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Major Paleozoic-Mesozoic unconformities in the Greater Caucasus and their tectonic re-interpretation: a synthesis

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Abstract

Four major unconformities are present within the Paleozoic-Mesozoic strata of the Greater Caucasus, a region that was derived from the Afro-Arabian margin of Gondwana during the Ludlow, then docked at the Laurussian margin near the European Alpine terranes, and moved eastwards during the Late Triassic-earliest Jurassic to occupy its present position. The Ordovician unconformity, which includes part of the Middle Ordovician, formed due to uncertain tectonic activity on the Gondwanan margin. The mid-Permian unconformity, which encompasses the Guadalupian to early Lopingian, might have resulted from the Saalian Orogeny accompanied with strike-slip activity. The Triassic/Jurassic unconformity, which encompasses the mid-Rhaetian to early Sinemurian, developed after the long-distance movement of the Greater Caucasus Terrane along a shear zone or, alternatively, after the global sea-level fall. These three mentioned major unconformities are correlated with similar unconformities in some European, north-central African, and Arabian basins. The mid-Jurassic unconformity, which encompasses the mid-Bathonian to the Early Callovian, might have been caused by arc-arc collision in the Caucasian sector of the northern Neotethys or by the major sinistral transtension from Europe to the Himalayas.

Keywords: Unconformity, Palaeotectonics, Paleozoic, Mesozoic, Greater Caucasus.

Introduction

The Greater Caucasus is a large region, which stretches between the Black Sea and the Caspian Sea, and it embraces some areas of southwestern Russia, northern Georgia, and northern Azerbaijan (Fig. 1). The whole Caucasus is a large Alpine-type region, which is presentely located at the junction of the Eurasian, Anatolian, Arabian plates and Iranian terranes (Bird, 2003). It is composed of two principal domains (terranes), which are the Greater Caucasus and the Lesser Caucasus. They are divided by the Transcaucasian depressions, which are named the Rioni Depression and the Kura Depression (Fig. 1). The geological record from this region provides many new and intriguing information to recognize and explain the tectono-sedimentary events common for the entire Tethys. Unfortunately, the Greater Caucasus is less known than the adjacent European, Asian, and African regions. The use of traditional, but outdated and false concepts like "geosyncline paradigm" and "formational analysis" by the Russian geologists additionally minimizes the significance of information from this region for the international scientific community. The Paleozoic-Mesozoic sedimentary succession of the Greater Caucasus is characterized by the presence of several *major unconformities* (Ruban, 2006a). However, the stratigraphical data on these unconformities are "dispersed" in numerous references, published mostly in Russian.

This article presents a brief synthesis of knowledge on the major Paleozoic-Mesozoic unconformities of the Greater Caucasus, including new data collected by the author and new data from recent studies by Kotlyar et al. (1999, 2004), Davydov and Leven (2003), and Gaetani et al. (2005). In addition, this article presents a new tectonic interpretation of the major unconformities, according to recent models of the regional evolution of the Greater Caucasus (Tawadros et al., 2006; Ruban, in press), and it also demonstrates that they may be traced in some other regions.

Geological setting

The geological history of the Greater Caucasus has been briefly reviewed by Tawadros et al. (2006), who presented a new model of the tectonic

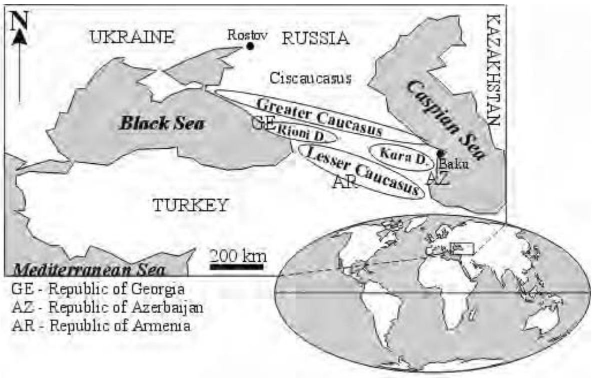

Fig. 1 - Geographic location of the Greater Caucasus.

evolution of this region. To develop this new model, various palaeontological, stratigraphical, and palaeomagnetic data and global plate reconstructions (Dercourt et al., 2000; Cocks and Torsvik, 2002; Stampfli and Borel, 2002; Vai, 1991, 2003; von Raumer et al., 2002, 2003; Vai, 2003; Golonka, 2004; Scotese, 2004; Torsvik and Cocks, 2004) were taken into account. A key point in this model is the activity of planetary-scale strike-slip movements on the northern periphery of the Palaeotethys Ocean (Arthaud and Matte, 1977; Swanson, 1982; Vai, 1991, 2003; Rapalini and Vizán, 1993; Stampfli and Borel, 2002; Ruban and Yoshioka, 2005). To develop this model, it was argued first, that the Greater Caucasus was located somewhere close to the Carnic Alps and Bohemia in the Middle-Late Paleozoic. This was concluded from the similarities of their sedimentary successions and palaeontological records. The next step was to explain how the studied terrane might have reached its present position. This involved the idea of long-distance displacements along the major shear zone. As for the pre-Ludlow time, the position of the Greater Caucasus was evaluated approximately with the global reconstructions of Stampfli and Borel (2002), which permit to understand the palaeogeodynamics of the Hunic terranes in the whole. According to this new model of Tawadros et al. (2006), the following five tectono-depositional phases are recognized within the Paleozoic-Mesozoic history of this region (Tawadros et al., 2006) (Fig. 2): (1) *Gondwanan Phase* (before the Ludlow, the Greater Caucasus was a part of the Afro-Arabian margin of Gondwana open to the Prototethys and then Rheic oceans), (2) *Hunic Phase* (from the Ludlow and until the end-Devonian, the Greater Caucasus and the other European Hunic terranes were shifted to the Laurussian margin and docked somewhere near the Carnic Alps and Bohemia), (3) *Proto-Alpine Phase* (the Greater Caucasus was located at above-mentioned place until the Late Triassic), (4) *Left-Shear Phase* (the clockwise rotation of Africa provoked the left-shear displacements along the Northern Palaeotethyan Shear Zone and, during the earliest Jurassic, the Greater Caucasus reached its present position), and (5) *Arc Phase* (until the end of the Mesozoic, the Greater Caucasus was dominated by the parallel arcs and elongated sea basins on the northern margin of the Neotethys Ocean).

The sedimentary history of the Greater Caucasus has been also reviewed by Tawadros et al. (2006), whereas Ruban (2006a) has presented a composite lithologic section (Fig. 3). Although numerous unconformities are known within the Paleozoic-Mesozoic strata of the Greater Caucasus, only four of them may be called major (Ruban, 2006a). As described below, the major unconformities are present in strata of *Ordovician*, *mid-Permian*, *end-Triassic-early Jurassic*, and *mid-Jurassic* age. The chronostratigraphic framework and numerical ages used in this paper are all taken from Gradstein et al. (2004). The term "unconformity" is used following Bates and Jackson (1987) and Catuneanu (2006).

Major unconformities

Ordovician unconformity

The first Paleozoic unconformity described in this article is present in strata of Ordovician age (Ruban, 2006a). The Ordovician unconformity, which is present between the Upper Formation of the pre-Middle Paleozoic metasedimentary complex and the siliciclastic strata of the ?Ordovician-Silurian Urleshskaja Formation (Fig. 3), has been observed in outcrops in the valley of the Khasaut River (Robinson, 1965). It seems that the Cambrian complexes were altered by metamorphism (Robinson, 1965), and this unconformity is essentially a nonconformity (*sensu* Bates and Jackson (1987) and Catuneanu (2006)). However, the structural framework of the Lower Paleozoic complexes of the Greater Caucasus remains a subject for further discussions.

Below the unconformity, the upper part of the

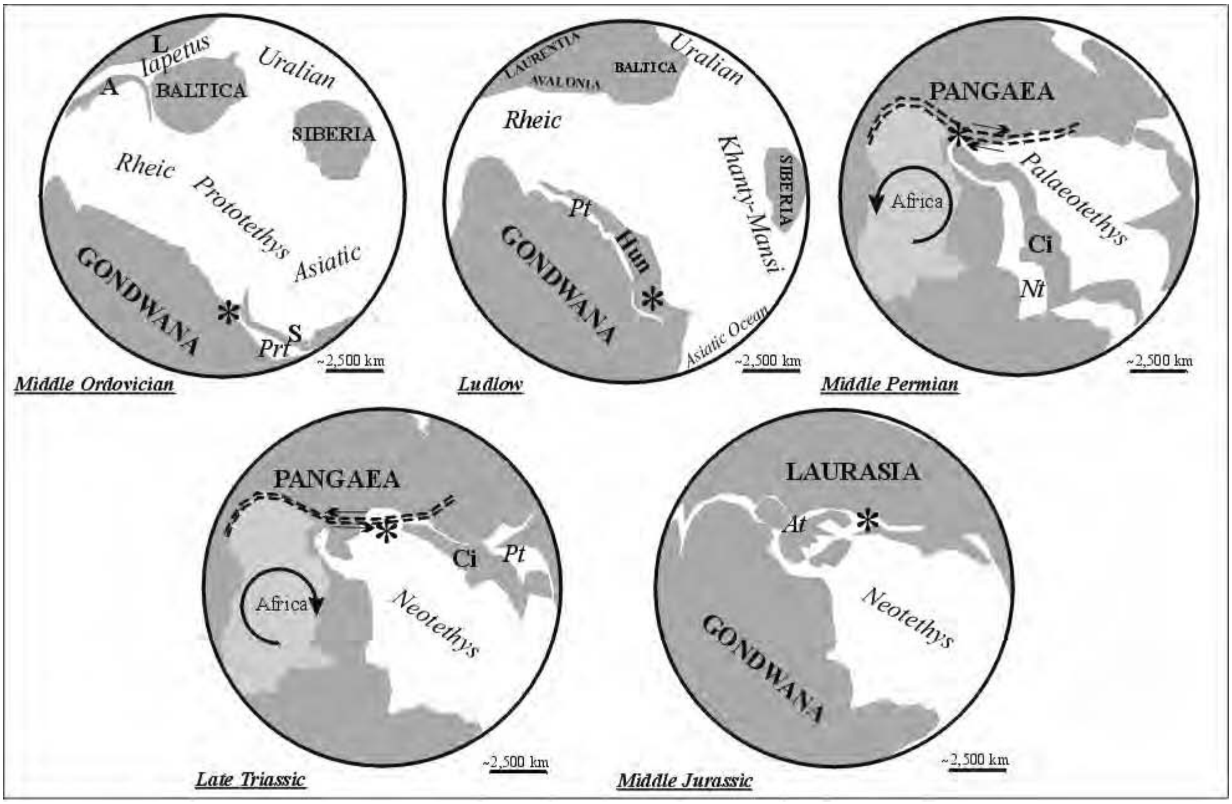

Fig. 2 - The palaeotectonic position of the Greater Caucasus Terrane (marked by asterisk). The palaeotectonic maps are simplified from Stampfli and Borel (2002). Abbreviations: A - Avalonia, S - Serindia, L - Laurentia, Prt - Prototethys, Pt - Palaeotethys, Hun - Hun Superterrane (European+Asiatic Hunic terranes), Ci - Cimmerian Superterrane, Nt - Neotethys, At - Alpine Tethys.

Upper Formation of the pre-Middle Paleozoic metasedimentary complex is composed of phyllites with rare interbeds of sandstones up to 900 m thick. This metasedimentary complex is thought to be of Ordovician age (Paffengol'ts, 1959, 1965), and it overlies the ?middle Cambrian carbonates with *Archaeocyathus* sp. Following these assumptions, the uppermost horizons of the Upper Formation may be upper Cambrian - lowermost Ordovician.

Above the unconformity, the lower Urleshskaja Formation consists of sandstones and conglomerates of unestimated thickness (Obut et al., 1988). The succession starts with the conglomerates, dominated by quartz pebbles, up to 6 m thick (Robinson, 1965). The few microfossils found in these strata (i.e., *Gleocapsamorpha* cf. *prisca* Zall., *Monotrematum* sp., *Trematosphaeridium* sp., *Protolophosphaeridium* sp., and *Turuchanica* sp.) suggest an Early-Middle Ordovician age (Potapenko, 1982; Obut et al., 1988). Within the Urleshskaja Formation, the boundary between the Ordovician and the Silurian deposits corresponds with the appearance of fine-grained siliciclastic rocks (Obut et al., 1988).

Thus, the age of the lower part of the Urleshskaja Formation is unclear, and we cannot conclude, how long was the hiatus, established since the Early Ordovician. If possibly sedimentation restarted already in the Middle Ordovician or even early as suggested from microfossils, this means hiatus was only 10-15 Ma long. In contrast, if this hiatus embraces the most part of the Ordovician, it could have lasted up to 40 Ma.

Mid-Permian unconformity

The second major Paleozoic unconformity in the Greater Caucasus is of Permian age, and it encompasses almost the entire Gaudalupian Series, the Wuchapingian and the lower Changhsingian stages (Fig. 3). Kotlyar et al. (1999, 2004) state that this is an angular unconformity between the Bol'shelabinskaja and Kutanskaja formations

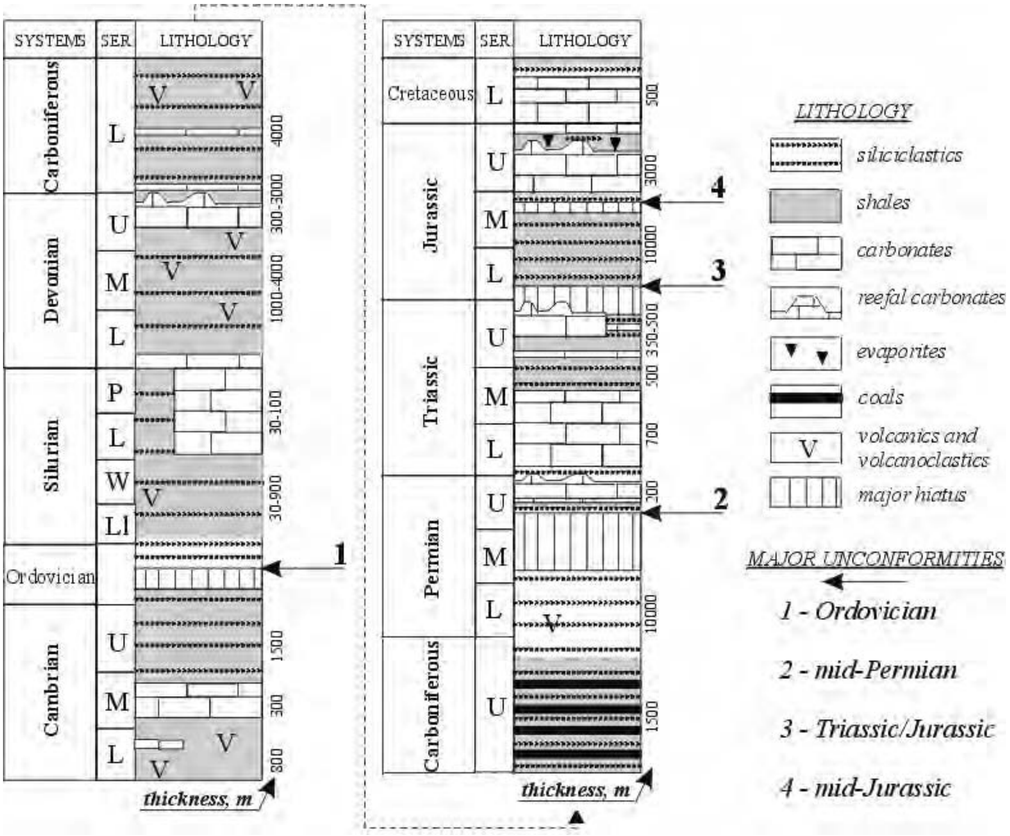

Fig. 3 - The composite Paleozoic-Mesozoic lithologic section of the northern Greater Caucasus (slightly modified from Ruban, 2006a).

in the northern part of the Greater Caucasus, whereas Kotlyar (1977) mentions that the Kutanskaja Formation overlies locally the Bol'shelabinskaja Formation without unconformity. In the southern part of the Greater Caucasus, there is no major unconformity in the Permian strata, which are of marine origin (Miklukho-Maklaj and Miklukho-Maklaj, 1966).

Below the unconformity in the northern Greater Caucasus, the molassic Bol'shelabinskaja Formation consists of siliciclastic red-beds (Miklukho-Maklaj and Miklukho-Maklaj, 1966; Tawadros et al., 2006). The estimations of its thickness vary significantly between 500 m (Miklukho-Maklaj and Miklukho-Maklaj, 1966) and 10,000 m (Kotlyar, 1977). The age of these deposits was established by Davydov and Leven (2003) as the Sakmarian, although the fossil remains from these strata are very poor, and include *Walchia* and *Acanthodes*. The author has also found some unidentified and possibly reworked crinoids. Miklukho-Maklaj and Miklukho-Maklaj (1966) hypothesized that the upper horizons of the Bol'shelabinskaja Formation may belong to the "Upper Permian", which is the Guadalupian Series in the recent chronostratigraphic framework (Gradstein et al., 2004).

Above the unconformity in the northern Greater Caucasus, the Upper Permian Kutanskaja Formation, and overlying Nikitinskaja and Urushtenskaja formations consist of siliciclastics, shales, and carbonates with a total thickness of about 200 m. The age of these overlying strata has been established with numerous palaeontological data (foraminifers, brachiopods, ammonoids, bivalves, gastropods, etc.) as Late Changhsingian (Kotlyar et al., 1999, 2004; Gaetani et al., 2005).

Thus, it seems that the lack of sedimentation lasted during the Guadalupian, Wuchiapingian and early Changhsingian, i.e., its duration was15-20 Ma.

Triassic/Jurassic unconformity

The first major Mesozoic unconformity in the

Greater Caucasus marks the Triassic/Jurassic boundary (Ruban, 2006a) (Fig. 3). This is an angular unconformity or nonconformity at the base of the Lower Jurassic strata (Rostovtsev et al., 1992). Latter are folded less intensively, and they overlie various complexes of the Paleozoic and Triassic.

Below the unconformity in the western Greater Caucasus, the Khodzinskaja Group is composed of limestones (up to 500 m thick), which contain very abundant and diverse marine fauna including ammonoids, foraminifers, brachiopods, bivalves, algae, corals, sponges, echinoids, and bryozoans (Dagis and Robinson, 1973; Jaroshenko, 1978; Rostovtsev et al., 1979; Prozorovskaya, 1979; Gaetani et al., 2005; Ruban, 2006b). The age of this group is established as Norian-Early Rhaetian (Prosorovskaya, 1979; Rostovtsev et al., 1979; Gaetani et al., 2005), although Dagis and Robinson (1973) and then Tozer (1988) suggested the undifferentiated “Norian-Rhaetian sandwich”, and Krystyn (1990) showed some doubts about the presence of Rhaetian strata in the Greater Caucasus.

Above the unconformity in the Greater Caucasus, there are several siliciclastic formations that are up to 1,000 m thick (Rostovtsev et al., 1992). A late Sinemurian age for these strata is established with ammonites, foraminifers, and brachiopods (Antonova and Pintchuk, 1991; Rostovtsev et al., 1992; Prosorovskaya, 1993; Ruban, 2004a; Ruban and Tyszka, 2005). The presence of the Hettangian deposits in this region is not confirmed yet, although it is sometimes questionned (Rostovtsev et al., 1992; Ali-Zadeh, 2004).

Thus, the hiatus on the Triassic-Jurassic transition embraced a half of the Rhaetian, the Hettangian and the early Sinemurian. Consequently, It lasted not more than 5-10 Ma.

Mid-Jurassic unconformity

The second major Mesozoic unconformity in the Greater Caucasus is of Middle Jurassic age (Ruban, 2006a) (Fig. 3). This is an angular unconformity. The underlying strata are folded, whereas the overlying strata are only slightly deformed so as to create a monocline. However, in some southern areas of the Greater Caucasus, this mid-Jurassic unconformity is absent (Rostovtsev et al., 1992).

Below the mid-Jurassic unconformity, there are Sinemurian-Bathonian siliciclastic and argillaceous strata up to 10,000 m thick (Rostovtsev et al., 1992; Ruban, 2006a). Above this unconformity, there are siciliclastic and carbonate strata overlain with evaporites up to 3,000 m thick (Rostovtsev et al., 1992; Ruban, 2006a).

The duration of the hiatus, which the mid-Jurassic unconformity corresponds to, varied significantly within the Greater Caucasus (Rostovtsev et al., 1992). In some areas, the lack of sedimentation was established already in the end-Bajocian, while in the other areas, this occurred only in the end-Bathonian. The restart of sedimentation took place also at a diffirent time - it varied between the mid-Bathonian and mid-Callovian (Rostovtsev et al., 1992). Above the mid-Jurassic unconformity in the Laba-Malka Area, the Kamennomostskaja Formation consists of conglomerates, shales, and sandstones with a total thickness of about 7 m (Fig. 4). Very abundant fossil remains, including ammonites, bivalves, brachiopods, belemnites, and plants have been collected from this formation (Lominadze, 1982; Rostovtsev et al., 1992; Pugatchev and Ruban, 2005; Ruban, 2004b, 2005; Gaetani et al., 2005). Its age, which has been established with ammonites and bivalves, is usually assumed as Early-Middle Callovian (Rostovtsev et al., 1992; Ruban, 2004b, 2005) or Middle-Upper Callovian (Lominadze, 1982). However, Gaetani et al. (2005) estimated, that the age of these deposits is the latest Bathonian-earliest Callovian, established with dinoflagellate cysts. In spite of above-mentioned differences and uncertainties, the mid-Jurassic hiatus in the Greater Caucasus lasted not more than 3-4 Ma.

Tectonic re-interpretation

A tectonic interpretation of the *Ordovician unconformity* should be based on the assumption, that the Greater Caucasus was located somewhere on the Afro-Arabian margin of Gondwana during the early Paleozoic (Tawadros et al., 2006) (Fig. 2). This is particularly supported by the presence in the studied region of carbonates with archaeocyaths; these carbonates are also known in the other peri-Gondwanan terranes (Gandin et al., 1987; Cocozza and Gandin, 1990; Courjault-Radeé et al., 1992; Debrenne et al., 1993, 2002; Geyer and Landing, 1995). At this location, two significant events during the Ordovician might have provoked tectonic activity within the Greater Caucasus. The first event involved the con-

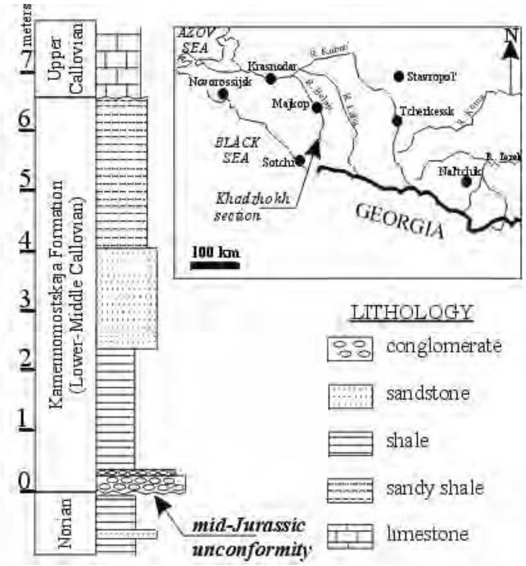

Fig. 4 - The Khadzhokh section (modified from Ruban, 2004b).

vergence along Avalonian-Cadomian arc, which was located off Gondwana. However, if Avalonia merged far northwards with Baltica and Laurentia, then Cadomia might have collided with Gondwana (Stampfli and Borel, 2002; Torsvik and Cocks, 2002; von Raumer et al., 2002, 2003). The second Ordovician event was the amalgamation of the Serindia terranes with Gondwana (Stampfli and Borel, 2002; von Raumer et al., 2002, 2003).

A tectonic interpretation of the *mid-Permian unconformity* should be based on the assumption that the European Hunic terranes collided with the northern margin of the Palaeotethys (Tawadros et al., 2006) (Fig. 2). According to Sampfli and Borel (2002), amalgamation of the Hunic terranes with Eurasia occurred during the Devonian, and resulted the Variscan (Hercynian) Orogeny, which became a remarkable Late Paleozoic tectonic event (Matte, 1986, 1991; Vai and Cocozza, 1986; Franke, 1989; Vai, 1991, 2003; Carmignani and Sassi, 1992; Krainer, 1993a; Bouchot et al., 1997; Dercourt et al., 2000; Franke et al., 2000; Schönlaub and Histon, 2000; Vai and Martini, 2001; Hoepffner et al., 2005, 2006). The Greater Caucasus as a Hunic terrane was a part of the Variscan (Hercynian) Orogen. Regional unconformities known within the Carboniferous sedimentary complexes (see e.g., Paffengol'ts, 1959; Davydov and Levin, 2003), although they are not so major, were, consequently, a result of the this orogeny. Latter was followed by uplift, and then extension and final collapse of the Variscan Cordillera during the Late Paleozoic (Faure, 1995; von Raumer, 1998; Stampfli and Borel, 2002). In the Alpine region of Europe, a mid-Permian unconformity is equated with the Saalian tectonic event (Stille, 1924; Krainer, 1993a). Dextral displacements along the planetary-scale shear zone at the northern margin of the Palaeotethys occurred during the Late Paleozoic (Arthaud and Matte, 1977; Swanson, 1982; Krainer, 1993a; Rapalini and Vizán, 1993; Trümpy, 1998; von Raumer, 1998; Stampfli and Borel, 2002; Vai, 2003; Ruban and Yoshioka, 2005). These displacements perhaps together with the post-orogenic deformations might have resulted the mid-Permian unconformity in the Greater Caucasus.

A tectonic interpretation of the *Triassic/Jurassic unconformity* is based on the assumption that the Greater Caucasus began to move eastwards during the Late Triassic, and reached its present position during the Early Jurassic (Tawadros et al., 2006) (Fig. 2). Possible deformations associated with such a movement and the subsequent collision of the studied terrane with the Russian Platform might have formed this unconformity. However, Ershov et al. (2003) suggested the regional orogeny, which lasted from the Carnian and until the Sinemurian. Gaetani et al. (2005) concluded that a strike-slip regime was present in the Greater Caucasus during the Triassic, and they also expressed some doubts about the appearance of collision during the latest Triassic. Alternatively, a global sea-level fall occurred at the Triassic-Jurassic transition (Embry, 1997; Hallam and Wignall, 1999; Hallam, 2001; Hesselbo et al., 2004, 2007; Haq and Al-Qahtani, 2005; Miller et al., 2005), and it may have resulted in the formation of the Triassic/Jurassic unconformity. The onset of the new subsiding basins after the collision of the Greater Caucasus with the Russian Platform led to an Early Jurassic transgression over those parts of the Greater Caucasus, where Triassic strata did not accumulate. In this case, the tectonic mechanism becomes unnecessary.

During the Jurassic, the Greater Caucasus was located on the nothern active margin of the Neotethys Ocean, where parallel island arcs and basins existed (Tawadros et al., 2006) (Fig. 2). Ershov et al. (2003) suggested that there was an "orogeny" and partial closure of the Greater Caucasian Trough during the Bajocian-Bathonian. Ruban (in press) introduced a different model, in which, during the Middle Jurassic, the

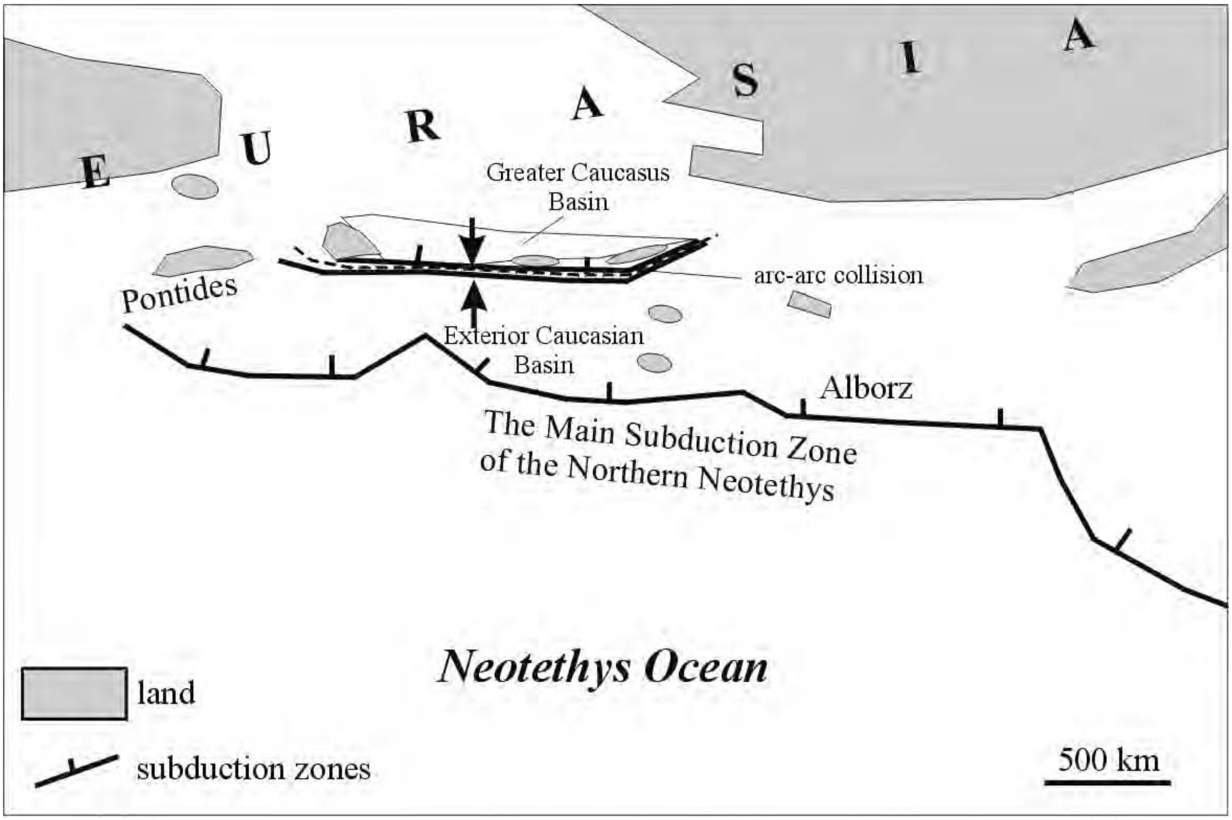

Fig. 5 - The Middle Jurassic tectonic setting in the Caucasian region (from Ruban, in press).

Northern and Southern Transcaucasian island arcs collided and a basin between them was closed (Fig. 5). Such arc-arc collision might have been able to induce the lack of sedimentation, which resulted in the formation of the *mid-Jurassic unconformity*. However, other explanations (e.g., oblique-wrench break-up) are also possible. Moreover, it is conceivable that this unconformity may be associated with a global eustatic fall, which occurred during the Bathonian (Haq et al., 1987; Haq and Al-Qahtani, 2005). However, Hallam (2001) argued that this fall was a regional event, which may be explained only with tectonics.

Discussion

The tracing of four major unconformities in the Paleozoic-Mesozoic strata in the Greater Caucasus (Fig. 3) would help to understand their extent and relation to the planetary-scale tectono-sedimentary events.

The *Ordovician unconformity* of the Greater Caucasus has some analogues in the Pennine Inliers and Midlands Platform of the British Isles and also in the Brabant Massif and Condroz Inlier, where hiatuses are known within the Ordovician strata, while in many other terranes of Avalonian Europe, there are no unconformities similar to that in the studied region (Verniers et al., 2001, 2002). In some basins of Germany, no large Ordovician hiatuses are found (Stratigraphische Tabelle von Deutschland, 2002). However, significant hiatuses are present within the Ordovician strata of Hessen, Lausitz, and Frankenwald (Servais et al., 1998). An unconformity is established at the base of the Ordovician succession within the Moesian terrane (Yanev, 2000). In Turkey, the Late Ordovician hiatus is known, whereas the Early Ordovician hiatus is established within the Istanbul Terrane only (Kozur and Göncüoglu, 1998; Goncuoglu and Kozlu, 2000). However, Göncüoglu and Kozlu (1997) suggested earlier a significant hiatus within the Taurides, which corresponded to the Middle Ordovician. In NW Spain, stratigraphic gaps are present in the Middle Ordovician strata (Gutiérrez-Marco et al., 1999, 2002). In the Montagne Noire, a significant unconformity, similar to that in the Greater Caucasus, is established within the Ordovician (Simien et al., 1999). In Sardinia, the Sardic angular unconformity separates Upper Cambrian-Lower Ordovician strata from Upper Ordovician-Devonian strata (Stille, 1939; Vai and Cocozza, 1986; Leone et al., 1991; Vai and Martini, 2001; Cherchi et al., 2002; Villas et al., 2002). In the Gerrei Tectonic Unit of Sardinia, an unconformity of the Sarrabese Phase is present at the top of the Lower Ordovician (Corradini et al., 2002). Minor, but angular mid-Ordovician unconformities are present in the sedimentary basins of the Northern and Central Africa (Guiraud et al., 2005). In this region, the Cambrian-Ordovician and Ordovician-Silurian transitions are equated with the Sardinian and Taconian orogenic events. One of minor tectonic phases, i.e., the "pre-Caradocian" phase, occurred during the mid-Ordovician (Guiraud et al., 2005). In Morocco, the unconformities are known at the Cambrian-Ordovician and Lower-Middle Ordovician transitions and within the Upper Ordovician, but hiatuses associated with them were not very long, and a broad span of the Ordovician deposits is established there (Geyer and Landing, 1995; Chacrone et al., 2004; Guiraud, 2005). Hoepffner et al. (2006) suggested the "Pre-variscan" tectonic events were very localised in Moroccan domains. On the Arabian Platform, hiatuses are recognized within uppermost Lower Ordovician strata and within Upper Ordovician strata (Sharland et al., 2001). Thus, the Ordovician unconformity of the Greater Caucasus has good analogues in the other Early Paleozoic Gondwanan tectonic blocks. Surprisingly, this unconformity has also close analogues in the eastern North America, where the Middle-Late Ordovician Taconic orogeny is known in the Appalachians (Drake et al., 1989; Hatcher, 1989; Swezey, 2002; Thomas et al., 2002; Hibbard, 2004), and the Early Ordovician Penobscot tectonic event occurred in the Gander Zone (Colman-Sadd et al., 1992; Hibbard and Samson, 1995; Hibbard, 2004; Schoonmaker and Kidd, 2006). Also, the Owl Creek unconformity is traced within the Lower Ordovician strata of the Appalachians (Swezey, 2002).

The *mid-Permian unconformity* of the Greater Caucasus is correlated with Permian unconformities in the Alpine region of Europe, particularly in the Carnic and Southern Alps, the Dolomites, and the peri-Adriatic areas (Krainer, 1990,1993a, b; Venturini, 1990, 2002; Cassinis et al., 1998, 1999; Schönlaub and Histon, 2000; Cassinis and Rocnhi, 2001; Vai and Martini, 2001; Ronchi and Santi, 2003; Vai, 2003). The mid-Permian Saalian unconformities are also present in some areas of the Spanish Pyrenees and Northeastern Iberia (Sopeña et al., 1977, 1988; Arche and López-Gómez, 1996; Vera, 2004). Unconformities are present within the Permian strata of the North Sea (Glennie, 1992, 1997, 2000). In the basins of Germany, an unconformity encompasses the Sakmarian-Roadian to the Capitanian-Wuchapingian (Schneider, 2001; Stratigraphische Tabelle von Deutschland, 2002). Mid-Permian unconformities are present in the Balkan terranes, although not elsewhere (Yanev, 2000). Thus, the mid-Permian unconformity of the Greater Caucasus is evidently traced within Europe, especially within the Rotliegend type area where the Saalian and Altmark unconformities have been identified (Kozur, 1980; Glennie, 1997). However, the sediment preservation above the unconformity began later in the Greater Caucasus than in many other mentioned European regions. In Northern and Central Africa, the lack of sedimentation occurred in many areas during the Permian, and somewhere it was established around the mid-Permian (Guiraud et al., 2005). On the Arabian Platform, the pre-Khuff unconformity (Sharland et al., 2001; Al-Husseini, 2004) may be correlated with the mid-Permian unconformity in the Greater Caucasus. However, in some areas of Oman, the Middle Permian-Early Triassic Khuff Formation overlies the Early-Middle Permian Gharif Formation conformably (Al-Husseini, 2004; Osterloff et al., 2004).

The *Triassic/Jurassic unconformity* of the Greater Caucasus may be correlated with the Early Cimmerian unconformity in European basins. However, this unconformity divides the Norian and Rhaetian strata (Jacquin and de Graciansky, 1998), whereas the Triassic/Jurassic unconformity in the Greater Caucasus was established later, during the mid-Rhaetian (Fig. 3). Embry (1997), Hallam and Wignall (1999), Hallam (2001), Hesselbo et al. (2004, 2007), Haq and Al-Qahtani (2005), and Miller et al. (2005) inferred a major sea-level fall and consequent hiatuses or unconformities at the Triassic-Jurassic transition from both the global and European stratigraphic record. Latest Triassic hiatuses have been identified in Germany (Stratigraphische Tabelle von Deutschland, 2002). In Northern and Central Africa, the Eo-Cimmerian unconformities are present in many basins at the Triassic-Jurassic transition (Guiraud et al., 2005), as well as in Arabia (Sharland et al., 2001).

The *mid-Jurassic unconformity* of the Greater Caucasus is difficult to be traced within Western Europe, because Bathonian and Lower Callovian hiatuses in Europe are quite minor and occur only locally (Jacquin and de Graciansky, 1998; Jacquin et al., 1998). The global evidence for a mid-Jurassic unconformity seems to be unclear (Hallam, 2001). In German basins, the Bathonian-Callovian interval is marked by local unconformities only (Stratigraphische Tabelle von Deutschland, 2002). No major Bathonian-Callovian unconformities, but only minor regressive episodes or local unconformities, are known both in Northern-Central Africa (Guiraud et al., 2005) and in Arabia (Sharland et al., 2001). In the Atlasic Domain, however, significant deformations occurred at the end of the Dogger (Guiraud et al., 2005). In general, sinistral transtension from Alpine Europe toward Himalayan Asia (Vai, 1991, 2003) might have resulted in these minor hiatuses and regressive episodes, and, therefore, a global-scale mechanism to explain the mid-Jurassic unconformity in the Greater Caucasus may be hypothesized.

Conclusions

This article presents a synthesis of knowledge on the major Paleozoic-Mesozoic unconformities in the Greater Caucasus with the following conclusions:

1) four major unconformities are present in the studied region, i.e., the Ordovician, mid-Permian, Triassic/Jurassic, and mid-Jurassic unconformities;

2) a tectonic re-interpretation of these unconformities relates them to the evolution of the Afro-Arabian margin of Gondwana during the Ordovician, post-collisional Variscan events during the Permian, left-shear displacements during the Late Triassic-Jurassic, and the arc-arc collision during the Middle Jurassic;

3) the Ordovician, mid-Permian, and Triassic/Jurassic unconformities are correlated undoubtedly with similar unconformities in the basins of Europe, Africa, and Arabia, whereas the evidences of such correlation for the mid-Jurassic unconformity are less clear.

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Taxonomic diversity structure of brachiopod associations at times of the early Mesozoic crises: evidence from the Northern Caucasus, Russia (northern Neotethys Ocean)

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Abstract. The Northern Caucasus is a large region of southwestern Russia that was located on the northern periphery of the Neotethys Ocean during the Triassic-Jurassic interval. Several crises impacted the evolution of the local fauna of brachiopods during this time as evidenced by changes in the taxonomic diversity of brachiopod associations in the region. The taxonomic diversity structure determines the relative importance of superfamilies to govern the species diversity, and the changes in it are measured with coefficient of rank correlation calculated for any two associations. The available stratigraphic ranges of species, which belong to 113 genera and 22 superfamilies, indicate that a recovery after the Permian/Triassic mass extinction is expressed by a rapid change in the taxonomic diversity structure in the Early Triassic-Anisian. The regional Ladinian crisis, which occurred after an abrupt deepening of the marine basin, did not result in major changes in the structure. The Triassic/Jurassic and Pliensbachian/Toarcian mass extinctions did not produce remarkable turnovers among brachiopods, but those superfamilies which dominated the Early Triassic species diversity of brachiopods rose again after these extinctions. The Pliensbachian/Toarcian event diminished significantly the importance of the Late Triassic superfamilies. The potential Aalenian mass extinction did not affect the taxonomic diversity structure. The changes in this structure recorded in the Northern Caucasus did not correspond to those seen in the Alpine Region.

Key words: brachiopods, diversity, Jurassic, mass extinction, Northern Caucasus, Triassic

Introduction

Mass extinctions are among the most spectacular events in the Earth's history. Interest in them has grown thanks to the studies of Sepkoski (1982, 1993, 2002) and his coworkers (Sepkoski *et al.*, 1981; Raup and Sepkoski, 1982). However, we are still far from understanding the biological and geological mechanisms of these events as suggested from the present syntheses (Taylor, 2004; Over *et al.*, 2005; Erwin, 2006; Roopnarine, 2006; Twitchett, 2006). The assessment of rates of background extinction is also a matter of criticism (Boucot, 2006). One intriguing question concerns the evolutionary consequences of mass extinctions. Jablonski (2004) notes that, in spite of the severity of mass extinctions, these events were not able 'to re-set the evolutionary clock' completely. However, studies of foraminifers suggest that the Permian/Triassic extinction resulted in the reorganization of their assemblages, because their Triassic and Jurassic assemblages were similar to those of the Cambrian and Ordovician (Ruban, 2001). Although we still have only limited knowledge of the major or first-order mass extinctions (the so-called 'Big Five'), information on the minor or second-order mass extinctions is even more limited. It is unclear whether those biotic crises were really less intense than any of the 'Big Five' (Ruban and Tyszka, 2005).

The rich paleontological record of the Northern Caucasus—a large northern Neotethyan region (Figure 1)—allows examination of the early Mesozoic crises among brachiopods, including the influences of the Triassic/Jurassic (T/J) and Pliensbachian/Toarcian (Pl/To) mass extinctions. The former is usually mentioned among the 'Big Five', whereas the latter is considered a minor extinction (Little and Benton, 1995; Hallam and Wignall, 1997; Hallam, 2002; Pálfy *et al.*, 2000, 2002; Taylor, 2004; Hesselbo *et al.*, 2007).

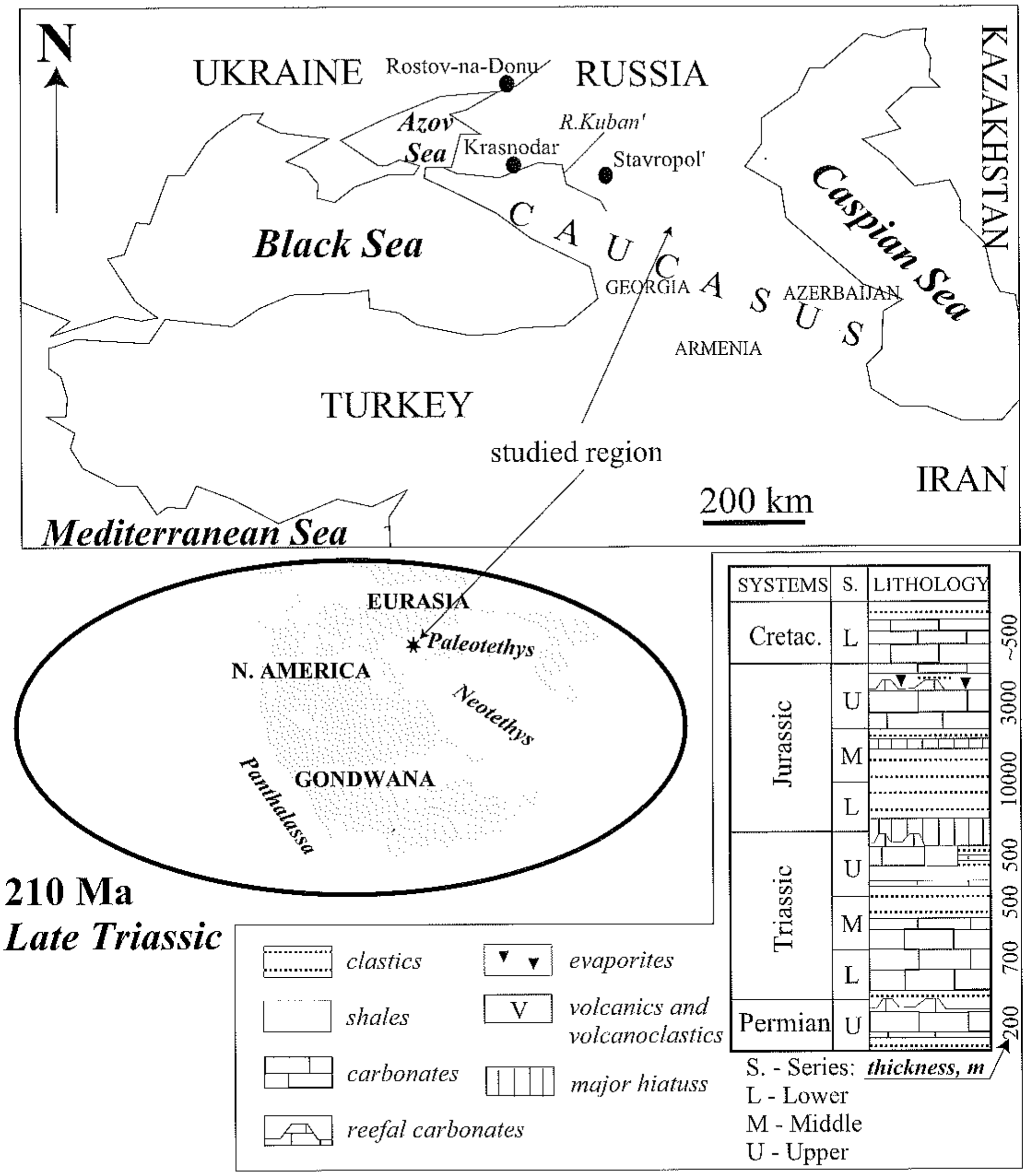

Figure 1. Geographical and paleogeographical (after Scotese, 2004) location of the Northern Caucasus. Generalized composite lithologic section after Ruban (2006c).

Geological setting

The Northern Caucasus is a large region, located in the southwest of Russia (Figure 1). Geographically it corresponds to the northern slope of the Main Caucasus Range, whereas geologically it is a northern part of the Greater Caucasus Terrane. This terrane was identified by Gamkrelidze (1997) and Tawadros *et al.* (2006). It was one of the so-called European Hunic terranes (Stampfli and Borel, 2002; Tawadros *et al.*, 2006), which were derived from the Gondwanan margin in the mid-Paleozoic. Subsequently, the Greater Caucasus Terrane docked somewhere near the Carnic Alps and in Late Triassic-Early Jurassic times, when sinistral strike-slip movements occurred on the Eurasian margin, it was transported eastward to its present position at the south margin of Baltica (Tawadros *et al.*, 2006). Subsequently elongated sea basins divided by arcs evolved in the Jurassic (Ershov *et al.*, 2003; Ruban, 2006a; Tawadros *et al.*, 2006). Thus, during the early Mesozoic, the Northern Caucasus was located in the northern part of the Neotethys Ocean.

The stratigraphy and lithology of the Triassic-Jurassic deposits within the studied region were summarized by Ruban (2004, 2006b,c) and Gaetani *et al.* (2005) (Figure 1). Marine Triassic deposits are known only in the western Northern Caucasus, whereas the Jurassic sedimentary complexes are known in most of the studied region. In general, the 700 m thick Induan-Anisian carbonates are overlain by Ladinian-Carnian turbidites with a thickness of ~500 m. The Norian-lower Rhaetian interval is represented by carbonates including reefal limestones with a total thickness of about 500 m. Locally this sedimentary complex is replaced laterally by a 350 m thickness of intercalated shales and siliciclastics, which are middle Norian in age. The Triassic-Jurassic transition is marked by a major hiatus. The overlying Sinemurian-Bathonian sedimentary complex is up to 10,000 m thick and is dominated by shales and siliciclastics with interbedding of carbonates and coal.

Both Triassic and Jurassic strata contain very rich fossil assemblages, which include brachiopods, bivalves, ammonoids, foraminifers, corals, sponges, and crinoids. As suggested by the newest paleogeodynamic reconstructions (Ruban, 2006a), the study region was a part of the same marine basin, and there is no evidence on the paleobiogeographical differentiation within the Northern Caucasus. The T/J mass extinction was not documented in the Northern Caucasus because of the presence of the noted major hiatus. However, this event may be recorded by the changes in the Early Jurassic assemblages in comparison with those of the Late Triassic as recorded here. The Pl/To mass extinction was documented by Ruban (2004) and Ruban and Tyszka (2005) with data on brachiopods and foraminifers, respectively. However, the influence of this event on bivalves is not clear (Ruban, 2006d). Additionally, the studies of Ruban (2004) and Ruban and Tyszka (2005) indicated an Aalenian mass extinction, which affected brachiopods and foraminifers both in the Northern Caucasus and some other regions of Europe. This may suggest a previously unsuspected Mesozoic mass extinction, although the existing biodiversity curves (see Taylor, 2004) are not detailed enough to document it globally.

Materials and methods

Data on the stratigraphic ranges (per-stage distribution) of the Triassic-Jurassic brachiopods was compiled from a number of available sources and published (Ruban, 2006b,c). Low resolution of the data in some original sources does not permit discussion of turnovers within given stages. In total, 113 genera which belong to 22 superfamilies have been accounted (Table 1). Brachiopod taxa were found in the deposits of most stages in the studied Triassic-Bajocian interval, except the Ladinian and the Hettangian. In the latter case the absence of brachiopods is explained by the presence of a major regional hiatus, whereas the enigmatic Ladinian crisis occurred due to the rapid deepening of the marine basin in the latest Anisian-Ladinian (Ruban, 2006b). Suprageneric taxonomy was verified using the revised edition of the "Treatise on Invertebrate Paleontology" (Williams *et al.*, 1997–2006). Additionally, the taxonomic system employed in the brachiopod database (version 1996) by Doescher (1981, 1990) proved useful.

This paper addresses the taxonomic diversity structure of the brachiopod associations. The latter are considered as entireties of taxa, which existed in each stage of the Triassic and Jurassic. Particular taxa of higher rank may play a different role in the determination of diversity of lower-rank taxa. This forms a taxonomic diversity structure, which evidently changed through geological time (Figure 2). A specific index was proposed to measure these changes (Ruban, 2001; Ruban and Tyszka, 2005). Rst is a coefficient of Spearman's rank correlation (Kendall, 1975) between two associations by presence/absence of higher-rank taxa, where the presence of each of these taxa is indicated by the number of lower-rank taxa, which belong to this higher-rank taxon in the particular association. In our case, the higher-rank taxa are superfamilies, whereas the lower-rank taxa are species (Table 2). The Rate of Transformation of the Taxonomic Diversity Structure (TTDSR) is estimated as 1/Rst. It illustrates the rate of change in the superfamily control of the species diversity, i.e., the changes in significance of each superfamily for the determination of the species diversity. It is always interesting to calculate Rst not only for the successive associations, but for those existing in different times, for example, the Anisian and Pliensbachian associations. This procedure may yield important results (Ruban, 2001).

Changes in taxonomic diversity structure

The taxonomic diversity structure of the brachiopod associations changed significantly during the Triassic-Bajocian in the Northern Caucasus (Figure 3, Table 3). The lower values of Rst in the Early Triassic-Anisian indicates high TTDSR. This was a result of brachiopod recovery and Anisian radiation after the devastating Permian/Triassic mass extinction. The

Table 1. Stratigraphic distribution of the Triassic-Bajocian brachiopod genera in the Northern Caucasus. N.I.—not identified. Stage abbreviations: T1—Induan + Olenekian, AN—Anisian, LA—Ladinian, CA—Carnian, No—Norian, RH—Rhaetian, HE—Hettangian, SI—Sinemurian, PL—Pliensbachian, TO—Toarcian, AA—Aalenian, BJ—Bajocian.

Superfamilies	Genera	T1	AN	LA	CA	NO	RH	HE	SI	PL	TO	AA	BJ
Rhynchonelloidea	*"Rhynchonella"*		1						2	1	2	2	2
Spiriferinoidea	*"Spiriferina"*								1	1			
Rhynchonelloidea	*?Rhynchonelloidea*											1	
Rhynchonelloidea	*Abrekia*	1											
Rhynchonelloidea	*Acanthothyris*											1	3
Dialasmatoidea	*Adygella*				1	1	1						
Dialasmatoidea	*Adygelloides*						1						
Koninckinoidea	*Amphiclina*					1	2						
Koninckinoidea	*Ampliclinodonta*					1							
Dialasmatoidea	*Angustothyris*		1										
Zeillerioidea	*Aulacothyris*									2	1		
Kingenoidea	*Aulacothyropsis*				1		4						
Norelloidea	*Austriella*					1							
Rhynchotetradoidea	*Austrirhynchia*						2						
Pennospiriferinoidea	*Balatonospira*				1								
N.I.	*Bobukella*				1	1							
Wellerelloidea	*Bodrakella*									1			
Wellerelloidea	*Calcirhynchia*								1	1			
Pugnacoidea	*Calvirhynchia*												1
Rhynchonelloidea	*Capillirhynchia*											1	
Wellerelloidea	*Caucasorhynchia*					1	1			1			
Dialasmatoidea	*Caucasothyris*					1							
Loboidothyridoidea	*Cererithyris*												1
Zeillerioidea	*Cincta*									2			
Wellerelloidea	*Cirpa*									1			
Dialasmatoidea	*Coenothyris*		2										
Hemithiridoidea	*Costirhynchia*		1		1								
Pennospiriferinoidea	*Costispiriferina*		1										
Pugnacoidea	*Crurirhynchia*					1							
Ambocoelioidea	*Crurithyris*	1											
Pugnacoidea	*Cryptorhynchia*												1
Dialasmatoidea	*Cubanothyris*					2	2						
Loboidothyridoidea	*Cuersithyris*									1			
Rhynchonelloidea	*Cuneirhynchia*									4			
Rhynchonelloidea	*Curtirhynchia*										1		
Rhynchotetradoidea	*Decurtella*		2										
Zeillerioidea	*Digonella*									1			
Pennospiriferinoidea	*Dinarispira*		2										
Athyridoidea	*Dioristella*		1		1								
Cancellothyridoidea	*Disculina*									1			
Wellerelloidea	*Euxinella*					3	6						
Hemithiridoidea	*Fissirhynchia*					1	1						
Hemithiridoidea	*Flabellirhynchia*									1	1		
Rhynchonelloidea	*Furcirhynchia*								1			1	1
Hemithiridoidea	*Gibbirhynchia*								1	2	1		
Hemithiridoidea	*Grandirhynchia*										1	1	1
Spiriferinoidea	*Guseriplia*						2						
Loboidothyridoidea	*Heimia*												1
Norelloidea	*Holcorhynchella*		1										
Rhynchonelloidea	*Homoeorhynchia*								1	2	1		
Pennospiriferinoidea	*Koeveskallina*		1										
Koninckinoidea	*Koninckina*				1	1							
Suessioidea	*Laballa*					2	3						
Pennospiriferinoidea	*Lepismatina*						1						
Dyscolioidea	*Linguithyris*								1				
Spiriferinoidea	*Liospiriferina*								2	4	1		
Loboidothyridoidea	*Loboidothyris*												1
Loboidothyridoidea	*Lobothyris*					2				3	1	2	2
Athyridoidea	*Majkopella*						3						

Table 1. Continued

Superfamilies	Genera	T1	AN	LA	CA	NO	RH	HE	SI	PL	TO	AA	BJ
Spiriferinoidea	*Mentzelia*		1		2	1	2						
Wellerelloidea	*Moisseievia*					2	1						
Loboidothyridoidea	*Monsardithyris*												1
Loboidothyridoidea	*Morrisithyris*												1
Retzioidea	*Neoretzia*						3						
Wellerelloidea	*Neowelerella*	1											
Norelloidea	*Norella*		1										
Athyridoidea	*Oxycolpella*					3	2						
Hemithyridoidea	*Parvirhynchia*											1	
Athyridoidea	*Pexidella*		1			1							
Norelloidea	*Piarorhynchella*		1										
Rhynchonelloidea	*Piarorhynchia*								1	4	1		
Norelloidea	*Praemonticlarella*										1		
Rhynchotetradoidea	*Prionorhynchia*								1	1	1		
Pennospiriferinoidea	*Pseudocyrtina*					1							
Pugnacoidea	*Pseudogibbirhynchia*										2	2	2
Kingenoidea	*Pseudorugitella*					2	2						
Rhynchonelloidea	*Ptyctorhynchia*										1		
Loboidothyridoidea	*Ptyctothyris*												1
Pennospiriferinoidea	*Punctospirella*		1										
Hemithiridoidea	*Quadratirhynchia*												2
Hemithiridoidea	*Rhactorhynchia*												3
Dialasmatoidea	*Rhaetina*				1	6	4						
Rhynchonelloidea	*Rhimirhynchopsis*					1	1						
Rhynchonelloidea	*Rimirhynchia*									1			
Wellerelloidea	*Robinsonella*						1						
Hemithiridoidea	*Rudirhynchia*								2				
Zeillerioidea	*Rugitela*												1
Norelloidea	*Scalpellirhynchia*								1				
Zeillerioidea	*Securina*								1	1			
Spiriferinoidea	*Sinucosta*		1			1	1						
Loboidothyridoidea	*Sphaeroidothyris*												2
Suessioidea	*Spinolepismatina*					1							
Spiriferinoidea	*Spiriferina*								4	3			
Hemithiridoidea	*Squamirhynchia*									1			
Pugnacoidea	*Stolmorhynchia*											4	2
Rhynchonelloidea	*Striirhynchia*												1
Loboidothyridoidea	*Strouditthyris*											1	
Dialasmatoidea	*Sulcatinella*		2										
Dialasmatoidea	*Sulcatothyris*				1								
Athyridoidea	*Tetractinella*		1										
Hemithyridoidea	*Tetrarhynchia*								1				1
Thecospiroidea	*Thecospira*					1							
Thecospiroidea	*Thecospiropsis*					1							
Loboidothyridoidea	*Triadithyris*					2	1						
Rhynchonelloidea	*Trichorhynchia*											2	1
Rhynchotetradoidea	*Trigonirhynchella*					1	2						
Loboidothyridoidea	*Tubithyris*												2
Wellerelloidea	*Volirhynchia*		2										
Loboidothiridoidea	*Wattonithyris*												1
Dialasmatoidea	*Wittenburgella*					1	1						
Zeillerioidea	*Worobievella*					1	1						
Zeillerioidea	*Zeilleria*					3	6		14	15		3	4
Spondylospiroidea	*Zugmayerella*						1						

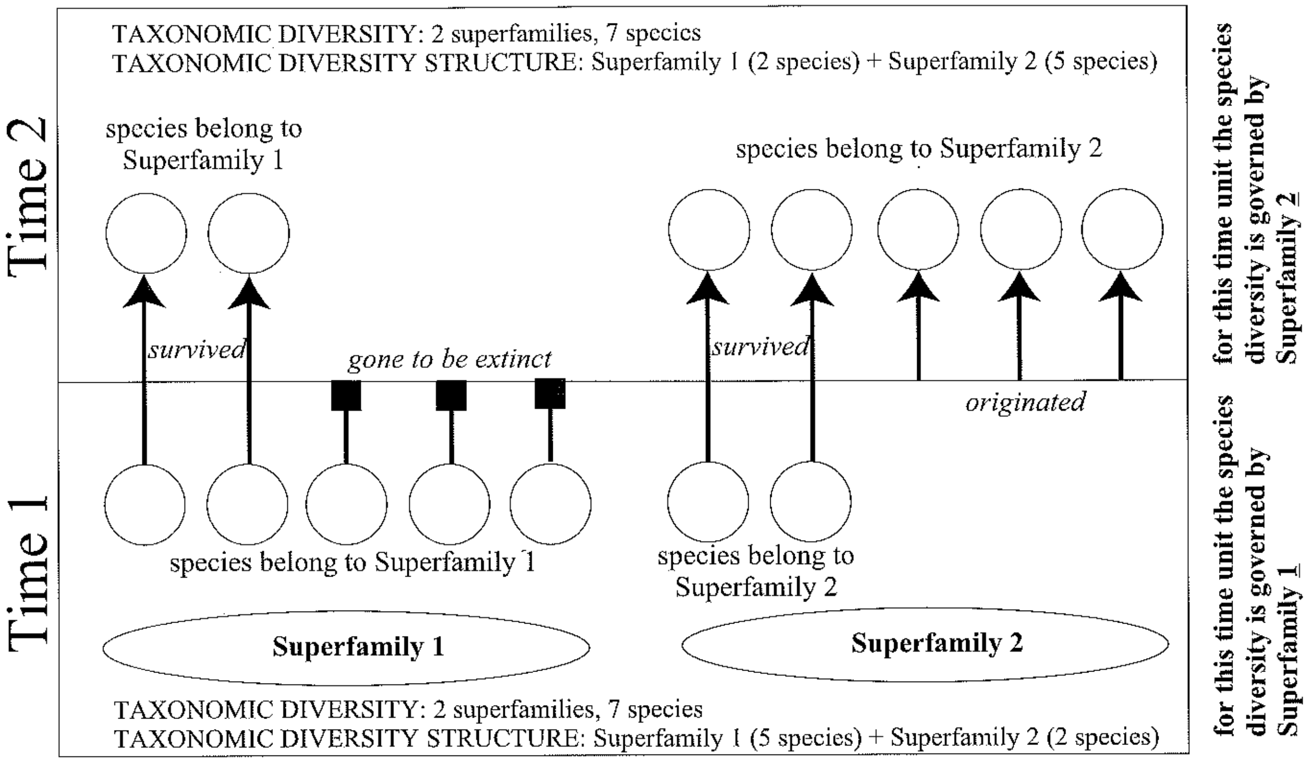

Figure 2. A concept of taxonomic diversity structure and its changes.

Table 2. Stratigraphic distribution of the Triassic-Bajocian brachiopod superfamilies in the Northern Caucasus. Number of species is indicated. Stage abbreviations—see Table 1. N.I.—not identified (genus *Bobukella* is not listed in "Treatise ..."). This matrix was used to calculate Rst (see Table 3).

Superfamilies	T1	AN	LA	CA	NO	RH	HE	SI	PL	TO	AA	BJ
N.I.				1	1							
AMBOCOELIOIDEA	1											
ATHYRIDOIDEA		3		1	4	5						
CANCELLOTHYRIDOIDEA									1			
DIALASMATOIDEA		5		3	11	9						
DYSCOLIOIDEA								1				
HEMITHIRIDOIDEA		1		1	1	1		4	4	3	2	7
KINGENOIDEA				1	2	6						
KONINCKINOIDEA				1	3	2						
LOBOIDOTHYRIDOIDEA					4	1			4	1	3	13
NORELLOIDEA		3			1			1		1		
PENNOSPIRIFERINOIDEA		5		1	1	1						
PUGNACOIDEA					1					2	6	6
RETZIOIDEA						3						
RHYNCHONELLOIDEA	1	1			1	1		5	12	6	8	8
RHYNCHOTETRADOIDEA		2			1	4		1	1	1		
SPIRIFERINOIDEA		2		2	2	5		7	8	1		
SPONDYLOSPIROIDEA						1						
SUESSIOIDEA					3	3						
THECOSPIROIDEA					2							
WELLERELLOIDEA	1	2			6	9		1	4			
ZEILLERIOIDEA					4	7		15	21	1	3	5

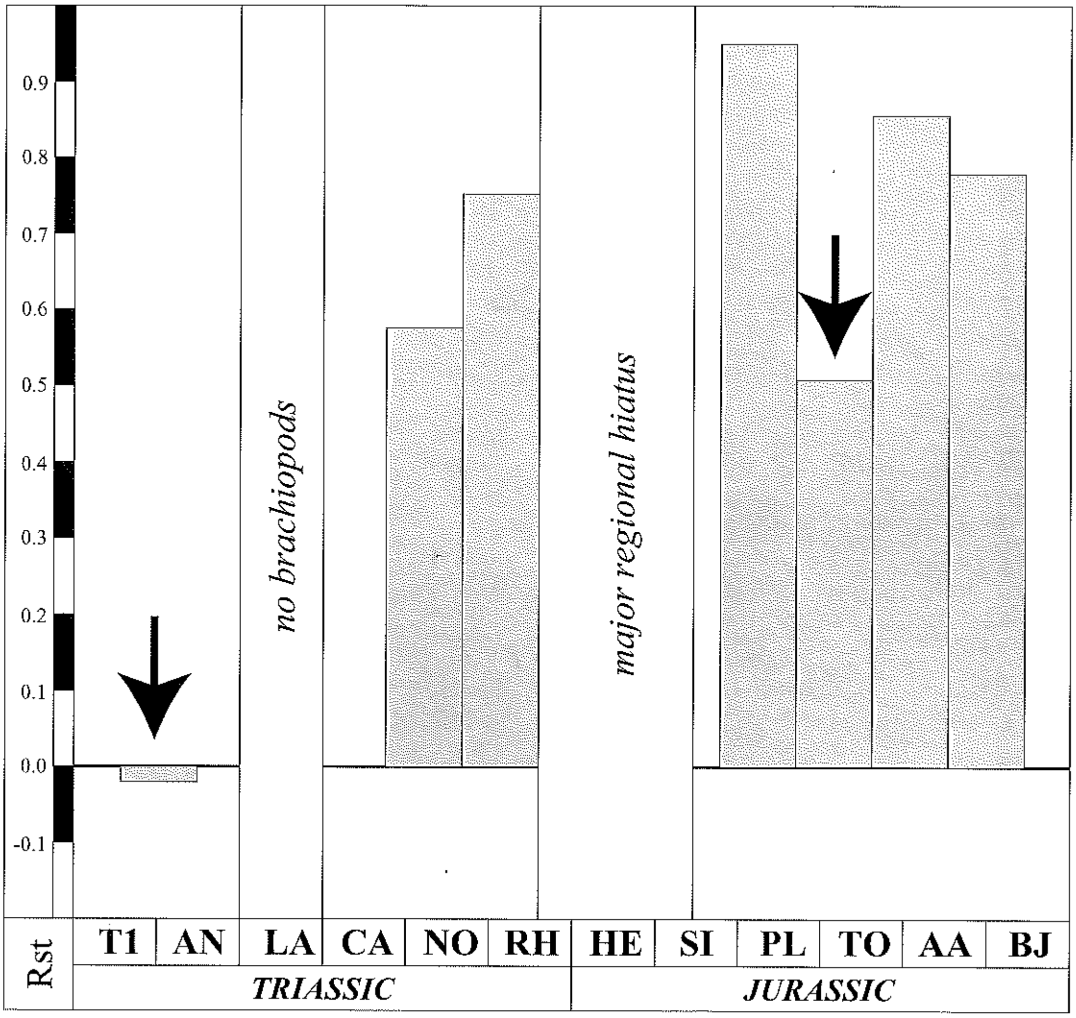

Figure 3. Changes in Rst values through the Early Triassic-Bajocian calculated for the brachiopod associations of the Northern Caucasus. Arrows mark TTDSR accelerations. Stage abbreviations—see Table 1.

Table 3. Rst values for the Triassic-Bajaocian brachiopod associations of the Northern Caucasus. Values higher than +0.2 are highlighted as bold. Significant values are given in italics. Stage abbreviations—see Table 1.

	T1	AN	LA	CA	NO	RH	HE	SI	PL	TO	AA	BJ
T1	1	−0.02	0.00	−0.25	0.02	0.09	0.00	0.05	**0.22**	**0.36**	**0.31**	0.10
AN		1	0.00	***0.58***	***0.49***	**0.39**	0.00	−0.07	−0.10	−0.03	−0.19	−0.22
LA			1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA				1	***0.58***	***0.46***	0.00	0.01	−0.09	−0.13	−0.24	−0.21
NO					1	***0.76***	0.00	0.08	0.13	−0.16	−0.07	0.04
RH						1	0.00	**0.31**	**0.31**	−0.18	−0.18	−0.18
HE							1	0.00	0.00	0.00	0.00	0.00
SI								1	***0.95***	**0.38**	**0.36**	**0.30**
PL									1	***0.51***	***0.52***	***0.47***
TO										1	***0.86***	***0.66***
AA											1	***0.78***
BJ												1

rate decreased significantly in the Late Triassic. During the Jurassic the rate was mostly low, although it accelerated occasionally in the Pliensbachian-Toarcian interval. The taxonomic diversity structure described at superfamily-species organization was stable enough both in the Late Triassic and late Early-early Middle Jurassic.

The species diversity of the Early Triassic association was ruled equally by only three superfamilies (Table 2). In the Anisian, two superfamilies, namely Dialasmatoidea and Pennospiriferinoidea, played the most important role in the taxonomic structure, although they did not dominate in comparison with other taxa. Dialasmatoidea was also the most diverse superfamily both in the Carnian and Norian. In the Norian this superfamily evidently dominated in the composition of the brachiopod species diversity. However, Wellerelloidea also began to diversify in the Norian and by the Rhaetian its representatives were as important as those of Dialasmatoidea. Zeillerioidea also radiated in the Norian-Rhaetian. However, it is difficult to find leaders, which rule the entire species diversity in the end-Triassic. The Sinemurian diversity was dominated by the Zeillerioidea and less by Spiriferinoidea and Rhynchonelloidea. These three superfamilies governed the Pliensbachian species diversity. The Toarcian and Aalenian taxonomic diversity structure was dominated by the Rhynchonelloidea, although Pugnacoidea began to diversify from the Aalenian. In the Bajocian, Loboidothyrioidea became dominant, although some other superfamilies also diversified in this age.

A comparison of nonsuccessive associations reveals some interesting patterns (Table 3). The Ladinian crisis related to the abrupt deepening of the marine basin (Ruban, 2006b) did not lead to significant changes in the taxonomic diversity structure of the regional brachiopod fauna, largely because Rst calculated for the Anisian, on one side, and Carnian, Norian, and Rhaetian associations, on the other, were reasonably high. Even if the T/J mass extinction occurred in the Northern Caucasus (although it is impossible to document it due to a major hiatus), it did not stress brachiopods enough to provoke any remarkable changes in the taxonomic diversity structure. There is a similarity in this structure between the Rhaetian, Sinemurian, and Pliensbachian associations. The Pl-To mass extinction, which depleted the Toarcian assemblages (Ruban, 2004), brought some changes to the taxonomic diversity structure of brachiopods. Relatively speaking TTDSR accelerated at the Pliensbachian-Toarcian transition (Figure 3). Additionally, there is a remarkable difference between the Late Triassic and the Toarcian-Bajocian associations. Rst calculated between the Rhaetian and Toarcian associations is below 0.00, although Rst between the Rhaetian and Pliensbachian associations is as high as 0.31. It is an intriguing question, whether those Late Triassic superfamilies which survived the T/J extinction, but did not survive the Pl/To extinction were 'dead clades walking' (the term of Jablonski, 2004). The Aalenian potential mass extinction did not result in significant changes in the taxonomic diversity structure of brachiopods, although their diversity decreased (Ruban, 2004). In general, all Sinemurian-Bajocian associations were quite similar, and the Rst value for each pair of them is higher than 0.30.

Surprisingly, it is evident that the taxonomic diversity structure of the Pliensbachian, Toarcian, and Aalenian associations was quite similar to that of the Early Triassic association. Rhynchonelloidea and Wellerelloidea were superfamilies which drove the Early Triassic associations and which also played an important role in the Early Jurassic associations. Thus, those superfamilies which were dominants in the Early Triassic became dominants in the Pliensbachian-Aalenian. However, the Early Triassic assemblage was of low diversity, suggesting the need for further studies.

It is possible to hypothesize that paleoenvironmental differences between stages might have reinforced dissimilarities between the relevant brachiopod assemblages. Changes in water depth or character of sedimentation and so on were responsible only for the "ordinary" changes in the brachiopod assemblages, reflected by the Rst values for successive associations. The Rhaetian and Sinemurian paleoenvironments were distinctly different, while the similarity between the respective associations is quite high. In contrast, the conditions in the Toarcian did not differ too much from those in the Pliensbachian, whereas an increase in turnover rate is documented (Table 3). Thus, it is unlikely that those changes in the brachiopods associations at the Triassic-Jurassic and Pliensbachian-Toarcian boundaries were caused by the differences in paleoenvironments.

Discussion

The patterns documented in the Northern Caucasus may be compared with those in the Swiss Alps and the Jura Mountains. The data on those regions have been summarized by Sulser (1999). The suprageneric taxonomy of the Alpine species has been verified in the same way as was done for the Northern Caucasus. It is necessary to note that no Early Triassic, Carnian,

Table 4. Rst values for the Triassic-Bajaocian brachiopod associations of the Alps and Jura (data from Sulser, 1999). There were no brachiopods in the Early Triassic, Carnian, and Norian. Values higher than +0.2 are highlighted as bold. Significant values are given in italics. Stage abbreviations—see Table 1.

	T1	AN	LA	CA	NO	RH	HE	SI	PL	TO	AA	BJ
T1	1	0	0	0	0	0	0	0	0	0	0	0
AN		1	***0.7***	0	0	**0.4**	0	−0.1	−0.1	−0.2	−0.2	−0.2
LA			1	0	0	0.1	0.2	0.1	−0.2	−0.3	−0.3	−0.3
CA				1	0	0	0	0	0	0	0	0
NO					1	0	0	0	0	0	0	0
RH						1	0.1	0.1	0.2	−0.2	0.2	**0.3**
HE							1	***0.6***	**0.3**	−0.2	0	−0.1
SI								1	***0.7***	0	**0.3**	**0.3**
PL									1	0.2	***0.4***	**0.4**
TO										1	**0.3**	**0.4**
AA											1	***0.9***
BJ												1

and Norian brachiopods have been reported from the Alps and the Jura (Sulser, 1999).

The calculation of Rst values for the associations of the Alpine brachiopods (Table 4) demonstrates significant turnover at the Triassic-Jurassic transition, evident from the low Rst values calculated for the Rhaetian and Hettangian and Rhaetian and Sinemurian assemblages. The same values in the Northern Caucasus are higher (Table 3). The next important conclusion is the slight increase in similarity between the Rhaetian and the Pliensbachian-Bajocian associations. This trend was interrupted in the Toarcian. Probably, the total poverty of this association explains the lack of similarity between the Toarcian association and those of other ages. Thus, the patterns documented in the Alps and the Jura contrast to those established in the Northern Caucasus. This might have been related to paleoenvironmental differences between these regions. The Aalenian potential mass extinction provoked a brachiopod diversity drop in the Alps and the Jura (Ruban, 2004), although its influences on the taxonomic diversity structure remain unclear.

Conclusions

This study established the influences of the early Mesozoic crises on the regional evolution of brachiopods. The P/T mass extinction in the Northern Caucasus resulted in a recovery with a consequent increase in the rapid changes in the taxonomic diversity structure of the Early Triassic-Anisian associations. The Ladinian crisis did not provoke any major changes in this structure. The T/J and Pl/To mass extinctions did not lead to significant turnover among brachiopods, but they permitted those superfamilies that dominated in the Early Triassic to rise again. The Pl/To event affected the superfamilies that dominated the species diversity in the Late Triassic. The data from the Alps and the Jura Mountains provide conclusions different from those made in the Northern Caucasus, e.g., a strong turnover at the Triassic-Jurassic transition is reported in the Alpine Region.

Were the early Mesozoic mass extinctions able to reset evolution? Even if our results presented here can be interpreted in the affirmative, such a reset was not complete and, therefore, they do not contradict the observations made by Jablonski (2004).

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Natura Nascosta | Numero 34 | Anno 2007 | pp. 16-27 | Figure 4

PALEOZOIC PALAEOGEOGRAPHIC FRAMEWORKS OF THE GREATER CAUCASUS, A LARGE GONDWANA-DERIVED TERRANE: CONSEQUENCES FROM THE NEW TECTONIC MODEL

Dmitry A. Ruban

Abstract - The Greater Caucasus is a large region between the Black and Caspian seas. The new model of its Paleozoic tectonic evolution, coupled with the analysis of distribution of deposits of distinct ages, makes it possible to propose a set of regional palaeogeographic frameworks. Until the mid-Silurian, this region was incorporated into the continental land mass of Gondwana, being subjected either partly or completely to the successive transgressions from the Prototethys Ocean. In the late Silurian-Devonian, terrestrial environments in the Greater Caucasus were related to islands or island chain along the Hun Superterrane, whereas transgressions from oceans located to the north (Rheic, Rhenohercynian, and Khanty-Mansi oceans) and south (Palaeotethys Ocean) established the marine environments. In the Carboniferous-Permian, the Greater Caucasus was linked to the continental landmass of the Laurussian counterpart of Pangaea, and transgressions occurred from the Palaeotethys Ocean. Carbonate platforms and reefs grew at least twice in the Paleozoic history of the study region. In the Famennian, an isolated carbonate platform appeared, whereas a rimmed shelf attached to the Pangaean margin is known from the Changhsingian. In both cases, the equivalents of these events are found in other parts of the "Tethyan Region".

Key words: palaeogeography, terrane, carbonate platform, Paleozoic, Tethys, Greater Caucasus.

Introduction

Present global reconstructions of Paleozoic plate tectonics (Cocks & Torsvik, 2002; Stampfli & Borel, 2002; Von Raumer *et al*., 2002, 2003; Scotese, 2004; Torsvik & Cocks, 2004) provide a new basis for discussion of the geological history of many regions. This is especially apt in those regions whose evolution has been described in terms of outdated concepts such as the "geosyncline paradigm". An important consequence of the development of new models of regional tectonic evolution is a reconsideration of existing palaeogeographic reconstructions.

The Greater Caucasus is a large region which stretches as a mountain chain between the Black Sea and the Caspian Sea and embraces the territory of southwesternmost Russia, northern Georgia, and northwestern Azerbaijan (Fig. 1). Due to the key position of this region between the Eastern European, Turkish and Iranian domains, reconstruction of its Palaeozoic geological history is significant for the understanding of processes that occurred within the "Tethyan Region". As well, the Paleozoic of this region is of interest because of its economic significance. In some other regions (northeastern Africa, Arabia,

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Fig. 1 - Geographical location of the Greater Caucasus.

Turkey) whose geological history was linked anyhow with the Greater Caucasus, Silurian strata are important source rocks for oil generation (SHARLAND *et al*., 2001; TAWADROS, 2001; TAWADROS *et al*., 2006; VAROL *et al*., 2006). Exploration of the same stratigraphic interval in the Greater Caucasus to evaluate its source-rock potential was suggested by TAWADROS *et al*. (2006). New models have been proposed to describe the geological history of the Greater Caucasus in the Mesozoic-Cenozoic (ERSHOV *et al*., 2003), and, particularly, in the Triassic (GAETANI *et al*., 2005) and Jurassic (RUBAN, in press). The model of NATAL'IN & ŞENGÖR (2005) also has some value in understanding the tectonic evolution of the Greater Caucasus. These replace the traditional "geosyncline" model (see e.g., LAZ'KO, 1975). For the Paleozoic, however, traditional palaeotectonic views have persisted and there has been no appropriate discussion of the regional palaeogeography in the global context. Recently, TAWADROS *et al*. (2006) proposed a comprehensive model of the tectonic evolution of the Greater Caucasus for the entire Phanerozoic (see below for details). In the present paper, the palaeogeographic consequences of this new model are examined, and special attention is given to the determination of the position of the Greater Caucasus with respect to the land masses and oceans existed at those times.

Geological setting

The Greater Caucasus Terrane was identified by GAMKRELIDZE (1997) and later, independently, by TAWADROS *et al*. (2006). At present it is located between the margin of the stable Russian Platform and the Lesser Caucasus Terrane (Fig. 1). It is part of a large orogen deformed and uplifted in the late Cenozoic (ERSHOV *et al*., 2003). The Paleozoic sedimentary complexes, whose total thickness exceeds 20,000 m, are exposed in its central part. The Paleozoic Greater Caucasus Terrane thus forms the core of the present Greater Caucasus. The Paleozoic deposits are dominated by shale and siliciclastic rocks, with the common addition of volcanoclastic and volcanic rocks (RUBAN, 2006) (Fig. 2). However, several episodes of carbonate sedimentation, in the mid-Cambrian, late Silurian-earliest Devonian, Late Devonian and Lopingian, are also known. Coal accumulated in the Pennsylvanian. Major unconformities are recognised within the Ordovician and Permian.

A new model of the tectonic evolution of the Greater Caucasus (TAWADROS *et al*., 2006), which is incorporated with plate tectonic reconstructions by STAMPFLI & BOREL (2002), suggests that this terrane was a part of the Afro-Arabian margin of Gondwana until the mid-Silurian, when margin-parallel breakup occurred (Fig. 3). A new Palaeotethys Ocean was formed, separating a string of terranes, together called the Hun Superterrane, from Gondwana. The Greater Caucasus Terrane was one of these terranes. These migrated from Gondwana towards Laurussia, reaching the latter's margin at some time in the Late Devonian. At the same time, the amalgamation of Pangaea began. Long-distance displacements along a major shear zone, which stretched along the northern Palaeotethyan margin and connected with the Intrapangaean shear zones (ARTHAUD & MATTE, 1977; SWANSON, 1982; RAPALINI & VIZÁN, 1993; STAMPLFI & BOREL, 2002; RUBAN & YOSHIOKA, 2005), resulted in the stacking of terranes westwards, so that the Greater Caucasus Terrane became located close to the Carnic Alps. The palaeontological and lithological records of these two regions are very similar. Some similarity is also observed between the Greater Caucasus and Bohemia. In the Late Triassic, the Greater Caucasus Terrane was repatriated eastwards to its present position along the above-mentioned shear zone. This tectonic model, which has been developed on the basis of palaeontological and lithological interregional comparisons, is also supported by the results of earlier palaeomagnetic studies (SHEVLJAGIN, 1986), which suggest the absence of links between the Greater Caucasus and Russian Platform before the end-Triassic.

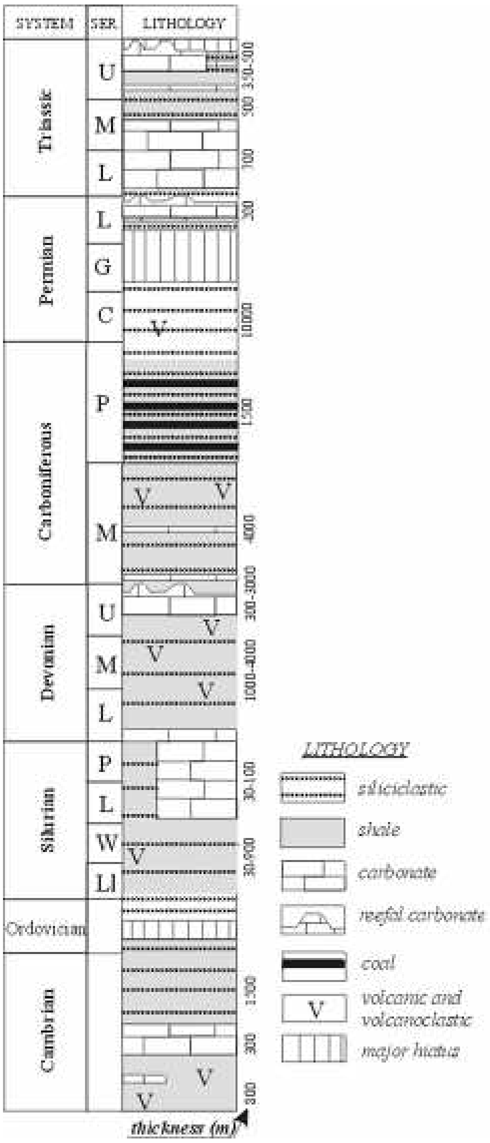

Fig. 2 - Composite section of the Paleozoic-Triassic deposits of the northern Greater Caucasus (modified after Ruban, 2006). No formal chronostratigraphic units are recognized regionally within the Cambrian-Ordovician.

Materials and methods

The proposed palaeogeographic reconstructions are based on analysis of distribution of the Paleozoic deposits within the Greater Caucasus and interpretation of global reconstructions. The distribution of deposits of distinct ages and their stratigraphic subdivision have been reviewed by Paffengol'ts (1959, 1965), Robinson (1965), Miklukho-Maklaj & Miklukho-Maklaj (1966), Zhamojda (1968), Kizeval'ter (1968), Kizeval'ter & Robinson (1973), Zanina & Likharev (1975), Kotlyar (1977), Potapenko (1982), Obut *et al.* (1988), Kovalevskij & Kotlyar (1991), Bogolepova (1997), Kotlyar *et al.* (1999, 2004) and Gaetani *et al.* (2005). Results from the author's own studies on the Permian Molasse (Cisuralian-Guadalupian), undertaken during past years in the Western Caucasus, were also useful. The following compilation of available data excludes literature citations, in order to avoid multiple repetition of the abovementioned sources.

These data permit the distinction of those parts of the Greater Caucasus that were submarine from those that were exposed as land. This simplest of reconstructions can be incorporated into global plate tectonic reconstructions using the new tectonic model of Tawadros *et al.* (2006). The global reconstructions of Stampfli & Borel (2002) are preferred because they seem to be the most comprehendsive and well argued. This incorporation allows us to identify the position of the Greater Caucasus relative to the then existing landmasses and oceans, and to relate the regionally documented marine and non-marine environments with them. This creates a set of palaeogeographic frameworks which clearly demonstrate the key features of the regional palaeogeography in the global context. Although further, more detailed studies are necessary, it seems that the drawing of such simple frameworks may form an essential basis for such studies and for further discussion. Moreover, it will be sufficient to correctly plot the Greater Caucasus on global maps constrained for the Paleozoic

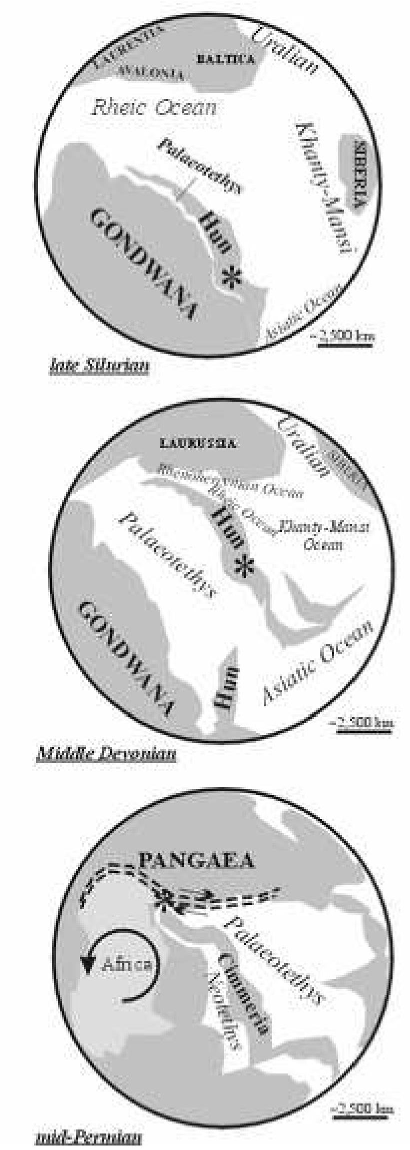

Fig. 3 - Palaeogeographical (asterisk) position of the Greater Caucasus. Palaeotectonic maps are simplified from STAMPFLI & BOREL (2002). Oceans are shown as white.

timeslices. Somewhat the same approach was used by RUBAN (in press) in his regional Jurassic reconstructions.

The palaeogeographical frameworks have been constrained for nine time intervals, each characterized by a lack of significant palaeogeographical change (Fig. 4). These intervals are as follows: Cambrian, Ordovician, Llandovery-Wenlock (early Silurian), Ludlow-Lochkovian (late Silurian-earliest Devonian), Pragian-Frasnian (Early-Late Devonian), Famennian (Late Devonian), Mississippian (early Carboniferous), Pennsylvanian-Guadalupian (late Carboniferous-Middle Permian), and Lopingian (Late Permian). Stratigraphic nomenclature used in this paper follows the recommendations of the International Commission on Stratigraphy (GRADSTEIN *et al*., 2004; see also official web site: www.stratigraphy.org). Formal stratigraphic names are written with an initial captial letter (e.g., Ordovician, Early Devonian, Changhsingian) to distinguish them from the informal names (e.g., late Paleozoic, early Silurian, mid-Permian). The own series names, which have been adopted formally (e.g., Ludlow, Pennsylvanian, Lopingian), are preferred.

Paleozoic palaeogeographic frameworks

The key elements of world palaeogeography are large continental landmasses, small continents, and large islands or island chains, whose size was comparable with that of small continents (COCKS & TORSVIK, 2002; STAMPFLI & BOREL, 2002; VON RAUMER *et al*., 2002, 2003; SCOTESE, 2004; TORSVIK & COCKS, 2004). Gondwana - an assembly of plates in the Southern Hemisphere - existed since the Neoproterozoic, although its final amalgamation might have occurred in the beginning of the Paleozoic. Baltica and Laurentia were individual plates until the mid-Paleozoic, at which time they amalgamamted to form a distinct continent, Laurussia. In the late Paleozoic, Gondwana and Laurussia were amalgamated in part, and a superconitnent Pangaea appeared. An example of a small continent is Siberia, but this and other "lesser continental landmasses", which corresponded to relatively small-sized plates or tectonic blocks, were located far from the sector that is meaningful for our study. Large islands or island chains (together called "island masses") were formed via the derivation of ribbonlike terranes. The latter usually moved from

Gondwana towards Laurussia, against the margin of which they docked. These island masses were Avalonia-Cadomia, Hun and Cimmeria. They were detached from Gondwana in the Ordovician, Silurian and Permian respectively (COCKS & TORSVIK, 2002; STAMPFLI & BOREL, 2002). In the Devonian, the Hun Superterrane was divided into the European Hunic terranes and Asiatic Hun terranes. Other island masses were Serindia and Kazakhstan, but both their palaeotectonic and palaeogeographic interpretation still seems to be incomplete. In the Paleozoic, several oceans stretched between Laurentia and Baltica in the north and Gondwana in the south. They may be referred together as the "Tethyan oceans". Although there was a Tethyan palaeobiogeographic realm, there was no unique ocean which might have been called "Tethys Ocean". The best nomenclature of these oceans was proposed by STAMPFLI & BOREL (2002), who identified the Prototethys (early Paleozoic), Rheic (early-middle Paleozoic), Palaeotethys (middle Paleozoic-early Mesozoic) and Neotethys (late Paleozoic-early Cenozoic). These oceans were formed each time new breakup occurred along the Gondwanan margin. The Protetethys Ocean should be distinguished from the Tornquist and Iapetus oceans, which also existed in the early Paleozoic. In the Silurian, the Rheic Ocean was unified geographically with the Prototethys. Additionally, the Rhenohercynian Ocean was opened along the southern margin of Laurussia in the Devonian. COCKS & TORSVIK (2002) and TORSVIK & COCKS (2004) generally support this nomeclature, although their plate tectonic reconstructions differ in somewhat from those of STAMPFLI & BORel (2002) and VON RAUMER *et al.* (2002, 2003).

The palaeogeographical frameworks derived for the Greater Caucasus are presented in Fig. 4 and described below.

Cambrian deposits are known in the central and western parts of the Greater Caucasus Terrane (Fig. 4A). A typical marine fauna, including trilobites, brachiopods and archaeocyaths, has been found there. Although the Cambrian strata outcrop in only few sections, we may hypothesize that the terrane was entirely marine at this time. In the early Paleozoic, the Greater Caucasus was a part the Afro-Arabian margin of Gondwana (TAWADROS *et al.*, 2006). Thus, the sea would have transgressed from the north, i.e., from the Prototethys Ocean.

Although it is generally assumed that no strata of Ordovician age exist in the Greater Caucasus Terrane (Fig. 4B), the presence of Lower and Upper Ordovician deposits is hypothesized here. If the former is true, this region was land at that time. Its location on the Gondwanan periphery allows us to conclude that it was a marginal part of that continental landmass. The Prototethys Ocean was situated somewhere to the north. An intriguing question is whether the study region was embraced by the Hirnantian glaciation, which occurred at the end of the Ordovician (BRENCHLEY *et al*., 1994; SMITH & PICKERING, 2003).

Lower Silurian deposits are confirmed only in the north-central Greater Caucasus Terrane (Fig. 4C). These mark a minor transgressive episode, enforced by the abrupt deepening of the terrane margin as indicated by the dominance of relatively deep-water facies. Therefore, land occupied most of the Greater Caucasus, which was still connected to Gondwana; the marine incursion may be linked to the Prototethys Ocean. These palaeogeographic changes are readily explained by the development of an active margin

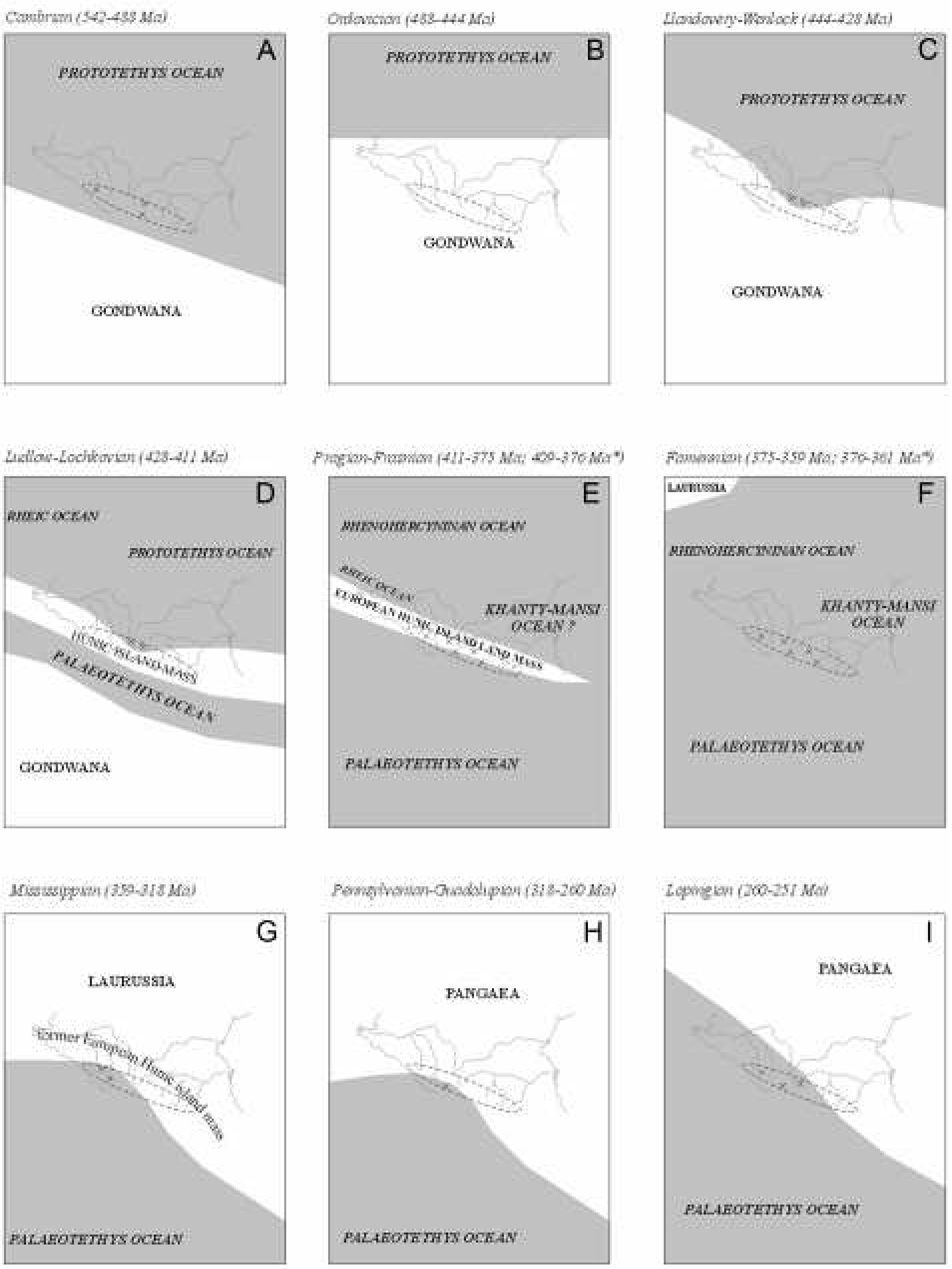

Fig. 4 – Palaeogeographic frameworks of the Greater Caucasus. A) Cambrian, B) Ordovician, C) Llandovery-Wenlock, D) Ludlow-Lochkovian, E) Pragian-Frasnian, F) Famennian, G)Mississippian, H) Pennsylvanian-Guadalupian, I) Lopingian. Present-day geographic outline is shown for general orientation within the deposit distribution for each particular age. Deposit distribution is shown by crosses; oceans are shown as gray; land is shown as white. Position of land and oceans is indicated approximately. The absolute ages are taken from GRADSTEIN *et al.* (2004) and KAUFMANN (2006) (the latter is marked by *).

on the periphery of Gondwana after the partial closure of the Prototethys Ocean (STAMPFLI & BOREL, 2002).

The distribution of upper Silurian deposits was the same as that of the lower Silurian, although succeeding Lochkovian deposits cover a slightly larger area (Fig. 4D). Thus, the general palaeogeographic situation in the northern part of the Greater Caucasus was the same as in the early Silurian. However, dramatic changes occurred to the south. A new ocean opened along the Gondwanan margin; it separated the Hun Superterrane, part of which was the Greater Caucasus Terrane, from Gondwana. Consequently, the land, evidently established in the study territory by the absence of upper Silurian strata in its southern, western and eastern parts, may be referred to the Hunic island mass.

Devonian (Pragian-Frasnian) strata are widely distributed throughout the entire Greater Caucasus (Fig. 4E). However, these mostly comprise thick (up to 4,000 m) volcanic and volcanoclastic deposits. Such a great intensification in regional volcanic activity may be explained in two ways: 1) active contact between tectonic blocks within the assembly of the European Hunic terranes, and 2) location of the Greater Caucasus close to the northern active margin along this superterrane, where the oceans closed (RUBAN & KHOLODKOV, 2006). In the southern part of the Greater Caucasus, marine facies with *Amphipora* and *Favistella* are known. Thus, the volcanic islands of the Greater Caucasus were part of the European Hunic island mass, which separated the closed Rheic Ocean and extended Rhenohercynian Ocean from the large Palaeotethys Ocean. The marine basin periodically transgressed some areas of this island mass, as confirmed by the local presence of rare mid-Devonian carbonates with marine fauna. It is possible to hypothesize that the Greater Caucasus lay on the eastern edge of the European Hunic island mass. If so, the Khanty-Mansi Ocean was located to its north. This ocean moved close to the European Hunic terranes after the partial closure of the Rheic Ocean (STAMPFLI & BOREL, 2002).

Famennian deposits are known throughout the entire Greater Caucasus Terrane (Fig. 4F). In its western and northern parts they are represented by carbonates with abundant marine fauna and reefs. However, relatively deep-water facies are distributed through the southern part of this terrane. Thus, there was no land in the latest Devonian within the study region. The remnants of the Rhenohercynian and Khanty-Mansi oceans united with the Palaeotethys Ocean, which reached its maximum size at that time, to form a single water mass. In the Late Devonian, the European Hunic terranes reached the Laurussian margin. It is possible to say that these terranes abutted Laurussia at their western edge, whereas the Greater Caucasus Terrane was on the eastern edge.

Marine Mississippian deposits are known in the western part of the Greater Caucasus Terrane (Fig. 4G). From the beginning of the Carboniferous, the European Hunic terranes became amalgamated with the Laurussian margin, and the activity on the major shear zone led to their westward stacking (see above). Thus, the sole possibility to explain the marine sedimentation in the western Greater Caucaus is to assume a marine incursion from the Palaeotethys Ocean. Land present in the central and eastern parts of the study region may be assigned to the continental landmass of Laurussia.

Late Carboniferous to mid-Permian (Pennsylvanian-Gaudalupian) strata are known within the western and central Greater Caucasus (Fig. 4H). However, marine facies are known only along its southwestern periphery. Coal-bearing and molassic deposits (the latter dominated by siliciclastic sediments of variegated colour) accumulated in the other areas. Thus the marine basin, again referred to the Palaeotethys Ocean, inundated only a small part of the study terrane, whereas the remainder was land included in the continental landmass of the Laurussian counterpart of the supercontinent of Pangaea.

Late Permian (Lopingian) marine deposits, which were carbonates with the richest fossil assemblages (foraminifers, brachiopods, bivalves, gastropods, trilobites, etc.), are distributed across the western and central parts of the Greater Caucasus Terrane (Fig. 4I). This transgression evidently occurred from the Palaeotethys Ocean, whose narrowing began due to the opening and rapid growth of the Neotethys Ocean in the south. Non-marine environments, if they existed in the eastern part of the Greater Caucasus, are referred to the continental landmass of Pangaea, whose breakup had already begun (STAMPFLI & BOREL, 2002).

Discussion

Two recognizable episodes of carbonate platform and reef growth occurred within the Greater Caucasus in the Famennian and Changhsingian (RUBAN, 2005, 2006). For the Famennian, RUBAN (2005) hypothesized the presence of a large carbonate platform of rimmed shelf type. However, the present reconstruction (Fig. 4F) does not support such a conclusion. There was no sufficiently large landmass on whose margin such a shelf might have been located. Possibly this was an isolated carbonate platform associated with the drowned land formerly existing along the axis of the Greater Caucasus Terrane. Although Frasnian reefs are much better known, Famennian reefs were also widely distributed globally (WEBB, 2002). They are known along the southern margin of Laurussia and in Kazakhstan, South China and Western Australia. It is possible to say that they developed along the entire northern and eastern periphery of the Palaeotethys Ocean, but were absent on its southern periphery. If so, we may confirm that the Famennian was the time when the Greater Caucasus Terrane reached or almost reached the Laurussian margin.

The late Changhsingian reefs, known in the western part of the Greater Caucasus, bounded the carbonate platform attached to the continent (RUBAN, 2005). The latter was the Laurussian counterpart of Pangaea. Other carbonate platforms, such as those in the Dinarides (SREMAC & MARJANAC, 2003; VLAHOVIĆ *et al*., 2005), existed on the margins of the Palaeotethys and Neotethys oceans. They were precursors of the large carbonate platforms which appeared in the western part of the "Tethyan Region" in the Mesozoic (GOLONKA, 2004; VLAHOVIĆ *et al.,* 2005).

Conclusions

The interaction of global tectonic processes in the "Tethyan Region", i.e., between Laurussia and Gondwana, created a complicated geological history for the Greater Caucasus. The constrained palaeogeographic frameworks (Fig. 4) suggest that the Palaeozoic environments interpreted within the Greater Caucasus were related to several major elements of the global palaeospace, namely the Gondwana and Laurussia continental landmasses, the Hunic island mass (i.e., a unique island or a chain of lesser islands), and the Prototethys, Palaeotethys, Rheic, Rhenohercynian and Khanty-Mansi oceans.

Further studies are necessary to refine our knowledge of the Palaeozoic evolution of the Greater Caucasus. The key topics for these are as follows: 1) justification of the position of the Greater Caucasus in the Cambrian-Ordovician, 2) exploration of the possible regional appearance of the Hirnantian glaciation, and 3) discussion of the mid-Devonian palaeoenvironments, when intense regional volcanism occurred.

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Late Paleozoic Transgressions in the Greater Caucasus (Hun Superterrane, Northern Palaeotethys): Global Eustatic Control

Trangresiones del Paleozoico tardío en el Gran Caucaso (Superterreno Hun, PaleoTesis Norte)

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Abstract

The Greater Caucasus (a mountain chain in southwesternmost Russia, northern Georgia, and northwestern Azerbaijan) is a Gondwana-derived terrane, which was included into the Hun Superterrane (late Silurian-Late Devonian) and then docked at the Laurussian margin of the Palaeotethys Ocean close to the terranes of the present Alps (Late Devonian-Middle Triassic). The Upper Paleozoic sedimentary complex, up to 20,000 m thick, provides a good record to discuss global eustatic changes. Three transgressions are reported in this region, which occurred in the Lochkovian, Frasnian-Famennian, and Changhsingian. The first of them embraced the northern part of the Greater Caucasus, the second was larger and covered this region entirely, whereas the third occurred in its western part only. All of them corresponded evidently to global eustatic rises, and, therefore, their explanation does not require an implication of the regional tectonic activity. These regional transgressive episodes are also known from the Southern and Carnic Alps, Arabia, and Northern Africa. A correspondence between the Late Permian marine sedimentation in the Greater Caucasus and non-marine sedimentation in Spain is established. Thus, they were of planetary extent and the present global eustatic curve is confirmed. The regional transgressions resulted in carbonate deposition, biotic radiations, and reefal growth.

Key words: palaeogeography, Late Paleozoic, sea-level changes, eustasy, Greater Caucasus, Paleotethys, Russia

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INTRODUCTION

The global sea-level fluctuated strongly during the Late Paleozoic. Well-known earlier reconstructions of this eustasy were made by Vail et al. (1977), Johnson et al. (1985), Ross & Ross (1985), Hallam (1992), Ronov (1994), and Hallam & Wignall (1999). Recently, Haq & Al-Qahtani (2005) have proposed a new global eustatic curve. In general, it is concluded that the sea level dropped gradually during the Late Paleozoic, with a pronounced drop in the mid-Permian. Second-order fluctuations were superposed on this trend. Unfortunately, our knowledge of the Paleozoic sea-level changes remains limited (see also Miller et al. 2005). For example, the present curve of Haq & Al-Qahtani (2005) suggests a major regression in the end-Permian, although Hallam & Wignall (1999) argued for a major transgression at this time. By the same token, sea-level changes at the Frasnian-Famennian transition are not clear (Racki 2005). Verification of proposed eustatic curves as well as their details, improvement, and justification is possible only by careful comparison of numerous regional data from across the world. An example from the Jurassic demonstrates that such analysis would significantly contribute both to the identification of the global sea-level changes and their explanation (Hallam 2001). A reconstruction of the global eustatic curve is an enormously difficult task and some doubts are even expressed as to its existence (e.g., McGowran 2005). However, such a curve will be an important key to explain the changes in world palaeogeography, sedimentary environments, and biotic evolution. In the regional record, we document the global sea-level changes by the transgressive and regressive episodes. However, the latter may also reflect (and almost always do anyway!) the regional tectonic influences. Thus, our task is to differentiate between the eustatic- and tectonic-induced regional sea-level changes. Hallam (2001) made an intriguing conclusion, that transgressions are more evident when traced globally, than regressions, which reflect mostly the regional tectonic movements. In the author's opinion, this does not diminish the importance of world correlation of regressive episodes and unconformities, but emphasizes the need for global tracing of the regional transgressions.

The Greater Caucasus Terrane, presently included into the Alpine Mediterranean Belt and located in the Southwest of Eurasia (Fig. 1), provides an exceptional Late Paleozoic record. According to the present tectonic model (Tawadros et al. 2006; Ruban et al., 2007), this region was one of the Hunic terranes identified by Stampfli & Borel (2002), and therefore, its record is meanful for both the Afro-Arabian margin of Gondwana and Variscan Europe. This article is the first, which attempts to give a comprehensive, although brief synthesis of knowledge on the Late Paleozoic transgressions, which occurred in the Greater Caucasus.

GEOLOGICAL SETTING

The Greater Caucasus pertains to a large mountain chain, which is located in the Southwest of Eurasia and connected with the other mountains originated during the Alpine phase of orogenic activity. The Greater Caucasus embraces southwesternmost Russia, northern Georgia, and northwestern Azerbaijan. The Paleozoic sedimentary complexes, whose total thickness is up to 20,000 m, are known in the central part of this territory. They are exposed both in numerous little outcrops and in the continuous sections along the river valleys. Deposits of all three Upper Paleozoic systems are known in the Greater Caucasus (Fig. 1). The Devonian is dominated by volcanics and volcanoclastics, and carbonates are known in the Upper Devonian. The Mississippian is composed of shales, sandstones, and rare carbonates, whereas the Pennsylvanian is represented by non-marine coal-bearing strata. The Cisuralian-

Guadulupian is a typical molasse, whereas the mid-Permian corresponds to a major hiatus. Only in the Changhsingian, did marine sedimentation recommence, when accumulation of sandstones and shales was followed by a remarkable episode of carbonate sedimentation.

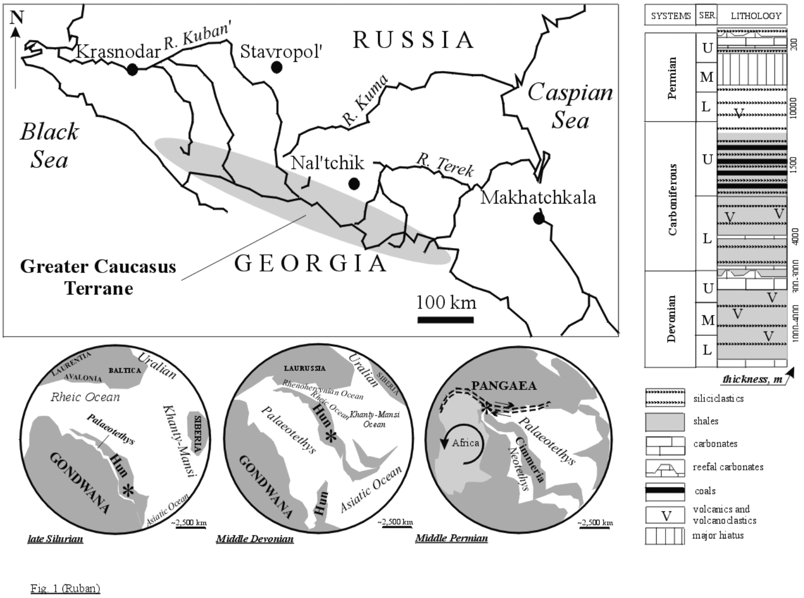

Fig. 1. Location of the Greater Caucasus Terrane and a composite lithologic section of the Paleozoic deposits exposed in the northern Greater Caucasus (after Ruban (2006) with additions). The base palaeomaps are simplified from Stampfli & Borel (2002).

The Greater Caucasus Terrane has been identified by Gamkrelidze (1997) and later by Tawadros et al. (2006) and Ruban et al. (2007). The latter authors have also developed a new model, which describes the evolution of the Greater Caucasus (Fig. 1). Until the mid-Silurian, this terrane was a part of the Afro-Arabian margin of Gondwana, i.e., it lay on the southern periphery of the Prototethys and Rheic oceans. In the Ludlow, a breakup occurred along the Gondwanan margin and a ribbon of terranes, called the Hun Superterrane, was formed (Stampfli & Borel 2002; Stampfli et al. 2002; von Raumer et al., 2002, 2003). A new ocean, i.e., the Palaeotethys, was originated in between the Hun Superterrane and Gondwana. This ocean grew in size, whereas the oceans, located between the Hun and Laurussia, were closed. Thus, the Greater Caucasus Terrane together with the other Hunic terranes moved northward. In the Late Devonian, it reached the Laurussian margin. The right-lateral displacements along the major shear zone (Arthaud & Matte 1977;

Swanson 1982; Rapalini & Vizán 1993; Stampfli & Borel 2002; Ruban & Yoshioka 2005) led to the stacking of the Greater Caucasus Terrane somewhere close to the Carnic Alps and Bohemia. In the Late Triassic, the direction of the displacements along the above-mentioned shear zone changed to left-lateral (Swanson 1982; Rapalini & Vizán 1993; Ruban & Yoshioka 2005). The Greater Caucasus Terrane then rapidly reached its present position at the south of Baltica plate.

METHOD: A CONCEPTUAL FRAMEWORK

According to Catuneanu (2006), transgression is defined as a landward migration of the shoreline. It is strongly recommended to make a distinction between transgressions and deepening pulses. Although they are linked in some cases, their true relationships are very complicated (see also Catuneanu 2006). Not in all cases does a transition to facies formed at greater depth, recorded in the sedimentary succession, mark a landward shift of the shoreline. Transgression may have a number of mechanisms, which are distinct in isolated (where are, therefore, not influenced by the global eustasy) and open or half-open basins (Fig. 3).

The Greater Caucasus Terrane was embraced during the Late Paleozoic by marine basins, directly related to the oceans extant at those times. Thus, they were open basins. Consequently, we need to examine two possible explanations of documented transgressions. If they corresponded to the global eustatic events recorded by the curve of Haq & Al-Qahtani (2005), they were eustasy-dominated. When such correspondence is not found, this means tectonic factors were more significant. Alternatively, this also may indicate inaccuracies in the global eustatic curve. The Late Paleozoic transgressions, which occurred in the Greater Caucasus, were recorded thanks to the careful analysis of data on the spatial distribution of deposits of a particular age. These data are contained particularly in the comprehensive overviews by Paffengol'ts (1959), Milukho-Maklaj & Miklukho-Maklaj (1966), Kizeval'ter & Robinson (1973), Obut et al. (1988), Kotlyar et al. (1999, 2004) and Gaetani et al. (2005). The periods, when marine facies became the most wide-spread, were the times of transgressions. Each regional transgressive episode is characterized here in a similar way, i.e., its age, area, sedimentary environments, and possible controls are considered.

A RECORD OF THE REGIONAL TRANSGRESSIONS

Three transgressive episodes may be recorded in the Late Paleozoic history of the Greater Caucasus, namely the Lochkovian, the Frasnian-Famennian, and the Changhsingian episodes.

The Lochkovian regional transgressive episode (D1-RTE) is recorded in the northern part of the Greater Caucasus (Fig. 3). Carbonates with shale interbeds of the upper member of the Manglajskaja Formation, up to 10 m thick, are known there (Obut et al. 1988). In some sections, the lowermost Devonian is represented by shales, siltstones, sandstones with carbonate lenses, whose total thickness reaches 100-150 m. The age of the above-mentioned strata is established precisely with conodonts, and these deposits also contain bivalves trilobites, and tentacultes. The Lochkovian trangsression is evident in the valley of the Malka River, where the Devonian deposits, including basal sandstones with gravels, overlie the lower Silurian strata with an evident disconformity (Obut et al. 1988). Thus, it seems that transgression was directed eastward. At the beginning of the Devonian, the Greater Caucasus Terrane together with the other Hunic terranes moved northward (Stampfli & Borel 2002; Tawadros et al. 2006; Ruban et al., 2007). The absence of the Lochkovian deposits in the southern part of the Greater Caucasus Terrane may be explained by the inclusion of the latter into a large island, which existed along the central axis of the Hun Superterrane. If so, the documented transgression occurred from the Rheic Ocean. This episode was relatively short, because already in the late Early Devonian the sea became restricted in the Greater Caucasus, and volcanoclastic deposition started. D1-RTE undoubtedly corresponded to global eustatic rise (Fig. 3). Even if any regional tectonic activity might have affected the relative sea-level, such influences were minor.

The Frasnian-Famennian regional transgressive episode (D3-RTE) is recorded in the entire Greater Caucasus (Fig. 3). This transgression started in the early Frasnian or even in the end-Givetian, when siliciclastic deposits of the Semirodnikovsksja Formation (its total thickness reaches 1,700 m) were deposited on the Early-Middle Devonian complex composed of volcanics and volcanoclastics. However, the transition between under- and overlying deposits was gradual, and the amount of conglomerates increases upwards (Kizeval'ter & Robinson 1973). These strata are overlain by the carbonates, including reefal limestones, of the Pastukhovskaja Formation, up to 3,000 m thick. The age of these strata is established as Famennian (Kizeval'ter & Robinson 1973). In the southern part of the Greater Caucasus, the upper Frasnian-Famennian Kirarskaja Formation consists of sandstones and shales with limestone interbeds. Stratigraphic relationships between the Devonian formations are not well-justified, and therefore, it becomes difficult to evaluate the direction of this transgression. In the Late Devonian, the Greater Caucasus Terrane was docked at the Laurussian margin, as well as other so-called European Hunic terranes, although a narrow remnant of the Rhenohercynian Ocean remained open between the latter and Laurussia (Stampfli & Borel 2002; Tawadros et al. 2006). It should be further investigated, whether the opening Palaeotethys or closing Rhenohercynian Ocean embraced the studied terrane. This transgression ended at the Devonian/Carboniferous boundary, because it is marked by an erosional surface (Kizeval'ter & Robinson 1973). During D3-RTE, the global eustatic level fluctuated (Fig. 3), and this regional transgression may be related to the pronounced eustatic rise, which occurred in the late Frasnian-early Famennian (Haq & Al-Qahtani 2005). It is necessary to point out the existing misinterpretation of eustatic changes at the Frasnian-Famennian boundary (Hallam & Wignall 1999; Kalvoda 2002; Racki 2005). Earlier eustatic rise in the late Givetian-early Frasnian may have initiated a marine incursion in the studied territory and deposition of conglomerates. Their long accumulation in the Frasnian may be easily explained by the remarkable global regression (Haq & Al-Qahtani 2005), which did not permit a transition to sandstones and shales or carbonates. Thus, as in the previous case, the regional transgressive episode and associated events corresponded well to the global eustasy, and implication of any regional tectonic activity is not necessary.

The Changhsingian regional transgressive episode (P3-RTE) is recorded in the western part of the Greater Caucasus (Fig. 3). This transgression started with the deposition of sandstones, shales, and carbonates of the Kutanskaja and Nikitinskaja with a total thickness exceeding 50 m (Miklukho-Maklaj & Miklukho-Maklaj 1966). But its peak was reached, when the carbonate-dominated Urushtenskaja Formatio with a thickness of more than 100 m, was formed. This formation also includes reefs. All these strata overlie unconformably the Carboniferous-Permian molasse and other older sedimentary complexes. The age of these deposits is now evaluated with brachiopods, foraminifers and other fauna as the late Chaghsingian (Kotlyar et al. 1999, 2004; Gaetani et al. 2005). However, there is some evidence for a conformable contact with the underlying deposits locally (Miklukho-Maklaj & Miklukho-Maklaj 1966). It seems that transgression occurred from the southwest, because the Early-Middle Permian marine environments were established only there. In the Late Permian, the Greater Caucasus Terrane was amalgamated with the Laurussian margin of Pangaea, and it was located somewhere close to the terranes of the present Alps (Tawadros et al. 2006; Ruban et al., 2007). The central and eastern parts of the Greater Caucasus, where the Lopingian deposits are absent, were evidently included into the continental land mass. This transgressive episode was the shortest. It was ended already by the earliest Triassic, because an unconformity is established at the base of the Triassic sedimentary complex (Miklukho-Maklaj & Miklukho-Maklaj 1966; Gaetani et al. 2005). P3-RTE corresponded to a low-amplitude, but still globally-recognizable eustatic rise (Fig. 3). Moreover, recent studies argue that this global transgression strengthened at the Permian/Triassic boundary (Hallam & Wignall 1999; Wignall 2004; Racki & Wignall 2005; Erwin 2006), which is not reflected on the curve of Haq & Al-Qahtani (2005). This well explains marine deposition until the earliest Triassic in the Greater Caucasus. The age of the Abagskaja Formation, which overlies the Urushtenskaja Formation and consists of limestones of about 25 m thickness (Miklukho-Maklaj & Miklukho-Maklaj 1966), is considered as latest Permian-earliest Triassic, because of an extremely impoverished faunistic complex (Miklukho-Maklaj & Miklukho-Maklaj 1966). This biotic crisis is explained by the devastating mass extinction occurring directly at the Permian/Triassic boundary. This gives us the age of the Abag Formation. Thus, the end-Permian regional transgression occurred from the Palaeotethys Ocean thanks to the global eustatic rise. No tectonic forces are necessary to explain this regional episode, although the origin of the Alpine-type structures in the entire Proto-Alpine Region and associated extension (Krainer 1993) might have reinforced transgression.

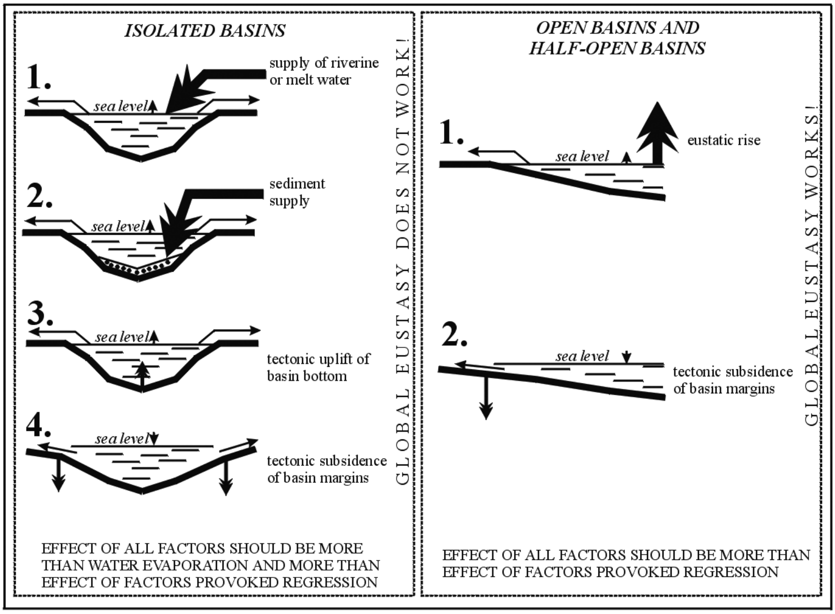

Fig. 2 (Ruban)

Fig. 2. Mechanisms of transgressions in isolated and open and half-open basins. In each particular case, the mechanism of transgression may be complicated and may have included elements from two or more idealized models.

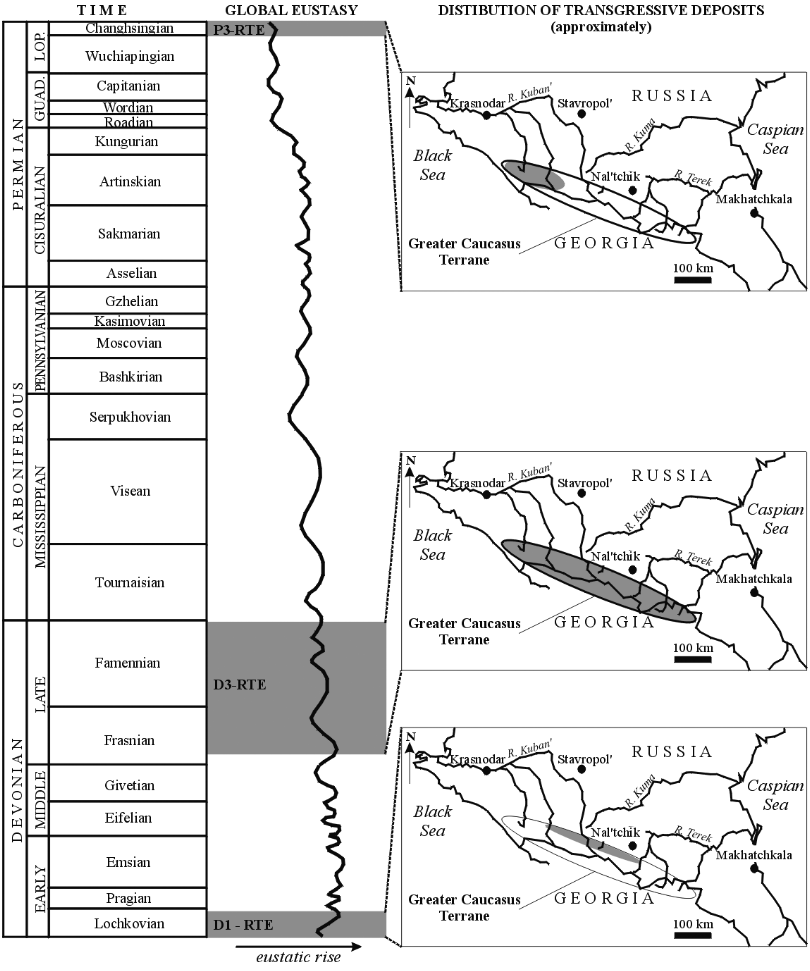

Fig. 3. The Late Paleozoic global eustatic curve (after Haq & Al-Qahtani 2005) and regional transgressive episodes (highlighted by gray). Abbreviations: Guad. - Guadalupian, Lop. - Lopingian. See text for explanation of the regional transgressive episodes.

DISCUSSION

It is important to look for analogues of the Late Paleozoic transgressions, which occurred in the Greater Caucasus. In the Austrian and Italian Southern and Carnic Alps, the Lochkovian and Lopingian transgressions were remarkable events (Krainer 1993; Schönlaub & Histon 1999; Venturini 2002). Although the evidences for Late Devonian shoreline shifts are less clear, a transgressive surface at the base of the lithostratigraphic unit named "calcari a goniatiti e climenia", whose age is late Frasnian - early Famennian, has been documented in the Carnic Alps (Venturini 2002). In Arabia, transgressions occurred in the end-Silurian, twice in the Famennian, and in the entire Lopingian (Sharland et al. 2001; Haq & Al-Qahtani 2005). In Northern Africa, the Famennian transgression is evident, whereas there was a significant regression in the Lochkovian and at the Permian/Triassic boundary; however, a transgression is known in the Lopingian (Guiraud et al. 2005). Thus, in spite of observed time differences, which may be caused by improperly understood stratigraphic framework and imperfect correlations both in the Greater Caucasus and other regions or by regional tectonic influences, we can suggest that the Late Paleozoic transgressions in the Greater Caucasus were analogous to those in other regions. This indicates their global extent, and also supports the curve of Haq & Al-Qahtani (2005).

It is very intriguing that the latest Permian transgression in the Greater Caucasus coincided with the onset of the Buntsandstein sedimentation in Spain, particularly in the Cordillera Ibérica and the Cordillera Costero-Catalana (Vera 2004). Such a correspondence can be explained by the relation of the Late Permian sedimentation (either marine or non-marine) in the Carnic Alps, Spain, and the Greater Caucasus to the beginning of extension, which embraced at least entire Southern Europe (see e.g., Krainer 1993; Stampfli & Borel 2002).

All three Late Paleozoic transgressions in the Greater Caucasus were expressed by carbonate deposition (see above). Moreover, D3-RTE and P3-RTE occurred at times of reefal growth on the periphery of carbonate platforms (Ruban 2005, 2006). In the Late Devonian, rimmed shelf was attached to the Hun island, whereas in the Lopingian, a carbonate platform of the same type was attached directly to the continental margin of Pangea. Although Khain (1962) argued for tectonic control of the Late Devonian and Late Permian reef distribution in the Greater Caucasus, we may now postulate that the appearance of these reefs might have resulted directly from the eustatically-driven transgressions. By the same token, all reported regional transgressive episodes undoubtedly coincided with biotic radiations. Available data on brachiopods suggest their Early and Late Devonian and Late Permian diversifications (Ruban 2006). The same events are also known in the regional evolution of other fossil groups like bivalves, trilobites, corals, and bryozoans (Paffengol'ts 1959; Miklukho-Maklaj & Miklukho-Maklaj 1966; Nalivkin & Kizel'vater 1973; Obut et al. 1988; Kotlyar et al. 1999, 2004). Transgressions led to the appearance of relatively shallow-marine environments on shelves, which were favorable for marine fauna. When reefal communities grew up, this accelerated biotic radiations as this was previously hypothesized by Ruban (2006).

CONCLUSIONS

Three regional transgressive episodes are known in the Late Paleozoic history of the Greater Caucasus Terrane. They were the Lochkovian, Frasnian-Famennian, and Changhsingian transgressions. Attempted comparison of them with the present global eustatic curve (Haq & Al-Qahtani 2005) and data from other regions (Alpine Europe, Northern Africa, and Arabia) suggests that all these transgressions were eustatically-controlled, and the role of regional tectonic activity to explain them seems to have been insignificant. However, the specifics in the regional tectonic evolution may explain why other transgressions documented by the global curve did not appear in the studied region. Thus, a conclusion that transgressions can be traced globally, analogous to the changes in the global sea level made by Hallam (2001) for the Jurassic, can now also be inferred for the Late Paleozoic. It is also possible to state, that the global eustatic curve of Haq & Al-Qahtani (2005) is confirmed with the data from the Greater Caucasus Terrane.

Another important conclusion from the study is that all three regional transgressions were expressed by carbonate deposition and biotic radiations, and two of them also coincided with reefal growth.

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