Lithological spectra patterns in the Permian continental stratigraphic records, the East of the Russian plate

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Abstract. Stratigraphic sequences are interrupted cyclic records. Only 5-10% of the stratigraphic record is preserved in continental sediments. The most of the sedimentary history is not recorded in the sections due to the lack of sedimentation or erosion of sediments. Therefore, the lithological data series on continental sections very often represent records of a random process. This paper analyses the spectra of grain size, carbonate content and magnetic susceptibility of three continental sections of the Middle -Upper Permian (the Monastery Ravine and the Kzyl Bairak outcrops on the Volga river bank, the Sheremetievka outcrop on the Kama river bank) to estimate a quantity and a quality of stratigraphic records.

1. Introduction

Benoit Mandelbrot directly compared the stratigraphic record to a fractal in his famous book [1]. Studies [2-9] have shown that a mesh with numerous holes is much denser than a natural stratigraphic record [10]. Breaks, disconformities and diastemas dominate geological history, with sedimentation periods making up only its minor portion in the form of fractal dust with a dimension of less than 1 [6].

Unfortunately, little is known about the distribution of hiatal time intervals, mainly because their absolute durations are technically difficult to measure. However, numerous assessments of sedimentation rates [2-5] indirectly give an idea of the scale and distribution of stratigraphic breaks. According to these studies, log-log plots of sedimentation rate (R) vs. time interval (T) show that the longer the time interval, the lower the sedimentation rate:

\[ R(T) \propto T^A, \]

where exponent A (A<0) depends on the depositional environment.

Sadler [3] demonstrated the validity of this empirical rule on more than 25,000 sedimentation rate assessments from more than 700 published sources. He also found that the slope of the straight line in the log R(T) - log T field (Exponent A) varies depending on depositional environments with rivers, lakes, carbonate platforms and reefs, terrigenous shelves, shallow sea and abyssal ocean floor. According to [3], the decreased sedimentation rates over increased time intervals could be due to
measurement bias, post-sedimentary compaction, long-term evolution of geological systems, or episodic sedimentation.

Thus, a stratigraphic record is a very complex sequence, in fact a random sequence. It is a very difficult task to reveal some cyclic patterns in sections and evaluate their duration. This question is of great interest from the point of view of estimating the age, duration of various stratigraphic units, and sediment accumulation rates based on the calibration of the duration of the detected cycles with variations in orbital parameters. Numerous works have shown that the orbital Milankovitch’s theory of climate variations explains well the Pleistocene cycles [11 – 13]. Indeed, this linear approach to the spectral analysis of stratigraphic records has yielded outstanding results. An analysis of the records of oxygen-isotopic curves in marine sediment strata has brought us closer to understanding the nature of the Quaternary glaciation [Shackleton et al. 1990]. In addition, interpretations of sedimentary successions [14] are based on relative fluctuations in sea level. Moreover, high-order cycles are due to the influence of variation of orbital parameters on the global climate. Variations in various lithological parameters reflect climatic changes (changes in sea level) in different ways. Therefore, the choice of the most informative parameters for distinguishing climate cycles is very important.

In this paper, various lithological parameters were analyzed in order to reveal cyclic patterns in continental sections with a number of interruptions and erosions.

2. Object

A Figure 1 shows the position of the investigated sections: the Monastery Ravine section, the Sheremetievka section and the Kzyl Bairak section on banks of the Volga and Kama rivers.

![Figure 1. Objects map (investigated sections are marked by red triangles).](image-url)

The Monastery Ravine section is located on the right bank of the Volga River, in the vicinity of the village of Monastyrskoye, 12 km upstream of the town of Tetyushi. The Il’insky Gully lies 2 km southwest of the Monastery Ravine. The outcrops in the thalweg and slopes of these gullies represent one of the most complete and readily accessible sections of the Biarmian and Tatarian series in the region of the Kazan Povolzhye. The Monastery Ravine section was described first by Forsh N.N. during
the geological mapping of the Volga region in 1938 [15]. He divided the section into 5 formations according to lithological criteria; these formations are used recently (Figure 2). The general construction of the Monastery Ravine section can be seen in the ‘Main Wall’ on the left slope of this gully [15].

The Urzhumian stage (upper part of the Biarmian series) includes three formations: the First, the Second and the most part of the Third Formation.

The lower part of the First Formation is exposed near the mouth of the Monastery Ravine on the steep bank of the Volga River, while the upper part of the Formation is exposed in the right slope of the gully, where it forms a series of ledges. The thickness of the formation is ca. 26 m. Generally, the First Formation is composed of red-bed shales and is distinctly subdivided into two parts. The shales of the lower part of the Formation are gypsiferous, containing many interbeds (3–20 cm thick) of gray and pink marls and argillaceous dolomites, more rarely of brown siltstones and sandstones. In the upper part of the Formation, shales are more homogenous and have a few interbeds of terrigenous and carbonate rocks. The shales often bear thin lenses of palygorskite.

Fossils occur rarely in the Formation and mostly in its upper part. The first bed with fossils lies 10 m below the top of the Formation and is composed of reddish-brown thinly bedded shales containing small (3–4 mm) distorted valves of conchostracans. Seven metres above this bed, dull-red shales, along with conchostracans, contain the isolated scales of the fishes. The scales are 2–5 mm in size, black, not oriented and regularly distributed in the rock.

The Second Formation is exposed in the second right tributary, and also in the thalweg and slopes of the Monastery Ravine. The thickness of the formation is ca. 30 m. Its lower boundary is drawn at the base of the 0.3 m thick bed of pinkish-gray, dolomitic, heterogeneous marl. In the bottom of the ravine, this bed forms a waterfall, first from the mouth. The formation is distinct in its cyclic structure and high content of carbonates. The section contains three argillaceous-carbonate members: at the bottom, in the middle, and at the top. These members are separated by two members of sandy-argillaceous rocks. The argillaceous-carbonate members are composed of greenish and pinkish-gray dolomites, argillaceous limestones and marls (0.2–1.5 m thick), containing thin (usually 10–30 cm) bands of red shales. The sandy-argillaceous members are composed of reddish-brown shales and siltstones with lenticular interbeds of brownish sandstones (up to 2 m).

Fossils are represented by non-marine ostracods, bivalves, fishes, amphibians, and plants.

The bed of the greenish-gray siltstone (5–20 cm), 6.5 m above the base of the formation, contains numerous scales of the fishes. The large (0.5–3.0 cm) reddish-brown scales occur parallel to the bedding planes and mainly concentrate in the thin (3–5 mm) bed, which also yields small amphibian bones. Eight meters below the top of the formation, the bed (0.1 m) of reddish-brown evenly and thinly laminated shales contains molds of the ostracods, fragments of the small-leafed plants.

The Third Formation is well exposed in the first right tributary and in the thalweg of the mainstream of the Monastery Ravine. The slopes of the ravine expose only the lower part of the formation; because of the slides, the primary structure of beds is distorted here by many small gliding planes. The thickness of the formation is ca. 32 m. Its lower boundary is drawn at the top of the upper dolomitic bed of the Second Formation. In the thalweg of the ravine, this bed forms the ledge, third from the mouth of the ravine. The formation is distinct in the predominance of sandstones and siltstones in the succession. Carbonate beds are rare and thin. Reddish-brown shales and siltstones are most widespread and are usually intercalated by thick lenses of yellowish-brown, obliquely laminated sandstones. Carbonate rocks are represented by gray, nodular, and muddy limestones and marls. The cyclicity of the formation is distinct.
Different levels within the formation contain the remains of non-marine bivalves, ostracods, conchostracans, fishes, and tetrapods, and imprints and fragments of plants. Gray and brown siltstones 1–1.5 m above the base of the formation contain coaly remains. The bed of reddish-brown and greenish-gray siltstone eight metres higher than the previous one contains the ostracods and rare amphibian vertebrae. The argillaceous limestone, four metres above, contains the ostracods, a few small bivalves and conchostracans.

The Severodvinian (Lower part of the Tatarian series) includes the upper 12 m of the Third Formation and almost the total Fourth Formation.

The Forth Formation (thickness 38 m) is exposed in the thalweg and the slopes of the first left tributary of the Monastery Ravine. It is represented by the alternation of siltstones, shales and sandstones with marls and limestones showing the distinct cyclicity. Sandstones are usually bluish or yellowish-gray, and recognised in three levels as lenses 2.50–8.0 m thick. Together with shales and siltstones, they form three argillaceous-sandstone members. Carbonate rocks concentrate mostly in the lower and upper parts of the formation, where they, together with shales, form separated argillaceous-carbonate members 4.5 m thick at the bottom and 7.8 m at the top of the Formation. The lower boundary of the Formation is drawn at the base of the bed of light-gray argillaceous limestone with a distinct vertical structure overlying the upper argillaceous-sandstone member of the Third Formation. The Formation contains the ostracods, the charophytes, conchostracan shells, fragments of the bivalve, scales of the fishes. The thickness of the Formation is ca. 33 m.

The Fifth Formation and its boundary with the Fourth Formation is exposed 2 km southwest, in the upper reaches of the Il’insky Gully. In this gully, the section of the Formation is represented by the member (10–15 m) of yellowish-brown obliquely laminated sandstones, with conglomerate lenses, consisting of fragments of local rocks. Sandstones frequently contain silicified lenses and interbeds of red-bed siltstones, shales and marls. The lower part of the Formation (shales and marls) contains ostracods and fragments of bivalves. The apparent thickness of the Formation is 18 m.

The Kzyl Bairak section is located on the right bank of the Volga River in the vicinity of the villages Kzyl-Bayrak, Krasnovidovo, Antonovka and the town Kamskoe Ustiye. The section includes the First and the Second Formations (Figure 3) within the Urzhumian stage [16, 17].

The First Formation (thickness 41 m) is composed of red-bed shales, gray and pink marls and argillaceous dolomites, more rarely of brown siltstones and sandstones. Fossils occur rarely in the Formation and mostly in its upper part. Shales contain small (3–4 mm) distorted valves of conchostracans and the isolated scales of the fishes. The scales are 2–5 mm in size, black, not oriented and regularly distributed in the rock.

The Second Formation (thickness 24 m) contains argillaceous-carbonate members. These members are separated by members of sandy-argillaceous rocks. The argillaceous-carbonate members are composed of greenish and pinkish-gray dolomites, argillaceous limestones and marls (0.1–2.0 m thick), containing thin (usually 10–50 cm) bands of red shales. The sandy-argillaceous members are composed of reddish-brown shales and siltstones with lenticular interbeds of brownish sandstones (up to 2 m). Fossils are represented by non-marine ostracods, bivalves, fishes, amphibians, and plants.

The Sheremetievka section is located on the right bank of the Kama River, in the vicinity of the villages Sheremeteivka and Nizhnyaay Uratma. The outcrop was formed in the 1990s during the construction of the highway Kamsky Polyany - Zainsk. The outcrop represents one of the complete Biarmian series sections of the Upper Kazanian substage overlaid by the Urzhumian rocks [16, 17].
The section is composed of 215 beds grouping up in the Prikazan beds (no.1-61, total thickness 21 m), the Pechishchi beds (no.62-98, total thickness 19 m), the Verkhnyi Uslon beds (no.99-165, total thickness 24 m), the Morkvashi beds (no.166-169, total thickness 2 m) and the First Formation (the Lower Urzhumian) beds (no.170-215, total thickness 17 m) (Figure 4).

The Prikazan beds are composed of gray and brownish-gray shales, siltstones and gray fine- and coarse grained calcareous sandstones.

The Pechishchi beds are represented by two members. The lower member includes gray and red shales, siltstones and sandstones (thickness 17 m). The upper member is composed of gray limestones, marls and calcareous shales (thickness 2 m).

The Verkhnyi Uslon beds are represented by two members. The lower member includes greenish-gray fine-grained sandstones, yellowish-gray siltstones, dark brown shales (thickness 18 m). The upper member consists of gray limestones, marls and calcareous shales (thickness 6 m).

The Morkvashi beds are composed of grayish brown sandstones from fine to coarse grains up the section.

The First Formation (the Lower Urzhumian) includes two members. The lower member is limestone, sandstone and shale alternation with non-marine pelecipods and plants (thickness 7 m). The upper member is composed of limestones and shales (thickness 10 m).

A Table 1 shows total thickness and a number of samples from each section.

| Section      | Stratigraphy                  | Total thickness, m | Number of samples |
|--------------|-------------------------------|--------------------|-------------------|
| Monastery Ravine | The Biarmian and Tatarian Series | 148                | 295               |
| Sheremetievka   | The Biarmian Series           | 82                 | 215               |
| Kzyl Bairak     | The Biarmian Series           | 65                 | 168               |

In the samples grain size fractions, CaCO$_3$/MgCO$_3$ ratio values and magnetic susceptibility were measured.

Recently many workers have successfully deciphered depositional environments with the help of granulometric analysis. The rock samples chosen for grain size analysis though compact but soft in nature and thus could easily be disaggregated without grain fracture. Due to this advantage of easy disaggregation, the conventional sieving method has been conveniently adopted.

Majority of the samples were found containing carbonate cement. The samples were broken onto pieces with the help of mortar and pestle and then boiled in 2 per cent, hydrochloric acid solution, to remove the carbonate cement. The specimens were left in this solution for 24 hours. Later, the samples were broken with the help of specially designed rubber hammer. The remaining pieces were dipped in the solution of hydrochloric acid. This process was repeated for several times to get better results out of the purity of the samples through sieving method. 100 grammes of each disaggregated sample was taken.
and sieved on a mechanically operated shaking machine. 7 sieves, graduated in 10, 5, 2, 1, 0.5, 0.25 and 0.1 mm, have been used for mechanical analysis. Every set of the sieves was shaken for at least 30 minutes, for almost complete separation of the grains of different sizes. The grains arrested by various screens were taken out and weighed. Using Sabanin’s method (e.g. [18]) the next step was removal of the grains <0.1 and <0.01 mm. The samples were dried in the drying chamber for two hours at 50°C; and finally, the samples were weighed within an accuracy of 0.01 g.

The obtained data, thus, was grouped into 3 classes on grain size: >0.1 mm (sand); 0.1-0.01 mm (silt) and <0.01 mm (mud).

The carbonate component was analyzed by insoluble residue, CaO, MgO and CO₂ contents measurement by method [19]. These data permit to have CaCO₃/MgCO₃ and/or CaO/MgO and/or Ca/Mg ratios values.

Magnetic Susceptibility (MS) of all samples has been measured using the KLY-2 system. Measurements of the bulk susceptibility MS produced on discrete samples (8 cm³) at a sensitivity of 4×10⁻⁸ SI and in low magnetic field (range of 300 A/m).

Variations of described lithologic parameters values along the sections are shown on Figures 2-4.

**Figure 2.** The Monastery ravine section. Lithologic parameters zonation: carbonate (yellow); high magnetic sandstones (red); low magnetic sandstones (pink); high magnetic mudstones (dark blue); low magnetic mudstones (blue)
Figure 3. The Kzyl Bairak section. 33 carbonate (yellow) zones; 15 sandstone (pink) zones, 37 mudstone (blue) zones (among them 21 bright-blue zones correlate with increasing of $\text{CaCO}_3/\text{MgCO}_3$ values)

Figure 4. The Sheremetievka section. Lithologic parameters zonation: carbonate (yellow); high magnetic sandstones (red); low magnetic sandstones (pink); high magnetic mudstones (dark blue); low magnetic mudstones (blue)

3. Methods

Spectral analysis aims to expand data series, most often in a uniform grid (or with uniform spacing) on a harmonic that is a sum of sine and cosine of the same argument. Most stratigraphic records consist of approximately sinuous oscillations, and the above function group is used for this reason. This method used for spectral analysis is Fourier analysis. Any sine curve can be decomposed into sine and cosine
curves. It is obviously convenient to decompose a time series into oscillations to know how many of them are contained in it. A simple spectrum shows relative amplitudes (or, precisely, squared amplitudes) and wavelengths and periods of all regular components of a time series. Generally, the horizontal axis plots frequency (1/period) with highest values, i.e. shortest oscillations, on the right. If the data are a function of time, the frequency is measured in the number of cycles per unit time (for instance, cycles per thousand years). If a dimensional scale with sediment thickness or occurrence depth is used, some researchers use wave number (1/wavelength in thickness) instead of frequency. However, the term "frequency" is used most often, even if a unit does not contain a time component, e.g. cycles per metre. Spectral analysis consists in measuring amplitudes as positive and negative deviations from the zero line. However, although the zero line is in some cases defined as an average of data values, a more complex procedure involving cases with more complex trends is normally used. Generally, amplitude is plotted versus frequency to produce an amplitude spectrum. If amplitudes are low, their logarithms are used.

In this research, the fractal characteristics of the stratigraphic record are described by spectral analysis of two groups of objects. The first group is a data series representing the lithological properties (particle-size contents, carbonate content and magnetic susceptibility) of the Permian from the Monastery Ravine and Kzyl Bairak outcrops on the Volga river and from the Sheremetievka outcrop on the Kama river [17]. The second group is gamma-ray logs from the Permian of the Melekess trough in the interfluve between the Volga and Kama rivers [20].

It should be noted that time series, even those on a regular spatial grid, in geology are never set on a uniform time scale, e.g. because of sedimentation rate variations, if a stratigraphic record is assumed to be the basic series. This causes frequency modulation in the spectra [21]. Nevertheless, stratigraphic records contain numerous breaks, and this causes phase modulation. Non-linearity in geological time series usually causes amplitude modulation [21]. These effects can distort energy spectra and create additional harmonics in them. The resulting distortions can be easily identified by analysing the variability of spectra from different parts of the time series.

Apart from the MEM spectra, the aforementioned paper [17] presented Fourier spectra (Figure 5), which have been used for comparison with the MEM results, more precise determination of oscillation periods and identification of new statistical parameters to analyse the nature and features of the spectra of various lithological parameters in the studied sections. The resulting Fourier spectra have been approximated by a power function:

\[ E(f) = a^f f^\beta, \quad (2) \]

where \( f \) is the oscillation frequency in cycles per decimeter, \( a \) is the spectrum amplitude at the highest frequency, and \( \beta \) is the power exponent reflecting the degree of association between high- and low-frequency signals.
4. Results and Discussion

The Fourier spectra have been approximated by a power function (2) with $a$, $\beta$, $R^2$ values represented in Figure 5 and Table 2.

Substantial variability of the power exponent $\beta$ in spectra of various lithological data series for a particular rock sequence indicates that it probably contains useful information. This is confirmed by the fact that the same lithological parameters from different sequences have similar $\beta$ values. The minimum absolute $\beta$ values are observed for the most complex parameters: magnetic susceptibility and $\text{CaCO}_3/\text{MgCO}_3$ ratio. The maximum absolute $\beta$ values are observed in the sand content variation series. Other, relatively simple, lithological parameters (mud, silt and carbonate contents) have intermediate values [17].
Table 2. The Fourier spectra characteristics

| Sections             | Fourier spectra characteristics | Lithologic data | a       | β       | $R^2$ |
|----------------------|---------------------------------|-----------------|---------|---------|-------|
| Sheremeteivka        | Magnetic susceptibility $\chi$   | 0.6563          | -0.517  | 0.42    |       |
|                      | Sand fraction                   | 0.1335          | -0.8712 | 0.62    |       |
|                      | Silt fraction                   | 0.1254          | -0.7425 | 0.54    |       |
|                      | Mud fraction                    | 0.1494          | -0.7652 | 0.59    |       |
|                      | CaCO$_3$/MgCO$_3$               | 0.0423          | -0.6074 | 0.45    |       |
|                      | Carbonate content               | 0.1599          | -0.7317 | 0.53    |       |
| Kzyl Bairak          | Magnetic susceptibility $\chi$   | 0.1454          | -0.7194 | 0.53    |       |
|                      | Sand fraction                   | 0.0285          | -1.0805 | 0.70    |       |
|                      | Silt fraction                   | 0.0305          | -1.097  | 0.71    |       |
|                      | Mud fraction                    | 0.0581          | -1.0192 | 0.67    |       |
|                      | CaCO$_3$/MgCO$_3$               | 0.0037          | -1.0541 | 0.69    |       |
|                      | Carbonate content               | 0.067           | -0.9972 | 0.66    |       |
| Monastery ravine     | Magnetic susceptibility $\chi$   | 0.02086         | -0.5905 | 0.50    |       |
|                      | Sand fraction                   | 0.0126          | -1.3368 | 0.76    |       |
|                      | Silt fraction                   | 0.0209          | -1.1317 | 0.70    |       |
|                      | Mud fraction                    | 0.0246          | -1.1877 | 0.73    |       |
|                      | CaCO$_3$/MgCO$_3$               | 0.0058          | -1.0958 | 0.75    |       |
|                      | Carbonate content               | 0.0262          | -1.1868 | 0.70    |       |

No relationship between the value of power exponent $\beta$ and sequence thickness indicates a weak effect of the series length on $\beta$ value. The resulting $\beta$ values show that the data series studied by the authors fall into the interval between white noise ($\beta = 0$) and Brownian noise ($\beta = -2$). Fig. 6 illustrates the nature of the noise through the relationship between $|\beta|$ and $R^2$. This relationship can be approximated by numerous methods if $R^2 \leq 1.0$.

Obviously, the $R^2$ value cannot reach 1 because of the permanent noise. Both estimates – linear and logarithmic approximations shown in Figure 6: produce $\beta$ values close to 2, which is the result of decreased noise in the data and improved approximation of lithological spectra for the studied sections, showing that the analysed data series most probably represent processes similar to Brownian noise.
Figure 6. Relationship between absolute value of power exponent $\beta$ and $R^2$ for the studied sections, with linear approximation shown by the solid line and logarithmic approximation shown by the dashed line. Vertical interrupted lines indicate linear approximation estimates for $R^2 \approx 1$ ($|\beta| \approx 1.82$) and logarithmic approximation estimates for $R^2 \approx 0.86$ ($|\beta| \approx 2.0$).

An important finding in the paper by [17] is that the sand content variation series with higher absolute values of power exponent $\beta$ to a great extent reflect the primary structure of geological processes and can thus be used as parameters to identify major cycles in a section.

Another important finding in the spectral analysis of the above series of lithological parameters is thicknesses of cycles in the studied sections (Table 3).

| Sections         | Thickness, m | $T_1$, m | $T_2$, m | $T_3$, m | $T_4$, m | $T_5$, m | $T_6$, m |
|------------------|--------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Sheremetievka    | 82           | $\sim 12.6$ | -         | $\sim 20.7$ | $\sim 34.5$ | $\sim 87.3$ | -         |
| Monastery ravine | 148          | $\sim 12.8$ | $\sim 15.9$ | $\sim 21$ | $\sim 28.1$ | $\sim 62.0$ | $\sim 182$ |
| Kzyl Bairak      | 64           | $\sim 10.9$ | $\sim 16.5$ | -         | $\sim 31.2$ | $\sim 72.7$ | -         |

The relationship between $|\beta|$ and $R^2$ for the well data series shown in Figure 7 is similar to the relationship shown in Figure 6 and suggests that these data series represent processes that were initially close to Brownian noise.
Figure 7. Relationship between absolute value of the power exponent $\beta$ and $R^2$ for GR logs from the Kazanian penetrated by 37 wells in the Melekes trough, with linear approximation shown by the solid line and logarithmic approximation shown by the dashed line. Arrows indicate linear approximation estimates for $R^2 \approx 1$ ($|\beta| \approx 1.7$) and logarithmic approximation estimates for $R^2 \approx 1$ ($|\beta| \approx 1.99$).

Thus, spectra of GR variation series, representing sand and clay contents and having high absolute values of the power exponent $\beta$, can be used as an alternative to particle-size grading methods for the identification of cycles in a section.

5. Conclusions

In this paper, it is shown that cyclic sedimentological parameters, first of all, grain size, can be characterized in terms of spectral analysis to the interval 273 – 268 Ma.

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