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Thirty years of the first international stratotype: The Silurian-Devonian boundary at Klonk and its present status

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The first international stratotype, selected according to modern stratigraphic principles, is the section with the Silurian-Devonian boundary at Klonk in the Barrandian area, Czech Republic. Its approval at the XXIV IGC in Montreal, 1972 deeply influenced the further development of stratigraphic principles and praxis in achieving an objective base for definition of global chronostratigraphic units, later followed in establishments of GSSP in different parts of the global stratigraphic column. The procedure of the establishment, present status and correlative value of the Silurian-Devonian boundary stratotype are reviewed, confirming the suitability of its selection.

Introduction and history

In August 2002 we commemorated the official acceptance of the first global stratotype, i.e. the stratotype of the Silurian-Devonian boundary at Klonk near Suchomasty (central part of the Czech Republic). This decision, accepted by the International Commission on Stratigraphy (ICS) and the International Union of Geological Sciences (IUGS), was based on the Final Report of the Committee on the Silurian-Devonian Boundary presented at the 24th International Geological Congress in Montreal, 1972.

The decision on the stratotype (in the present nomenclature the Global Stratotype Section and Point—GSSP) was preceded by almost 12 years of intense work of the Committee on the Silurian-Devonian Boundary, whose first chairman was Prof. H. K. Erben (Germany), and the second, the admirably efficient Dr. D. J. McLaren, the director of the Canadian Geological Survey.

Activities of the Committee were summarized by McLaren (1977). The work of the Committee, however, had a long preceding background, as the problem of the Silurian-Devonian boundary had been topical since the second half of the 19th century. It is known in the literature as "The Hercynian Question", in which many outstanding geologists and palaeontologists of the 19th century took part, e.g. E. Kayser, J. Barrande, Ch. Barrois, J. M. Clarke, F. Frech, O. Novák, F. N. Tchernyshev, A.O.

New discoveries in different parts of the world at the beginning of fifties of the 20th century (especially the occurrence of "Silurian" and "Devonian" fossils in the same beds), revived the complex problem of the S-D boundary. This was reflected particularly by organizing two international Symposia (first in Prague, 1958, second in Bonn and Bruxelles, 1960), from which initiative the Committee on the Silurian-Devonian Boundary was established at the 21st International Geological Congress in Copenhagen (1960).

The Committee evolved a great activity. Whilst up to 1964 new results of investigation were concentrated in Circulars, since 1965 it became clear that direct visits and inspections of relevant regions and concrete sections are necessary. These were started in 1966 when diverse European regions were visited and the Chairman, Prof. Erben, achieved a broad collaboration with different working groups around the world and official bodies, namely the International Commission on Stratigraphy and the International Union of Geological Sciences.

A marked progress was reached at the International Symposium on the Devonian System held in Calgary, Alberta, 1967, where the majority of members of the Committee accepted the proposal to define the S-D boundary at the base of the *Monograptus uniformis* graptolite Zone, which was later confirmed by the preliminary ballot votes (25 Committee members in favour from the total number 32).

In 1968 D. J. McLaren, after resignation of Prof. Erben, accepted the chairmanship of the Committee and evolved his fruitful activities. The Third International Symposium on the Silurian-Devonian Boundary and Stratigraphy held in Leningrad in 1968 and connected with 6 meetings of the Committee and field-trips into different parts of the former Soviet Union, summarized the progress. At the 23rd International Geological Congress in Prague, on August 22, two proposals were made, namely to choose the S-D boundary in relation to the base of the *Monograptus uniformis* Zone, and to prepare preliminary submissions for the candidate stratotypes and horizons.

Between 1969 and 1971, 16 submissions were received for the following areas: Barrandian (Czechoslovakia), Royal Creek, Yukon Territory (Canada), Podolia and Tien Shan (USSR), Carnic Alps (Austria, Italy), Holy Cross Mts. (Poland), Algerian Sahara, Aragon (Spain), Roberts Mts., Nevada (USA), Gaspé, Québec and Canadian Arctic Archipelago, Australia, Rabat-Tiflet (Morocco), and North-west Thailand.

In 1970 and 1971 inspection field trips and meetings of the Committee were realized into most promissible candidate stratotypes (Roberts Mountains, Nevada, Barrandian, Morocco). In this time, the Barrandian area offered 14 sections of the S-D boundary studied in detail in different facies (see Chlupáč et al. 1972). After an extensive discussion and evaluation of all aspects and requirements on stratotypes, the final agreement was achieved and summarized into recommendation presented by D. J. McLaren at the 24. International Geological Congress in Montreal, 1972.

The recommendation (shortened version) stated that: 1. The Barrandian area in Czechoslovakia should be chosen as the type area of the physical definition of the Silurian-Devonian boundary. 2. The section at Klonk near Suchomasty is recommended as the type section (boundary stratotype) in which the selected physical horizon shall be defined. The Budňany Rock near Karlštejn serves as an auxiliary type section yielding supplementary palaeontological information. 4. The boundary horizon in the section at Klonk shall be defined within the Bed No. 20 immediately below the sudden occurrence of *Monograptus uniformis* and *M. uniformis angustidens* (description of the section in Geol. Newsletter 1969 and Chlupáč et al. 1972).

The Commission on Stratigraphy accepted the recommendation on August 23, 1972, the IUGS did the same on August 26 (details of the whole procedure see the final report by D. J. McLaren in A. Martinsson, ed.: *The Silurian-Devonian Boundary*, 1977).

The Klonk stratotype

The Klonk section is situated NE of the village Suchomasty, about 7 km S of the town Beroun, 40 km SW of Prague. From the regional geologic view it belongs to the central part of the Barrandian area where the closure of flat Silurian and Devonian synclinal structures is well expressed and observable further towards the SW in the Ordovician strata.

The stratotype itself is a large natural exposure of escarpment type. It consists of a well bedded uppermost Silurian (Přídolien) and lowermost Devonian (Lochkovian) sequence formed by the alternation of fine-grained, mostly dark grey limestone layers and dark calcareous shale layers (see Figures 1-7). The sequence shows a clear high-frequency cyclicity. The shales evidently represent the background sediment formed during longer time intervals, the limestones shorter intervals with more intense carbonate deposition. The differences in the two lithologies are partly reflected in the fossil content: the shale layers contain more common remains of planktonic and nektonic organisms (graptolites, nautiloids etc.), whereas the limestone layers are richer in benthos (bivalves, gastropods, trilobites etc.), though the differences are not very sharp, and, e.g.

Figure 1 The steep slope of Klonk viewed from the W and the marble monument explaining its significance (right). The Silurian-Devonian boundary is indicated by a white line.

Figure 2 The relevant part of the exposure at Klonk with the Silurian-Devonian GSSP (white line in the middle). Helicopter view from a distance about 80 m.

Figure 3 The proper Silurian-Devonian boundary interval at Klonk with the Silurian-Devonian boundary bed No. 20, the Bed 21 with the first *Warburgella rugulosa rugulosa* indicated by W.

cephalopods, graptolites, phyllocarids and pelagic crinoids are present in both types of rocks. At the boundary proper, no marked change in lithology is observable.

The wider boundary interval at Klonk was described particularly by Chlupáč et al. (1972), Chlupáč and Kukal (1977), Hladil (1991, 1992), Kříž (1992), Chlupáč and Hladil (2000) and in diverse special papers. It was also incorporated into many Guidebooks of symposia, conferences and excursions dealing with variable geoscience problems. After the inspection of the Silurian-Devonian Boundary Committee in 1970, the Subcommittee on Devonian Stratigraphy visited Klonk in 1977, 1986 and its part in 2001, the Subcommittee on Silurian Stratigraphy in 1992. The average number of visits by groups or individual foreign specialists currently ranges around 3 to 6 yearly.

The status of investigations

The establishment of the stratotype and its approval were important but not the last steps. The role of the stratotype as the international standard should be further analyzed using different methods to increase its correlation potential. The following are some topics studied during the last 30 years after the stratotype approval and serving this purpose.

Significant palaeontologic and biostratigraphic works were concentrated on microfossils, namely conodonts (Jeppson 1988, 1989 - the Silurian part, M. A. Murphy, P. Carls, J. I. Valenzuela-Ríos in progress), chitinozoans (Paris et al. 1981—particularly important results supplementing the boundary correlation potential, comp. also Brocke et al. 2002), ostracods (Krůta 1986, 1990, Hansch 1993), microvertebrates (Märss 1997—preliminary results), spores and other palynomorphs (J. B. Richardson—personal communication, studies by other authors in progress).

The works on macrofossils markedly progressed not only in the study of Klonk, but also of the auxiliary stratotype at Karlštejn-Budňanská skála, and other reference sections in the Barrandian. This concerns, particularly, the assemblages of trilobites (Chlupáč 1983, 1987), graptolites (H. Jaeger 1977), bivalves (Kříž 1999), brachiopods and combined communities (Havlíček and Štorch 1990,

Figure 4 The Silurian-Devonian boundary interval at Klonk. Occurrences of selected fossils (after Chlupáč et al. 1972 and other authors) and simplified distribution of microfacies (after Hladil 1991). Lithology: 1—dark grey micritic and biomictic limestones, 2—fine-grained and lighter bioclastic limestones, 3—coarser biomictic and bioclastic limestones, 4—dark grey calcareous shales and clayey limestones. Microfacies (generalized intervals, not individual occurrences): A—hemipelagic laminites with muellerisphaerids, B—current laminites with nautiloids, C—bioclastic accumulations washed out of micrite, D—graptolite-bearing shales, E—spiculites, F—muddy limestones with nondepositional and erosional surfaces.

1999), nautiloids (Manda 2001, combined: Kříž 1998), phyllocarids (Chlupáč 1994a). All these studies showed concordant results documenting the suitability and easy recognition of the S-D boundary defined 30 years ago.

The first results of sedimentological research at Klonk were published in papers by Chlupáč and Kukul (1977) and Davies and MacQueen (1977). The first authors interpreted the sediments of the boundary interval as deposits of pelagic open-sea environment, but in an area not too distant from land (e.g. within the reach of fine-grained terrigenous supply), the depth of the basin was estimated at several tens to several hundreds of metres below the wave base, but with influences of periodical strong bottom traction currents. Davies and MacQueen (1977) regarded the boundary bed No. 20 according to its textures as distal turbidite. The lower coarser-grained parallel laminated part of this bed would correspond to Bouma Division B, the upper part consists of ripple-bedded fine-grained limestone (Bouma Division C) and the uppermost part with parallel lamination corresponding to Bouma Division D.

According to Hladil (1991, 1992) the coarse grains of the lower part are not primary, but originated by diagenetic recrystallization of lime mud. He has accepted turbidite origin only for several beds in the upper part of the Přídolí (= Požárý) Formation, but it is possible

Figure 5 The Silurian-Devonian boundary interval, the detailed lithologic scheme. According to the trench excavated in 2002 in proximity of the original excavation published in 1972, 1977. Lateral changes of biotrital input within some beds are demonstrable. 1—dark grey calcareous shales, 2—dark grey platy micritic to biomictic limestones (wackestones to packstones) largely with parallel lamination, 3—unsorted fine-grained bioclastic limestones (packstones to grainstones), 4—unsorted coarse-grained bioclastic limestones (grainstones).

that the material of former turbidites was reworked by subsequent bottom traction currents. According to Hladil the base of the Devonian part of the Bed 20 represents a semi-lithified surface with a break in deposition possibly lasting several hundreds of years and with the change of direction of bottom currents. Discussion of some taphonomic problems (Hladil and Beroušek, 1992) indicated the environment of passive continental margin.

The rate of sedimentation was estimated at about 20 m per million years (Chlupáč and Hladil 2000). The high-frequency cyclicity, expressed by couplets of dark limestones and calcareous shales (104 in the Lower Lochkovian part of the Klonk section) was calculated by Chlupáč (2000). He estimated the duration of one couplet to 17 000 to 21 000 years under the presumption that the bedding couplets reflect periodical changes, possibly influenced by earth-axis precession.

Further laboratory studies are in progress, as the team of workers organized by the University of Jülich (Germany) realized in 1999 a 57.3 m deep drilling Klonk 1 just behind the slope of Klonk to gain unweathered samples of rocks for geochemical and other studies (preliminary report in Mann et al. 2001).

A geophysical magnetostratigraphic study of Klonk, made by Crick, Ellwood et al. (2001), showed a correlatable curve representing three magnetostratigraphic zones and numerous subzones within the boundary interval correlated with SE Morocco. Klonk was also sampled by several authors for palaeomagnetic studies but the results have not yet been published.

Geochemical studies are in progress, data on the carbon and oxygen isotope record were published (Hladíková et al. 1997) as well as some results from the boring (Mann et al. 2001).

Recognition of the boundary

The main results of investigations useful for practical identification of the S-D boundary (based on the study of Klonk and other reference sections), made after 1972, can be summarized as follows:

1. The S-D boundary as defined in 1972 represents a global bioevent easily recognizable in different faunal groups:

2. Graptolites. The significance of the onset of *Monograptus uniformis* (including subspecies *uniformis uniformis* and *uniformis angustidens*), and the last Silurian zonal index *Monograptus transgrediens* was confirmed.

3. Trilobites. The onset of the proetid *Wurgella rugulosa* and its subspecies of global distribution, and accompanying forms (in the Barrandian particularly *Tropidocare index*, *Ceratocephala lochkoviana* etc.) are suitable means for recognition of the Lochkovian base. An another related proetid—*Tetinia minuta* is the index of the critically uppermost Silurian strata, just before the onset of *W. rugulosa* group. However, *T. minuta* is common and limited to the shallow-water bioclastic limestones and so far known only from the Barrandian. The important and easily recognizable Silurian genus *Prionopeltis* does not pass the S-D boundary.

4. Chitinozoa. The onset of *Angochitina chlupaci* at the S-D boundary is a good marker. Occurrences of *Desmochitina urna*, *Ligonochitina klonkensis* a.o. in the uppermost Silurian part of different sections can facilitate the correlation. The maximum occurrence of *Calpichitina annulata* falls close to the S-D boundary in the Barrandian (Paris et al. 1981, Brocke et al. 2002).

5. Conodonts. The S-D boundary falls within the lower part of the *Icriodus woschmidt* Zone, above the *Ozarkodina eosteinhornensis* Zone. The (Sub)Zone *Oulodus elegans detortus* characterizes the critically uppermost Silurian according to Jeppson (1988, 1989). Further exact studies are in progress.

6. The bivalves of the uppermost Přídolian are characterized by the *Snoopya* Community Group (still with the index *Cardiola*-like genus *Cardiolinka*), whereas the lowest Lochkovian is marked by the onset of the *Antipleura-Hercynella* Community Group (Kříž 1999) with many new elements, not limited to the Barrandian (*Silurina* seems to be particularly typical).

7. Nautiloid cephalopods markedly reflect the bioevent at the S-D boundary: the most characteristic and common Přídolian orthoconic nautiloid *Orthocycloceras fluminese* became extinct together with the genera *Cumingoceras*, *Corbuloceras* and the representatives of the orders Ascocerida, suborder Tarphicerina and families Mandaloceratidae, Hemiphragmocerotidae etc. At the base of the Lochkovian, the lineages of otherwise Silurian genera continue in their development, such as *Plagistomoceras*, *Pseudocycloceras*, *Parakionoceras*, *Projovalania* etc., a new immigrant being *Endoplectoceras* (Manda 2001).

8. Brachiopods. The most typical Přídolian brachiopod *Dayia bohémica*, occurs in masses in shallow-water bioclastic limestones but overlaps into other facies also (found even at Klonk below the Bed 20). The Lochkovian base is marked by increase of brachiopod diversity—*Plectodonta mimica*, *Glossoleptaena emarginata*, *Linguopugnoides carena* a.o., which are common in the basal facies. The Lower Lochkovian brachiopod assemblage in the shallow-water bioclastic facies (the Kotýs Limestone) is still markedly richer (large strophomenids—*Barbaestrophia*, *Quasistrophonella*, *Protocy-*

Figure 6 Members of the Subcommittee on Devonian Stratigraphy and some guests taking part in the field conference and establishment of the monument below Klonk in 1977. SDS members from the left: G. M. Philip (Australia), P. Carls (Germany), D. C. McGregor (Canada), J. L. García-Alcalde (Spain), H.P. Schönlaub (Austria, before). A. W. Norris (Canada), H. Lardeux (France), T. Mizens (USSR), A. E. H. Pedder (UK), I. Chlupáč (Czech.), P. Sartenaer (Belgium), D. Brice (France), H. Hollard (Morocco), R. J. Prokop (Czech., in background), P. Bultynck (Belgium), V. Turek (Czech, in background), W. Ziegler (Germany), A. Galle (Czech, in background), W. A. Oliver (USA), E. A. Yolkin (USSR), J. I. Tesakov (USSR), M. Szulczewski (Poland), J. A. Talent (Australia).

mostrophia a. o., specific rhynchonellids, spiriferids etc., see Havlíček and Štorch 1990, 1999).

9. Crinoids. The broader S-D boundary interval is characterized by maximum development of the large pelagic camerate *Scyphocrinites* and closely related genera (*Carolicrinus*, *Marhuocrinus*). Though the first occurrences fall already in the Lower Přídolian, the mass development is clearly concentrated in the uppermost Přídolian *Monograptus transgrediens* Zone and in the few first

Figure 7 Some members of the Silurian-Devonian Boundary Committee at the section Čertovy schody near Suchomasty in 1970. From the left: J. Marek (Czech.), P. Sartenaer (Belgium), D. J. McLaren (Canada), W. Ziegler (Germany), A. Martinsson (Sweden, right in foreground).

metres of the Lochkovian (here accompanied by *Monograptus uniformis* and the *Warburgella rugulosa* group). The easy recognition of *Scyphocrinites* (and related genera, e.g. *Carolicrinus*, see Prokop and Petr 1986) with characteristic columnals and swimming organs (loboliths) is a good guide for the identification of the proximity of the S-D boundary.

10. Some other groups. The common phyllocarid crustacean *Ceratiocaris (Bohemiacaris) bohémica* can be used as the Upper Silurian (particularly Přídolí) index, whilst *Ceratiocaris cornwallensis damesi* is typical for the lowest Devonian (Lochkovian), being accompanied by arizoids in different sections. The evolution of pterygotid eurypterids, namely *Acutiramus*, was not interrupted by the S-D boundary bioevent and the Lochkovian *Acutiramus perneri* can be regarded as a direct descendant of the index Upper Silurian *Acutiramus bohemicus* occurring in the same facies realm (Chlupáč 1994b). The land plant *Cooksonia* overlaps the boundary as proved even at Klonk.

Evidently, the increasing knowledge of the broader boundary interval at Klonk and at other localities and areas adds to the number of auxiliary criteria for boundary recognition. The role of auxiliary biostratigraphic and other indicators cannot be underestimated, as just these data markedly increase the practical suitability of the chosen limit.

Remark. In the Final Report of the Subcommittee on Devonian Stratigraphy summarizing the results of the Subcommittee work for the last 30 years (Courier Forschungsinstitut Senckenberg, vol. 225, 2000) all text figures including the biostratigraphic scheme of fossil distribution at Klonk in the article on the S-D boundary were changed from another article causing thus a bad confusion (the correction was made only in separate reprints with limited circulation). Therefore, we illustrate here the correct scheme of the S-D boundary interval at Klonk with some new additions (Figure 4).

Conclusion

Klonk became a worldwide known locality and in 1977 a marble monument was established below the steep cliff that includes the natural outcrop proper. The Klonk section is protected by law as a National Nature Monument, where any destructions of the sequence are prohibited. It also belongs to the wider protected region named the "Bohemian Karst" which covers, together with the protected areas at the territory of Prague, all the most important outcrops of Silurian and Devonian strata in the central part of the Barrandian area.

The basic significance of Klonk, however, is not only the standardization of the Silurian-Devonian boundary. The main result and lesson is that the establishment of this first international stratotype influenced progress in stratigraphy and the thinking of geologists. It documented the practical usefulness of the stratotype principle (or GSSP) for concrete and unambiguous definition of global stratigraphic units, necessary for wide correlations and understanding within the geologic community. It tested the procedures and requirements necessary for the establishment of global stratotypes (GSSP), for which the procedure followed in the S-D boundary selection became not only recommended, but the generally followed example (see the International Stratigraphic Guide (Hedberg, ed. 1976, Salvador, ed. 1994), ICS Guidelines and Statutes (Cowie et al. 1986, Remane 1975, Remane et al. 1996). Other stratotypes and boundary intervals within the Phanerozoic are receiving similar attention.

Acknowledgements

For critical reading the manuscript and valuable advices the authors are indebted to Prof. Dr. W. A. Oliver, Jr. (U.S. Geological Survey and Smithsonian Institution, Washington) and Doc. Dr. Z. Kukal (Czech Geological Survey, Prague).

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