Supplementary data 2. Clast morphology of glacial sediments in complex metamorphic lithology of the Rodna Mountains.

1. Geological setting

The Rodna Mountains are part of the Inner Eastern Carpathians and appear as a horst of the crystalline basement of the Dacia tectonic mega-unit, built up by the Bucovinian nappe stack (Subbucovinian and Infrabucovinian nappes) (Schmid et al., 2008). Geological structures of the Subbucovinian nappes flank the Rodna horst in the NW and SE: they build the highest summits of the massif around Pietrosu peak (2303 m a.s.l.) in the NW and Ineu peak (2279 m a.s.l.) in the SE (Fig. S1). The Subbucovinian nappe consists mainly of Cadomian-age mica schists and paragneisses of the Rebra series with subordinate amphibolites and limestones. The Infrabucovinian nappe builds the central, strongly uplifted part of the Rodna horst (Fig. S1), where it forms a large tectonic window with Cadomian-age gneisses and paragneisses of the Bretila series and Palaeozoic metasediments, which belong to the Rusaia, Repedea and Cîmpoiasa series (Kräutner et al., 1982. 1983) (Fig. S1). The Rodna crystalline massif is unconformably overlaid by post-tectonic Late Cretaceous-Early Miocene autochthonous sedimentary cover which forms the mountain foreland and fills the Borşa graben in the north. The crystalline basement and its post-tectonic cover are dissected by a system of faults and dislocations running W-E, and NE-SW (Tischler et al., 2007; Gröger et al., 2008) (Fig. S1). The Rodna horst is delineated by the Rodna fault to the south (Someşul Mare fault) and Bogdan-Dragoş Vodă fault system to the north (Tischler et al., 2007) (Fig. S1).

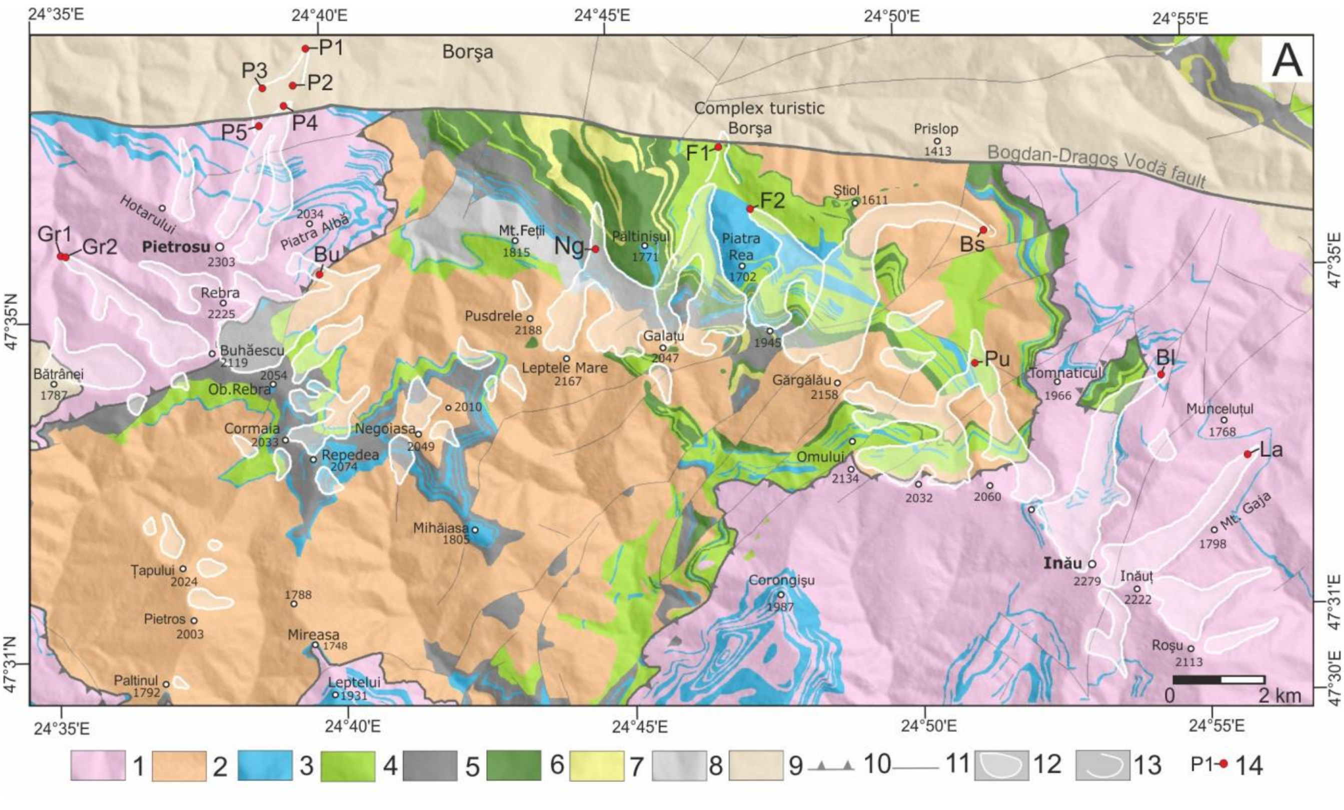


Figure S1. Schematic geological map of Rodna Mountains after Kräutner et al., (1982, 1983) with the marked extent of maximal Pleistocene glaciation and localisation of moraine sediment sites. Legend: 1 - quartz mica schist and paragneisses (Rebra series), 2 - gneisses and paragneisses (Bretila series), 3 - limestones and dolomites, 4 - sericite and chlorite schists, 5 - sericite and graphite schists, 6 - green schists, 7 - quartzite, 8 - metagraywackes, 9 - Post-orogenic flysch (Palaeogene), 10 - tectonic contact between Subbucovinian and Infrabucovinian nappes, 11 - faults, 12 - LGM glacier extent, 13 - the extent of pre-LGM glaciation, 14 – location of clast morphology measurement sites.

2. Methods of clast morphology analysis

Analyses of clast shape and roundness are commonly used in glaciated environments to distinguish between different erosional, transportation and depositional clast histories (Benn and Ballantyne, 1993, 1994; Glasser et al., 2009; Brook and Lukas, 2012). In this study analyses of clast morphology was used in order to characterise sedimentological properties of moraine sediments in complex metamorphic lithology and to determine the possible differences between the glacial sediments of the last and older glaciations.

Field sampling was undertaken at the latero-frontal moraines of the LGM (Pietroasa unit, 11 sites) and the older, pre-LGM till deposits (Şesura unit, 4 sites) (Fig. S1). Sampling sites were located along scarps of road cuttings. At each site the three orthogonal axes, a, b, c (long, intermediate, short) were measured for 50 clasts using a steel ruler. Clast roundness was determined visually for each clast on a modified Powers (1953) scale. Due to the potential influence of varying lithology on clast shape (Lukas et al., 2013), measurements were confined to one dominant type of clast lithology in the selected valleys (quartz mica schist, gneisses, and sericite and chlorite schists). Tertiary diagrams following Sneed and Folk (1958) were generated in the TRIPLOT Excel spreadsheet (Graham and Midgley, 2000). The C_{40} index (percentage of clasts with c/an axial ratio≤0.4) was subsequently calculated for each sample site. The RA ratio (the percentage of angular and very angular clasts in any sample) and RWR ratio (the percentage of rounded to well-rounded clasts; Lukas et al., 2013) were calculated for each site. In order to distinguish the transportation and depositional clast histories co-variance plots using both RA-C_{40} and RWR-C_{40} were presented (Benn and Ballantyne, 1994, Lukas et al., 2013).

3. Results of clast morphology analysis

Ternary diagrams and roundness histograms for the sampled moraine sites are shown in Fig. S2, while the RA-C_{40} and RWR-C_{40} bivariate scatterplots are illustrated in Fig. S3.

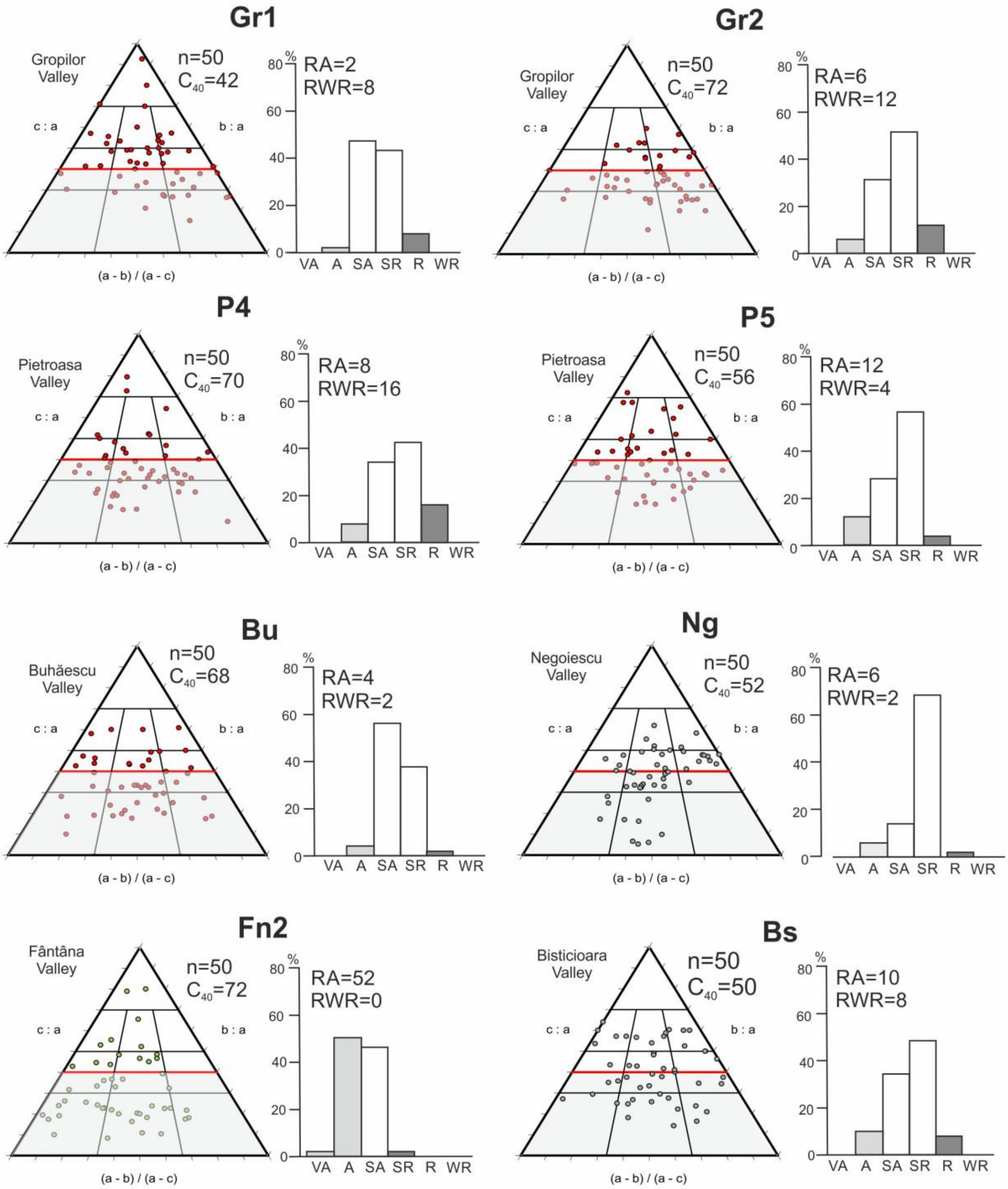
Sandy boulder-gravels, with minor cobbles and pebbles, dominate terminal moraine deposits in the Rodna Mountains. The petrographic composition of clasts is crystalline, but occasionally sandstone and calcareous conglomerate (Şesura unit, Pietroasa valley) and limestone clasts (Şesura unit, Fântâna valley) can be observed.

Sediments of the Pietroasa unit consist of diamict with a sandy-silty matrix supporting cobble- to boulder-sized clasts. These clasts are predominantly subrounded and some of the clasts display evidence of striae. The C_{40} indices for the Pietroasa moraine unit range considerably between 42 % and 82 %, indicating that terminal moraines contain a high proportion of platy and blade-like clasts. The clast shape varies between individual metamorphic lithologies (Fig.S2).

Morainic clasts of quartz mica schist show about 18 % more platy clasts than do gneiss clasts, and sericite and chlorite schist about 11 % more (Fig. S2). RA values are generally low (2 – 14 %: mean 11.8 %), however, one sample from the ablation moraine cover in Fântâna valley (Fn2) has a significantly higher RA value (52 %) (Fig. S3A). RWR values are low and range between 0 and 16 % (Fig. S3B). The typical clast roundness distribution of Pietroasa moraines reflects the predominance of sub-rounded (ca 40 – 60 %) and sub-angular (20 – 40 %) clasts, with a lower occurrence of rounded and angular clasts (Fig. S2). The co-variant plot demonstrates a narrow distribution of RA/C_{40}, further suggesting active glacial transport (lodgement till) of debris, except for the Fn-2 site, where the high RA index suggests more passive transport of debris (Fig. S3).

The glacial deposits of the Şesura unit feature an abundance of boulders with mean a-axis length above 1 – 1.5 m and maximal lengths of ca 3 – 5 m, which appear to be intensely weathered. Numerous road cuttings reveal subsurface sediments: the best exposures are at site P2 (Fig. S1), located east of Pietroasa Monastery. Sediments at this site comprise diamict with a sandy-silty matrix encapsulating cobble- to boulder-sized clasts. These clasts are predominantly subrounded (angular: 6%; subangular: 24%; subrounded: 64%; rounded: 6%) (Fig. S2). Roadside sections in the marginal part of glacial deposits at the Şesura site indicate a 5 – 6 m thick sand-silt diamict with subrounded mica-schist clasts, resting on flysch bedrock

Pietroasa moraine unit



Lithology

- quartz mica schist and paragneisses (Rebra series),
- gneisses and paragneisses (Bretila series)
- sericite and chlorite schists

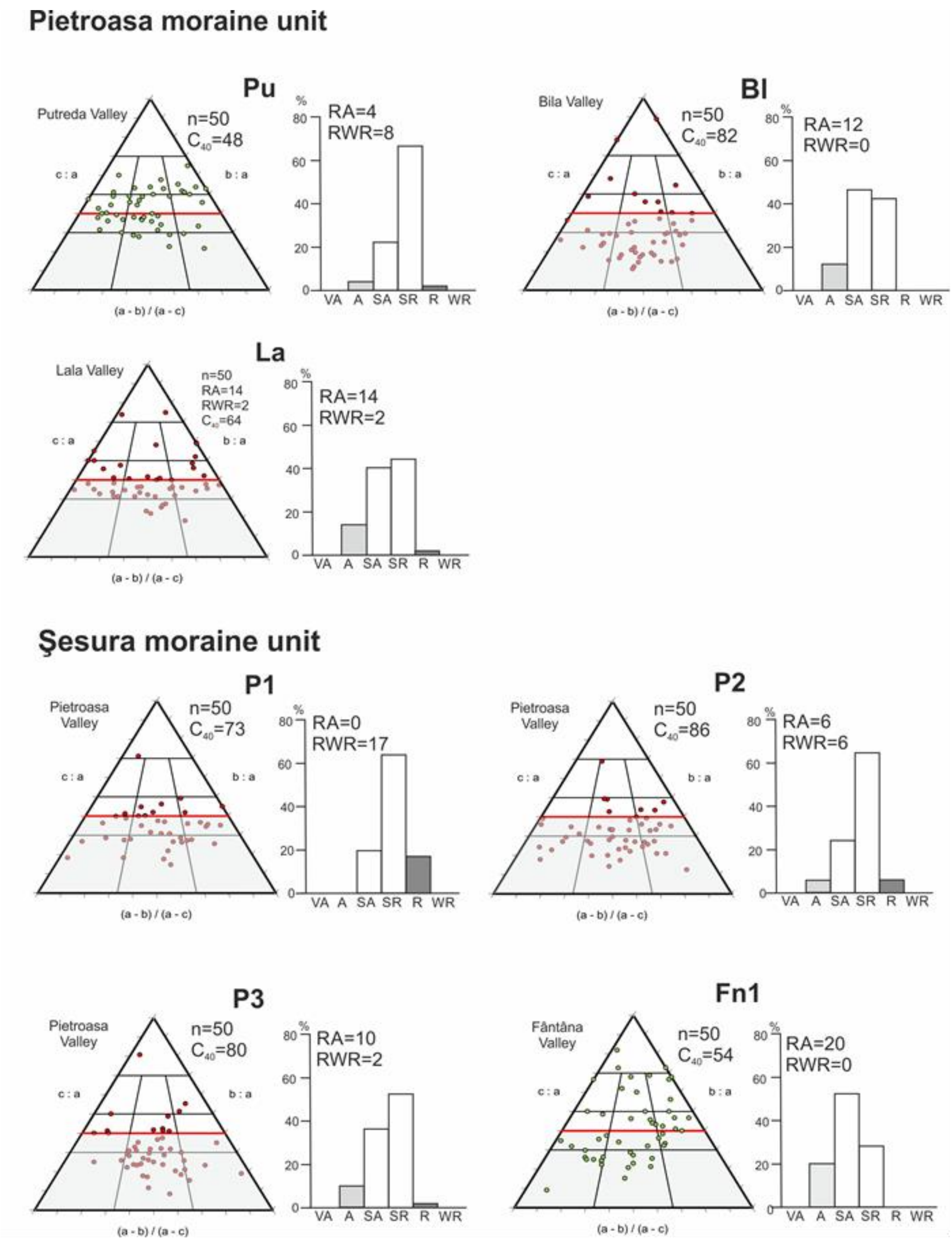


Figure S2. Clast shape data (ternary diagrams) and roundness (histograms) for sampled Pietroasa and Şesura moraines in Rodna Mts. Site locations are depicted in Fig. S1. Abbreviations: n=number of sampled clasts; RA and C_{40} are defined in the text.

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The C_{40} index for the Şesura moraine unit ranges between 54% and 86%, thus aggregating predominantly blade-shaped clasts. The quartz mica schist clasts of the Şesura unit have higher contents of platy clasts (mean C40 = 80%) compared to the Pietroasa unit morainic deposits (mean C40 = 65%). However, this relationship is not visible for sericite and chlorite schist clasts. The lower RA values (0 – 20 %, mean 9 %), along with slightly higher RWR values (6.3 %) for the Şesura unit moraines point to the presence of more rounded clasts compared to Pietroasa unit. The co-variant plots show RA/C_{40} indices similar to the Pietroasa unit (Fig. S3), indicating predominant active transport processes.

The dominant metamorphic lithologies in the Rodna Mountains are characterised by rather soft and highly anisotropic rocks (mica schists, paragneisses). Moraine clasts commonly display a high proportion of platy clasts (evident in high C_{40} values) and strong rounding (as expressed by low RA values) (Fig. S3). Our clast data indicate that pronounced clast reworking was effective enough to remove the primary angularity of clasts. According to Lukas et al. (2013), roundness is the dominant discriminator of glacial reworking for soft and high-anisotropic rocks, while plainness (C_{40} index) is similar to extraglacial clasts.

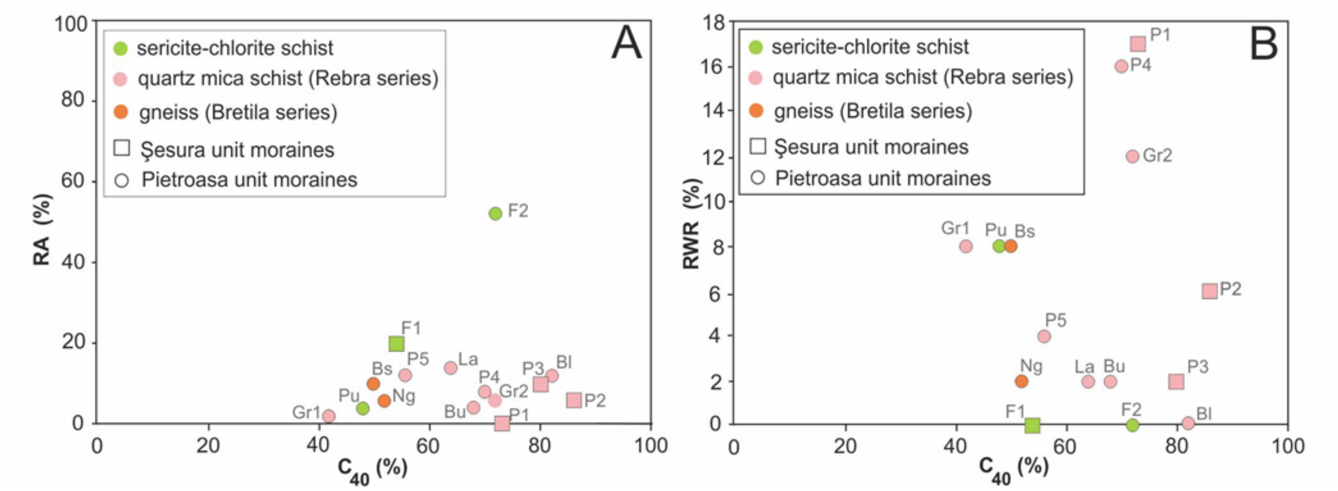

Figure S3. A – Co-variance plot for the Pietroasa and Şesura unit moraines in Rodna Mountains, using possible variations of RA versus C40-index. Each plotted point represents a sample group of 50 clasts. Site locations are depicted in Fig. S1. B – Co-variance plot for the Pietroasa and Şesura unit moraines in the Rodna Mountains, using possible variations of RWR versus C40-index.

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