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THE DYNAMIC TIME-WARPING APPROACH TO COMPARISON OF MAGNETIC-SUSCEPTIBILITY LOGS AND APPLICATION TO LOWER DEVONIAN CALCITURBIDITES (PRAGUE SYNFORM, BOHEMIAN MASSIF)

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(9 figures)

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ABSTRACT. The effectiveness of alignment of magnetic susceptibility (MS) stratigraphic sections by means of the dynamic time warping (DTW) approach was tested with positive results. The DTW is a robust and effective tool for the alignment of the sequential MS data which is particularly sensitive to MS-log patterns, their details, successions, distortion or absence from logs. Moreover, the DTW performance proved to be appropriate for sections which involve a great deal of irregularly spread compacted or thick-bedded intervals and variously positioned and sized gaps. In view of the fact that the lateral changes in short- to medium-term sedimentation rates and local variations in diagenetic compaction are not exceptional but rather common features of the compared sedimentary sections, the DTW becomes a significant tool for stratigraphic comparison of sections with good potential of becoming an alternative to cyclostratigraphic correlation methods. Conditions governing the formation of Lower Devonian (Pragian) carbonate clinoforms obviously appear to be this case, and testing of the DTW on this type of MS sections suggests that the computationally robust results remain approximately the same, even if the importance of high values (peaks) is nonlinearly decreased or increased. In such cases the DTW outperforms the distortion-based vector quantisation (VQ), continuous density hidden Markov models (CDHMM), wavelet transformation (WT) or cross-correlation (CC) based approaches. The near absence of artificially introduced preconditions or predefined elements is also an advantage. The alignment of the sections using the DTW gives us warning about distorted intervals, thus reducing the risk of assembling quite different types of rhythmic patterns or cycles together. The overall ambition of this paper is to introduce the DTW alignment technique as an effective tool for MS log correlation. Extensive testing of the requirements for input data and constraints according to maximum differences between the compared stratigraphic segments are reserved for other studies. For the Pragian of the Barrandian area (specifically, calciturbidite-dominated clinoforms), the DTW-based interconnection between the relevant points of two sections has a resolution which is close to sampling distances (several cm) and is about two orders of magnitude higher compared to that which can be achieved by the bio-, chemo- or lithostratigraphic tools. The first results confirmed the presence of numerous visible and hidden gaps and condensations in the sections.

KEYWORDS: Dynamic time warping, geophysical log correlation, magnetic susceptibility, Lower Devonian, Barrandian area.

1. Introduction

Since the 1990s, detailed studies on climatically-driven fluctuations of magnetic susceptibility (MS) in stratigraphic sections have been rapidly growing in number. The same trend continues in the Palaeozoic MS studies (e.g., Ellwood et al., 2009; Da Silva et al., 2009; Hladil et al., 2009) where particularly the carbonate rocks are in the centre of attention. In this case, the application principles for MS techniques follow the basic presumptions that the pure carbonate rock material is a weakly diamagnetic medium where the delivered and diagenetically modified background sediment components can be detected. Although the interregional spread of coeval fluctuations of non-carbonate, iron-rich components is traditionally seen as offering a good example of eustatic and palaeogeographic control (Ellwood et al., 2000), there is also a very significant material link to interregional dispersal of the finest weathering products which are primarily mediated by atmospheric mineral dust and aerosols (Kukal, 1971; Elrick & Hinnov, 1996; Hladil et al., 2006).

These dust components are regularly enriched in iron (Waeles et al., 2007; Aumont et al., 2008; Tagliabue et al., 2009; Hladil et al., 2009), and are specifically related to the carbonate environments. In these environments, all other types of terrigenous flux are often reduced because the main carbonate factories are usually shallow-water places far from siliciclastic depocentres (Darwin, 1842; Dvorak, 1980; Leinfelder, 1997; Tcherepanov et al., 2010). In very rough terms, the related iron cycle and input are the principal prerequisites for both preserved and even diagenetically modified magnetic signals from the carbonate rocks.

The increased activity in acquisition, processing, understanding and comparison of the MS logs resulted in launching of a new international framework IGCP 580 which, however, may bring a real problem with the correlation of complicated MS records over large distances or between different facies successions in basins. The necessity to address this potential problem arose in the course of our most recent correlation studies (e.g. Boulvain et al., 2008 and this volume). This problem may be at least threefold, and relates to the overall feasibility, certainty and resolution of log correlation solutions (referred to the development and applications of commercial software packages in general), the nature of the facies (including sources, tectonic and climatic settings in the compared basins; e.g. Da Silva et al., 2009) and, finally, to the fact that the compared stratigraphic sections and MS logs are very probably much less regularly developed than usually admitted (hidden and irregular gaps and stratigraphic condensations in the sections, in general; e.g., Ager, 1973; Fryda et al., 2002; Westphal et al., 2008; Marton et al., 2010; Vacek et al., 2010). However, the problem of a complex and latently inherited irregularity in detailed stratigraphic logs seems to be often underestimated (e.g., Barthes et al., 1999; Lu et al., 2004). With the awareness of possible complications with a detailed comparison of geophysical logs, a search for an appropriate method to deal with such a degree of partly latent irregularity was started.

2. Problem description and suggested solution

The general concept of the correlation of laboratory-measured MS outcrop-logs as the current approach to the analysis of mainly pre-Cenozoic limestones has been developed since 1990s (Crick et al., 1997; Ellwood et al., 2009). This concept is based on massive sampling of a succession of strata with the shortest possible spacing of the samples (few cm) in a single 'vertical' succession. The samples are measured using high-sensitivity susceptibility bridges in laboratories (values are reported as mass-related MS; e.g. Crick et al., 2001; see also Hladil et al., 2006, 2009 for various aspects of sampling strategies and 'strengthening' of the primary input data).

Although we often recommend the use of non-preprocessed (not adapted) MS data which contain maximum information, there exist many well established procedures which modify the data sets before the MS stratigraphic correlation. For example, standardization of raw data has been recently suggested (Ellwood et al., 2009). Moreover, the data sets are often subject to cubic smoothing spline, which has theoretically been supposed to transform the detailed and often highly oscillating arrays of primary data into series 'with eliminated undesired noise' that may better approximate the main cyclic changes on the fluctuating MS magnitude. However, with presence of gaps or condensed intervals (or any distortions or changed features during sedimentation or diagenesis), such effort may also lead to artefacts where some cycles can be joined together or omitted. Using an almost unrealistic precondition about the existence of steady-state and very consistent sedimentary and diagenetic regimes, the attempts for Fourier transform analysis of the power and frequencies have frequently been made (e.g. Ellwood et al., 2007). The common arguments for the effectiveness and correctness of these techniques are twofold: First, the modified (cleaned) data sets are 'robust', and, secondly, the analysis is based on sections in sediments with no significant gaps, condensations or any latent distortions regarding the relationship between the scales of time and cumulated sediment thickness. The graphic correlation of two sections in XY-plots is used for the verification of the correspondence between the interpreted cyclic structures or that in combination with biostratigraphic zones. However, the techniques of cycle determination (some cycles can be merged together, some omitted; see above) and often imprecisely determinable and relatively wide biozones naturally lead to some misgivings about unequivocal conclusiveness of such proof (Slavik, 2004a, b; Slavik & Hladil, 2004; Hladil et al., 2009).

The concern that an unpredictable distortion may exist in the regularity of stratigraphic sections is not unwarranted. Strong irregularity implied by sedimentary dynamics (Ager, 1973) is an accepted fact in sedimentology today, and can be explicitly derived from any natural sequence stratigraphy sections (e.g. Loucks & Sarg, 1993; Belopolsky & Droxler, 2003; Zampetti et al., 2004), studies on long-term or high-frequency changes in sedimentary environments (e.g. Worsley & Davies, 1979; Schlager et al., 1998; Miall & Miall, 2004; Thomas & Ridd, 2004) or from the model results (e.g. Bitzer & Salas, 2002). Some of this irregularity is also due to complex feedbacks between astro-climatic control and biological and depositional processes. Sedimentary and biotic conditions form a mosaic which reflects the same physical controls in a different way (Wright & Burgess, 2005; Valentine & Jablonski, 1993). Moreover, the numbers of cycles are not comparable to Milankovitch bands. For example, there are carbonate settings which seem to be governed by strongly expressed millennial cycles (Elrick & Hinnov, 2007; Tucker et al., 2009). In this case, the ultimate control is rather seen in direct fluctuations of solar output (Tucker et al., op. cit.), and even this type of rhythms cannot be free of modifications by terrestrial feedbacks (Pap et al., 1994; Glassmeier et al., 2009). Some doubts about causes of varying solar irradiation exist also with long-term cycles (e.g. the role of interplanetary dust or processes in the Sun's interior; Hladil & Kalvoda, 1993; Filip, 1997; Muller & MacDonald, 1997; Berger, 1999; Foukal et al., 2006). Moreover, there is also much evidence for extraordinary local variability and selectivity in the recording of the Milankovitch rhythms (e.g. Prokoph & Thurow, 2000). And in the context of the increased degree of irregularity, also an old problem of autocyclicity versus allocyclicity is intensely revisited today (e.g. Burgess, 2006; Dennielou et al., 2006; Pomoni-Papaioannou, 2008).

Compared to depositional processes, the diagenetic distortion of time-to-thickness scales is perceived to a lesser degree, but there is also a significant experience with irregular shifts due to pressure-solution compaction (Tucker & Wright, 1990; Einsele & Ricken, 1991; Westphal et al., 2004, 2008; Westphal, 2006). A certain degree of irregularity, as a result of this selective diagenetic change, is inherent in all MS sections (Riedinger et al., 2005; Hayashida et al., 2007; Riquier et al., 2010), but this change seems to influence the gross results of MS correlation to a lesser degree than usually assumed (Hladil et al., 2006; Riquier et al., op. cit.).

All the above mentioned characteristics related to the nature of the MS record have a potential to increase the complexity of the record to a considerable degree. And this is particularly the case of dm–m (~10–100 kyr) resolution in distal parts of calciturbidite sequences. Consequently, the complex structure of the record must frequently be higher than any regular cyclic imprint. This determines our tendency to avoid any data reduction. Such conclusion is based on evidence from almost all MS logs from limestone sections where MS patterns (often specific or unique) are highly indicative of certain time intervals (e.g. Crick et al., 2001; Hladil et al., 2006; Nawrocki et al., 2008; Da Silva et al., 2009; Boulvain et al., 2008 and this volume), notwithstanding the fact that these patterns are preserved incompletely or with some distortion. The essential question is how to recognize and map in detail such an unknown biaxial distortion in the MS logs, i.e., the latent but not unimportant differences between positions at the time and thickness-related scales as well as varying expressions of MS amplitudes of the potentially occurring successive patterns. In very rough terms, we must consider that patterns may typically have different shapes and intensities, together with shifts forward or backward and a possible occurrence of missing or added parts of the record. Such problem is solved in the field of speech recognition, where we also deal with differently or imperfectly expressed words (patterns), together with irregularities in tempo, with missing and redundant segments, and so forth. Here, if we have a single-parameter record, the DTW method provides a most useful and efficient technique to analyse and compare the records. The field of speech recognition is not the only discipline where DTW has been used to solve the above described type of problem. Other examples relate to chromatogram evaluation in biochemistry (van Nederkassel et al., 2006; Christin et al., 2008), genetics (Tsiporkova & Boeva, 2007), physiological activity records in medical sciences (Tormene et al., 2009; Boucheham, 2010), as well as many other disciplines today. The DTW methods show also a potential to be developed for purposes of large-volume data, as indicated by the recent papers in the field of mining of sequential data (e.g., Capitani & Ciaccia, 2007; Al-Naymat, 2009).

This means that the DTW can certainly be viewed as an appropriate and applicable approach to the analysis of signals of this type, particularly for a detailed comparison of MS logs. However, only limited attempts has been made to employ the DTW in fields of geophysics and well-log correlation where rather the back-propagation neural-network and marker-based techniques prevail (Luhti & Bryant, 1997; Zoraster et al., 2004; Zoraster & Paruchuri, 2006; or commercial Petrel packages). Some approaches to the analysis of geophysical data may benefit from the DTW in combination with hidden Markov models (HMM), as the DTW-HMM-based pattern mining experiments have been recently developed by several teams (Hu et al., 2006; Chen et al., 2008). Therefore, the authors believe this is the first attempt to introduce the DTW approach in the analysis and comparison of MS logs.

3. The DTW – essentials of the method

Dynamic time warping (DTW) is an algorithm that allows finding an optimum match between two given numerical sequences (e.g. time-dependent series), where measuring of similarity between the sequences is sensitive to variation in speed and distortion or incomplete expression of the detected patterns. In this procedure, the sequences are warped non-linearly. This technique was primarily developed and applied in speech signal processing (Sakoe & Chiba, 1978; Rabiner & Juang, 1993). Much like all methods used in mathematical modelling, this method also has some obvious intrinsic restrictions which relate to the purpose and construction of the algorithm. One example of the restrictions imposed on the matching of the sequences is on the monotonicity of the mapping in the time dimension (monotone function is a function which preserves the given order). Moreover, DTW is particularly suited to matching sequences with missing information, provided there occur long enough segments for matching. The optimization process is performed using dynamic programming (Cormen et al., 1990).

Suppose we have two numerical sequences:

$A = a_1, a_2, ..., a_i, ..., a_I$ and

$B = b_1, b_2, ..., b_j, ..., b_J,$

where a_i is the i-th element of the sequence A and b_j is the j-th element of the sequence B. The length of the two sequences A and B can be different. The DTW algorithm searches in $i – j$ plain an optimal path given by a sequence of points:

$F = c_1, c_2, ..., c_k, ..., c_K,$

where $c_k = (i(k), j(k))$, and $k = 1, ..., K$.

K is the number of points of the sequence F. Sequence F can be considered to represent a function which approximately realizes a mapping from sequence A onto sequence B which minimizes their distances. This mapping function is called warping function. When there is no sequence difference this warping function coincides with the diagonal line $j = i$. It deviates further from the diagonal line as the sequences difference grows.

As a measure of the difference between two points a_i and b_j a distance:

$d(c) = d(i, j) = || a_i – b_j ||$

is employed between them. Then the weighted sum of distances of the warping function F becomes:

$$E(F) = \sum_{k=1}^{K} d(c(k)) \cdot w(k)$$

where $w(k)$ is a nonnegative weighting coefficient, which is introduced to allow that the $E(F)$ measure is a flexible characteristic (Sakoe & Chiba, 1978). $E(F)$ is a reasonable measure for goodness of warping function F. It attains its minimum value when the warping function F is determined optimally. Such an optimal warping function gives minimal global distance for all possible warping functions. We can write:

$$D(A,B) = \min_F \left[\frac{\sum_{k=1}^{K} d(c(k)) \cdot w(k)}{\sum_{k=1}^{K} w(k)} \right]$$

Denominator $\Sigma w(k)$ is employed to compensate for the effect of different numbers of points which form the given warping function.

In the parameter pattern alignment, several restrictive conditions are used for the warping function to fulfil a purpose and have desirable properties (* = geological or more common meaning):

1. Monotonic conditions. (* The given order is preserved, not going back in time; i.e., naturally, not to solve tectonic repetition, duplexes or bedding-parallel fault separate intervals with overturned beds.):

$i(k-1) \leq i(k)$ and $j(k-1) \leq j(k)$

2. Continuity conditions. (* All points are matched, each point of the 'correlated' MS logs must be considered and evaluated and, thus, no important features are lost.):

$i(k) - i(k-1) \leq 1$ and $j(k) - j(k-1) \leq 1$

3. Boundary condition. (* The beginning and terminal points of two compared segments are involved; in two-axis plot for aligned segments of logs the alignment path starts at the bottom left and ends at the top right. Remark – but even 'chronostratigraphically' incorrect setting of these points, e.g. to 10–20% length of the segment, cannot substantially change the results.):

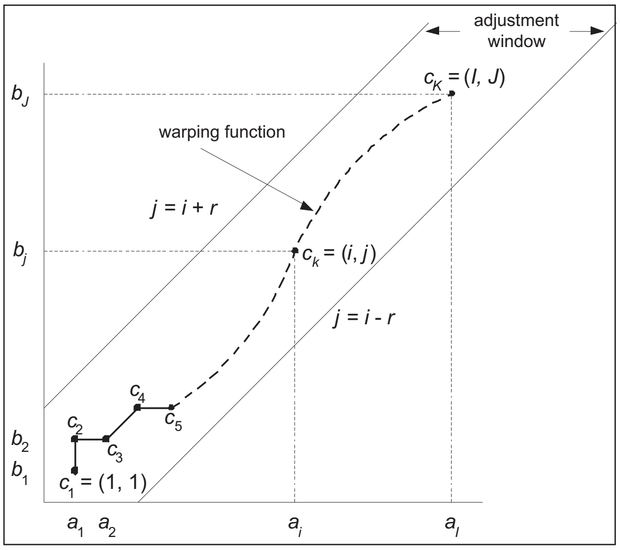


Figure 1. Warping function and adjustment window definition. Warping function (also known as "common time axis") maps metres of the compared section to metres of the reference section, so that the cumulative warping distance (cost) was a minimum one. The adjustment window puts restriction on how far can the warping function diverge from the linear function, i.e, how much 'distortion' is allowed to the compared section to match the reference one. The diagram illustrates the chapter on DTW method (see the text for the meaning of the symbols).

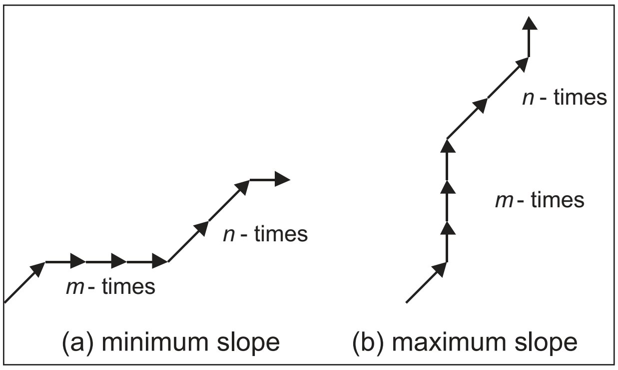


Figure 2. Slope constraint on the warping function. Warping function is usually not allowed to be either too steep or too flat, to obtain good results. Values of *m* and *n* define the acceptable "steepness" limits (see the The 'DTW – dynamic time warping' chapter for definition of these aspects).

$i(1) = 1, j(1) = 1$ and $i(K) = I, j(K) = J$

4. Adjustment window condition. (Fig. 1) (* A good alignment path cannot lie in 'extremely corner positions' of a two-axis plot for aligned logs; e.g., one of the compared logs must not represent only a small fragment of the other segment. This restriction, if not too narrow, mostly relates to stratigraphically preposterous data on input and also absurd solutions. Remark – the solution itself usually demonstrates whether the task is feasible or not, or which problems deserve some attention.):

$| i(k) - j(k) | \leq r$

5. Slope constraint condition. (Fig. 2) (* It prevents that unrealistically short parts within the sequences are 'successfully' matched to unrealistically long ones.)

Neither too steep nor too gentle a gradient should be allowed for the warping function F because such deviations may cause undesirable axis warping. The slope constraint is realized as a possible relation among several consecutive points on the warping function. To put it concretely if point $c(k)$ moves forward in the direction of i (or j) axis consecutive m times, then point $c(k)$ is not allowed to step further in the same direction before stepping at least n times in the diagonal direction.

The effective intensity of the slope constraint can be evaluated by the following measure:

$P = n/m.$

The larger the P measure, the more rigidly is the warping function slope restricted. When $P = 0$, there are no restrictions on the warping function slope. When $P = \infty$ (when $m = 0$) the warping function is restricted to diagonal line $j = i$.

In the dynamic time warping algorithm, the dynamic programming technique can be applied for the minimization of the global distance $D(A, B)$ (Cormen et al., 1990).

Initial condition:

$$g_1(c(1)) = d(c(1)) \cdot w(1)$$

Dynamic programming equation:

$$g_k(c(k)) = \min_{c(k-1)} \left[g_{k-1}(c(k-1)) + d(c(k)) \cdot w(k) \right]$$

Weighting coefficient can be calculated as:
$w(k) = (i(k) - i(k\text{-}1)) + (j(k) - j(k\text{-}1))$
The time-normalized distance is then:

$$D(A,B) = \frac{1}{N} g_K(c(K))$$

where $N = I + J$.

By realizing the restriction on the warping function described in previous sections several practical algorithms can be derived (Sakoe & Chiba, 1978). As one of the simplest examples, the algorithm in which no slope constraint is employed (that is $P = 0$) is following:

Initial condition:
$g(1, 1) = 2d(1, 1)$
Dynamic programming equation:

$$g(i,j) = \min \begin{bmatrix} g(i, j-1) + d(i,j) \\ g(i-1, j-1) + 2d(i,j) \\ g(i-1, j) + d(i,j) \end{bmatrix}$$

Calculation details can also be found in Sakoe & Chiba (1978).

In this work, the DTW with classical dynamic programming was used, as described above. For the purpose of this study, the DTW program used in speech processing was adapted and run by M. Vondra.

4. Regional geology and sections for testing the technique

The examined geological objects are located in central European Barrandian area. In Lower Devonian, the relevant basins were located between the Gondwanan and Laurussian continental margins and flooded by sea. This complex of basins is often referred to as the 'Prague basin' (see Gnoli, 2003 for relationships). Oceanic carbonate sedimentation prevailed, and limestones were resting on thinned parts of continental crust of peri-Gondwanan type which are understood to be a late stage of 'Perunica microcontinent' (palaeolatitudes ca. 20–10° S, drifting to the N, approaching southern Laurussia margin – e.g., Galle et al., 1995; Hladil & Bek, 1999; Strnad & Hladil, 2001; Fatka & Mergl, 2009). In geological structures of the Bohemian Massif, the relevant unit is Bohemicum (Tepla-Barrandian), and the fault-separated and folded belts of Lower Devonian limestones SW of Prague belong to different parts of the Upper Allochthon Unit of the Prague Synform (Melichar, 2004). The present distances between these belts are several times shorter than in the Early Devonian, mainly due to the Late Devonian (Frasnian) thrusting, slicing and folding of top-to-the-south shear sense (Melichar & Hladil, 1999; Melichar, op. cit.). In subsequent orogenic history, especially during the Famennian and Tournaisian, the sedimentary rocks passed through the burial-exhumation maximum temperatures which did not exceed 100–150 °C (Glasmacher et al., 2002; Suchy et al., 2002).

In this area, the correlation of Pragian carbonate facies is a long-lasting problem which requires constant effort and the utilization of several stratigraphical methods (Havlicek & Vanek, 1998; Slavik, 2004a; Budil et al., 2009). Therefore, we can primarily focus on these issues. In the Pragian, the rhythmically deposited, slightly clayey offshore limestones were associated with an oxygenated water column (Hladil et al., 2008). These are mostly calciturbidites and hemipelagites, but rarely also involve thin beds of materials deposited from other than turbidity bottom currents (Hladil et al., 1996; Vorel, 2006). Reefs or elevated open-sea swells with algae and subaerial type of lithification are absent from the sections we examined, although several islands and submarine highs must have existed on the palaeogeographical scale of tens of kilometres (Chlupac et al., 1998; Melichar & Hladil,

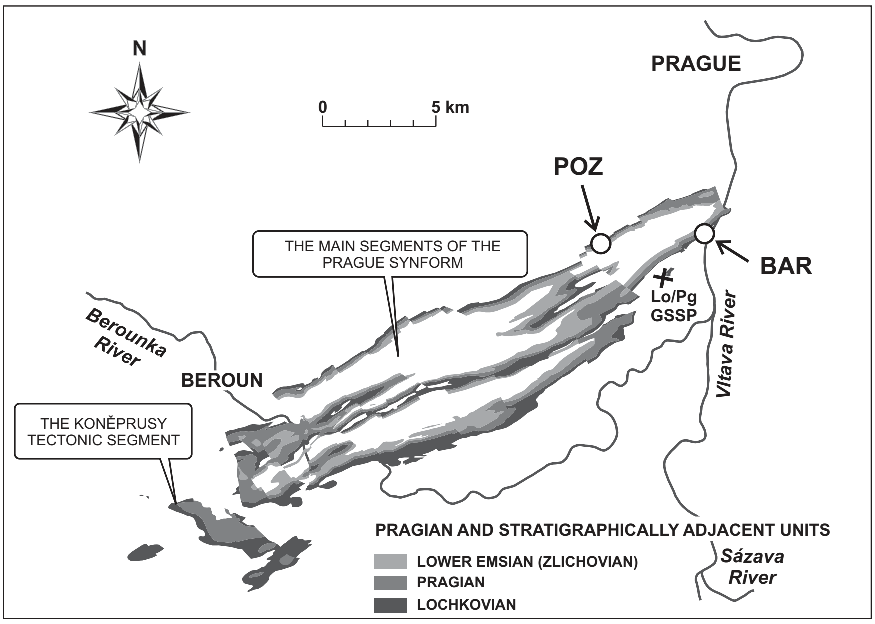


Figure 3. Location of the compared MS sections in the Lower Devonian sedimentary rocks of the Prague Synform, Barrandian area, on the SW periphery of Prague. POZ – stratigraphic section Pozar-3, BAR – Pod Barrandovem section. Note that the global stratigraphic section and point for the base of the Pragian stage (Lo/Pg GSSP, the Na Homolce section near Praha-Velka Chuchle) is located very close to the both POZ and BAR sections, although in a separate, tectonically controlled belt of outcrops.

1999; Strnad & Hladil, 2001). Distal offshore facies are predominant and typically contain very fine to medium silt-sized detrital muscovite with subordinate amounts of smectite-illite-mica SiO_2-depleted phases (usage as in van de Kamp, 2008), both dotted by ultra-fine Fe-oxide spots. Only the most proximal offshore facies in the lowermost parts of the Pragian are relatively pure limestones. Possibly the most obvious features are an elevated delivery of iron-rich dust from tropical NW of distant inner Laurussia (palynological and isotope-geochemistry evidence – Hladil & Bek, 1999; Janousek et al., 2000) and an elevated boring activity of microendolithic organisms (Mamet et al., 1997; Hladil, 2004). However, the $\delta^{18}O$ values on carbonate and apatite are slightly elevated (cooling in mixed oceanic water, or effect of salinity in basins separated by archipelagos? – Hladikova et al., 2000; Joachimski et al., 2009).

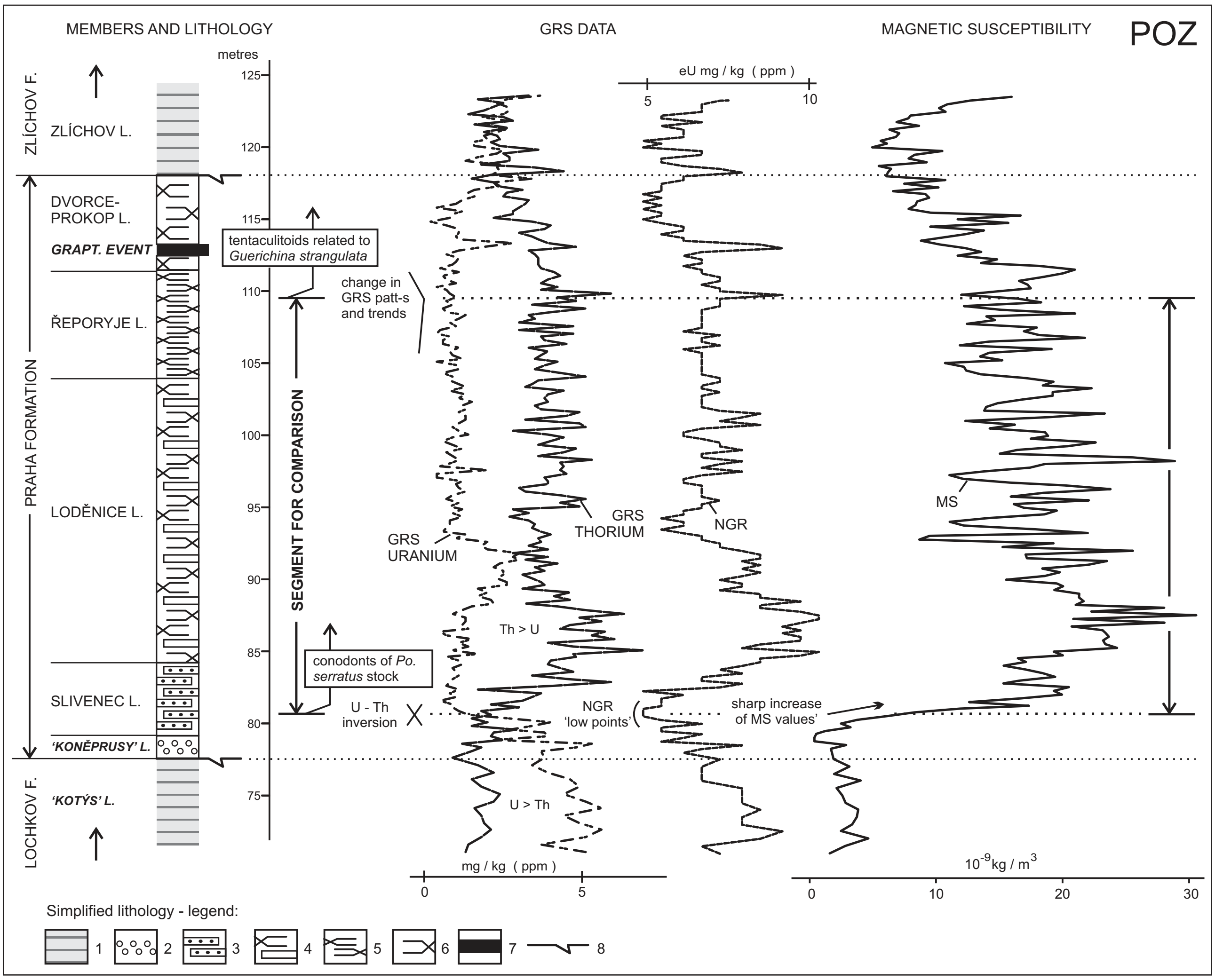


Figure 4. The Pozar-3 (POZ) section. The diagram shows the (chrono)segment of the MS log which was selected for comparison, together with the biostratigraphic and geophysical log markers for the beginning and end of this segment. This segment lies within the Praha Formation, thus comprising a major (inner) part of the originally established Pragian stage. Simplified lithologies (see explanations), largely calciturbidites alternating with proportionally thinner or eroded/recycled hemipelagites: 1 – peloidal and bioclastic packstones/grainstones, dark grey to medium grey limestones with cherts, alternating with interbedded black shales, planar beds, rare amalgamation of surfaces; 2 – grainstones/rudstones, coarse bioclastic, mostly crinoidal material deposited from medium to high-density flows, high-purity limestone of light grey or whitish colour, erosion surfaces; 3 – packstones/grainstones, grain- but also mud-supported rock types, mostly crinoidal, alternating with hemipelagic calcimuds, pinkish colour due to hematite and Fe-oxyhydroxides in altered spots and microborings in crinoid ossicles, fragments of trilobite carapaces etc.; 4 – calcisiltites, packstones, greatly varying rhytms of sedimentation and rock composition, lenticular, nodular, or flaser-bedded intervals but also thicker planar beds, varying colour (e.g., blackish, reddish, greenish; sharp or fuzzy-patchy transitions); irregular compaction and erosion features; 5 – calcimuds and calcisiltites, alternating and recycled tentaculitoid (dacryoconarid) ooze materials, rhythmically bedded, thin nodular beds, impure limestones of purplish-red colour, common periods of non-sedimentation; 6 – calcisiltites and packstones, elevated proportion of silt-sized carbonate-lithic particles, still predominance of dacryoconarids among skeletal components, thicker beds with undulated surfaces, alternating with laminated hemipelagites, medium grey to yellowish colour of rocks, common bioturbations of *Chondrites* and *Zoophycos* type; 7 – packstones with flaser bedding, usually 8 black shale interbeds, rare fragments of graptoloids in shale and limestone, dark grey colour of rocks, hardgrounds on the top of the individual limestone bed series, sporadically colonized by deep water corals; 8 – slight disconformity to unconformity (sequence boundary). Note that the Praha F. (~ originally defined Pragian stage) differs remarkably from the underlying and overlying units in the prevalence of Th over U and elevated MS values.

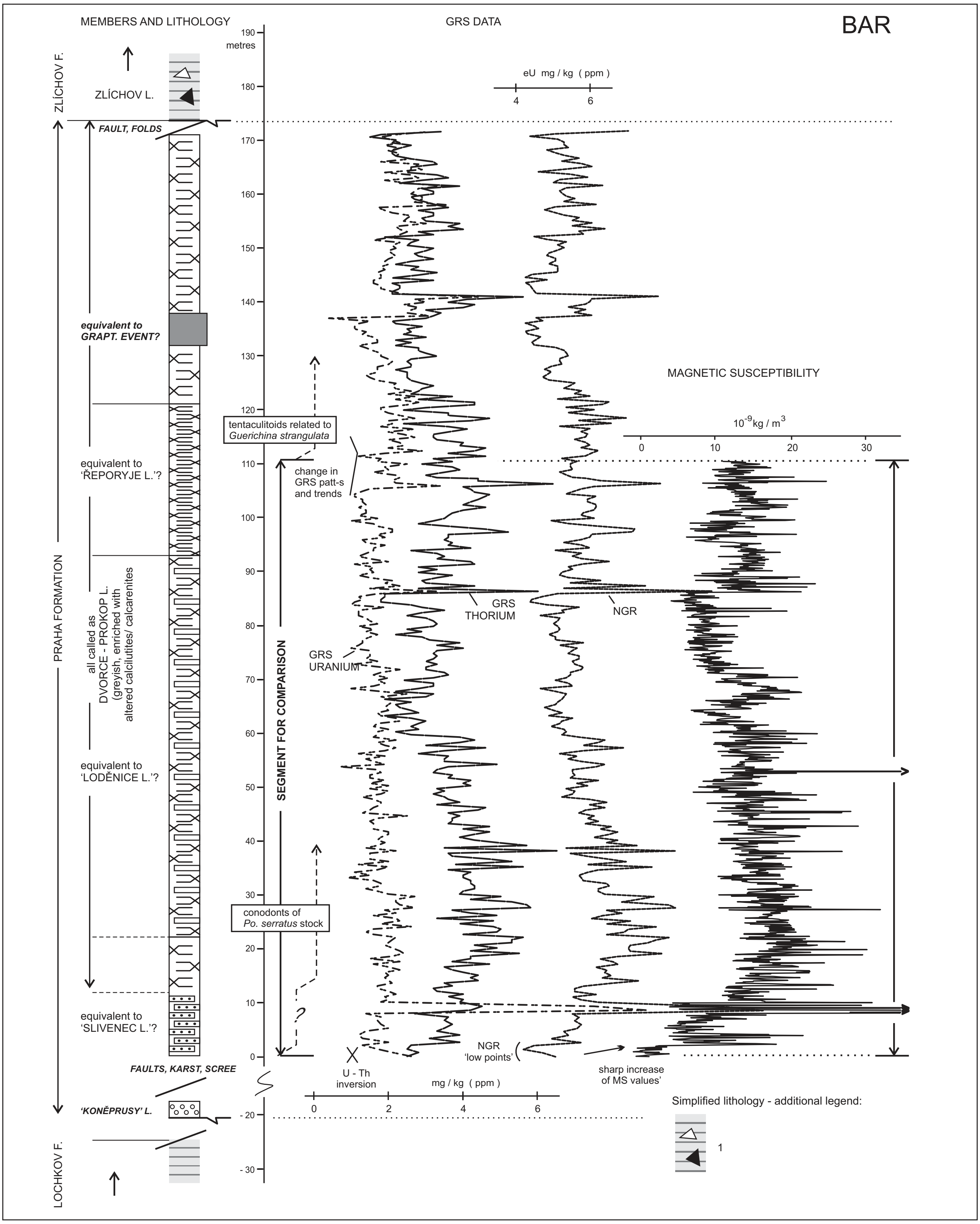


Figure 5. The Pod Barrandovem (BAR) section. The overall explanations are identical to those in Fig. 4, with two differences. First, the colour hues of all lithological types from the Slivenec to Zlichov Ls. are very slight, with prevailing medium grey tones, and second, these rock types generally show an elevated proportion of silt-sized carbonate-lithic component at the expense of the usually predominant dacryoconarid calcimuds. Also the Graptolite-Event interval is less distinctly visible. The dominance of grey, together with higher amount of additional silt- to fine sand-sized carbonate detritus (calcilutites/calcarenites, micropeloids, peloids, etc.), caused an incorporation of all these lithological types into the Dvorce-Prokop Mb. Additional explanations: 1 – channelized breccia flow deposits. Note that the total thickness of the Praha F. in BAR is higher than in POZ (ca. ×4.5), and also the compared (chrono)segment has a higher thickness (precisely ×3.873). The Lochkov and Zlichov Fs. are fault-separated, the former much more strongly than the latter. The Pragian rocks were a tectonically competent ramp during the eo-Variscan deformation, which left the stratal succession undisturbed.

The MS signal from these rocks is mostly controlled by the presence of paramagnetic phases which correspond to the above mentioned micas and other impurities in limestone of 'dust' origin (Hladil et al., 2008; Vacek et al., 2010), but the bacterially induced and often (internally) recrystallized hematites, iron oxyhydroxides or more or less oxidized pyrites are other major components that influence the general magnetic behaviour of these rocks (Schnabl et al., 2009; Koptikova et al., 2010). The amounts of detrital and diagenetic maghemite-magnetite are really small in the Pragian limestones (Schnabl et al., op. cit., Zwing, 2003), almost negligible compared to other Devonian limestones in the Prague Synform or in the world (e.g., Kukal, 1964; Kent, 1979; Krs et al., 2001; Grabowski & Nawrocki, 2001; Szaniawski, 2008; Riquier et al., 2010). Although the rocks were mostly remagnetized (remanence) during the Late Devonian deformation (burial depths of several kilometres) and display Carboniferous-Permian and even younger overprints (a few km or shallow subsurface), the moderate p/T conditions and slight hydrothermal or subsurface-weathering effects were of relatively low potency to change the MS record (slight, rare and mostly no phase changes – Zwing, op. cit.; Schnabl et al., op. cit., Koptikova et al., 2010). Only the pressure-solution compaction and processes in stylolites can be considered effective in this direction (Evans & Elmore, 2006), but these are concentrated in the finest and most condensed sediments which were even primarily rich in carriers of the MS signal.

Among tens of available sections in the 'traditional Pragian' (Chlupac et al., 1992: p. 167; Chlupac, 1993), two sections were selected for this purpose. These are Pozar-3 (POZ) and Pod Barrandovem (BAR) sections – Figs 3, 4 and 5. These sections were selected basically of five reasons. First, they provide some of the most complete stratigraphic records in the Pragian of the Prague Synform and the whole Barrandian area, as suggested by bio- and lithostratigraphic data (Chlupac et al., 1998) and the refined conodont biostratigraphy (Slavik, 2004a, b; Slavik et al., 2007). Secondly, these sections exemplify two different carbonate clinoforms (Melichar & Hladil, 1999) and the facies difference was even expressed by different lithostratigraphic members (Chlupac et al., 1998). Thirdly, an extraordinarily detailed documentation is available from these sections (e.g., systematic outcrop photographs with mm–cm resolution, rock sampling with several-centimetre steps, orientated thin sections and trace element analyses spaced in 0.X–X m scale, insoluble residues and MS–GRS logs), and this documentation makes the potential feedback between the DTW results and features of these two sections much more feasible than in any other outcrops (see Discussion in this paper). Fourthly, these systematically collected data have been published (Slavik et al., 2000, 2007; Koptikova et al., 2010) or processed for publication. And finally, the global stratotype section and point (GSSP) for the base of the Pragian is located just beside the sections (Chlupac et al., 1985; Chlupac & Oliver, 1989; Chlupac et al., 1998), which makes the stratigraphic linkage easier.

The POZ section (GPS coordinates of Lo/Pg point: 50° 01′ 40.26′′ N, 14° 19′ 37.60′′ E) (Figs 3 and 4) is typical for the entire northwestern limb of the Prague Synform. Described from the base to the top, this section consists of these following units, which are used in liberal terms as facies or rock types (Havlicek & Vanek, 1998) but also as formal stratigraphic members (Chlupac et al., 1998):

1) Whitish to pale-coloured, crinoidal 'Koneprusy Limestone'; an older, spatially separated and non-reef-type facies compared to the Koneprusy L. of the Koneprusy tectonic segment (see Havlicek & Vanek, 1998; Hladil, 1997 for lithologies and fauna); no microborings are filled with hematite.

2) Pinkish Slivenec Limestone. The 'Koneprusy' and Slivenec facies are rich in crinoidal limestones transported from the upper slope bathymetric zones. The main lithological differences are that calcimud-supported rocks are present and a lot of delicate microborings in the bioclasts of the latter facies were filled with hematite (Mamet et al., 1997; Hladil, 2004).

3) Variegated, greenish or blackish Lodenice Limestone, with a fining-upward trend, irregular bed geometries and chaotic rhythms in the successions of beds.

4) Reporyje Limestone – purple-coloured dacryoconarid-rich calcisiltites and muds; 'red beds'. Characteristic are symmetrical cycles which consist of very thin distal calciturbidites, hemipelagites and background pelagic sediment.

5) Dvorce-Prokop Limestone. In the northwestern limb of the Prague Synform, this member (or traditional lithotype – Chlupac et al., 1992, 1998; Havlicek & Vanek, 1998) is relatively thin, and was defined only for the upper part of the traditional Pragian succession of beds. The Graptolite Event (dark grey beds and black shales) splits this unit into two successions of the Lower and Upper Dvorce-Prokop Ls. This interval brings a considerably high stratigraphic potential for a global correlation of the Pragian-Emsian strata (Hladil et al., 1996; Hladil & Kalvoda, 1997).

A stripe of outcrops marked by the 'eye-catching' presence of all these members in the given succession (and Graptolite E.-interval of black shales!) occurs exclusively in or along this narrow tectonic belt of the NW limb of the Prague Synform (ca. 1 × 25 km), stretching WSW–ENE. Sedimentologically, these outcrops display a series of extremely wide and flat aprons, fans and lobes in a nearly transverse cross-section, and our data confirm the SSE- to SE-heading downslope sediment-transport trajectories (see also Chlupac, 1957; Hladil et al., 1996; Chlupac et al., 1998). The observed transverse continuity of some calciturbidite beds over 10–20 km implies a tectonic shortening by the factor ca. 1/10–1/20 (thrust faults and missing facies in NNW–SSE direction; Melichar & Hladil, 1999). The POZ section is located, therefore, in a different clinoform structure than other sections in this direction (BAR, and also Lo/Pg GSSP Na Homolce).

The BAR section (Lo/Pg-point-related GPS coordinates 50° 02´ 07.98´´ N, 14° 24´ 07.76´´ E; Figs 3 and 5) exposes the succession of the beds of the traditional Pragian in a thickness of ca. 180 m. An elevated thickness of calciturbidite beds is typical for SE limits of the NE tip of the Prague Synform. In spite of some similarities which are seen in faunal and lithological evolution in the Pragian between the POZ and BAR sections (Hladil et al., 1996; Chlupac et al., 1998; Slavik, 2004b; Slavik et al., 2007), almost the whole thickness of these limestones was assigned to the Dvorce-Prokop Limestone where the main characteristic for mapping geologists and stratigraphers was the colour of these rocks: it is mostly grey and yellowish-brownish on weathered surfaces with pressure-solution sutures (Chlupac et al., 1998). The high thickness and dominance of grey colour of rocks in the historically quarried outcrops of the BAR section have one common cause: these calciturbidites contain lots of calcimud and calcisiltite, fine-lithoclastic components which relate to cannibalization of an unknown middle/upper carbonate slope (unknown due to tectonics and erosion of the synform). These 'additional' components may represent about one half of the total mass of these rocks. The microfacies, rock fabrics, rhythms and architecture are indicative of an infill of a seafloor depression (sag) or a thicker accumulation in a steep lower slope/toe-of-the-slope zone (Slavik et al., 2000). Constraints on the correlation precision have been formulated for the biostratigraphy of the traditional Pragian stage worldwide, as well as the Barrandian area and particularly the BAR section. The lower and upper thirds are relatively well mapped and correlated in the light of the latest data (e.g., by conodonts – e.g., Slavik, 2004b; Slavik et al., 2007), whereas the middle part is usually problematic due to endemism, low abundance and diversity of conodont populations (Carls et al., 2008a, b). The same trend was generally observed for tentaculitoids, where biostratigraphic markers also exist in the lower and upper parts of the Pragian, but the middle part displays, for a long period of time, only the all-Pragian species *Nowakia acuaria* and rare endemics (Carls et al., opera cit.).

The selection of MS segments in POZ and BAR sections, to be compared by means of the DTW technique, follows the principles of the 'best biostratigraphic markers' and 'biostratigraphy-independent proof' (Figs 4 and 5). Both the POZ and BAR within-Pragian (chrono)segments were delimited in the same way. The base of the segments corresponds to first appearance data (FAD) of conodonts of *Polygnathus serratus* stock (Slavik et al., 2007 and refinement in the sections), and the upper end of the sections is set at FAD of tentaculitoids related to *Guerichina strangulata* (Carls et al., opera cit.). The former points correspond with a major reversal in Th/U ratios (a strong prevalence of Th replaced that of U), together with a minimum in the NGR values and a sharp increase in MS of rocks, and the latter points are linked to a change in GRS patterns and trends. This delimitation of the stratigraphic segments (BAR and POZ and vice versa) for DTW alignment of MS logs (G = correlation or comparison) has at least two advantages. First, it is the best determinable (chrono)segment at the given conditions and, secondly, this may considerably increase the resolution of the stratigraphic correlation in the middle part of traditional Pragian stage.

It is worth of noting here that the overall stratigraphy of the Pragian stage is a 30-years old problem, which has not yet been resolved to satisfaction of the stratigraphers. It is because of the fact that the present GSSP of the 'Emsian' base in the Zinzilban Gorge, Uzbekistan (Yolkin et al., 1997, 2000) points to an extremely low stratigraphic level, which is very deep in the traditional Pragian (Carls et al., 2008a, b). In the Barrandian area, it lies at, or closely below, the Slivenec/Lodenice Ls. transitions or 'time'-equivalent horizons (Fig. 5). For the preservation and further use of the Pragian stage, it is reasonable to consider moving the global GSSP higher up the section, where the boundary conforming with the traditional Czech Pragian and German Emsian must be elaborated at levels below, or at, the Graptolite E. Interval (Carls et al., opera cit.; or previous papers Kalvoda, 1995; Hladil et al., 1996; Hladil & Kalvoda, 1997).

MS data: Data for this study originate from the regular 5-cm sampling of the POZ section and 10-cm sampling in the BAR section; the POZ MS segment between 80.90 and 109.30 m consists of 569 samples and the BAR segment between 0 and 100.00 m contains 1101 samples. The sections were sampled by J. Hladil and L. Koptikova in 2004–2008, and the MS measurements on ca. 25-g samples of fresh rocks employed the KLY-2 bridge. In this case, the regular single-row data were used.

5. Results

If we use simple DTW algorithm with no slope restriction ($P = 0$), we obtain warping function as shown in Fig. 6. Although the absolute increments in thickness of strata measured perpendicular to bedding are lower for the POZ than for the BAR where the Pragian stratal succession is several times thicker (×3.873), the proportions of this limestone-column thickness change vary a lot. This variability, relative shortening or swelling, can be demonstrated by means of the calculation of the dynamic warping function on MS records. It is between two sections, where one of them may be apprehended as an 'unwarped standard' (or 'etalon') to which the second one is calculated, and the desired warping function is searched. Hence, we can compare POZ to BAR, or vice versa, BAR to POZ. The task is practically the same for both variants but a slight difference can be seen in the fact that the POZ to BAR variant is based on comparison with relatively more copious information in the BAR etalon, whereas the alignment, in geological terms understood as 'correlation' or comparison, of BAR to POZ provides a good resolution when visually inspected in the middle parts of the segments (Fig. 6, lower right; between 95 and 100 m of original POZ and 40 and 60 m of computed BAR). This impression is, again, caused by the fact that BAR is richer in the original MS-pattern structure. Technically, this must be caused by the fact that the number of regularly spaced MS

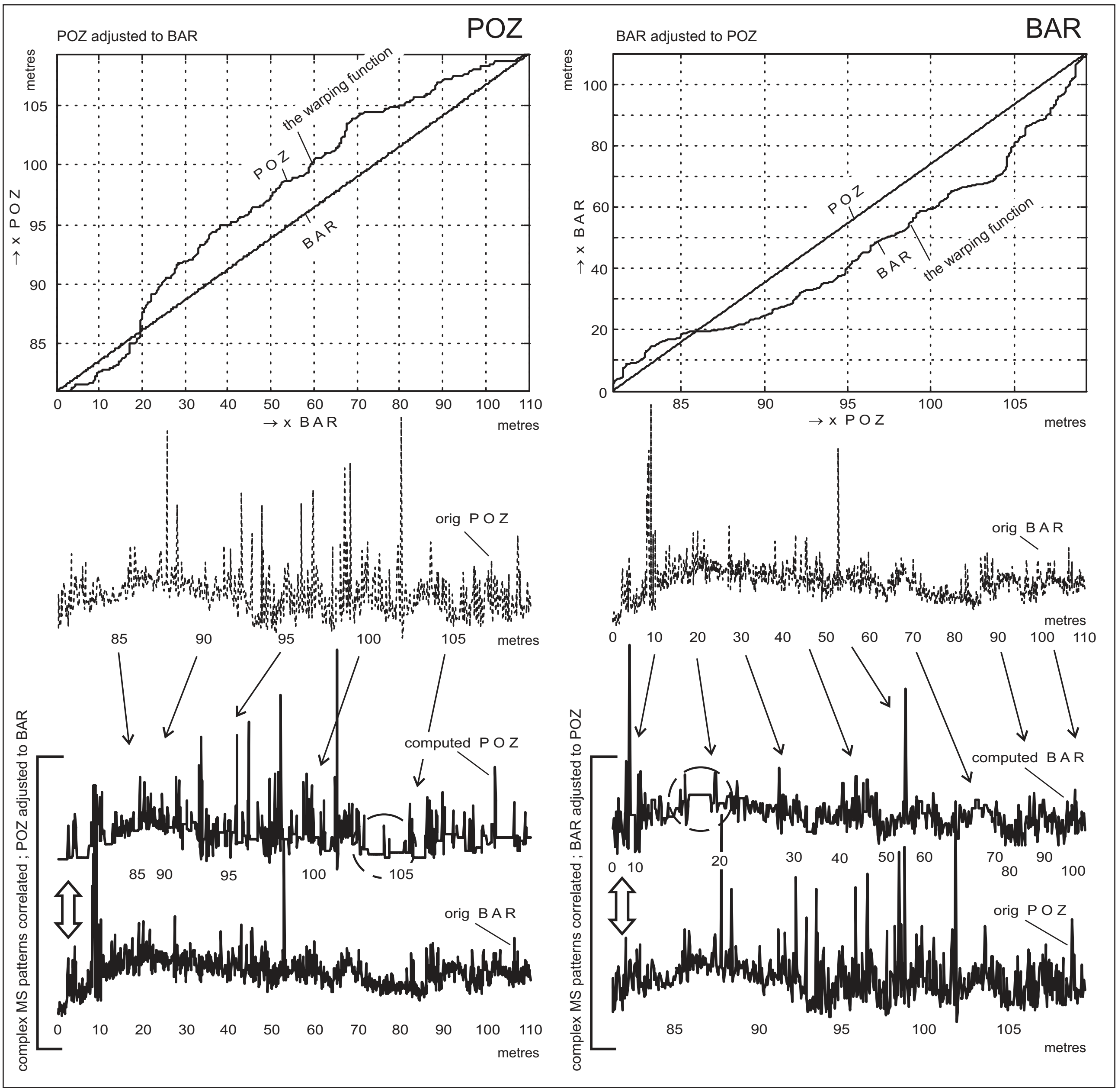


Figure 6. Warping function for MS data from POZ and BAR sections. A simple DTW algorithm with no slope restriction was used. The lower part of the figure contains a graphic expression of the DTW-calculated juxtaposition of aligned parts of the MS records – the main features of relative shifts in thickness and degree of gapping are indicated this way. The dashed-line circles highlight the major hiatuses indicated by means of the DTW procedure.

samples is higher in BAR (×1.935; 1101 : 569), and, geologically, we can't resist mentioning that the thicker time-equivalent BAR segment also contains a higher number of beds which are discernible in very detailed photos of the section (×2.115; 4452 : 2105).

In the context of this case, practically the only way to slightly modify this robust solution is the variant nonlinear scaling of the MS amplitudes. The strong weakening of the lowest or highest (or any within-interval) data separately (or sharply) generates inappropriately large dimensions of gaps along the DTW x-arrangement. Broad internal segments appear with a tendency to lose a good match; or, in terms closer to DTW-alignment method, the 'optimization' search for the best warping function may have problems with connectedness, and is 'more competitive and less distinct'. This is understandable because such intervention can be perceived as an operation that must necessarily deform natural patterns, to the point that these series theoretically need not be (and practically cannot be) numerically arranged to give meaningful results.

The only case where we found the reduction of some values possible and potentially important is as follows. Because the measured data can be loaded by a random error which can particularly be related to sampling strategies and material variation of rocks (due to the risk of missing some of short-living MS 'peaks' or 'troughs' in the highly differentiated vertical structure of the section,

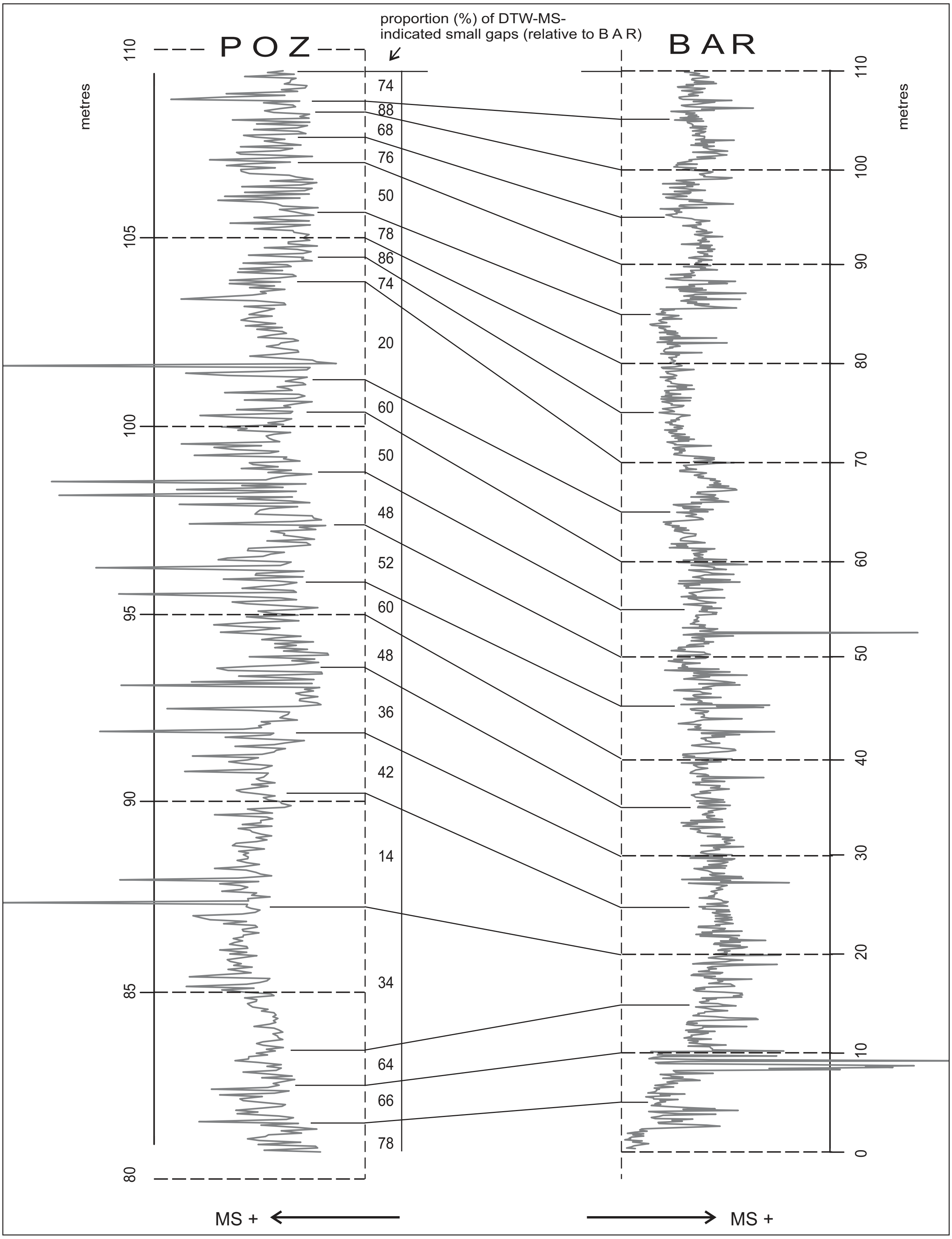


Figure 7. Original MS logs; POZ compared to BAR. The trends in change of thicknesses are shown. The shifts indicated by means of the DTW alignment procedure can be considered a latent combination of sedimentation rate, hiatuses and diagenetic pressure-solution compaction. The proportions of the DTW-calculated class of gaps in chosen intervals, i.e., POZ to BAR where the former is more gapped than the latter, are shown in numbers (summed according to detailed numerical results which are in the background of this study). Particularly, the small gaps of about roughly millennial and longer ($n \times 10$ kyr) durations may have a potential to be a cause of these latent shifts, because we often cannot reliably measure the absolute lengths of these relatively short-term interruptions in sediment flux and preservation.

or using a sample which is not the most representative of the given horizon; Hladil et al., 2006, 2009), it is good to suppress the peaks values by nonlinear scaling of a distance measure. The nonlinear function would sufficiently maintain low values and decrease high values. Based on the tuning that considered the effectiveness of the information mining and compactness of the pattern evolution, such an appropriate nonlinear function can be very close to the radix of 2. However, we can consider also a strong suppression of peaks by the radix of 3. Under this condition, the warping function for the use of nonlinear function:

$$d'(c) = \sqrt{\|a_i - b_j\|}$$

was also applied to this case. However, even the warping function calculated in this way does not differ substantially from the strict application of the simple DTW. In such a case, nearly a half of the x-positions remain practically the same, with no difference or less than 2 per cent relative to the length x, and the manifestly modified positions have a difference smaller than 0.05 x. This sort of experiments with parameters of the computational procedure only confirmed our assumption (based on the quality of the results achieved by the simplest setting), that, for given BAR and POZ segments, the solution is robust enough for a real use.

It is quite likely that any computational modification related to the magnitude of verified MS peaks lacks the common, more universal validity within the context of whole-section ranges or their parts. Considering the complexity and also selectivity of all possible influences related to sedimentary, diagenetic and MS-signal parameters (compare the chapter Problem description above; or Tribovillard et al., 2002; Hladil et al., 2006; Mabille & Boulvain, 2007), the origin of MS values of every point in the MS section may have some specifics or at least nuances. Hence, every intervention into the MS-pattern shape is usually based more on oversimplified presumptions than on basic and realistic analysis of the shape of the data, point by point. And this is the principal reason why we give preference to the basic DTW algorithm that does not a priori exclude any potential specifics.

Nonetheless, the experience obtained during this initial stage of application of DTW techniques to the alignment of MS logs suggests a number of broad areas of research activity aimed at finding optimum methods of usefulness and risk assessment of input data and computational parameters. This particularly relates to possible corrections when strong facies changes are involved in the sections.

The DTW results suggest a detailed scheme for alignments of individual, most likely highly synchronous bands and points between the POZ and BAR sections. The numerical background data allow the points and patterns between the two sections to be compared with a precision of a few centimetres. The image of arrangement of gaps provided by the DTW belongs to the most interesting findings (Figs 6 and 8E). The number of ‘relative gaps’ (= the significant parts of one record missing in the compared record) is higher for POZ where the succession of beds is thinner and contains a smaller number of recognizable beds. Major gaps were indicated close to 104.5 and 105.5 m marks in POZ, and above 19 m mark in BAR (Fig. 6; marked by dashed-line circles; see chapter Discussion). Moreover, if the back projection of the DTW results to the original MS data is used (Fig. 7; length of the ‘time’ interval POZ to BAR as 1 : 1), relative ‘thinning’ and ‘thickening’ on both sides can be also compared. The relative thickening indicated by DTW for the upper part of the BAR segment is in full agreement with the previous assumptions based on lithological and faunal characteristics, e.g. homogenized beds, abundance of *Chondrites* and *Zoophycos* tracemakers and presence of rostoconch molluscs (based on our own data but indicated also by Chlupac, 1957; Havlicek & Vanek, 1998; Slavik et al., 2000).

The superstructural DTW- and MS-data-based alignment of the POZ to BAR sections (Fig. 7) allows also the assessment of lithological relationships. Using the warping function images, we ascertain that the ‘alignment’ of the POZ Slivenec, Lodenice and Reporyje limestone types is not very different if compared with their somewhat hidden counterparts in the ‘all-encompassing range of the BAR Dvorce-Prokop limestone series’ (Figs 4 and 5; 6 and 7). These lithological and biofacies counterparts (Havlicek & Vanek, 1998) have practically the same stratigraphic position, only with a slight shifts which can be explained by local specifics of these two different slopes and parts of palaeobasins.

6. Discussion

Studies applying new methods to log analysis and correlation must respect the issues of how successful was the application in terms of geological facts. The feedback from available data packages on sedimentology and diagenesis of these sections is important.

For this purpose, several descriptors of lithology of these two sections were designed and used. These descriptors render information generalization and belong to two groups (Fig. 8D and G). First, two ratios describing the rock type and diagenetic features were used: The calculated ratio ‘compactites’ to ‘cementites’ (and/or uncompacted calcimud ‘recrystallites’; Fig. 9F) is a cumulative thickness-related ratio of markedly diagenetically/pressure-solution compacted rocks to only slightly compacted or uncompacted parts of successions of centimetre-scale beds (CP/CM). The diagenetically uncompacted rock types occur largely within calciturbidites, and especially in some calcisiltites/calcimudstones with dacryoconarids and also crinoidal grainstones with well-preserved cements. The second ratio relates to proportions between hemipelagites and calciturbidites (HP/CT; Fig. 8D). These ratios are based on cumulative thicknesses of compared rock types which were assessed for the each 1/100 part of the POZ and BAR sections (Fig. 8C). Secondly, the other group of numerical data contains counts at the end of each of these 1/100 parts, and relates to four parameters: number of

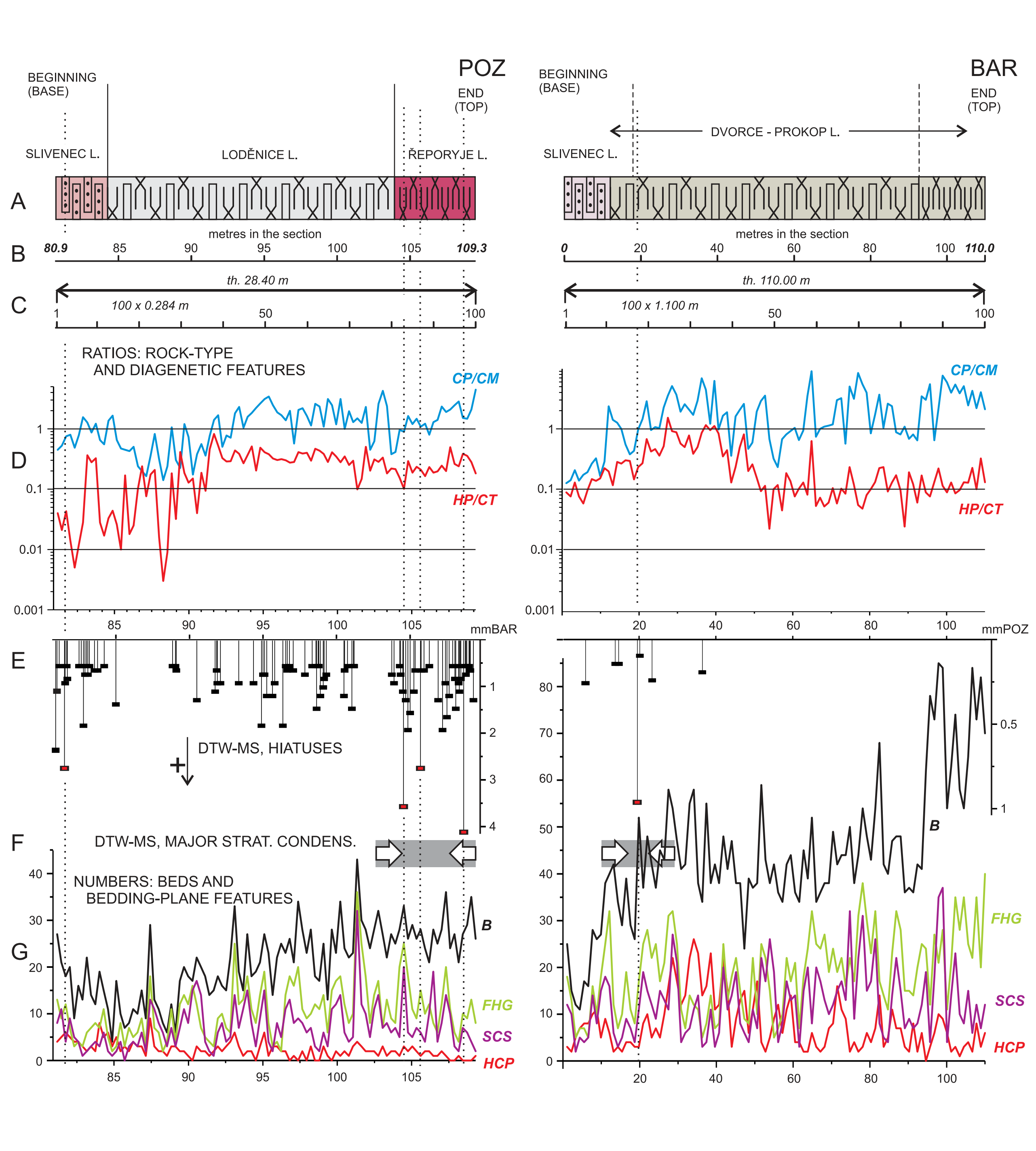


Figure 8. A feedback from sedimentological analysis to verify the stratigraphic gaps inferred in both successions POZ and BAR, compared segments only; graphs to numerical data. The diagram is vertically arranged according to sections (POZ and BAR) and horizontally according to type of data. A – Members and lithologies (see explanations to Figs 4 and 5; the colour fills denote the mean colour characteristics of rocks). B – The primary scale in meters, the basal binding of all data (~ metre marks for the sections and all background analytical and image documentation, the latter allowing the reproducibility and/or future completion of any type of data with a mm–cm resolution). C – The subdivision of the entire thicknesses of the compared segments into one hundred partial intervals (applied to allow quantification of changing lithological parameters along the sections). D – The observed changes related to basic rock characteristics and diagenetic compaction: CP/CM – a calculated ratio ‘compactites’ to ‘cementites’ (see Discussion for details); HP/CT – a cumulative thickness-related ratio between hemipelagites and calciturbidites. E – Arrangement of the DTW(MS)-indicated hiatuses, i.e., hiatuses with respect to the compared section (magnitude of hiatuses: mmBAR – missing metres of the BAR, mmPOZ – missing metres of the POZ). F – The DTW(MS)-indicated parts of the compared segments where the overall stratigraphic condensation may reach the maximum values. G – The observed changes with respect to frequency of beds, bedding-surface features related to possible loss of the direct stratigraphic record and extraordinarily high-compacted horizons; all counts per a partial interval (C): B – number of beds, FHG – discernible firmgrounds or hardgrounds, SCS – visibly scoured surfaces, HCP – high-compacted ‘shale’ or considerably low-carbonated ‘interbeds’. See the Discussion for interpretation.

Figure 9. A feedback from sedimentological analysis, continuation; examples of outcrops and thin sections. A – Major stratigraphic gaps indicated by DTW in a general view of the upper part of the POZ section (see also Figs 6 and 8). The pronounced hiatuses around 104.5 and 105.5 are marked by a yellow line, and an accompanying swarm of gaps of lesser magnitude (see Fig. 8E/POZ) can also be located. The group of moderate gaps around 101 m mark is also recognizable. Orange ellipses with numbers are the metre marks in the section. B – Similarly, a part of the BAR section, where a major gap was indicated by means of DTW above the 19 m mark. Location of this gap is connected to the presence of a prominent HCP 'shale' horizon (marked by a yellow line), and accompanied by a visible interruption in bed rhythms as well as overall lithology descriptors (e.g. HP/CT and CP/CM ratios, both increased). The interval close below the gap shows more compact and clearly separated beds compared to the interval close above the gap which is dominated by strong pressure-solution effects on both CT and HP calcimuds. The number of cm-scale beds B moderately increased at and just above the gap (see also Fig. 8). A slight bedding-parallel slip along the HCP horizon is also discernible in this figure, and regional cleavage (at about 60° to bedding) is locally visible. C – An example of a corroded hardground with small pits and bumps, covered by a thin, graded calciturbidite bed with crinoid ossicles; POZ, Slivenec L., close to the base of the segment (79.95 m), vertical section, surface of the documented cliff face. D – Strongly compacted hemipelagite. The dish-shaped shelly microremains were often deposited with convex sides down, and broken tentaculitoid (styliolinid) shells indicate the compaction ratio of at least 1 : 6 (e.g., in the central lower part). POZ (86.05 m), thin section normal to bedding, transmitted white light, microscope, one nicol, moderately enhanced contrast. E – Tentaculitoid (dacryoconarid) calcimud type of a thin, distal calciturbidite with several fragments of echinoderm ossicles (pinkish and brownish dotted) and trilobite carapaces (beige white to white). In spite of low porosity and almost complete absence of cements in such originally very finely particulate but highly polydisperse material, the penetrative compaction is low (the fossils with surrounding parts of the rock are not 'flattened'). The pressure-solution compaction concentrates only to the upper part of this distal turbidite blanket, and few tectonic stylolites cut the rock at an angle of about 45°. POZ (105.00 m), thin section normal to bedding, white light, thin-section scanner image, enhanced contrast. F – Another type of tentaculitoid calcimud rock which dominates the compared segments; an example of slightly diagenetically compacted to almost uncompacted 'calcitic recrystallite'. Some of the shells have Fe-rich fills with dolomite crystals (selectively), and some of them show repeated insertions of one shell into another. POZ (108.05 m), thin section normal to bedding, same imaging conditions as for D.

beds (B), discernible firmgrounds or hardgrounds (FHG), visibly scoured surfaces (SCS) and strongly compacted carbonate-depleted 'shale interbeds' (HCP). Plotting of these data demonstrates a 'frequency change' (Fig. 8G). The estimated error from the determination and classification does not exceed 5 %.

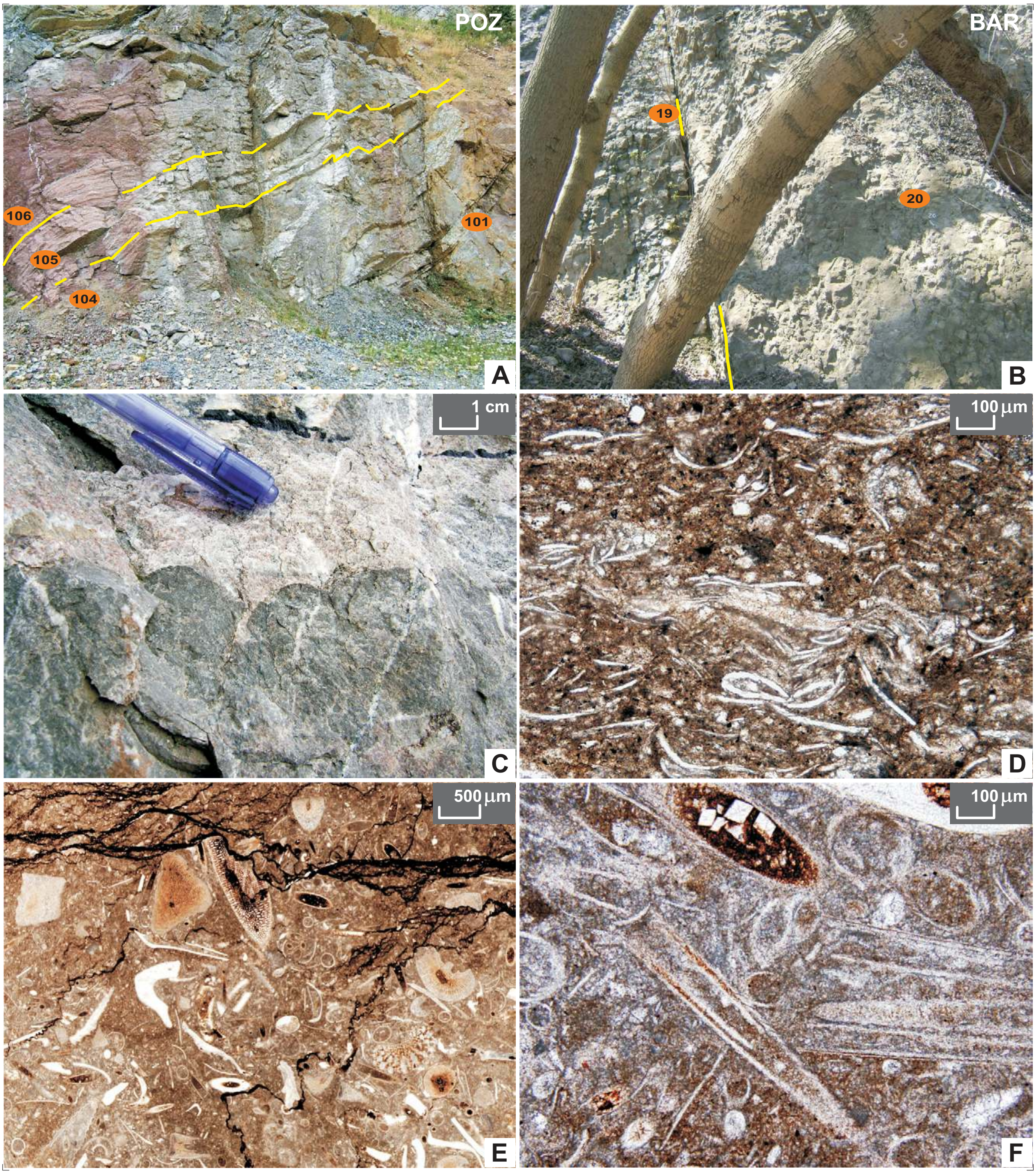
From the behaviour of the CP/CM and HP/CT ratios (Fig. 8D), one can conclude that the respective curves are similar and display approximately the same gross trends. However, the correlation coefficients for these data, within POZ and within BAR, are insignificantly positive with values of 0.477 and 0.278, respectively. This suggests that the amounts of deposited (preserved) hemipelagites (HP) and of rocks affected by intense pressure-solution compaction (CP) are more similar in the long than short intervals. This sort of variation is mainly (but not only) determined by the amounts of recycled HP component which were involved in calciturbidites (CT) and activated the origin of CP-rocks in them.

The correlation of the numbers of beds (B) and highly compacted 'shaly interbeds' (HCP) provides coefficients -0.118 and 0.002 (within POZ and within BAR, respectively); these values are close to zero and the uncertainty is the highest. The same coefficients are 0.707 and 0.515 when calculated for B and firmgrounds-hardgrounds (FHG) and 0.583 and 0.378 for B and scoured surfaces (SCS). Most likely, this only shows that 'with increased number of beds also the number of hardgrounds or scoured surfaces can be increased'. If the higher B was only a function of decreased CT thicknesses and HP starvation, this finding would have an expectable meaning 'that numerous thin beds with lots of of hardgrounds and/or scoured surfaces signalize the stratigraphic condensation and possible occurrence of gaps'. However, we can demonstrate that this is true only in part (e.g., at 101 and 104.5 marks of POZ; Fig. 8E–G). All other situations are strongly indicative of a very complex and changeable control on the above mentioned lithological descriptors.

In the next step, we extracted all obvious 'geological gaps' from the DTW-alignment numerical outputs, which were corresponding to a 'repetition of one x-value in the aligned row of positions' more than two times. These gaps were expressed according to their positions in the compared segments, both for POZ and BAR, and their magnitude in metres of 'missing intervals relative to other section' was shown (Fig. 8E). Such an arrangement permits a visual and numerical comparison between the positions and significances of geological gaps on one side and sets of overall lithological descriptors on the other side.

Making an attempt to compare all these descriptors with the DTW results (Fig. 8 as a whole), we can conclude that the DTW-indicated highest loss of the direct stratigraphical record may be related to a combination of CP/CM values of about 1, HP/CT of about 0.2 and only slightly to moderately elevated counts for B, FHG, SCS and HPC.

A significant question also arises in this approach. Is it possible to locate the DTW-indicated gaps in the sections? The answer is unequivocal. Major stratigraphic gaps can be located without any problems and match the indicated levels perfectly (see Figs 9A and B). Moreover, the scrutiny of all these numerous gaps, even of a smaller magnitude, offers reliable counterparts in the detailed photographs of the lithological structure of the sections. Minor differences in X–X0 cm scale or problems with 'hidden' gaps were observed, but they represent less than 10 % of the lowest-magnitude gaps. Although this finding seems to contain a very positive message, this message cannot be overestimated. It is constrained by two factors: these sections are very rich in short-term gaps, and the biostratigraphical and lithological tools have limited capabilities to discern, at the given conditions of Palaeozoic and Pragian calciturbidites, the real duration of hiatuses of kyr–n×10kyr scale. On the other hand, this is precisely the reason why we start with this very detailed



MS outcrop logging of long sections and why we suggest the DTW method for understanding the relationships between the logs.

Many other methods have been either already used for similar log comparisons made or have this potential. A not uncommon practice in the correlation of logs is to use cross-correlation (CC; e.g., Holland et al., 2000). CC is used to measure the similarity between two signals, to detect a known signal in a noisy one, or to search for cyclic data. The cross-correlation in signal processing resembles convolution of two functions. However, the typical convolution involves reversing and shifting of a signal together with multiplying by another signal, whereas this type of correlation only involves shifting it and multiplying (but no reversing). The CC method suits well to the cases when the signal is recorded in time. A strong nonlinearity of relationships between the scales based on time and thickness together with the presence of visible or hidden gaps (see Problem description, above) are usually developed to a degree which would constrain or directly forbid good CC results. On the other hand, CC completed by complexity analysis of log data may have potential to provide a more robust image, but the mining of the pattern correlative information remains quite weak and mainly inaccurate (e.g. Al-Naymat, 2009; Ferreira et al., 2009).

A quite common practice with well-logs is based on wavelet transformation (WT; e.g. Prokoph & Barthelmes, 1996). The WT approach is widening the possibilities to analyse and visualize the cyclic patterns, especially in the case of their problematic manifestation in the record. The analyses help also to identify the discontinuities, unique patterns, or indirectly, indicate the degree of irregularity or a tendency to decay of the patterns. In general, the Morlet wavelet has proved to be the most appropriate to resolve the specific peaks or rhythms, if these are involved and of detectable quality. However, many advantages of these techniques are also huge disadvantages, particularly in the context of the detailed linkages between the nodes of our MS logs and the applied wavelet types. The inherited aspect of this method is that the length of scrutinized intervals cannot be neglected, so broad zones adjacent to the start and end points or to any switch of parameters are marked by artefacts. Vice versa, with strongly deformed and intermittent records, the WT selectivity for shapes and size of the patterns/intervals may present structures of different classes as structures of the same class (e.g., Li et al., 2005; Choudry et al., 2007). Further, several other approaches can be considered which are also available for the task of aligning sequences with varying speed, and/or signal intensity, namely: continuous density hidden Markov models (CDHMM, e.g. Leggetter & Woodland, 1995) or distortion-based vector quantisation (VQ, e.g. Soong et al., 1987; Munawer Al-Otum, 1998).

A correlation of two geophysical logs often involves the techniques of vertical shifting of one log relative to another until their characteristics were aligned as indicated by the maximum value of the cross-correlation function. Particularly the correlation of logs with extremely varying thicknesses of stratigraphic intervals is somewhat risky in this respect. In such situations, the piling-up of the preconditions and variously inferred corrections has a tendency to complicate the computing system with an increased risk of misinterpretation. Therefore, the professional well-log software products in general purposely combine the true computational routines with intuitive settings which allow the user to make many ad-hoc corrections, interventions or decisions.

Why DTW? In spite of the fact that each of the above mentioned methods may have some specific advantages which may suit to the solution of some types or aspects of the MS records, the DTW outperforms VQ and CDHMMs for sparse amounts of training data, although with more data, the performance of each model can be almost indistinguishable (Yu et al., 1995). Thus, we chose the DTW as the most robust solver which is particularly appropriate for a solution of the alignment between two records which obviously (or potentially) contain numerous shifts and gaps, and differ in the expression of patterns. For our case of MS-signal, these features of irregularity are also extended to two dimensions, since both the sedimentation rate and signal intensity recording power may vary in time (actually, signal intensity also depends on sedimentation rate, so the problem dimension is '1.5', not two). The extension of the problem for two-dimensional fields like planar warping in images is nondeterministic-polynomial-time-complete (NPC), while the problem for one-dimensional signals like time series can be solved in polynomial time (Levin & Pieraccini, 1992). The NPC problems are usually intractable exactly except of those of small dimension. And this is another reason why we resorted to the DTW solution.

7. Conclusion

The DTW algorithm in its simplest form is well applicable to MS log correlation to achieve reliable and effective optimum results related, in geological terms, to a very detailed stratigraphic-correlation analysis. This method is particularly suited to the solution of scientific and technical problems of a given class, with lots of shifts and variously expressed patterns together with obvious or hidden gaps. Moreover, the DTW algorithm was even primarily designed for such a type of comparison of two records. The suggested application of DTW in MS log analysis follows not only from its roots in the field of speech recognition but particularly from rapidly developing and successful DTW applications in fluid and gas chromatography, genetics and medical disciplines, where the tasks similar to MS log correlation are performed. Appropriate data for a meaningful use of DTW alignment must be numerous and systematic (no very short sections with less than a few hundreds of points, and no significant gaps in sampling). The problems related to the adaptation of the method (and/or adjustment of data) for the work with MS logs from very different places of the world and based on very different facies can certainly be expected to be the key area for further research. Concerning the example from Palaeozoic calciturbidites, stratigraphic correlation by means of the DTW alignment of MS logs provides a resolution by two orders of magnitude higher than could be achieved using only the methods of biostratigraphic correlation. The results enable us to assess the significance of stratigraphic gaps of variable extent.

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