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Petrography and major element geochemistry of Late Triassic Carpathian Keuper sandstones: Implications for provenance

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Abstract. Modal analysis, bulk-rock geochemistry and Fe-Ti mineral chemistry of the Late Triassic Carpathian Keuper sandstones indicate that their mineralogy being mainly quartz-dominated, with variable amounts of feldspars and rock fragments and are classified as quartz arenites, sub-litharenites and sub-arkoses, suggesting derivation mainly from acid igneous rocks, gneisses and older sandstones. These are common constituents of the basement rocks in the area studied and the surroundings. Their bulk-rock geochemistry supports the petrographic results and indicates that they are virtually Fe-rich, lithic sandstones/quartz arkosic sandstones. Fe-Ti oxide minerals chemistry suggests a metamorphic rather than igneous sources. Based on the mineralogical and geochemical indicators, the probable provenance of the Keuper sandstones was mainly the metamorphic and igneous rocks of the crystalline cores of the Western Carpathians and the foreland of the Bohemian Massif which were weathered and deposited in the continental mainly fluvial and littoral environments of deposition of the Keuper Formation.

Keywords: Modal Analysis, Chemistry, Provenance, Keuper, Triassic, Carpathians, Slovakia.

Pétrographie et géochimie des éléments majeurs des grès du Keuper des Carpathes (Trias supérieur) : implications sur la provenance.

Abstract. L'analyse modale, la géochimie sur roche totale et la chimie des minéraux à Fe-Ti des grès du Keuper des Carpathes occidentales indiquent que leur minéralogie est principalement dominée par le quartz, avec des quantités variables de feldspaths et de fragments lithiques, et qu'ils peuvent être rangés dans les quartzarenites, les sub-litharenites et les sub-arkoses, suggérant une source à partir de roches ignées acides, de gneiss et d'anciens grès. Ces derniers sont des composants fréquents des roches du soubassement de la région étudiée et des environs. La géochimie sur roche totale confirme les résultats de la pétrographie et indique qu'ils sont virtuellement riches en Fe, grès lithiques/grès arkosiques à quartz. La chimie des minéraux à oxydes de Fe-Ti suggère une source plutôt métamorphique. Sur la base des indicateurs minéralogiques et géochimiques, la source probable des grès du Keuper est principalement les roches métamorphiques et ignées des noyaux cristallins des Carpathes occidentales et l'avant-pays du massif Bohêmien, altérés et déposés dans des environnements continentaux fluviatiles et littoraux de la formation du Keuper.

Keywords: Analyse modale, géochimie des grès, provenance, Keuper, Trias, Carpathes, Slovaquie.

INTRODUCTION

Provenance analysis serves to reconstruct the predepositional history of a sediment or sedimentary rock. This includes the distance and direction, size and setting of the source region, climate and relief in the source area, and the specific type of sedimentary rocks (Pettijohn *et al.* 1987, von Eynatten & Gaupp 1999). Many attempts have been made to refine provenance models using the framework composition (Valloni & Maynard 1981, Dickinson 1985, Zuffa 1987, Fornelli & Piccarreta 1997, McCann 1998), geochemical features (Bhatia & Crook 1986, Roser & Korsch 1988, Morton 1991, Armstrong-Altin *et al*. 2004) and heavy mineral assemblages (Morton 1985, Basu & Molinaroli 1989, 1991, Nachaev & Isphording 1993, Morton & Hallsworth 1994, Acquafredda *et al.* 1997, Chaodong *et al*. 2005).

The Carpathian Keuper Formation (V. Uhlig 1903 *in* Andrusov 1959), one of the common Triassic formations of the Western Carpathians of Slovakia, is represented by a variegated shale-claystone complex of Late Triassic (Carnian-Norian) age, with alternations of sandstones and dolostones. The first Carpathian geologist, D. Štúr (1868 *in* Andrusov 1959), named it "variegated marly Keuper" and correlated it with German Keuper deposits.

The typical development of the Carpathian Keuper Formation is bound to the Envelope (Tatric) and Križna (Fatric) tectonic units as well as to the Klippen belt (Andrusov 1959) within the mountain ranges of the Western Carpathians (Fig. 1a). The sedimentary succession of the Carpathian Keuper Formation in the Envelope unit consists of thick detrital facies with variegated red, violet and green shales and silty shales. Calcareous and arkosic sandstones alternating with conglomerates and quartzites also dominate in these rocks (Al-Juboury 1992).

The Keuper Formation of the Envelope unit contains, as a rule, a greater portion of clastic materials, whereas that of the Križna unit shows more dolostone alternations (Andrusov 1959).

A detailed sedimentological and petrographic study of the Carpathian Keuper rocks (Al-Juboury 1992) has revealed that their palaeoenvironment was generally continental: littoral, shallow-marine and lagoonal (supratidal) with hypersaline conditions during deposition of dolostones.

The aim of this paper is to attempt to reconstruct the provenance of the Late Triassic Carpathian Keuper sandstones of the Western Carpathians of Slovakia using an integrated provenance approach involving modal analysis, bulk rock geochemistry and mineral chemistry of detrital Fe-Ti oxides. The location of the study area within the main structural units of the Carpathian region is illustrated in Figure 2.

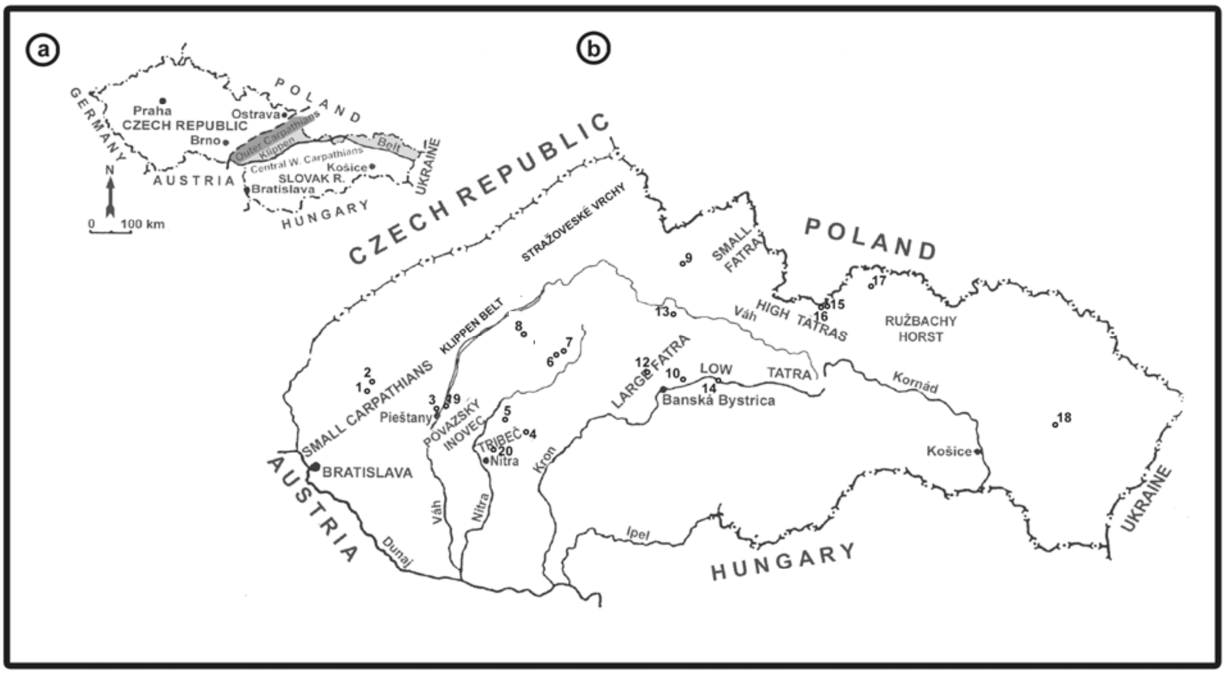

Figure 1. a, Map of the Czech and Slovak republics illustrating the location of the Western Carpathians Mountains (outer, Envelope or Tatric; central, Fatric or Križna; and the Klippen Belt). b, Location of the studied Keuper profiles in the Central Western Carpathians. Profile numbers: 1-Vysoká 754; 2- Buková 452 (Záblatie); 3- Banka; ; 4-Velké Pole; 5- Brodzany; 6-Čierna Lehota; 7-Valaská Belá; 8-Drietoma; 9-Zázrivá; 10-Mytyčky; 11- Dedošova; 12-Belanská; 13-Ráztoky; 14-Valaská; 15-Ždiar; 16-Široké Sedlo; 17-Zálažny; 18-Laborca; 19-Beckov; 20-Jelenec.

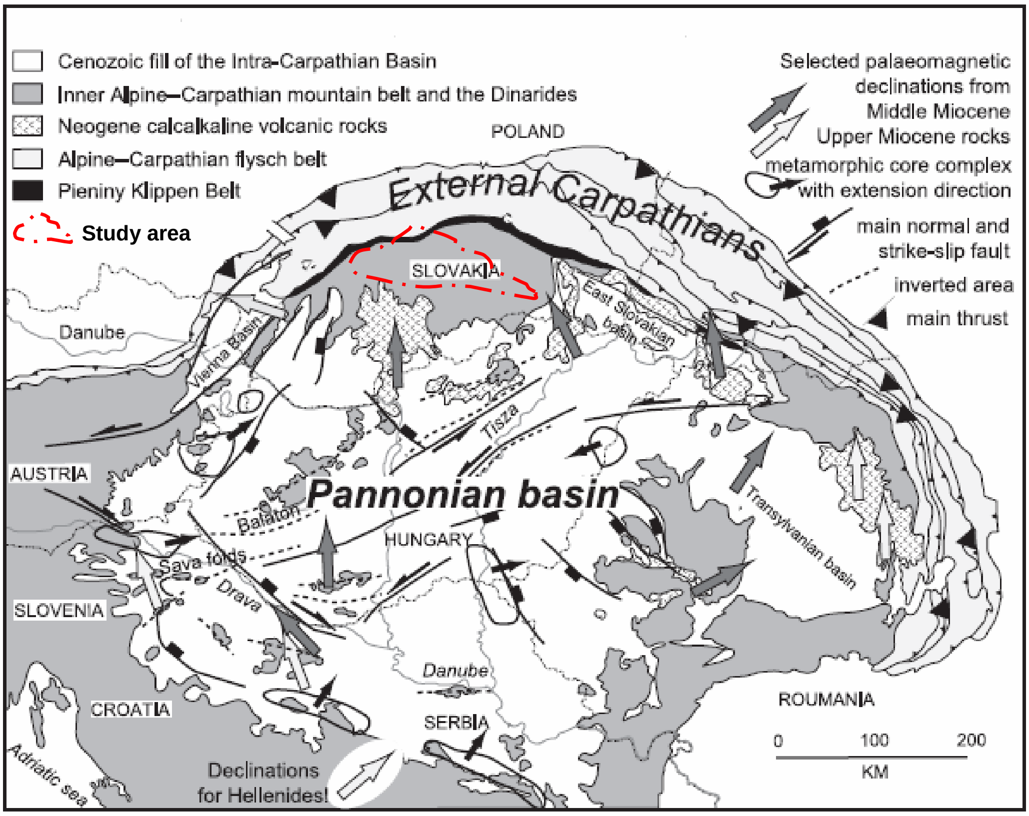

Figure 2. Geological map showing the main Miocene structural elements of the Carpathian area with the location of the study area (modified from Csontos & Vörös 2004; reproduced by kind permission of Elsevier).

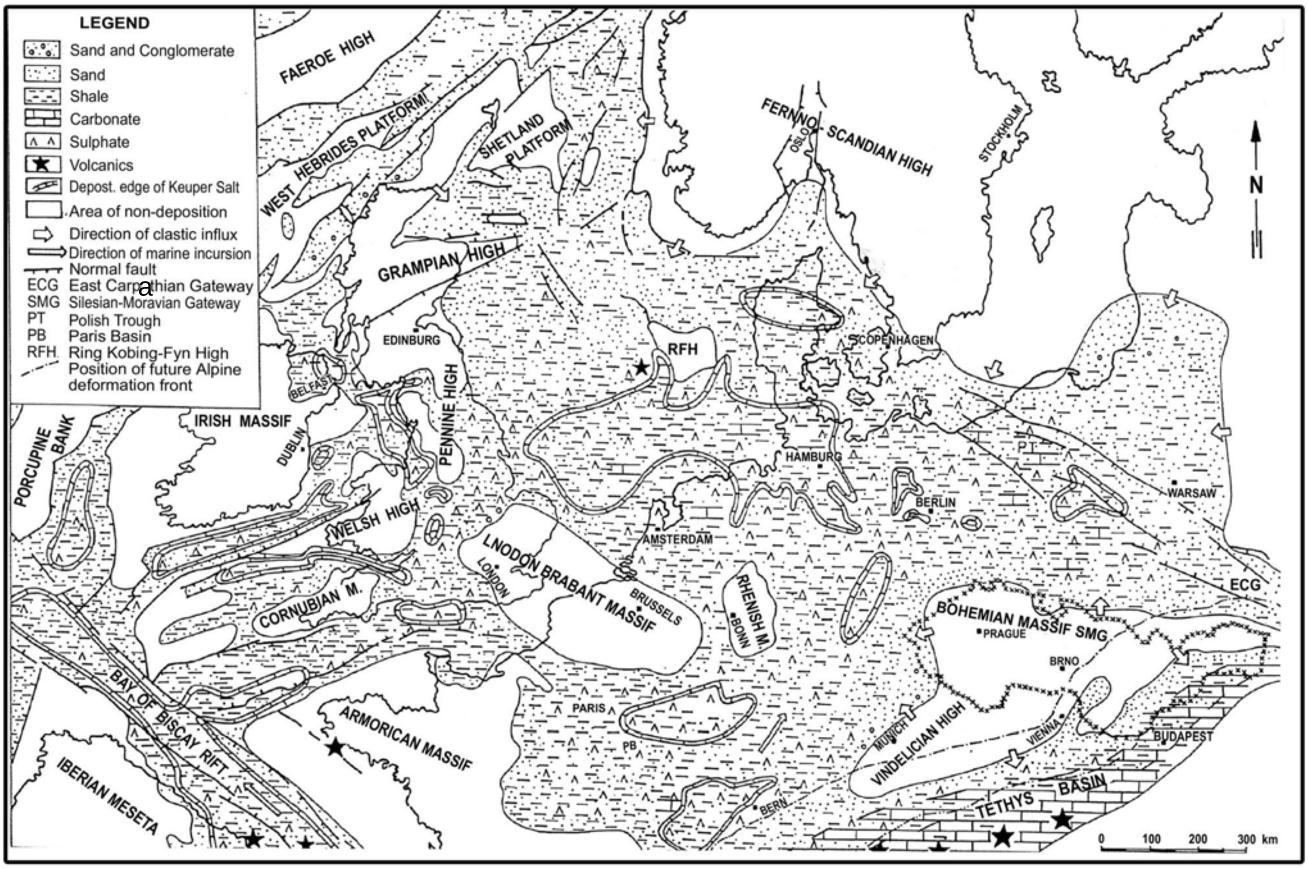

Figure 3. Carnian – Norian paleogeography of the Keuper in western and central Europe (modified from Ziegler 1982).

GEOLOGICAL BACKGROUND

The Triassic series in western and central Europe consists of continental to brackish marine red beds, shallow marine carbonates, sulphates and halites (Bachmann & Lerche 1999, 2000). Sedimentation patterns were influenced by frequent sea level oscillations and an overall eustatic sea-level rise during the Triassic (Vail *et al.* 1977, Haq *et al*. 1987).

In the southern parts of the north-west European basin (Polish Trough PT, Fig. 3) and on the northern shelves of the Tethys, the interplay between sea-level changes, clastic influx and subsidence gave rise to the development of the so called "Triassic German Facies Province" (Bachmann & Lerche 1999, 2000). This province is characterized by the classical tripartite subdivisions of the Triassic series into the Early Triassic (Scythian) largely continental Buntsandstein clastics, the Middle Triassic (Anisian and Ladinian) Muschelkalk carbonates and evaporites, and the Late Triassic (Carnian to Norian) Keuper playa and tidal flat deposits (Ziegler 1982).

For the Keuper period, two basins were recognized in Europe, the Germanic and Carpathian basins. The lithology and facies of the Carpathian Keuper Formation are considerably similar to those in the German regions although the Rhaetian stage was not recognized in the Carpathians (Andrusov 1959). The Germanic and Carpathian Keuper formations were deposited in two regions that were separated from each other by an emerged land, the “Czech Platform” (Fig. 3). In the north, within middle and northern Germany and in Poland, north of Western Carpathians, the Germanic Keuper is considered as continental lagoonal facies. In the south of this region, deposition of shallow marine sediments is regarded as belonging to the Alpine domain.

During the earliest Carnian, a probably eustatically-induced regional regression in western and central Europe interrupted the Muschelkalk carbonate sedimentation and triggered the Keuper clastic-evaporitic depositional regime. At the same time, the marine connection between the Tethys and the north-west European basin (Polish Trough Basin) through the East Carpathian and Silesian-Moravian gateways became interrupted (Ziegler 1982), (Fig. 3). This may have been caused either by their rapid infill with clastics, possibly combined with a reduced subsidence rate, or even by the temporary uplift of the southern parts of the Polish Trough (Ziegler 1982). During the deposition of the Keuper formations, strong clastic influx from eastern sources, mainly from the East European Craton and Bohemian Chains, dominated sedimentation patterns in western and central Europe (Würster 1968). This was induced by the up-arching of the East European Craton and an accentuation of the Vindelician – Bohemian High (Fig. 3). The Keuper formation reaches thicknesses of more than 2000 m in the Polish Trough and in the North German Basin.

During the Late Triassic, shallow seas and deltaic complexes, immense tidal flats, lagoons and sabkhas occupied the southern and eastern parts of the north-west

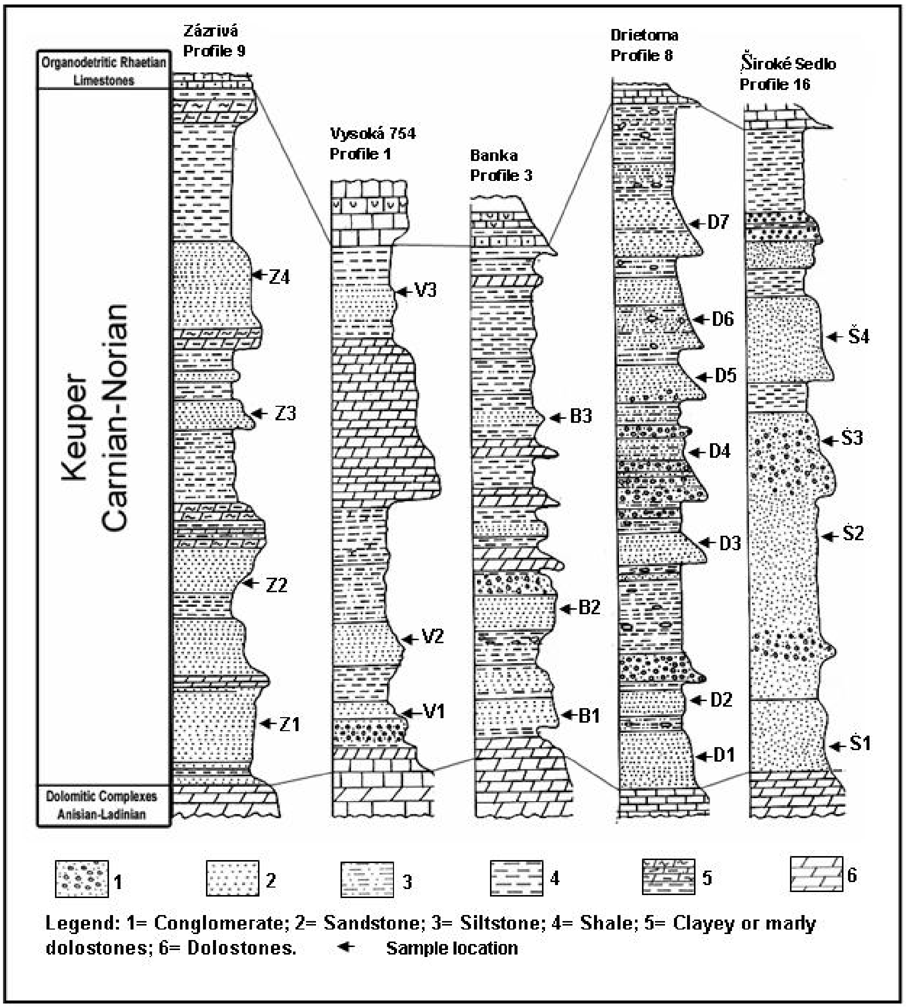

Figure 4. Representative lithologic profiles of the studied sections. Note the common occurrence of clastics in the Keuper of the Klippen belt (profile 8, Drietoma) and in profile 16 of Široké Sedlo of the (Fatric) Križna unit.

European basin, the rapidly expanding Paris basin and the northern parts of the Tethyan shelves. The climatic conditions during the deposition of the Keuper series varied between semi-arid and semi-humid, this was probably induced by sea-level oscillations. During periods of desiccation of lagoons, appreciable thicknesses of Keuper salts accumulated in the areas of rapid subsidence.

MATERIALS AND METHODS

The database for this study consists of 20 sections from the Keuper succession in the Tatric Fatric units, and the Klippen Belt (Fig. 1b). Representative logs of the studied sections are illustrated in Figure 4.

Detailed size analysis and X-ray diffraction determination of the Keuper sandstones were already performed previously (Al-Juboury 1992). The petrography of 50 samples collected from the sandstone beds intercalated between the shale, dolostones of the Keuper succession was determined by point-counting (400-500 points per thin section). Medium to coarse sandstones were analysed using the Gazzi-Dickinson method to minimize the dependence of rock composition on grain size (Dickinson 1970, Ingersoll *et al*. 1984, Zuffa 1985). The results of petrographic investigation are summarized in Table I**.**

The Rg-Rv-Rm diagram of Critelli & Le Pera (1994) and Critelli *et al.* (1995) is used (Fig. 5), to give detailed information about source area or provenance of the studied sandstones.

The analyzed petrographic data have been plotted in QFL ternary diagram (Ingersoll & Suczek 1979) to interpret their source terrains (Fig. 6).

Estimation of sorting was done using the comparison charts of Longiaru (1987), and the roundness values of individual mineral grains were obtained by comparison with the Powers photographic charts (Powers 1953).

Chemical analysis of the bulk sandstone samples for major oxides was done by using the atomic spectrophotometer method in the laboratories of the Geological Institute of the Faculty of Natural Sciences, Comenius University, Slovakia. Selected Fe-Ti oxides minerals were analyzed by JEOL-JXA-733 Super probe analyzer. Polished thin sections of the concentrates were examined with scanning electron microscope connected with EDAX attachment and identified as highly altered and fractured Fe-Ti oxide minerals.

Table I. Framework grain mode parameters and matrix and cement distributions of sandstones from the Keuper Formation of the Western Carpathians of Slovakia.

Location	**n (section)**	**Parameters**	**Q**	**F**	**L**	**Qm**	**Lt**	**Qp**	**Li**	**Ls**	**Lm**
Klippen Belt	15 (2,8)	Mean Range Std Dev.	62.64 44.1-73.2 9.30	4.11 2.0-9.9 2.32	5.73 0.8-11.3 3.13	50.98 31.5-64.5 9.42	17.39 6.6-28.5 6.3	11.66 3.6-18.0 5.31	1.5 0-5.1 1.34	3.71 0.3-7.6 2.33	0.52 0.1-2.1 0.71
Tatric	10 (3,17,19)	Mean Range Std Dev.	67.81 39.2-78.3 8.92	4.53 0.9-16.7 2.56	4.48 0.4-16.5 3.4	54.8 30.9-70.7 9.06	17.48 5.1-35.2 6.7	13.0 2.6-20.1 5.85	1.23 0-4.5 1.22	2.94 0-5.9 1.6	0.31 0-1.3 0.55
Fatric	25 (1,4-7,9- 16,18,20)	Mean Range Std Dev.	77.11 48.6-95.4 11.2	3.75 0.2-10.6 2.25	2.20 0.5-16.7 4.88	60.05 23.1-76.6 12.8	19.26 0.5-43.2 14.8	17.06 4.3-29.7 7.2	0.8 0-3.4 0.5	1.2 0-4.5 1.1	0.2 0-0.7 0.23

Location	**n (section)**	**Parameters**	**Matrix %**	**Cements %**			**Misc. %**
				carbonate	**clayey-ferruginous**	**silica**	
Klippen Belt	15 (2,8)	Mean Range Std Dev.	18.4 2.3-28.7 10.12	2.26 0.6-24.5 7.90	4.48 0.6-20.3 5.01	0.95 0.1-8.8 2.23	0.94 0.3-2.5 0.66
Tatric	10 (3,17,19)	Mean Range Std Dev.	17.7 0-38.8 11.2	2.9 0.5.2 1.2	1.3 0-14 2.54	0.6 0-12.7 2.88	0.54 0-1.7 0.7
Fatric	25 (1,4-7,9- 16,18,20)	Mean Range Std Dev.	8.8 0.6-32.8 13.1	2.6 0-19.8 5.8	1.3 0-10.5 2.3	3.54 0.2-20.5 3.9	0.70 0.2-2.7 0.56

Key: Q= total quartzose grains; F= total feldspar grains; L= total lithic fragments; Qm= monocrystalline quartz grains; Lt= total lithic fragments including polycrystalline quartzose grains; Qp= total polycrystalline quartzose grains; Li= total igneous lithic fragments; Ls= total sedimentary lithic fragments; Lm= total metamorphic lithic fragments; Misc= Miscellaneous grains. See Figures 1 and 4 for the precise location of samples and profiles.

Standard wet-chemical analyses were made on 20 bulk samples of sandstone representing the studied profiles for the Keuper Formation. The representative chemical analysis for the sandstones from the main tectonic units (i.e. Klippen belt, Envelope and Križna) is summarized in Table II.

RESULTS

Petrography

Petrographic investigation with the help of modal analysis for the estimation of the composition of sandstones (Table I) indicates that they are mainly lithic arenites, sub-arkoses and quartz arenites. These rocks show a laminated texture, especially in lithic arenites (Plate 1, a). The Keuper sandstones are generally, moderately/poorly sorted, sub-angular, sub-rounded. The main mineralogical constituents are quartz, feldspars, and lithic fragments.

Quartz

Monocrystalline (Qm) and polycrystalline (Qp) quartz occur throughout the sequence of the Keuper sandstone. They range in amount 3-77% and 2-30% for Qm and Qp respectively. Qm is commonly rounded to sub-angular, with some grains showing evidence of embayment (Plate 1, b-c), suggesting a volcanic origin (Boggs 2006).

Most polycrystalline quartz grains (Qp) consist of >3 crystals (Plate 1d). The contacts between the sub-grains are straight to suture, the latter occurs more commonly. The sub-grain size is variable, even within a single composite grain of Qp. Chert (microcrystalline Qp) was also recognized.

Inclusions are present within both Qm and Qp grains, but they are more common in Qm. They include zircon, tourmaline, rutile and muscovite microliths. Clay rims are commonly present with the development of quartz cement overgrowths (Plate 1, e-f).

Feldspar

Plagioclase (P) and K-feldspar (K) occur throughout the sequence of the Keuper sandstone (2-17% in amount for total feldspars). Plagioclase grains range from large, euhedral, compositionally zoned crystals to subangular grains. Twinning is common. K-feldspar is much less abundant than plagioclase (Plate 1g).

Orthoclase and microcline are the predominant K-feldspar types. Perthitic and microperthitic feldspars is rarer. K-feldspar grains are typically small, showing variable degree of roundness. Feldspar (F) grains may be fresh and unaltered but, more commonly; they are replaced by carbonates or altered into sericite and clay minerals.

Lithic fragments

Lithic fragments were found in a range of 0.4-17% in the studied sandstones. Lithic-sedimentary (Ls) and lithic-plutonic (Lp) grains occur in variable proportions throughout the sequence of the Keuper sandstone.

Lithic-sedimentary fragments are dominantly composed of carbonates and mudstones. Finely crystallized clasts and fragments of crystallized dolomite forming the common types of the lithic carbonates. Generally, the fragments are sub rounded; however, few rounded clasts are observed (Plate 1, h). The source of these lithic fragments is believed to be from the underlying Middle Triassic carbonates. Lithic plutonic (Lp) are rare. They include clasts of quartz and feldspar and are probably granitic in origin.

Using the petrofacies Rg-Rv-Rm diagram of Critelli & Le Pera (1994) and Critelli *et al.* (1995) (Figure 5), indicates that the mean sandstone studied in the Tatric, Fatric and Kippen belt lies generally in similar petrofacies area and are quartzlithic, with plagioclase always more abundant than K-feldspar. The common lithic fragments are represented by felsitic and metasedimentary rock fragments. These components reflect the contribution of plutonic and metamorphic source rocks.

The dominant accessory heavy minerals are composed mainly of opaque minerals (ilmenite, magnetite hematite and leucoxene). The non-opaque minerals include; zircon, tourmaline, rutile, garnet, apatite and monazite. The above association reflects a source area dominated by igneous, metamorphic and sedimentary terrains. The magmatic and crystalline core rocks of the Western Carpathian Mountains as well as the older Early and Middle Triassic rocks are the most probable source for the heavy minerals of the Keuper rocks (Al-Juboury *et al.* 1994).

Plate 1. Photomicrographs of selected sandstone samples of Keuper Formation.
(a) Laminated texture in fine-grained lithic arenites. (b) Mosaic interlocking of monocrystalline quartz grains in quartz arenites showing faint demarcation lines (black arrow) between primary grain and secondary quartz overgrowths. Note the straight to concavo-convex contacts and polycrystalline quartz grain (white arrow). (c) Monocrystalline quartz grain (Q) with observed embayment in micritic carbonates cement. Black clast is an argillaceous rock fragment. (d) Polycrystalline quartz (P) and chert (microcrystalline silica) fragments (white arrow) in mosaic texture of quartz arenites. (e) Highly corroded quartz grains (Q) with common inclusions of zircon, apatite and mica. (f) Highly compacted quartz grain (Q) showing mutual boundaries and sutured contacts and highly altered orthoclase (F) into clay minerals. (g) lithic subarkose cemented by crystalline calcite cement, note the common presence of plagioclase and alkali feldspars (arrows). (h) lithic arenites with common carbonate rock fragments and chert (Ch) clasts which are cemented by carbonates. Note the highly rounded carbonate fragments (white arrow). Scale bars= 0.2 mm.

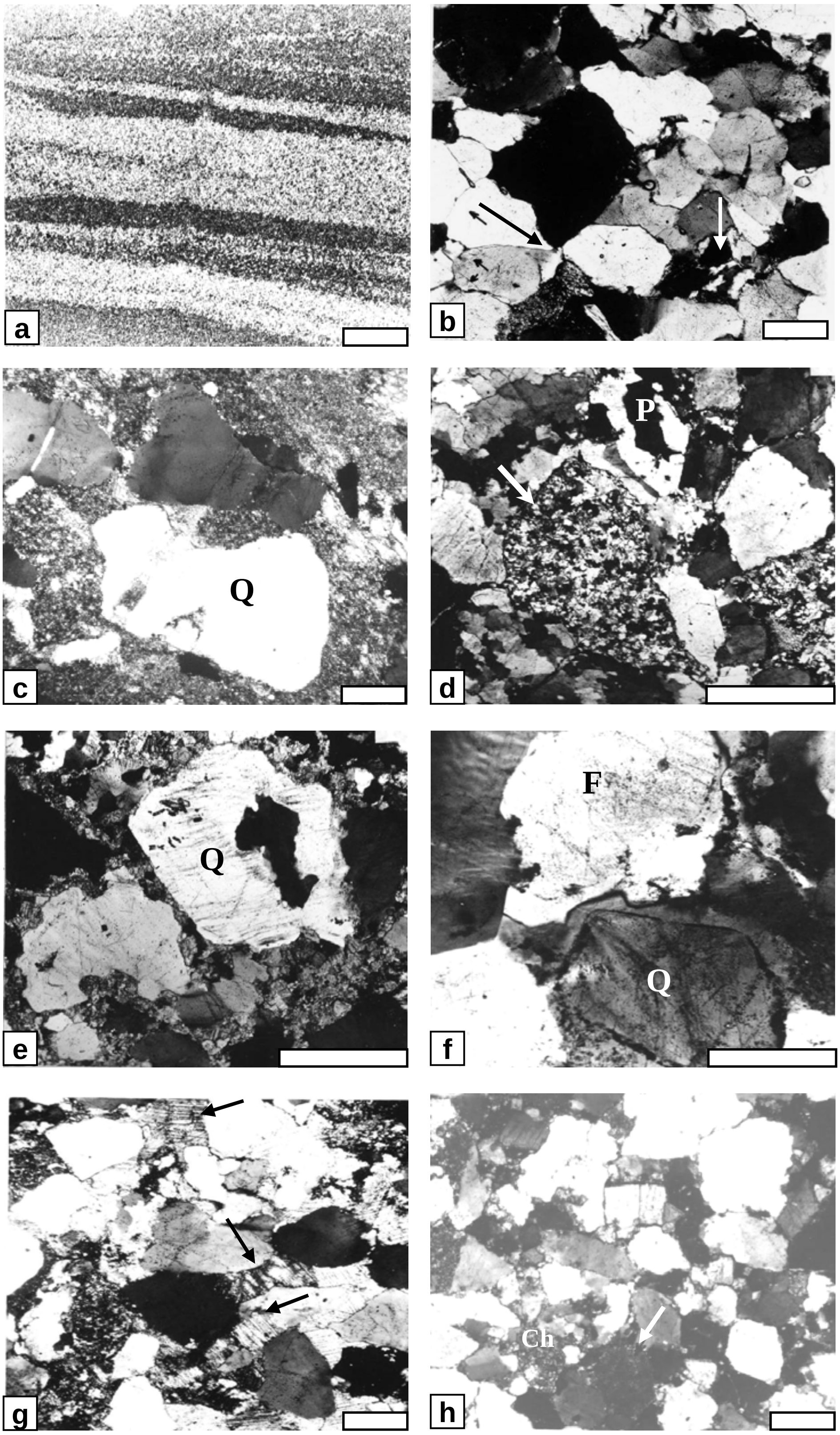
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Table II. Representative chemical analyses of sandstones from the Keuper Formations, Western Carpathian, Slovakia. Major oxides in wt%, total Fe as Fe_2O_3. Types: QZA=Quartzarenites, SLA= sublitharenites, SA=subarkose, LA=litharenites, LSA=lithic subarkose (carbonate- rich). Crystalline rock analyses data after (Pin *et al.* 2004; Krist *et al.* 1992), CIA= Chemical Index of Alteration.

Location/Profile/number of samples	**Sandstone type**	**SiO_2**	**TiO_2**	**Al_2O_3**	**Fe_2O_3**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**L.O.I.**	**Total**	**CIA %**
Klippen Belt/ Drietoma/ 4	SLA	75.41	0.42	9.62	3.95	0.08	0.01	2.99	1.68	0.79	0.00	4.87	99.82	64
Klippen Belt/ Záblatie / 2	SA	89.83	0.26	1.99	3.22	0.02	0.01	0.88	0.15	1.29	0.00	2.14	99.79	46
Envelope (Tatric)/ Beckov/ 3	LSA	42.17	0.62	13.55	3.32	0.02	3.22	16.15	0.67	2.93	0.27	17.14	100.06	41
Križna(Fatric)/ Vysoká754/ 3	QZA	95.07	0.12	0.98	1.56	0.01	0.00	0.35	0.29	0.68	0.00	0.30	99.36	43
Envelope (Tatric)/ Banka/ 3	SA	82.96	0.28	2.99	3.03	0.03	1.38	2.46	0.36	2.16	0.06	3.97	99.68	38
Križna (Fatric)/ Ždiar/ 4	SA	83.90	0.30	5.56	2.33	0.02	0.50	0.98	1.93	0.51	0.00	3.93	99.96	62
Križna (Fatric)/ Zázrivá/ 4	SLA	71.40	0.83	9.66	5.48	0.05	1.51	1.76	1.94	2.13	0.00	3.95	98.71	62
Andesitic basement rocks, Klippen belt		60.9	0.55	16.3	5.08	0.13	3.22	6.68	2.05	1.43	0.24	3.17	99.75	61
Gneissic rocks of west Carpathians		73.4	0.24	13.8	1.87	0.01	1.56	0.64	1.66	3.79	0.14	1.37	98.48	69

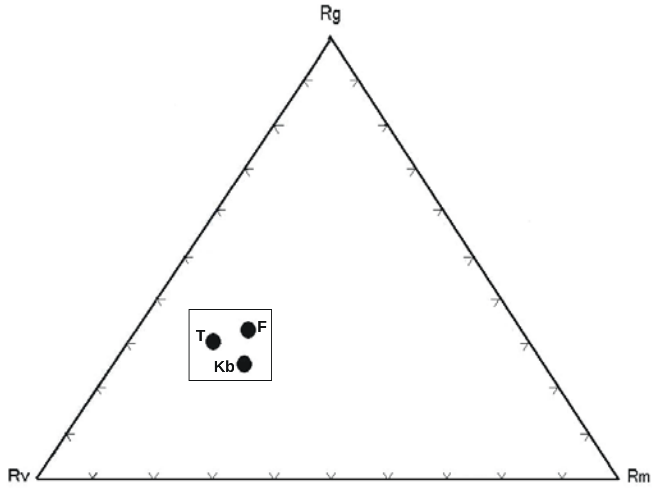


Figure 5. Rg-Rv-Rm diagram of the Keuper sandstones. Rg is the counts of quartz, K-feldspars, plagioclase, mica and dense or heavy minerals in granitic and⁄or gneissic rocks, whereas, Rv and Rm are the counts of these minerals in volcanic and metamorphic rock fragments and aphanitic metamorphic and volcanic lithics as well. T= mean sandstone composition from Keuper in Tatric unit, F= mean sandstone composition in Fatric unit, and Kb= mean sandstone composition in the Klippen belt.

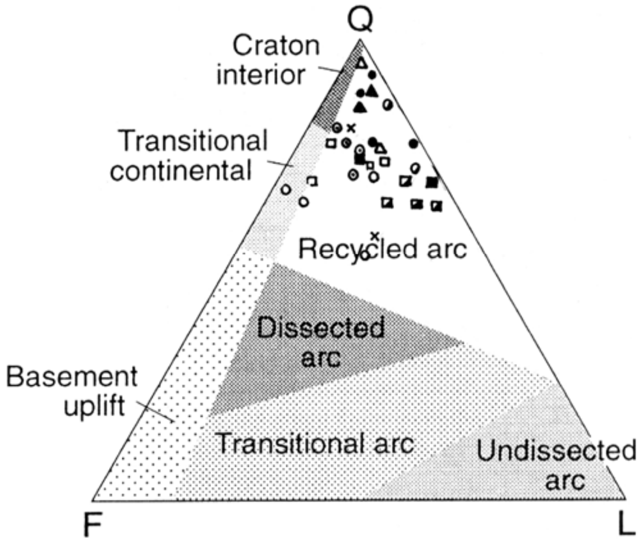


Figure 6. Sandstone modal data (40 samples) plotted on a Quartz-Feldspar-Lithic fragment (Q-F-L) diagram. Tectonic discriminations fields defined by Ingersoll and Suczek (1979). Solid square = sandstones from the Klippen belt, Cross = sandstones from Tatric unit, open and solid triangles and circles and open squares are samples from different profiles of Križna (Fatric) unit.

Diagenesis

Keuper sandstone have been affected by diagenesis leading in particular to reductions of the feldspar and unstable lithic fragments. Matrix percentages are therefore high, much of this occurring as crushed lithic grains, small quartz grains, and phyllosilicates (particularly sericite, pseudomatrix) (Plate 2, a), and as epimatrix and orthomatrix (Table I). Hematite and clayey cements are important cement in some samples (Plate 2b,e). Poikilotopic, pore-filling and patchy carbonate (sparry calcite, micrite) and cementation by quartz are common in some samples (Plate 2, c-d).

Compaction is reflected by deformation of the soft labile fragments, directional orientation and/or bending of mica, the highly sutured contacts of the detrital grains, and the variable degrees of fracturing of the studied sandstones, some of fractures are healed by calcite especially in highly compacted quartz arenites (Plate 2, f-g). Sometimes, the quartz grains are deformed in the highly sutured pressure-solution contacts. The deformed grains show some micro cracks with common fluid inclusions (Plate 2, h).

Modal composition

The sampled Late Triassic Keuper sandstones (50 samples) have a mean quartzo-lithic composition of $Q_{84}F_7L_9$. On the basis of their composition, the sandstones of the Keuper of the western Carpathians are of variable types: lithic sub-arkose, sub-arkose, sub-litharenites**,** and quartz arenites. These types of sandstone were recorded in both Envelope and Križna Keuper units with a slight abundance of sub-arkose in the examined sandstone of the Envelope units of the Považsky Inovec and the Small Fatra mountains (sections 3, Banka and 13, Ráztoky respectively, Fig. 1).

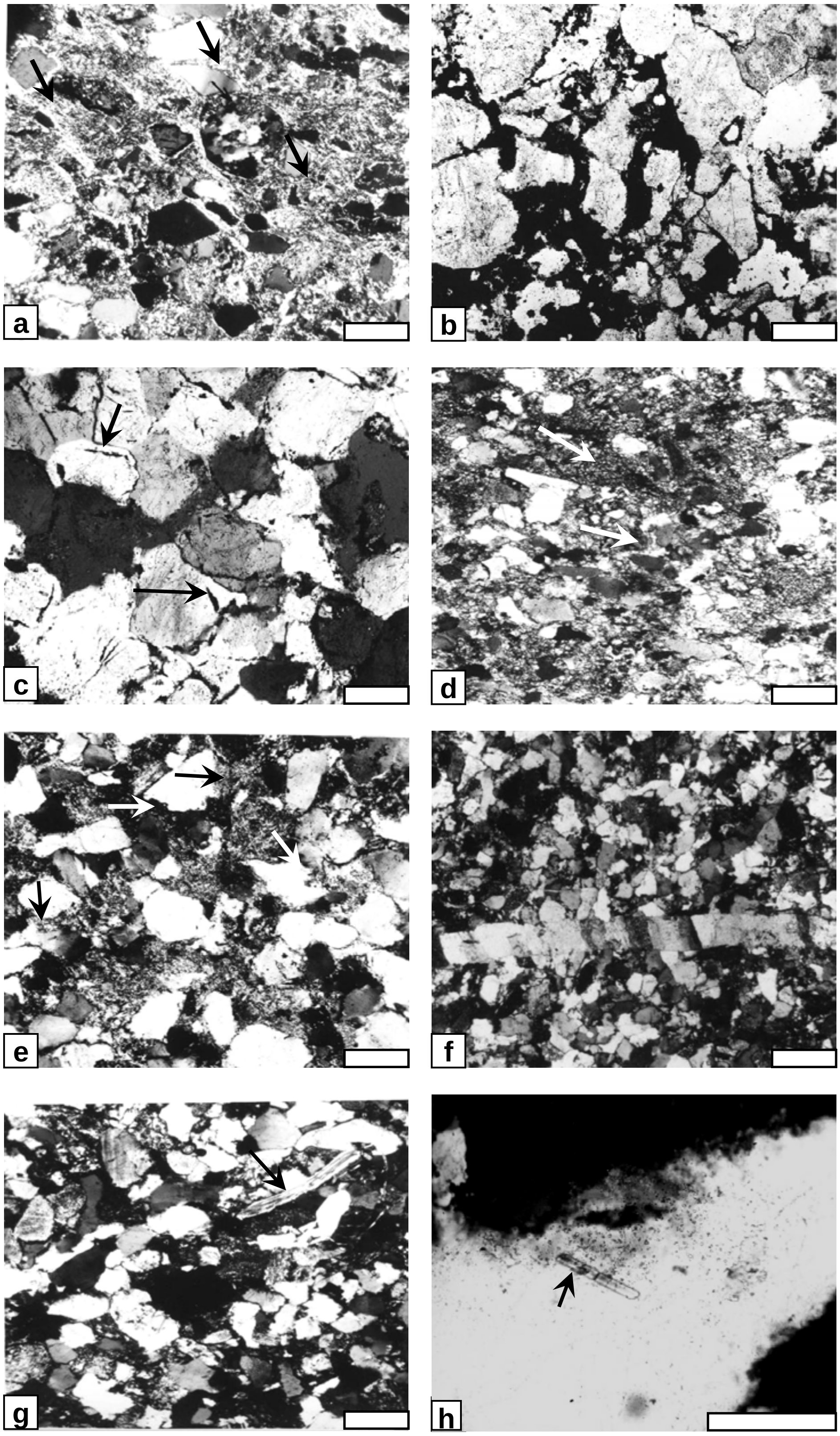
To interpret the tectonic discrimination source fields, the Keuper sandstones were plotted on the QFL ternary diagram of Ingersoll & Suczek (1979), the studied sandstones fall in the craton interior, recycled arc province and partly in the transitional continental fields (Fig. 6). The source of these sediments are uplifted terrains of folded and faulted strata from which recycled detritus of sedimentary and meta-sedimentary origin were input in the basin (Dickinson & Suczek,1979, Boggs 2006).

Geochemical analysis

The geochemistry of the Keuper sandstones (Tab. II) supports the petrographic results. The Keuper sandstones are geochemically classified using Pettijohn classification diagram (Pettijohn 1975) into lithicarenites, sublitharenite, subarkose and quartzarenite (Fig. 7, a).

Besides the quartz arenites, other sandstones also show high content of SiO_2. The source of silica is mainly quartz, chert, quartzite, feldspars and clay minerals. Al_2O_3 and K_2O content may relate to the presence of potassium feldspars (orthoclase and microcline), illite and mica. The source of Na_2O is principally related to plagioclase feldspar. Ti-opaque minerals and rutile are the main holders of TiO_2. Higher content of iron may be related to the abundance of iron oxide heavy minerals and partly to Fe- containing clay minerals. MgO content is related mostly to the presence of dolomitic materials as fragments or cement. Calcite cement and rock fragments are the main source for CaO.

To make use of the chemical parameters, the ratio of SiO_2/Al_2O_3 against that of quartz, quartzite and chert /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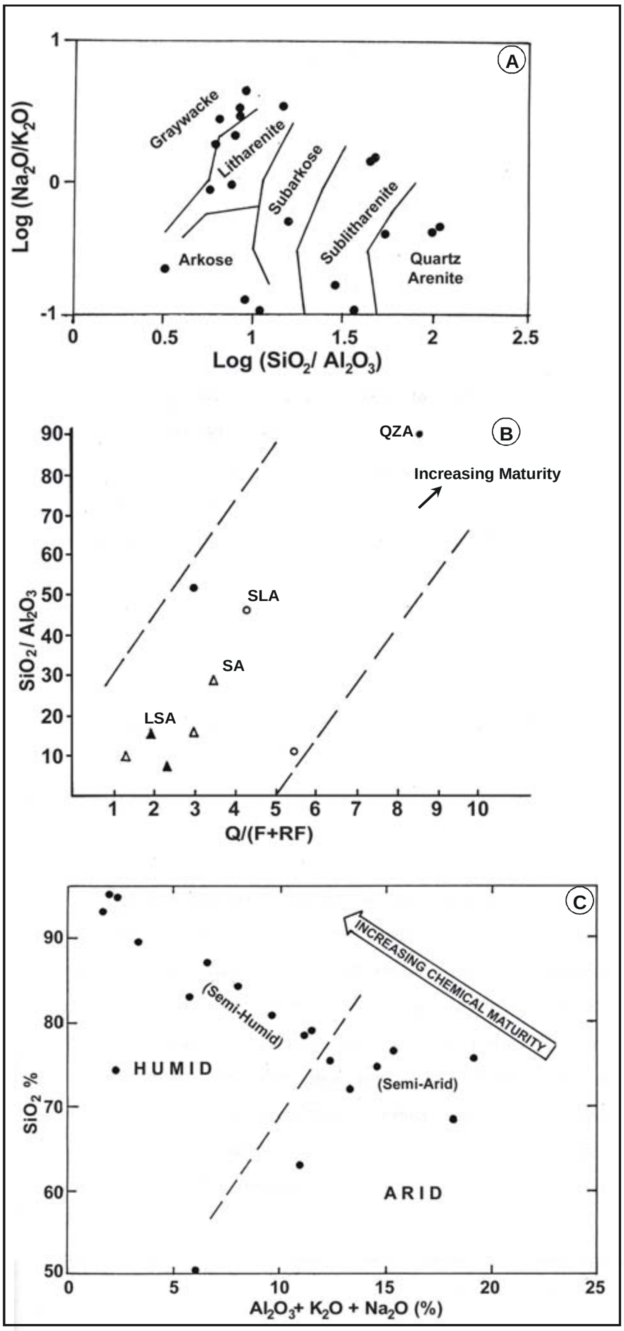

Figure 7 A. Chemical composition of Keuper sandstones plotted on Pettijohn scheme (Pettijohn 1975). B: The ratio SiO_2/Al_2O_3 and Q/ (F+RF) (quartz + quartzite + chert)/(feldspar + rock fragments) in the different types of Keuper sandstones. Solid circles = quartz arenite (QZA), open circles = sublitharenites (SLA), solid triangle = lithic subarkose (LSA) and open triangle = subarkose (SA). C: Chemical maturity of the Keuper sandstones expressed by bivariant plot SiO_2 versus Al_2O_3+ K_2O + Na_2O. Fields after Suttner & Dutta, (1986).

Table III. Electron probe microanalysis of representative Fe-Ti oxide grains from Carpathian Keuper sandstones (wt% oxide), grains selected from samples (Drietoma D2 and Ždiar Ž3); * All Fe is expressed as FeO

N°	MgO	Al_2O_3	TiO_2	Cr_2O_3	MnO	FeO*	Total
1	0.31	0.35	55.8	0.10	1.47	39.22	97.25
2	0.31	0.10	57.92	0.03	0.20	38.23	96.79
3	0.39	0.20	57.24	0.05	0.80	37.22	95.90
4	0.15	0.01	58.18	0.03	1.74	35.84	95.95
5	0.13	0.44	60.95	0.03	0.32	36.54	98.41
6	0.08	0.00	58.93	0.00	0.69	36.47	96.17

(feldspar + rock fragments), (Q/F+RF) was plotted (Fig. 7b) which is interpreted to reflect the maturity of sandstones (Pettijohn 1975). Higher SiO_2 ratio coincides with higher silica phases of quartz, quartzite and chert which in turn reflects that such sandstones are mature.

A bivariant plot of SiO_2 against total Al_2O_3+K_2O+ Na_2O proposed by Suttner & Dutta 1986) was used in order to identify the maturity of the Keuper sandstones as a function of climate (Fig. 7c). This plot revealed the semi-arid to semi-humid climatic conditions for the samples investigated.

Iron oxides which form a large portion of the heavy minerals in the samples examined are represented mostly by ilmenite, titaniferous magnetite, leucoxene, and hematite. Chemical analysis of Fe-Ti oxides (Table III) revealed that the total oxides generally are low and this may be related to the alteration on these grains. Most of Fe-Ti oxide minerals studied are polymineralic grains with mixture of two or more phases. The chemical composition of some grains indicates a coexisting mixture of ilmenite and titano-magnetite. The highly TiO_2 concentrations may indicate the metamorphic source rocks origin of the studied grains (Basu & Molinaroli 1989, 1991). By comparing the present chemical results with that mentioned by aforementioned authors, it appears that Keuper ilmenites generally were derived from metamorphic and partly from igneous sources.

The Chemical Index of Alteration (CIA) for the Keuper sandstones is deduced using the formula CIA = $[Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)]*100$, given by Nesbet & Young (1982) to interpret the weathering index Table II. The variation in CIA values may reflects changes in he proportion of feldspars and the various clay minerals in the samples analyzed. Size sorting during transportation and deposition generally results in some degree of mineral,

Plate 2. Photomicrographs of selected Keuper sandstone, illustrating the various diagenetic events: (A) Directional orientation of sericitic, micaceous matrix (arrows) in lithic arenites. (B) Angular to sub-angular quartz grains in ferruginous clayey cement. Grains are highly stained by iron pigments. (C) Syntaxial secondary silica overgrowth indicated with ferruginous dust rings in quartz arenites (arrows). (D) Cementation by dolomite in lithic arenites (arrows), note the floating nature of medium sized quartz grain and inhibiting of secondary quartz overgrowth. (E) Clayey matrix and cement in lithic arenites (black arrows), note various type of grain contacts and partial corrosion of detrital grains (white arrows). (F) Calcite healed fracture in quartz arenites. (G) Various mineralogical components of Keuper lithic arenites. Note the slight bending of mica lath between detrital grains (arrow). (H) Intensively deformed quartz grain, due to pressure dissolution. Faint fractures form planes of deformation with abundant fluid inclusions. Note the presence of apatite inclusion (arrow) in quartz grain. Scale bars= 0.2 mm.

differentiation which may modify the CIA (Pettijohn 1975, Nesbet & Young 1982). Higher values in CIA for the subarkose and sublitharenite samples may coincide with the common abundance of sericitic matrix materials as a result of intensive weathering.

DISCUSSION

In the west Carpathians of Slovakia, the Triassic series constitutes a good example of Alpine-type deposition, with variable sedimentary facies related to intensive sea-floor spreading of the Tethys in the latest Triassic and break-up of extensive carbonate shelves (Michalík 1978, Michalík *et al.* 2002).

The composition of sandstones of the siliciclastic strata of the Carpathian Keuper Formation which alternates with shale, conglomerate and/or dolostones document the combination of metamorphic and igneous source rocks. The mainly quartz-dominated mineralogy of the sandstones, suggests their derivation mostly from acid igneous rocks, gneisses and older sandstones.

Petrographic evidence suggests that the Carpathian Keuper sandstones were derived from a stable cratonic area. They are relatively quartz-rich and show some evidence of recycling, suggesting derivation from older granitic and gneissic outcrops and associated platform sediments (Dickinson 1985, 1988). This suggests that the dominant control on sediment petrography within the basin was the source area (the crystalline cores of the Western Carpathians and the Bohemian Massif). Granitic and gneissic rocks predominate in these crystalline complexes (Uher & Broska 1995, Kovāčik 1999; Faryad *et al.* 2003). Petrographic and geochemical investigation of older Paleozoic (Cambrian and Devonian) sandstones of the region revealed that these sandstones are quartz-rich and arkosic (Gilíková *et al.* 2003). Their mineralogical constituents reflect derivation from intermediate and acid igneous rocks similar to those of the Keuper sandstones.

Strong clastic influx from eastern sources (mainly from the Bohemian Massif) dominated sedimentation in the region during Late Triassic Carpathian Keuper sedimentation (Würster 1968). The area was affected by extensional tectonics, lithostratigraphic stretching and crustal thinning took place as a result of normal listric faulting. This extension connected with passive rifting processes could have been a source of detrital materials from the pre-Mesozoic basements (Jurewicz 2005).

Duration of rifting-related silicic magmatism has been recognized to persist as late as the Middle Triassic. The poorly consolidated epi-Variscan crust in the southern parts of central west Carpathians suffered Late Permian to Scythian rifting and Late Anisian break-up of the Meliata ocean, followed by its Middle to Late Triassic spreading (Plašienka 2001).

Opening of the Meliata ocean is attributed to back-arc rifting and extension triggered by the northward subduction of Paleotethys (Stampfli 1996). The northern Slovakocarpathian shelf of the Meliata ocean was still attached to the stable North European platform and shows zoning from slope facies deposited on transitional crust, carbonate reef bodies on a subsiding distal passive margin, and lagoonal to terrestrial environment (Keuper) landwards.

A complex interplay of other controls, however, may also have been superimposed upon the petrography, including source area relief and climate, depositional environments and processes, sedimentation rates and changes in source area.

The sandstone sequences have been subjected to several important diagenetic changes since their depositional history. Their paragenetic sequence begins with primary partial silica cementation, which was followed by formation of iron in the remaining pores. Both these stages involve quartz overgrowths produced as a result of pressure solution. Later stages proceeded by precipitation of Fe-rich clays and carbonate in new pore spaces created by partial replacement and corrosion of detrital quartz grains. The lack of quartz overgrowths in the later stages is believed to be due to inhibition of pressure solution. A high grade of diagenesis and compaction characterizes the studied rocks, which is best suggested by sutured contacts between the grains and also by the good crystallinity of the present illite as the common clay mineral found in the studied sandstone and associated shales (Al-Juboury & Ďurovič 1992).

The major-element concentration of the Keuper sandstones reveal the relative homogeneity of their source. Geochemically, the Keuper sandstone are classified as lithicarenites, sublitharenite, subarkose and quartzarenite.

Implication of the petrographic and major elements geochemistry of the Carpathian Keuper sandstones with other grain size data (Al-Juboury 1992), revealed that the sandstones were deposited mainly as beach or dune that dominates over fluvial deposition in semi-arid to semi-humid conditions.

Relative dryer periods interchange with playa lakes of relative wetter periods in an overall semi-arid mega monsoon climate resulting in the formation of Keuper in German and Paris Basins (Bourquin & Guillocheau 1996, Reinhardt 2000).

CONCLUSIONS

(1) The Keuper sandstones of the western Carpathians of Slovakia can be classified as sub litharenites, sub-arkoses and quartz arenites. They are well-cemented principally by secondary silica, carbonate, ferruginous and clayey sericitic materials.

(2) The petrographic data suggest a mainly recycled orogen source terrain on the basis of standard ternary diagram.

(3) The chemical data plots show the different types of the Keuper sandstones and reflect their maturity. Climatic conditions of semi-humid to semi-arid prevailed during the deposition of Keuper sandstones.

(4) The result obtained from the chemistry of selected Fe-Ti oxide minerals suggests the derivation of these minerals from metamorphic rather than igneous sources. This is indicated by higher content of TiO_2 and low content of MgO. The high MnO and MgO contents indicate a recycled–orogen provenance. The variable ratios of these two oxides do not eliminate entirely the recycled-orogenic provenance, and this coincides with the modal data which is

plotted mainly within the craton interior, transitional continental and recycled arc fields of tectonic provenances.

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