* weathered JM granite debris (R1) and modern fluvial (F1–F8) samples. F – feldspar, G – granite, Q – quartz. For sample locations see Fig. 1. The coordinate system is based on Hockey's (1970) modification of Sneed and Folk's (1958) clast-form triangle and was drawn using Graham and Midgley's (2000) spreadsheet method. Each sample contains 20 clasts of 8–16 mm *b*-axis length. For an explanation of the ternary diagram, see the caption to Fig. 4.

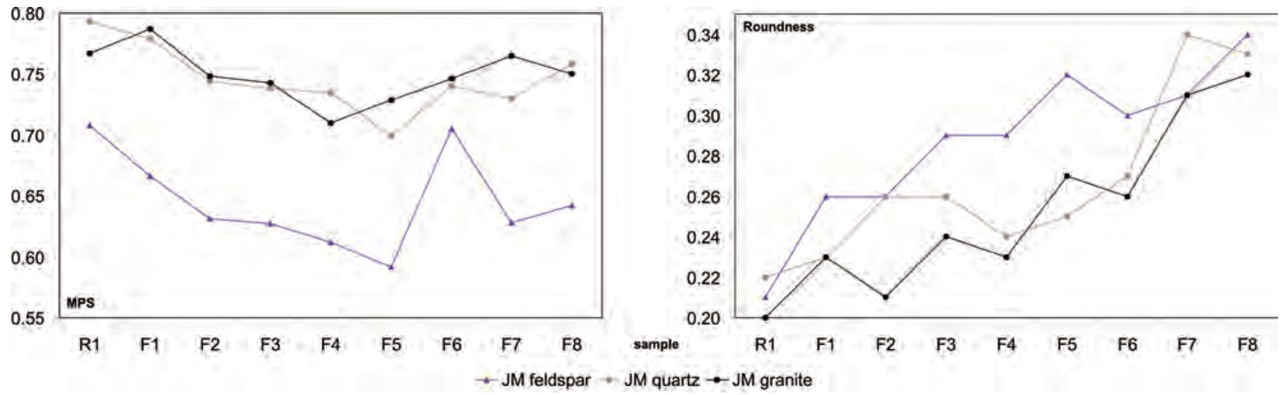


Fig. 6. Downstream trend of the average MPS and average roundness values for fluvial samples F1–F8 compared with *in situ* weathered bedrock debris sample R1 for JM quartz, JM granite and JM feldpsar. The location of the sample sites is shown in Fig. 1. Each sample consists of 20 clasts in the 8–16 mm fraction.

(MPS > 0.75). There is no significant change in the MPS values of JM and JMC feldspars and JMC gneiss between Mníšek and Nová Ves. The downstream decrease in the MPS values for the 8–16 mm fraction of the JMC metagranitoid is apparent at Nová Ves. The changes are thought to be due to the entrainment of some relatively local JMC clasts with lower sphericity.

Both near and nordic sandstone classes display considerable within-sample variation in clast sphericity and a slight downstream increase in MPS values. The dimension of the within-site variation in flint clast shape at Mníšek is greatly reduced at Nová Ves, where a significant increase in MPS, especially in the 8–16 mm fraction, occurs. Chert shows a very pronounced decrease of MPS values for the 8–16 mm fraction (Fig. 9).

Clast roundness

In situ weathered bedrock debris and fluvial deposits

We begin by assuming that the initial shape of fluvially transported sediment resembled the *in situ* weathered bedrock debris (sample R1). JM feldspar clasts in the *in situ* weathered bedrock display an average roundness of 0.21 (initial average roundness); 60% of them are VA and A (Fig. 6). After a fluvial transport path of only 3.5 km, SA JM feldspar clasts of average roundness 0.32 predominate in sample F5. The subsequent ~5 km of fluvial transport failed to further alter appreciably the roundness of the feldspars. JM quartz (initial average roundness 0.22) and JM granite (initial average roundness 0.20) clasts reached roundness values of 0.34 and 0.31 respectively following fluvial transport over 6.5 km. The ‘final’ average roundnesses (after 8.4 km of fluvial transport) of JM granite, JM feldspar and JM quartz clasts (0.32–0.34) are intermediate between SA and SR (Fig. 6). It should also be taken in account that some less rounded clasts (especially from the samples F4 and F6, see Fig. 6) are derived from the Jeřice River tributaries and experienced shorter transport distances than the material transported in the main stream.

Mníšek member

Glaciofluvially transported clasts of quartz, JM granite and JMC metagranitoids show the most pronounced downstream rounding, displaying a shift from mainly SA–SR (at Mníšek) towards a predominance of rounded particles (at Nová Ves) – see Fig. 7. A slightly less pronounced transformation in roundness is seen in the JM feldspars. The Nordic granitoids and JMC feldspars are not affected to any significant extent. The downstream rounding of all classes, with the exception only of flint, is connected with the elimination of most of the angular clasts. High-energy glaciofluvial transport apparently caused the fracturing of rounded to well rounded clasts of chert and both types of sandstone, and led to a corresponding rise in the proportion of SR clasts (Fig. 7). JMC gneisses and flint were changed but little in clast roundness during glaciofluvial transport.

Downstream changes of clast roundness in glaciofluvial material is illustrated in Figure 7; corresponding modifications in the modern fluvial sediments is shown in Figure 8. Comparison of roundness data and MPS values is presented in Figure 9.

Covariant plots of clast form, sphericity and roundness

The covariant plots of average MPS versus average roundness permit the clasts of local JM granite, JM quartz and JM feldspar in the *in situ* weathered JM granite debris show differences from clasts with those compositions in the glaciofluvial sediment (Fig. 9). Material of fluvial origin plots between these two classes. Clasts modified by short-distance fluvial transport do not differ greatly from those in the *in situ* weathered JM granite debris; further fluvial transport creates shapes which closely resemble glaciofluvially transported clasts. The use of the relatively insensitive clast average

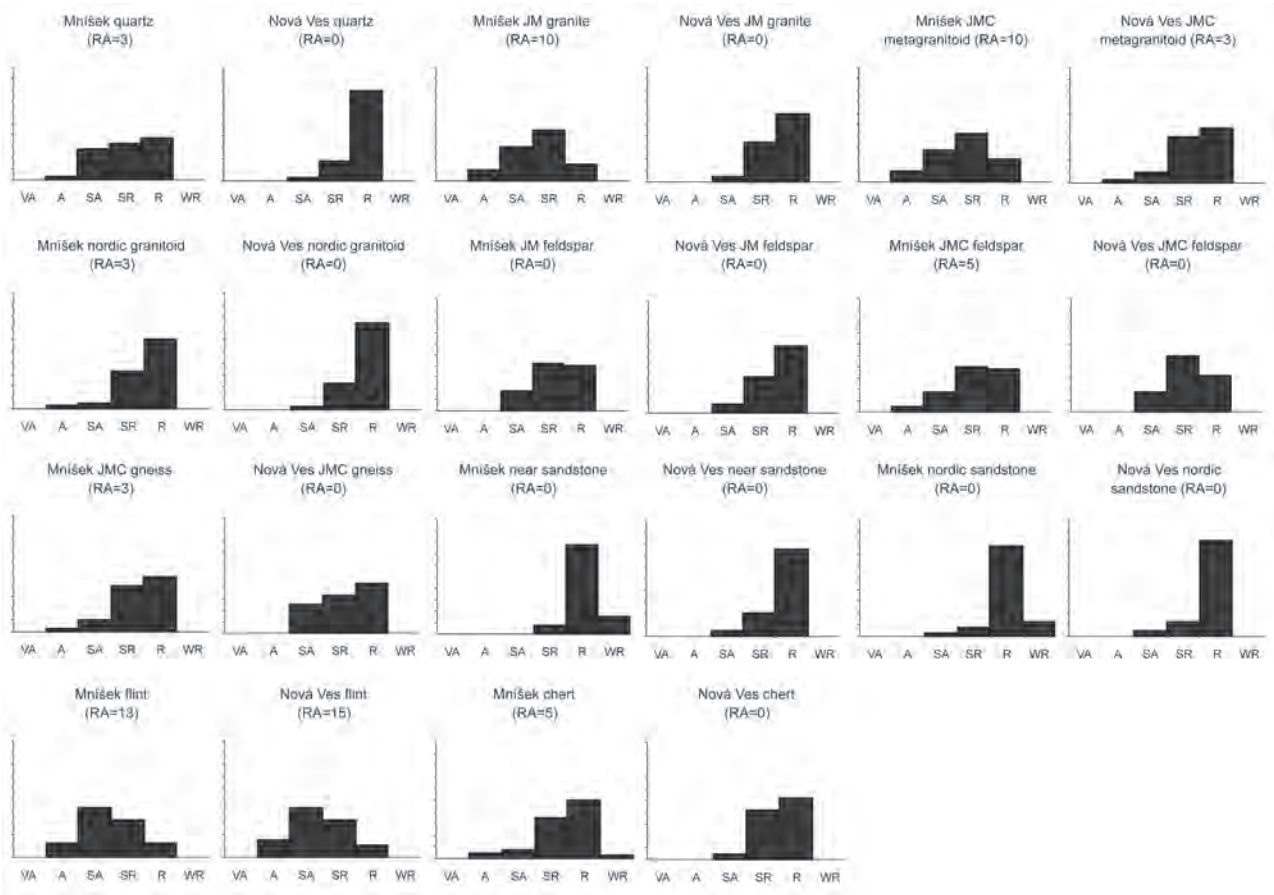


Fig. 7. Relative-proportion roundness histograms, Mníšek member; samples M5 for Mníšek and NV2 for Nová Ves. VA – very angular, A – angular, SA – subangular, SR – subrounded, R – rounded, WR – well rounded, RA – very angular and angular. Each sample consists of 40 clasts, 20 each from the 4–8 mm and 8–16 mm fractions.

MPS versus average roundness plots is manifestly of limited value in such circumstances, where short transport paths bring about only small shape changes.

On the other hand, the covariant plot of RA versus C_{40} allows a distinction to be made between clasts from *in situ* weathered JM granite debris, and those that have been fluvially and glaciofluvially transported (Fig. 10). The *in situ* weathered JM granite clasts show low C_{40} values and a predominance of VA and A clasts. Fluvially modified JM granite and quartz display low C_{40} values and a downstream rounding of clasts and thus decrement of the VA and A clasts. The downstream rounding of JM feldspar clasts is associated with an increase in low sphericity clasts and a corresponding increase in C_{40} values (Fig. 10). Glaciofluvially transported petrologies are characterised by low RA values and low to moderate C_{40} values.

Discussion

A number of important issues have emerged as a result of the work reported here. These concern (a) the influence of clast petrology on shape, (b) downstream changes in fluvially and glaciofluvially transported clasts and (c) the suitability of different methods for environmental discrimination.

The role of clast petrology on the final shape of particles in different sedimentary environments has been investigated in numerous studies (e.g. Goede 1975, Mills 1979, Bridgland 1986, Huddart 1994, Bennett et al. 1997, Sikorová et al. 2006). Boulton (1978) employed covariant plots of Krumbein's visual roundness versus Krumbein's (1941) intercept sphericity to distinguish different glacial environments (see also Dowdeswell et al. 1985, Gale and Hoare 1991, Bennett et al. 1997). However, the covariant plot of RA versus C_{40} *sensu* Benn and Ballantyne (1994) allows a much better distinction to be made between clasts from *in situ* weathered JM granite debris, and those that have been fluvially and glaciofluvially transported as is seen in Figure 10. Finally, covariant plots of RA versus C_{40} indices (Benn and Ballantyne 1994) show progressive down-valley changes in clast shape, especially for fluvially transported JM material. The following general observations may be made on the shape data from the Mníšek member, recent fluvial sediments and *in situ* weathered JM granite bedrock.

Quartz clasts have the highest initial MPS and *c:a* values, together with low C_{40} values. Their compact form does not change significantly during fluvial and glaciofluvial transport. However, different transport environments may be discriminated by use of the covariant plot of RA versus C_{40}. The downstream change of shape of quartz clasts is seen mainly in an increase in roundness values, i.e. decrease of the C_{40} values.

Quartz clasts are mainly of local (JM granite) or near (JMC granitoids) provenance (Nývlt and Hoare 2000). Most of those in the glaciofluvial sediments must first have been transported by ice over a distance no greater than ~30 km; a much shorter transport path is plausible, and indeed likely (Nývlt and Hoare 2000). Fluvial and glaciofluvial transport over distances <10 km was responsible for a marked downstream decrease in the sphericity of JM feldspars and the elimination of the most spherical JM granite clasts. Fluvial transport saw a more rapid increase in the average roundness of the JM feldspars. For angular and very angular clasts of JM quartz and JM granite to attain the same roundness values as JM feldspar, nearly double the transport distance is required (Fig. 6). The 'final' average roundness of all classes after fluvial transport of ~8.5 km is nevertheless very similar. At Mníšek, after <3 km of glaciofluvial transport, the local JM petrological classes display much higher roundness values than is the result of ~8.5 km of fluvial transport at F8. Less resistant petrologies (JM feldspar and JMC feldspar) round more quickly to begin with, but the more energetic glaciofluvial transport causes breakage of feldspar clasts and they are therefore less well rounded than the granitoids and quartz. More resistant rock types (quartz, JM granite and JMC granitoids) change their clast form more rapidly in the dynamic glaciofluvial environment. Since the form of local JM rocks (granite and feldspar) does not change significantly (Figs 4 and 5), differentiation is most effectively expressed in covariant plots of RA versus C_{40} (Fig. 10).

The clast-form of glacially transported near rocks (JMC rocks, near sandstone) have not been significantly influenced by subsequent glaciofluvial processes. Many of near sandstone clasts have been broken during the high energetic glaciofluvial transport, which is visible in the highest decrease of roundness, producing more subangular to subrounded clasts. JMC metagranitoids and feldspars were rounded less than their JM equivalents, JMC gneiss class shows on the other hand practically no change in roundness values. Nordic rocks were at some stage inevitably transported from the north within the

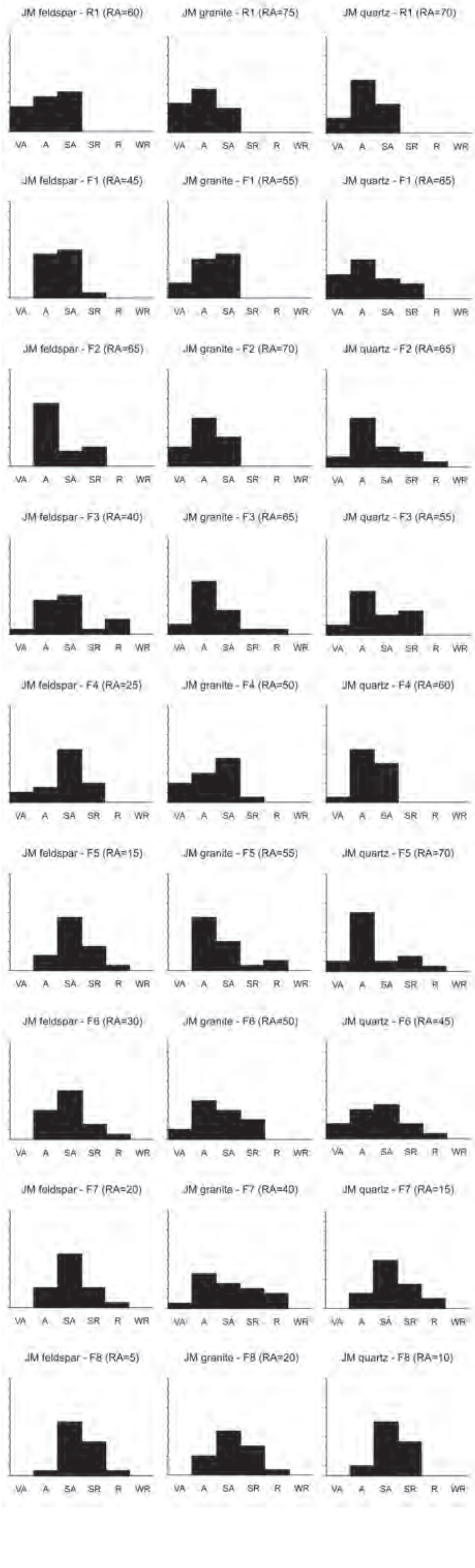


Fig. 8. Relative-proportion roundness histograms for JM granite, JM feldspar and JM quartz from *in situ* weathered JM granite bedrock and modern fluvial sediment samples. For an explanation of the roundness categories, see the caption to Fig. 7. The location of the sample sites is shown in Fig. 1. Each sample consists of 20 clasts in the 8–16 mm fraction.

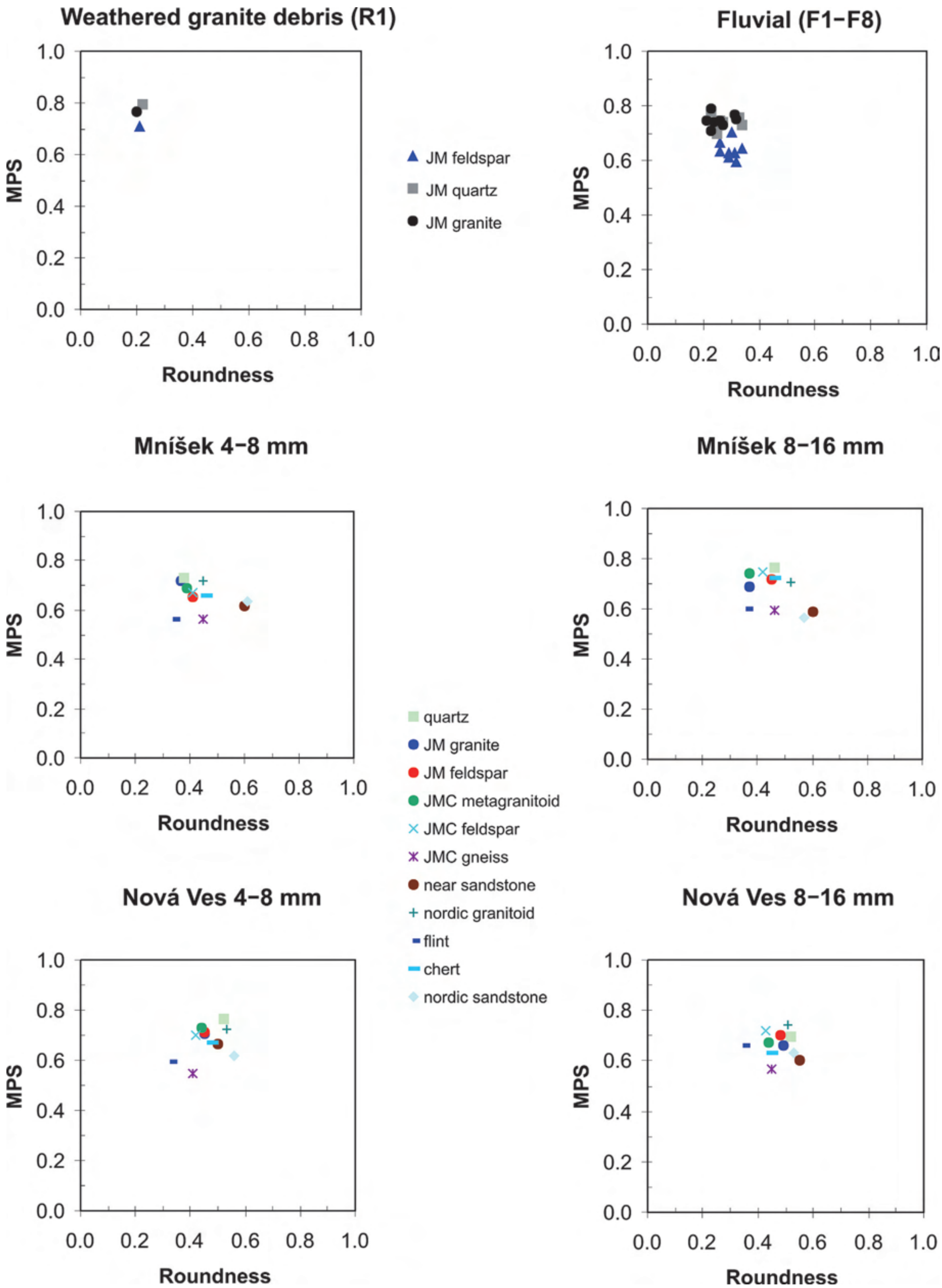
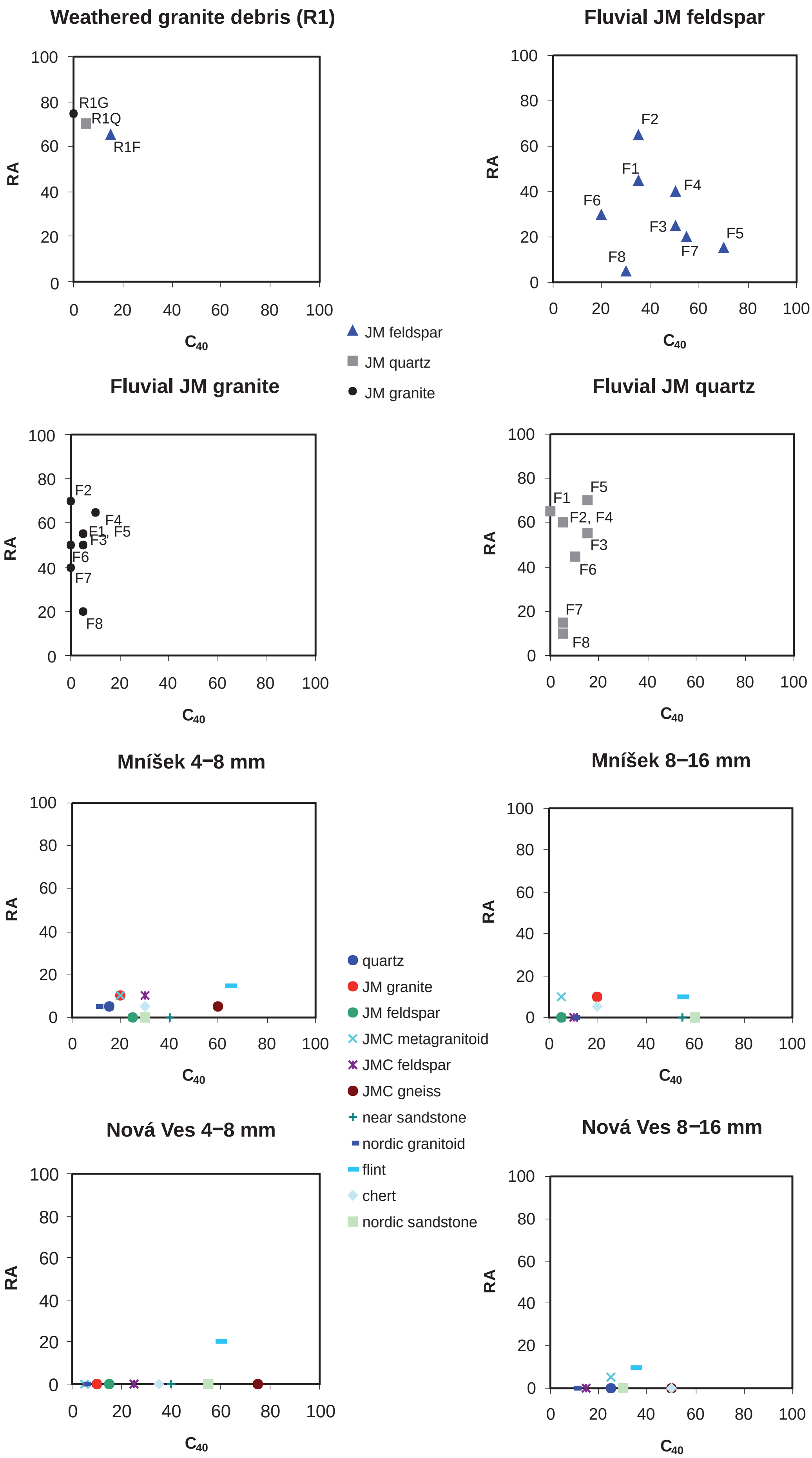


Fig. 9. Covariant plots of average roundness versus average MPS for *in situ* weathered JM granite debris (R1), fluvial (F1–F8) and glaciofluvial sediments of the Mníšek member – samples M5 for Mníšek and NV2 for Nová Ves. Each sample consists of 20 clasts; Mníšek member samples from the 4–8 mm and 8–16 mm fractions, *in situ* weathered JM granite debris and fluvial samples only from the 8–16 mm fraction.

> Fig. 10. Covariant plots of RA versus C_{40} for *in situ* weathered JM granite debris (R1), fluvial (F1–F8) and glaciofluvial samples of the Mníšek member – samples M5 for Mníšek and NV2 for Nová Ves. Each sample consists of 20 clasts; Mníšek member samples from the 4–8 mm and 8–16 mm fractions, *in situ* weathered JM granite debris and fluvial samples only from the 8–16 mm fraction.



Weathered granite debris (R1)
Fluvial JM feldspar
Fluvial JM granite
Fluvial JM quartz
Mníšek 4–8 mm
Mníšek 8–16 mm
Nová Ves 4–8 mm
Nová Ves 8–16 mm
RA
C40
R1G
R1Q
R1F
F1
F2
F3
F4
F5
F6
F7
F8
F2, F4
F1, F5
JM feldspar
JM quartz
JM granite
quartz
JM granite
JM feldspar
JMC metagranitoid
JMC feldspar
JMC gneiss
near sandstone
nordic granitoid
flint
chert
nordic sandstone

subglacial zone of the ice sheet, having been entrained from bedrock outcrops or from older (glacial, fluvial, marine, etc.) deposits. The class of nordic granitoids shows high sphericity and no significant influence by glaciofluvial transport could be seen. The glaciofluvial transport of Nordic flint and chert had its greatest influence on those clasts with the highest or lowest initial sphericity. The high dynamic glaciofluvial environment also caused breakage of many flint clasts and therefore the flint class is somewhat distinct in the covariant plot of average MPS versus average roundness from other classes at Nová Ves (Fig. 9). Flint always shows lowest roundness and highest C_{40} values from all glaciofluvially transported petrologies. The breakage of clasts is also common in nordic sandstones.

Different petrological classes show a diverse, mostly inconsistent, distribution of clast forms, illustrating the great influence of the clast petrology. This could be also caused by a relative transport immaturity of sampled sediments. The downstream rounding of angular material is well displayed in the samples of recent fluvial sediments (Fig. 6). The more dynamic glaciofluvial transport caused on the other hand breakage of softer or fragile petrologies (flint, sandstones, gneiss), decreasing the overall roundness of the classes at Nová Ves. This is also supported by the studies of nordic indicators, where diminishing amount even for nordic granitoids at Nová Ves in the contrary to nordic porphyries was found (Nývlt 2003b). This is well visible in the decrease of granitoid/porphyry ratio within the group of nordic indicators between both localities from 1.83 towards 1.19. We, therefore, could not agree with results of Bennett et al. (1997), who found relative small impact of the clast petrology on the final clast shape in high Arctic glacial and glaciofluvial environment. According to our results clast form and sphericity is mainly affected by resistance of the rock and attained roundness is controlled by the length, dynamic and type of transport and less importantly by rock resistance.

The second point is the suitability of different research methods for discrimination of diverse conditions during transport and accumulation of sediments within the glacial system. As it was already stated, a consistent approach to the study of clast shape within the glacial environment is needed (e.g., Benn and Ballantyne 1994; Bennett et al. 1997). The same procedures, diagrams and plots were used to compare our results with others with focus on the proglacial glaciofluvial environments. Ternary diagrams themselves do not help to distinguish between closely related types of deposits in this study. The employment of covariant plots of average MPS versus average roundness do not also bring much better results. On the contrary the covariant plot of RA versus C_{40} is the best tool to characterise *in situ* weathered JM granite debris, recent fluvial sediments and glaciofluvially transported material in this study (Fig. 10). However, the usage of a combination with above-mentioned covariant plots and other line diagrams yielded further details described above.

The class of nordic granitoids suggest the superb setting of the C_{40} index by Ballantyne (1982, 1986) for this study. All the clasts of this petrological class must have once been actively transported within the subglacial zone of the ice sheet on their transport path from Fennoscandia and Baltic region. They are also less weathered than local granitoid rocks, as all weathered nordic granitoid clasts has already been removed from the studied fractions by the active glacial transport. In both fractions more than 90% of clasts display a *c:a* index >0.4. From the statistical point of view and with the available nordic granitoids data from this study, the value of the index discriminating actively and passively glacially transported clasts might be set on 0.382 with the 99% significance level or on 0.396 with the 95% significance level. However, other far travelled petrological classes (nordic sandstone, chert, flint) show high values (between 25 and 60%) of the C_{40} index. This is caused by their brittleness, they often break into flakes during the active subglacial and high energy glaciofluvial transport producing elongated clasts with a very low sphericity index. For that reason they are not suitable for these studies. We therefore prefer more resistant rock types (such as quartz, quartzite and unweathered granitoids) than brittle rocks (like chert, some sandstones or flint) or less resistant rocks (like dolomite, gneiss, phyllite or some sandstones) for the study of the transport impact on the clast shape. This is not so much a preference as an absolute necessity!

Conclusions

The main supplier of the gravel fraction in the Mníšek glaciofluvial sand and gravel accumulations are the following granitoid rock: Jizera granite, Jizera Metamorphic Complex metagranitoids. They are present as clasts of granitoids or as separate mineral grains of feldspars and quartz, these built together more than 90% of the material in the gravel fraction. Near and nordic rocks comprise only less than 7% of the material in the pebble fraction.

The down-stream rounding of angular classes is well displayed in the samples of recent fluvial sediments and glaciofluvially transported quartz, JM and JLC rocks. The more dynamic glaciofluvial transport caused on the other hand breakage of softer or fragile petrologies (feldspar, flint, gneiss, sandstones) decreasing the overall roundness of these classes after the glaciofluvial transport. Clast form is mainly affected by the resistance of the rock and attained clast roundness is controlled by the length, dynamic and type of transport and less importantly by rock resistance. We, therefore, could not agree with results of Bennett et al. (1997), who found relative small impact of the clast petrology on the final clast shape in high Arctic glacial and glaciofluvial environment.

The covariant plot of RA versus C_{40} is the best tool for describing and illustrating clast shapes of *in situ* weathered JM granite debris, recent fluvial sediments and glaciofluvially transported material investigated in this study. However, the usage of a combination with other covariant plots and line diagrams depending on the data could yield further details.

The class of nordic granitoids suggest the superb setting of the C_{40} index by Ballantyne (1982, 1986) for this study. From the statistical point of view and with the data from this study, the value of the index discriminating actively and passively glacially transported clasts could be set on 0.382 with the 99% significance level or on 0.396 with the 95% significance level. Other far travelled petrological classes (nordic sandstone, chert, flint) are due to their fragility not suitable for these studies. We are not alone in preferring resistant rock types such as quartz, quartzite and granitoids for the study of the impact of the transport mode on the clast shape.

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