Detailed correlation of the Devonian deposits in the South Urals and some aspects of their formation

OLGA V. ARTYUSHKOVA & VICTOR A. MASLOV

Since the Late Emsian the geological history of Devonian sedimentation in the South Ural Basin of Russia was associated with the evolution of volcanism responsible for vastly different facies environments over a long period of time – from the Late Emsian until the Late Famennian. Maximum manifestations of volcanism took place in the Magnitogorsk Megazone; much less masses of volcanic rocks are characteristic of the Kuragan-Sakmara zone. A significant deepening of the basin was associated with rift basaltic volcanism at the end of the *costatus* Conodont Zone and continued through the *australis* and *kockelianus* zones. Prolonged deepening in the Frasnian began in the *punctata* Zone and continued until the tectonic calm of the Late *rhenana* Zone. Maximum shallowing occurred at the end of the *varcus* zone. Faunal changes followed with the more pronounced mass extinction of different faunal groups occurring at the F/F boundary.
• Key words: Devonian, South Urals, correlation, Zilair, Magnitogorsk megazones, Kuragan-Sakmara zone, conodonts, volcanic succession.

ARTYUSZKOVA, O.V. & MASLOV, V.A. 2008. Detailed correlation of the Devonian deposits in the South Urals and some aspects of their formation. *Bulletin of Geosciences 83(4)*, 391–399 (3 figures). Czech Geological Survey, Prague. ISSN 1214-1119. Manuscript received May 11, 2007; accepted in revised form August 18, 2008; issued December 31, 2008.

Olga V. Artyuszkova & Victor A. Maslov, Russian Academy of Sciences, Ufa Research Centre, Institute of Geology, Karl Marx Street, 16/2, Ufa 450000, Russia; stpal@anrb.ru

Devonian deposits in the South Urals are presently subdivided into small stratigraphical units correlated with each other on the basis of conodont research (Antsygin *et al.* 1993). In keeping with the zonation for the South Urals, the western slope involves the Zilim-Zigan and West Zilair zones with shelf deposits as well as the Kuragan-Sakmara and East Zilair zones with bathyal complexes. All the other zones are situated within the eastern slope and are characterized by paleoceanic basin deposits (Fig. 1).

The western slope of the South Urals shows a domination of carbonate sediments whereas the eastern slope is distinguished by the volcanogenic character of the rock sequence. Devonian carbonate deposits are well studied and subdivided into horizons on the basis of macrofossils (brachiopods and corals). For many years the subdivision of volcanic sedimentary complexes of the Magnitogorsk Megazone was based on their composition; in most cases their age was conventionally assigned either by identification of macrofossils from extremely rare biohermal limestone bodies or by the position of the strata in the sequence. Inevitably, the stratigraphy of these volcanic sedimentary complexes was a matter of various subjective speculations and caused many debates. Any correct correlation between them and the Devonian deposits of the western slope was apparently out of the question.

The application of the conodont fauna for subdividing and determining the age of the volcanic sedimentary rocks undertaken by us since 1973 has made it possible to change the situation. At present we have a very rich collection of conodont imprints from siliceous rocks throughout the whole Devonian sequence at the eastern slope and the Kuragan-Sakmara Zone of the South Urals. The age of the local stratigraphical units has been determined, and the volcanic sedimentary complexes have been correlated with the horizons of carbonate sections of the western slope. The revised stratigraphical scheme of the Devonian deposits within the Magnitogorsk Megazone is now characterized to an unprecedented level of detail (Maslov *et al.* 1993; Artyushkova & Maslov 1998, 2005; Maslov & Artyushkova 2000, 2002).

During the last two decades, new evidence on the Devonian stratigraphy in the South Urals has been gathered in quantity either by the authors or through their cooperation with other geologists. The obtained data and detailed paleontologic studies from some problematic stratigraphic intervals now make it possible to determine and equate in time major geological events of the region, which find their reflection in the facies specific nature and response of faunal assemblages.

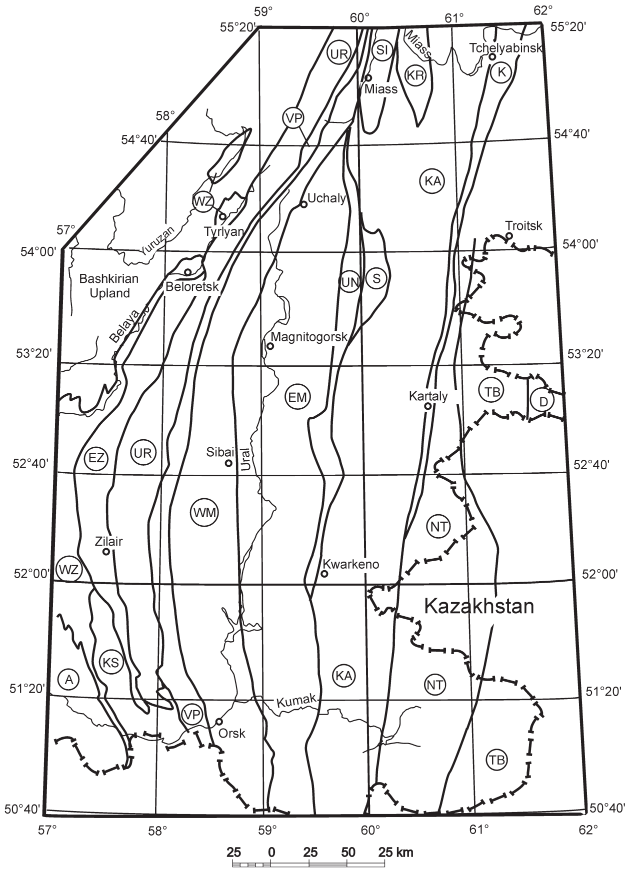

Figure 1. B – zonation scheme of the Palaeozoic deposits in the South Urals (sine 1998): A – Abzanovo zone, WZ – West Zilair zone, EZ – East Zilair zone, KS – Kuragan-Sakmara zone, UR – Uraltau zone, VP – Voznesenska–Pre-Sakmara zone, WM – West Magnitogorsk zone, EM – East Magnitogorsk zone, SI – Sysert–Il'menogorsk zone, KR – Kasargino-Reftinsk zone, UN – Ui–Novoorenburg zone, S – Suchtelinsk zone, KA – Kochkar–Adamovka zone, K – Kopeisk zone, NT – Nizhnesanarsk–Tekel'dytau zone, TB – Troitsk–Buruktal zone, D – Denisovka zone.

Stratigraphy and the main regional events

In Devonian time the South Ural Basin constituted a single intricately evolved water area, including a marginal sea with continental shelf, slope and rise zones and an "oceanic sector" within the Magnitogorsk Arc (Zonenshain *et al.* 1984, Ivanov *et al.* 1986, Korinevsky 1988, Puchkov 2000).

Early Devonian

The Early Devonian period shows evident 'heritability' of the main facies zones from Late Silurian time. Deposits of the Siyak Horizon (*Cladopora actuosa, Neomphyma originata, Lanceomyonia borealiformis* Zone) established at the base of the Lochkovian Stage are represented by gray bedded limestones with lens-shaped interbeds of clay shales. They make a gradual transition from underlying Silurian deposits. This level is marked by the appearance of the Devonian brachiopod genera *Neomphyma, Ivdelinia* and corals *Riphaeolites, Pachyfavosites*, and *Acanthophyllum*. There is also a drastic impoverishment of the Silurian fauna with only infrequent specimens of *Lissatrypa kuschvensis* (Tschern.) (Tyazheva *et al.* 1976). The very few conodonts are represented by *Icriodus woschmidti*. The Siyak Horizon is 45 to 70 m thick. From the Late Lochkovian to the Early Pragian (the Sherlubai and during the whole Kulamat time), reef limestones, up to 1000 m thick, formed a well-exposed continuous belt of 250 km length, fringing the Bashkirian Upland along the eastern latitudinal length of the Belaya and in the basin of the Bolshoi and Maly Ik Rivers (Krauze & Maslov 1961). Reef fragments found in the Beloretsk and Tirlyan synforms allow a reconstruction of their borders with the assumption of the existence of a barrier reef. The lowland area was supposed to be located in the west within the Bashkirian Upland and in the form of local elevations in the East-European Platform. Trans-reefal facies were probably eroded because of a pre-Emsian (pre-Takata) break. Terrigenous rocks are preserved locally as sandstones of the Khlebodarovo Formation (Tchibrikova 1977). At the continental slope and rise situated more to the south and east, within the Kuragan-Sakmara and East-Zilair zones as well as the Pre-Sakmara-Voznesenska Subzone, there accumulated siliceous-clayey, siliceous and silico-clastic deposits, sometimes with detached masses of biogenic limestones (upper Sakmara, Akchurino and Mazovo formations). In all probability, these organogenous limestones, spread widely in the sections of the Magnitogorsk Megazone between the latitude of Magnitogorsk and that of the town of Miass, were generated at elevated areas of the continental rise in the form of biohermal structures. It is possible that in the Early Devonian these structures constituted a carbonate platform. During that time interval the basin depths varied within the limits of the calcium carbonate compensation depth (CCD). No dated manifestations of volcanism can be found at that time in the South Urals (Figs 2, 3).

In Early Emsian time the sedimentation pattern changed to an essential degree. Facies environments became increasingly diverse both in the shelf zone and in the paleoceanic sector of the basin. Faunal assemblages underwent a rapid transformation accompanied by total extinction of Pragian taxa. Transgression that began during Takata time significantly enlarged the basin area. An important influence on the processes of sedimentation was also exerted by early manifestations of pre-arc Devonian volcanism (alkaline basalts of the Chanchar and Mostostroevsky complexes). The terrigenous composition of the Takata Formation (West-Zilair Zone) consisting mainly of different grain-sized quartz sandstones, some-

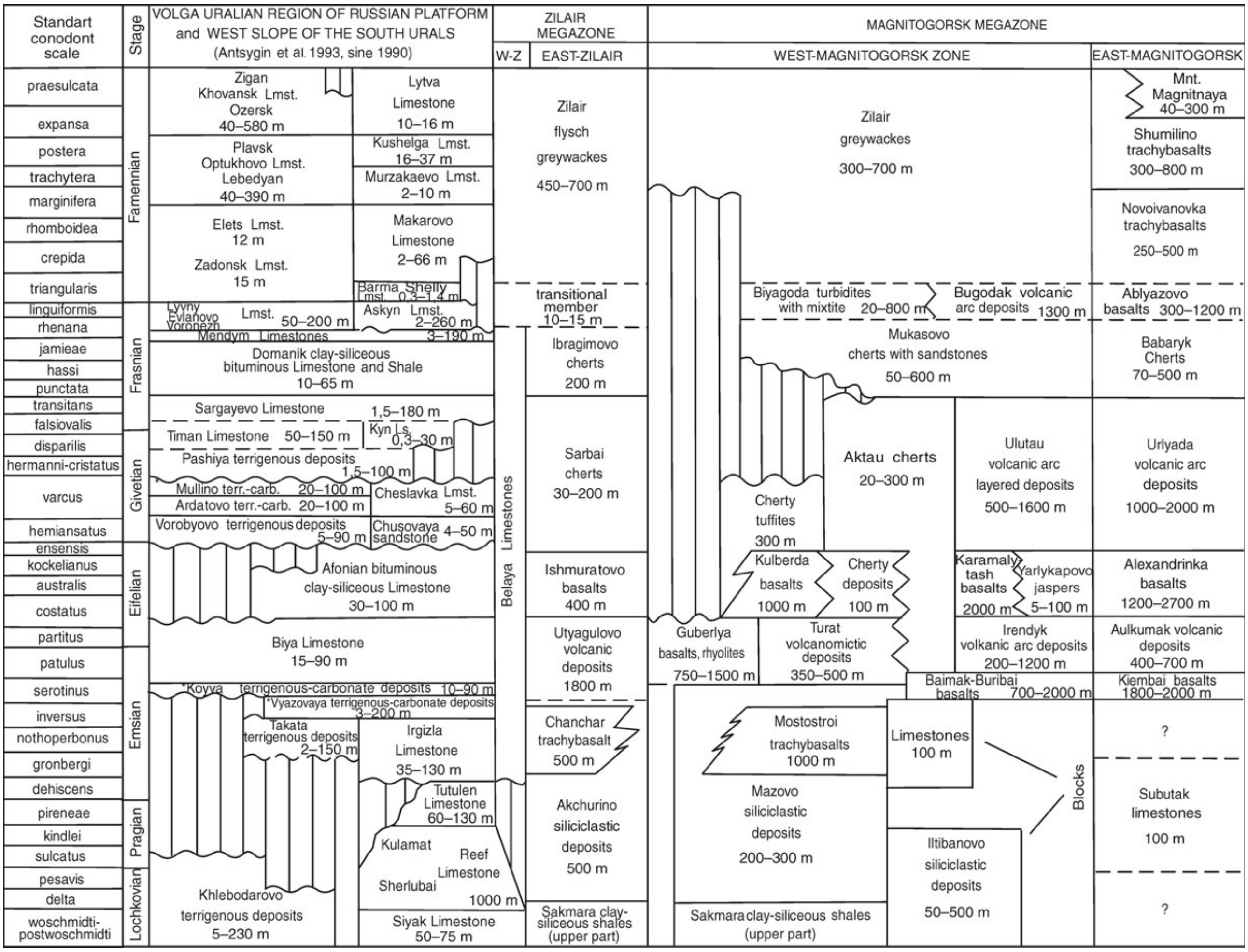

Figure 2. Stratigraphical and correlative scheme of the Devonian in the Volga-Urals region (Russian Platform), West and East slopes of the South Urals.

times of gravel size, unsorted clastic material, peculiar oblique bedding and absence of faunal remains, does not provide an unambiguous answer to the question of their origin. Sharing the opinion of Domrachev (1952), Nalivkin (1952), Adrianova & Spassky (1953, unpublished), we are inclined to think that the facies environments were formed in shallow sea waters with a markedly moving coastline. Clastic material was supplied mainly from the Bashkirian Upland. In the eastward direction to the open sea, sandstones were facially replaced by shallow-water bedded dark-colored limestones with *Favosites regularissimus* Yanet, which contain lens-shaped interbeds of quartz sandstones (Irgizla Formation, up to 80 m thick). Still further to the east there also appear bathyal complexes of the continental slope consisting of siliceous siltstones, cherts, sometimes monomictic clastites of different sizes (Khutorskaya Series in the East-Zilair Zone, upper Akchurino Series in the southern Kuragan-Sakmara Zone, and Mazovo Formation in the Pre-Sakmara-Voznesenska Subzone). Silicoterrigenous rocks with organogenous limestones found in a number of sections (Ryskuzhino, Uskul, Iltibanovo and Turgoyak series) along the marginal part of the West-Magnitogorsk Zone might have been deposited in a compensated trough with elevated seafloor areas, where biohermal structures were formed. To the north of the zone the basin depths were less than the CCD; perhaps, the floor underwent slow subsidence, so that sandy-siliceous deposits were spread there together with abundant organogenous sandstones in the form of relatively thick bioherms. As a whole, the Early Devonian interval, including the lowermost *serotinus* Zone, is characterized by a brief transgression (Vanyashkino Formation) that is most probably synchronous with the beginning of the Baimak-Buribai volcanism (Fig. 3) in the Magnitogorsk Megazone (Baimak-Buribai and Kiembai formations).

The subsequent history of Devonian sedimentation in the South Uralian Basin was associated with the evolution of volcanism responsible for vastly different facies environments over the long time span from the Late Emsian to Late Famennian. The bathymetry of the basin offered great contrasts. Maximum manifestations of volcanism took place in the Magnitogorsk Megazone. Much less mass of volcanic rocks are characteristic of the Kuragan-Sakmara Zone (Seravkin *et al*. 1992).

During the Late Emsian, from *serotinus* time on, the shelf-occupied area (western slope of the South Urals) remained virtually constant; horizons of Koiva quartz sandstones occurring in this region mark the beginning of a new transgressive cycle. Accumulation of silicites and manifestation of "early island-arc volcanism" (Seravkin *et al*. 1992) (Utyagulovo Formation in the Kuragan-Sakmara Zone) mark basin deepening and suggest that sedimentation took place in the continental slope environments. Early island-arc volcanites of the Baimak-Buribai and Kiembai formations were formed in the Magnitogorsk Megazone over a considerable area covered with rift-like units (Seravkin *et al*. 1992). Contrasting rhyolite-basaltic volcanism showed itself in deep-water settings, below CCD, as evidenced by the complete absence of limestones and the development of jaspers (Fig. 3B).

During the Late–Early Eifelian (*patulus–costatus* zones), the basin moved westward under conditions of compensated subsidence. Reef limestones of the Biya Horizon (*patulus-partitus* zones) accumulated on the shelf, and in the beginning of the *costatus* Zone they gave way to black and dark-gray bituminous limestones, siliceous and clay shales of the Afonino Horizon. Andesite-basaltic volcanism characteristic of primitive island arcs (Utyagulovo and Irendyk Formations) continued in the Kuragan-Sakmara and West-Magnitogorsk zones (Seravkin *et al*. 1992). This stage is associated with the generation of the thick Irendyk submarine volcanic ridge, which is about 400 km long, as seen in the present-day structure. The end of volcanism is marked in the *costatus* Zone by shoals of shell deposits and bioherms accumulated on the crests of the Irendyk ridge and comprising brachiopods, corals and crinoids (Gadilevo Series).

Middle Devonian

From the beginning of the *costatus* Zone till the very beginning of the Domanik time, pelagic sediments (the condensed siliceous section of the Aktau Formation) accumulated westward from the Irendyk Arc within the fore-arc basin below the CCD.

Such a dramatic change of sedimentation pattern at the boundary between the *partitus-costatus* zones was evidently induced by a sudden increase of sea level, resulting in the development of anoxic facies (Afonino Horizon) and biohermal growth in the elevated areas of the volcanic ridge (Fig. 3). In all probability, the distinct local deepening can be correlated with the Choteč Event (Walliser 1996).

Diffuse spreading that began from the *australis* Zone showing itself in the Kuragan-Sakmara and Kraka zones, with its maximum in the Magnitogorsk Megazone, promoted faster subsidence of the basin floor. During *australis–kockelianus* time there evolved thick volcanic units of the jasper-basaltic association: the Karamalytash and Gumbeika formations and synchronous jaspers of the Yarlykapovo Series in the Magnitogorsk Megazone; the Ishmuratovo Formation in the Kuragan-Sakmara Zone; and thick jasper-like radiolarian cherts in the Sukhteli and Kochkar-Adamovka zones. Siliceous-clayey-carbonate sediments of the Afonino Formation (infra-Domanik) accumulated within the shelf. This time interval is marked by one of the greatest stages of silica accumulation in the Devonian of the South Ural Basin. The faunal association changes drastically, with a major increase in diversity of conodonts, tentaculites and radiolarians.

The Givetian is marked by a gradual decrease in the basin depths, with a maximum fall of sea level during the Pashiya Formation time (Fig. 3A). At least two transgressive-regressive cycles are evident in the shelf zone, with their boundaries running in the lowermost Chusovaya and Pashiya formations. At that time the Kuragan-Sakmara Zone constituted a deep-water region, with mainly siliceous sediments. In the East-Magnitogorsk Zone there was an island arc, which supplied sedimentary material westward for the Ulutau Formation. The extinct Irendyk Arc then served as a barrier against clastic transport to the west. The explosive character of the Givetian volcanism favoured the generation of submarine elevations and temporary islands, formed by corals, stromatoporoids, brachiopods, with locally growing bioherms.

The end of the *varcus* Zone was characterized by shallow-water conditions on the shelf. At that time massive indistinctly-bedded stromatopore-coral limestones of the Cheslavka Horizon were generated with *Stringocephalus burtini*. By the beginning of the Pashiya time continued shoaling reached its maximum; at that stage the basin can certainly be identified as that of 'super-shallow' type. Indeed, over a vast territory the sedimentary environments were almost similar to littoral ones. Everywhere in the sections of the Pashiya Horizon (several metres to 40 m thick) one can find quartz sandstones and frequently ferruginous sandy-clays containing plant remains. The maximum depth of the break is observed in sections further to the west, where Pashiya sandstones are seen to overlie Emsian Biya limestones. By the beginning of Pashiya time the *Stringocephalus* fauna, Givetian corals and ostracodes became extinct, and Frasnian miospores of the *optivus-krestovnikovi* Zone make their first appearance (Avchimovich *et al.* 1993). The Pashiya Horizon is a distinct marker showing large regional shoaling comparable most probably to the Taghanik Event (Johnson & Sandberg 1988).

Terrigenous deposits of the Pashiya Horizon mark the beginning of a new sedimentation cycle. In Kyn (Timan)

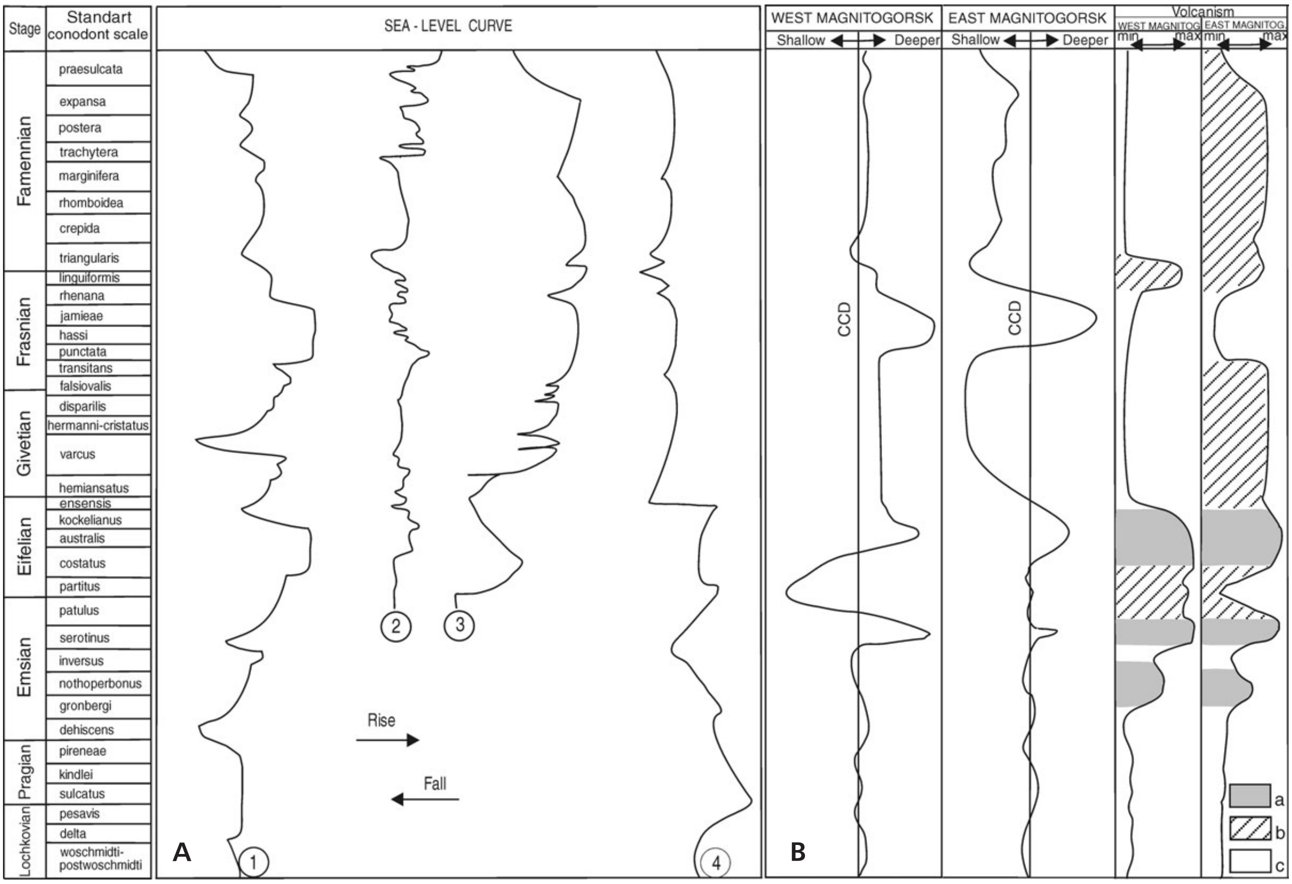

Figure 3. A – Correlation of the sea-level curve for the Devonian in the Middle and East Europe: 1 – on the West slope of the South Urals; 2 – on the Central area of the Russian Platform (Karaulov & Gretschischnikova 1997); 3 – on the southeastern Russian Platform (Yunusov *et al.* 1997); 4 – in the Czech Republic (Chlupáč 1988). • B – sea depth changes curve and volcanism intensity curve for the Devonian of the South Urals (Magnitogorsk megazone). a – rift basalts, b – volcano ark deposits, c – deposits without volcanites, CCD – Calcium carbonate compensation depth.

time, which terminates the Givetian, slow basin deepening takes place, and clay limestones, marls and clays are deposited. The Kyn Horizon is only insufficiently correlated with the international conodont scale. The horizon varies in thickness from 0.25 to 15 m (Abramova 1999). Faunistically, it is poorly characterized, with only rare finds of the brachiopod *Uchtospirifer murchisonianus* (Vern.) and ostracodes.

Late Devonian

The overlying deposits of the Sargaevo Horizon (Late *falsiovalis-transitans* zones) begin the Frasnian Stage (Fig. 2). Here, deep-water black and dark-gray bituminous limestones make their appearance; the fauna becomes much more diverse; ostracodes, tentaculites, goniatites and conodonts play an increasingly important part, alongside brachiopods, corals and stromatoporoids.

In Domanik time (*punctata-jamieae* zones), the basin deepening reached its maximum and covers the whole territory of the South Uralian Basin in question. An increase in depth was due to general stabilization of geodynamic conditions in the South Urals. The complete suppression of volcanism occurred in the Magnitogorsk Megazone. Most likely the basin floor underwent an irregular uncompensated subsidence at that time. The shelf zone extended westward as far as the East-European Platform and is characterized by a relatively intricate floor relief with isolated wide depressions and elevated areas. During that time interval, the black siliceous-clayey shales and bituminous limestones of the Domanik Formation were formed on the western slope of the South Urals, being rich in deep-water faunal remains of *Radiolaria*, *Styliolina* shells, goniatites and conodonts. The accumulation of these deposits still continued in Mendym time (Early *rhenana* Zone). The base of the Early *rhenana* Zone is associated with the onset of the goniatite *Manticoceras intumescense* Beyr. (Abramova 1999). Siliceous and siliceous-clayey sediments of the Ibragimovo Formation were accumulated further eastward within the continental slope. In and outside the Magnitogorsk Megazone, along the fringe of the

East-Uralian Upland (Sukhteli and western part of the Kochkar-Adamovka Zones) silica accumulation encompassed a vast region and continued into Askynian time, including the *Late rhenana* Zone. This stage is related to the generation of condensed siliceous sequences of the Mukasovo Formation as well as the Babaryk, Arsy and Solonchatka series. The silica accumulation process was periodically disrupted by volcano-terrigenous material brought by turbid flows and entrapped in the deepest basin reservoirs. It is best seen within the Kyzil-Urtazym Syncline of the West-Magnitogorsk Zone (Maslov & Artyushkova 2002). Available evidence suggests that the Irendyk and Ural-Tau ridges were submerged and overlapped with siliceous deposits during the *punctata-rhenana* zones time. This time interval represents the greatest and longest stage of silica accumulation in the South Uralian Basin; in the shelf zone it is marked by hypoxic shales of the Domanik Formation. Contemporaneous rocks on the western and eastern slopes of the South Urals are comparable in their thicknesses and vary from 20 to 150 m. The Domanik Event is clearly traced over a considerable territory of the East-European Platform; the associated deposits have been well studied in the sections of the South Timan (House *et al*. 2000). In the North American continent it is correlated with the New York Middlesex and Rhinestreet black shales (House *et al*. 2000, fig. 12).

Differentiation of the basin started in Mendym time (Early *rhenana* Zone) and is associated with a gradual uprising of the ocean floor, which becomes more pronounced during Askyn time (Late *rhenana* Zone); facies environments become much more diverse and find their reflection in the composition of the deposits and faunal assemblages. The shelf zone showed an alternation of relatively deep-water uncompensated depressions, with the accumulating Domanik-like facies, and shallow areas, in which psammitic and clay sediments were deposited and locally colonized by amphipores and stromatoporoids (Orlovka and Ust'-Katav formations). The transition zones between were occupied by reef-like structures "with indistinctly separated bioherms" (Chuvashov 1968). During Askyn time (possibly earlier in the Frasnian) in the eastern part of the East-European Platform, the Kama-Kinel system of depressions came into existence, individual branches of which can be traced as far as the western slope of the Urals. These depressions accumulated deep-water deposits throughout the whole Late Devonian.

Frasnian/Famennian boundary interval

The Late Askyn and Barma (*linguiformis* and Early-Middle *triangularis* zones, respectively) are important time intervals in the development of the South Uralian Basin. Shoaling that begins in the Late *rhenana* Zone is marked by the absence of any deposits of this stratigraphical interval in many sections and in some regions the duration of the break ranges into the *marginifera* Zone. In continuous sections, the Askyn reef-like limestones are overlapped by Barmian brachiopod-shell deposits (Abramova 1999, Abramova & Artyushkova 2004). In depression sections, well-exemplified by the Lemezinsky section, the *linguiformis* Zone contains thin-bedded black bituminous limestones rich in diverse faunas, primarily in goniatites of the genus *Manticoceras* and numerous conodonts (Abramova 1999, Abramova & Artyushkova 2004). By early Barma time, the richest and most diverse conodont assemblage of the *linguiformis* Zone almost entirely disappears. Brachiopods of the genera *Gypidula, Hypothyridina, Theodossia, Pseudoatrypa, Spinatrypa, Warrenella* and *Thomasaaria,* which formed the basis for the Askyn association, suffer complete extinction. Different *Manticoceras* species that constitute the main part of the Frasnian goniatite associations in the deep-water sequences (Abramova 1999, Abramova & Artyushkova 2004) also become extinct.

Within the West-Zilair Zone, the Frasnian/Famennian boundary interval is more clearly pronounced. The uppermost Askyn Horizon in the Yaumbaevo section, which we correlate with the *linguiformis* Zone, consists of loose crinoidal limestones. They are overlapped by polymictic flysch deposits of the Zilair Formation characterized 0.7 m above the base by conodonts of the Late *triangularis* Zone (Abramova *et al*. 1998). In the upper meridional part of the Belaya River, a gradual transition from Frasnian to Famennian deposits is found in the sections of Kagarmanovo, Ilyukhina Glade and the Chernaya River mouth (Yakupov *et al.* 2002, Abramova & Artyushkova 2004). Here, gray medium-bedded goniatite limestones of the *linguiformis* Zone, 2–3 m thick, are overlapped by intricately folded finely-plated siliceous-clayey shales and siliceous siltstones, not more than 20 m thick in total. At the contact between these limestones and silico-terrigenous rocks, a bed of greenish-gray ferruginous siliceous-carbonate shales, 0.1 m thick, can be seen overlapped by a stratum of variously plated cherts. The base of this cherty stratum shows thin interbeds of silicified limestones and carbonate concretions with conodonts characteristic of the *linguiformis* Zone. The upper half of the unit reveals some rare *Pa. triangularis* Sannemann, whereas the top contains a fairly rich conodont assemblage characteristic of the Late *triangularis* Zone. This assemblage dates the base of the overlying Zilair Formation. We consider the siliceous-clayey unit to be transitional between the carbonate section and the flysch Zilair Formation. In all probability, this type of stratigraphical section characterizes a relatively narrow transitional zone from shelf facies proper to a slope bathyal one.

At the continent slope within the boundary interval occur thin flysch deposits of polymictic composition similar to the rocks of the West-Magnitogorsk Zone. The same time interval coincides with the beginning of the final stage of Devonian volcanism in the Magnitogorsk Megazone. Volcanogenic facies of the matured island arc are widespread (Bugodak, Ablyazovo and Sheludivye Gory series) and reach their maximum development in the East-Magnitogorsk Zone. At some distance away from the zones of active volcanism, these volcanic complexes correlate in time with polymictic flysch, several to hundreds of metres thick, and associated with mixtite complexes (the Biyagoda Olistostrome).

Available information concerning the Frasnian/Famennian boundary interval from the South Ural sections makes it possible to say with certainty that the global biotic events known as the Kellwasser Crisis (Walliser 1986), with a mass extinction of many taxa belonging to different faunal groups, is well recorded in this region. Within the territory in question it is associated with dramatic changes of the biota at the boundary between the *linguiformis* and Early-Middle *triangularis* Zones. Sedimentologically, this event as prolonged as the time interval corresponding to the *linguiformis* to Early-Middle *triangularis* Zones is evidenced by: (a) a generation of brachiopod shell deposits; (b) black bituminous limestones very rich in goniatite shells; (c) stratigraphical breaks of different duration; (d) turbidites of the flysch facies with consedimentary olistostromes; and (e) an outbreak of matured island-arc volcanism.

The Famennian Late *triangularis* Zone is marked by the formation of flysch greywacke sequences of the Zilair Formation accumulated over a vast region of the West-Magnitogorsk Zone and in the Zilair Synform and by infilling a huge meridionally elongated trough (Puchkov 2000). At that time the shelf outer boundary moved westward, where there appeared relatively shallow sedimentation settings with sporadically dried-up shoals (this is indicated by some stratigraphical lacunas). Depressed areas were infilled with siliceous-calcareous and clay material. Volcanism terminating the island-arc stage lasted until the end of the Famennian; this was the time when the Novoivanovka and Shumilino series were formed (Figs 2, 3).

The main source of clastic material for the Zilair flysch was restricted to the active volcanism location in the East-Magnitogorsk Zone, from which it was supplied by turbid flows. The assumption is that the East Uralian Upland uplifted in the Famennian and might have served as a main source of clastics (Smirnov & Smirnova 1961, Veimarn *et al*. 1998) is not supported by the evidence. Other sources of clastic material were of less importance. Within the West Zilair Zone distal parts of the turbid flows are found as roofing slates (the rise of the Zilair Formation). This proven synchronic lower boundary pattern of the lower Zilair Formation established by conodont sequence in continuous sections (Artyushkova & Maslov 2005), does not permit any alternative opinion on the existence of the two basins (to the west and east) separated from each other by the "Uraltau Cordillera" (Mizens 2002, Gorozhanina & Puchkov 2001). Indirect evidence for the viewpoint of a single basin comes from the established stratigraphical interval encompassing the *marginifera* Zone and consisting of interbedded cherry and green clay siltstones, sometimes with the layers of pink limestones with many conodonts. Traced in the West-Magnitogorsk, West-Zilair and Kuragan-Sakmara Zones, it undoubtedly marks a deepening of the sea.

By the end of the Famennian, the basin depths gradually decrease, with their minimum occurring early in the Carboniferous period. Submarine volcanic activity reduces, and surface or shallow-sea facies begin to occur.

Conclusions

All the most clearly pronounced sedimentological events reflected in the sedimentary sequences of the western slope in the South Urals are sufficiently well correlated with manifestations of volcanic activity in the Magnitogorsk Megazone under submarine conditions (Fig. 3B).

The *gronbergi-inversus* zones show the very first manifestations of alkaline volcanism as in the passive continental margin (Seravkin *et al*. 1992). This event corresponds to the beginning of the Takata-Vanyashkino transgression.

During the *serotinus* Zone, relatively vigorous volcanism begins in the submarine riftogenous structures. Volcanogenic complexes of the rhyolite-basaltic copper pyrite-bearing unit were in the process of development (Lower Utyagulovo Formation in the Kuragan-Sakmara Zone, Baimak-Buribai and Kiembai formations in the Magnitogorsk Megazone). In the shelf zone this time is indicated by the beginning of the Koiva transgression.

At the end of the *costatus* Zone and mainly in the *australis-kockelianus* Zones, a new vigorous outbreak of riftogenic rhyolite-basaltic volcanism that occurred in the Kuragan-Sakmara (Ishmuratovo Series), West-Magnitogorsk (Karamalytash Formation) and East-Magnitogorsk (Gumbeika Series) zones coincided with basin deepening; the latter reveals itself primarily in the generation of deep-water jaspers and cherts as well as black bituminous limestones and siliceous-clayey rocks of the Afonino Horizon in the shelf zone.

In the succeeding time (after the *kockelianus* Zone), the territory of the Magnitogorsk Megazone developed under intense island-arc volcanism. In the West-Magnitogorsk Zone volcanism stopped, whereas in the East-Magnitigorsk Zone it continued with varying intensity up to the end of the Devonian, since it was related to mature still-functioning island arcs. From the end of the Givetian to the early Frasnian, a discrete wave of volcanism probably took place; from that time the section displays closely-spaced mixtite volcanomictic beds with fragmented *Stringocephalus* limestones, interbeds of volcanomictic sandstones with Givetian brachiopod coquinas and limestone bioherms. In the shelf zone on the western slope of the South Urals, this time interval shows the maximum basin shoaling.

The longest time span without any volcanic activity falls within the *punctata*-Late *rhenana* zones, when the relatively shallow-water regime abruptly changed to a deep-water one. Submarine volcanic structures were then submerged below the CCD. Relatively thick siliceous beds in the Magnitogorsk Megazone and Domanik facies in the shelf area were formed under stable hydrodynamics in the absence of near-bottom flows.

After a long dormant volcanic period and sedimentation the next extensive outbreak in volcanic activity falls within the Frasnian/Famennian boundary interval. Intense explosive volcanism accompanied probably by tsunamis resulted in the generation of thick creep mixtites (the chaotic complex of the Biyagoda Olistostrome) and also contributed to a distinct reduction of basin depths. At the same time limestone bioherms (at Lake Koltuban) were formed on the submarine elevations at a distance well-removed from the centers of volcanism. Brachiopod shell deposits of the Barma Formation accumulated under shallow-water conditions in the shelf zone. This was the time of an abrupt change in the sedimentation pattern. The beginning of collision tectonism and general land subsidence caused the accumulation of the flysch of the Zilair Formation in the West-Magnitogorsk and Zilair zones. Volcanic clastics were supplied to them mainly from persistent volcanism in the East-Magnitogorsk Zone.

Acknowledgements

The authors are grateful to N. Savage, B. Bushmann and V. Puchkov for review the manuscript and usefull comments and suggestions. This is a contribution to UNESCO-IUGS IGCP 499.

References

ABRAMOVA, A.N. 1999. *Frasnian stage at the western slope of the South Urals.* 55 pp. Institute of Geology, Ufa Scientific Center, Russian Academy of Sciences, Ufa. [in Russian]

ABRAMOVA, A.N. & ARTYUSHKOVA, O.V. 2004. The Frasnian/Famennian boundary in the Southern Urals. *Geological Quarterly 48(3)*, 217–232.

ABRAMOVA, A.N., MASLOV, V.A., ARTYUSHKOVA, O.V. & BARYSHEV, V.N. 1998. Lower boundary of Zilair Formation in the Yaumbaevo Section. *Annual Report 1996,* 32–34. Institute of Geology, Ufa Scientific Center, Russian Academy of Sciences, Ufa. [in Russian]

ADRIANOVA, K.I. & SPASSKY, N.Y. 1953 (unpublished). *Stratigraphy, fauna, materials on petrolium content of the Devonian deposites on the West slope of South Urals*. Baschkirian territorial Geolfund, Ufa. [in Russian]

ANTSYGIN, N.Y., POPOV, B.A. & CHUVASHOV, B.I. Eds. 1993. *Stratigraphic schemes of the Urals.* 151 pp. Ural Branch Russian Academy of Sciences, Yekaterinburg. [in Russian]

ARTYUSHKOVA, O.V. & MASLOV, V.A. 1998. *Stratigraphic subdivision of the Prefamennian volcanic deposits in Verkhneural'sk and Magnitogorsk locations on the palaeontological basis.* Institute of Geology, Ufa Scientific Center, Russian Academy of Sciences, Ufa. [in Russian]

ARTYUSHKOVA, O.V. & MASLOV, V.A. 2005. Conodont stratigraphy of sediments overlying the Mukasovo Formation in the South Urals (Famennian Stage, Zilair Formation). S*tratigraphy and Geological Correlation 13(2)*, 170–185.

AVCHIMOVITCH, V.I., TCHIBRIKOVA, E.V., OBUKHOVSKAYA, T.G., NAZARENKO, A.M., UMNOVA, V.T., RASKATOVA, L.G., MANTSUROVA, V.N., LOBOZIAK, S. & STREEL, M. 1993. Middle and Upper Devonian miospore zonation of Eastern Europe. *Bulletin des Centres de Recherches Exploration – Production elf-aquitaine (Sommaire – Contents) 17(1*), 79–147.

CHLUPÁČ, I. 1988. The Devonian of Czechoslovakia and its stratigraphic significance, 481–497. *In* MCMILLAN, N.J., EMBRY, A.F. & GLASS, D.J. (eds) *The Devonian of the World: Proceedings of the Second International Symposium on the Devonian System, Calgary, Canada. Volume 1: Regional Syntheses.*

CHUVASHOV, B.I. 1968. *Evolution and Bionomic Characteristics of Late Devonian Basin at the Western Slope of the Middle and South Urals*. 95 pp. Nauka, Moscow. [in Russian]

DOMRACHEV, S.M. 1952. Devonian of the West Preuralian. Devonian of the Karatau Ridge and adjacent regions of the South Urals. *Trudy vsesoyuznogo neftyanogo nauchno-issledovatelskogo geologorazvedochnogo instituta (VNIGRI)/ Proceedings of All-Union Scientific Research Geology and Prospect Institute, New Series 61,* 5–121. [in Russian]

GOROZHANINA, E.N. & PUCHKOV, V.N. 2001. Sedimentation model for the Cis-Arc Depression of the Magnitogorsk Island Arc in the Upper Devonian, 5–12. *In* PUCHKOV, V.N. & SALIKHOV, D.N. (eds) *Geology and Prospects for Expansion of Raw Material Base in Bashkortostan and Adjacent Regions (Proceedings of 4th Republican Geological Conference) 1*. Ufa. [in Russian]

HOUSE, M.R., MENNER, V.V., BECKER, R.T., KLAPPER, G., OVNATANOVA, N.S. & KUZMIN, A.V. 2000. Reef episodes, anoxia and sea-level changes in the Frasnian of the southern Timan (NE Russian Platform), 147–176. *In* INSALACO, E., SKELTON, P.W. & PALMER, T.J. (eds) *Carbonate Platform Systems: components and interactions. Geological Society of London, Special Publications 17*.

IVANOV, K.S. & PUCHKOV, V.N. 1986. New data on Paleozoic geology of the European slope in the Urals, 83–116. *In* IVANOV, S.N. & SAMYGIN, S.G. (eds) *Formation of the Earth's crust in the Urals*. Nauka, Moscow. [in Russian]

JOHNSON, J.G. & SANDBERG, C.A. 1988. Devonian eustatic events in the Western United States and their biostratigraphic responses, 171–178. *In* MCMILLAN, N.J., EMBRY, A.F. & GLASS, D.J. (eds) *The Devonian of the World: Proceedings of the Second International Symposium on the Devonian System, Calgary, Canada. Volume III: Paleontology, Paleoecology and Biostratigraphy.*

KARAULOV, V.B. & GRETSCHISCHNIKOVA, I.A. 1997. Devonian eustatic fluctuations in the North Eurasia. *Courier Forschungsinstitut Senckenberg 199,* 13–99.

KORINEVSKY, V.G. 1988. *Geological history of paleoceanic basins of the South Urals.* 47 pp. Masters thesis, Institute of Geological Sciences, Academy of Sciences, Moscow, USSR. [in Russian]

KRAUZE, S.M. & MASLOV, V.A. 1961. *Ordovician, Silurian and Lower Devonian at the western slope of the Bashkirian Urals*. 95 pp. Bashkir Branch, Academy of Sciences of the USSR, Ufa. [in Russian]

MASLOV, V.A. & ARTYUSHKOVA, O.V. 2000. *Stratigraphy of the Paleozoic formations in Uchaly location of Bashkiria.* 138 pp. Institute of Geology, Ufa Scientific Center, Russian Academy of Sciences, Ufa. [in Russian]

MASLOV, V.A. & ARTYUSHKOVA, O.V. 2002. *Stratigraphy and correlation of the Devonian deposits in Sibay-Baimak location of Bashkiria*. 198 pp. Institute of Geology, Ufa Scientific Center, Russian Academy of Sciences, Yekaterinburg. [in Russian]

MASLOV, V.A., CHERKASOV, V.L., TISCHENKO, V.T., SMIRNOVA, I.A., ARTYUSHKOVA, O.V. & PAVLOV, V.V. 1993. *Stratigraphy and correlation of Middle Paleozoic volcanogenic complexes in major copper-pyrite regions of the South Urals*. 217 pp. Institute of Geology, Ufa Scientific Center, Russian Academy of Sciences, Ufa. [in Russian]

MIZENS, G.A. 2002. *Sedimentary basins and geodynamic environments in Late Devonian – Early Permian of the South Urals*. 190 pp. Institute of Geology and Geochemistry, Ural Branch of the Russian Academy of Sciences, Yekaterinburg. [in Russian]

PUCHKOV, V.N. 2000. *Paleogeodynamics of the South and Middle Urals*. 146 pp. Dauria, Ufa. [in Russian]

SERAVKIN, I.B., KOSAREV, A.M., SALIKHOV, D.N., ZNAMENSKYI, S.E., RODICHEVA, Z.I., RYKUS, M.V. & SNACHEV, V.I. 1992. *Volcanism of the South Urals*. 197 pp. Nauka, Moscow. [in Russian]

sine 1990. *Decision of Interdepartmental Regional Stratigraphic Conference on the Middle and Upper Palaeozoic Russian Platform with the Regional stratigraphic schemes. The Devonian System*. VSEGEI (Russian Geological Research Institute), Leningrad.

sine 1998. *Legend for the South Uralian series of plane-table maps, the Russian Federation State geological maps in 1 : 200 000 scale (the second edition).* VSEGEI (Russian Geological Research Institute), St. Petersburg.

SMIRNOV, G.A. & SMIRNOVA, T.A. 1961. *Research materials on the paleogeography of the Urals. Famennian 3*. 85 pp. Ural Branch, Academy of Sciences of the USSR, Sverdlovsk. [in Russian]

TCHIBRIKOVA, E.V. 1977. *Stratigraphy of the Devonian and Older Paleozoic Deposits of the South Urals and Pre-Uralian Region (by Plant Microfossils).* 160 pp. Nauka, Moscow. [in Russian]

TYAZSHEVA, A.P., ZSHAVORONKOVA, R.A. & GARIFULLINA, A.A. 1976. *The Lower Devonian Corals and Brachiopods in the South Urals.* 228 pp. Nauka, Moscow. [in Russian]

VEIMARN, A.B., NAIDIN, D.P., KOPAEVICH, L.F., ALEXEEV, A.S. & NAZAROV, M.A. 1998. *Analysis of global catastrophic events under detailed stratigraphic investigations*. 190 pp. Moscow State University Publishing House, Moscow. [in Russian]

WALLISER, O.H. 1986. Towards a more critical approach to bio-events, 5–16. *In* WALLISER, O.H. (ed.) *Global bio-events, Lecture Notes in Earth Sciences 8*. Springer Verlag, Berlin & Heidelberg.

WALLISER, O.H. 1996. Global events in the Devonian and Carboniferous, 225–250. *In* WALLISER, O.H. (ed.) *Global Events and Event Stratigraphy in the Phanerozoic*. Springer Verlag, Berlin.

YAKUPOV, R.R., MAVRINSKAYA, T.M. & ABRAMOVA, A.N. 2002. *Palaeontological basis of the stratigraphical Palaeozoic scheme in the North-Zilair Megasynclinorium.* 158 pp. Institute of Geology, Ufa Scientific Center, Russian Academy of Sciences, Yekaterinburg. [in Russian]

YUNUSOV, M.A., MASAGUTOV, R.K., ARKHIPOVA, V.V. & YUNUSOVA, G.M. 1997. Devonian sea-level changes in the platform region of Bashkortostan. *Courier Forschungsinstitut Senckenberg 199,* 65–73.

ZONENSHAIN, L.P., KORINEVSKY, V.G., KAZMIN, V.G., SOROKHTIN, O.G., KOPOTEEV, V.A., MASLOV, V.A., ZAIKOV, V.V., RUDNIK, G.B., KASHINTSEV, G.L., MATVEENKOV, V.V., KHAIN, V.V., ZAIKOVA, E.V. & KABANOVA, L.Y. 1984. Structure and plate tectonic evolution of the South Urals, 6–56. *In* ZONENSHAIN, L.P & MATVEENKOV, V.V. (eds) *Evolution of the Uralian Paleocean*. Institute of Geology, Academy of Sciences of the USSR, Moscow. [in Russian]