ISOTOPIC MASS BALANCE OF METAMORPHIC FLUIDS IN THE GOGOŁÓW–JORDANÓW SERPENTINITE MASSIF, LOWER SILESIA, SW POLAND

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Abstract: This work aims at estimation of the amount of metamorphic fluids which led to the present-day variability of isotopic compositions, δD and δ18O, in serpentinites from the Gogółów–Jordanów Massif. This goal was achieved by means of a numerical model reproducing selected features of geological environment and a computer application supporting this model. The Gogółów–Jordanów Massif consists of peridotites transformed to a different degree into serpentinites and subject to brittle deformation that produced a complex fracture system. The potential tectonic control on the pattern of the fluid migration paths was investigated using palaeostress analysis based on slickenside measurements. Isotopic analyses were carried out for hydrogen and oxygen from serpentine, oxygen from magnetite, and hydrogen and oxygen from carbonates. The variability of δD and δ18O in the serpentinites along the modelled migration paths demonstrates that serpentinization of peridotites was caused by fluids derived from at least three sources revealing different isotopic characteristics. Fluids produced during the magmatic-hydrothermal stage played a major role in serpentinization, since they represent approximately 95% of all fluids interacting with the rock. In contrast, oceanic water represents only 1% of fluids involved in serpentinization. The calculated mean amount of fluid required for serpentinization of 1 m³ of peridotite is equal to 98·10⁶ kg.

Key words: serpentinization, stable isotope, tectonics, numerical modelling, Gogółów–Jordanów Massif, Lower Silesia, SW Poland.

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INTRODUCTION

For the last thirty years the vast amount of work has been done to document the origin, evolution and tectonic position of the Ślęza ophiolite complex (Majerowicz, 2006 and references therein). Consequently, there is no doubt today that the Ślęza complex represents a fossil remnant of ocean floor obducted on continental crust during the Variscan orogeny. Nevertheless, some open questions remain concerning the timing and mechanism of serpentinization that affected the ultramafic member of the Ślęza ophiolite. Uncertain is the source of serpentinizing fluids and the paths of their infiltration into the ultrabasic rocks. Some of these questions are addressed in the present paper that is focused on the mass balance of metamorphic fluids accompanying metamorphism of primary ultramafic rocks of the Gogółów–Jordanów serpentinite massif. Considerable progress in digital processing of data allows calculation of the mass of fluids (Taylor, 1977; Vollmer, 1976; Sverjensky, 1981; Zheng & Hoefs, 1993) using a channelized flow model (Fyfe et al., 1978; Thompson, 1987). A key role of the canalised fluid transfer in large-scale metamorphic processes, especially during serpentinization of ultramafic rocks and dehydration of serpentinites, is emphasized in the majority of up-to-date papers dealing with these issues (e.g., Oliver, 1996; Ord & Oliver, 1997; Barnes et al., 2004; Masters & Ague, 2005). Therefore, the model of fluid migration paths presented herein does not take into account the possibility of penetrative infiltration of fluids throughout the ultramafic rocks due to massive development of micro-cracks. The growth of such discrete fractures may be a consequence of volume-changing chemical reactions, connected for instance with hydration, resulting in local perturbations of the stress field (e.g., Watt et al., 2000; Malthe-Sørenssen et al., 2006). The common development of discrete fractures may produce local permeability changes that promote fluid flow. The modelling of fluid migration assisted by penetrative fracturing would require an application of the finite element method. However, this approach cannot be implemented to the presented numerical model.
Furthermore, any examples of fluid transport models successfully integrating canalised flow and penetrative migration are hitherto missing from scientific literature. The significance of the latter process has not been so far reliably estimated elsewhere and, thus, has been omitted here.

The modelling of the potential fluid paths was supported by a palaeostress analysis based on slickenside data, which were processed using Tectonics FP software. A simplified model of the Gogołów–Jordanów serpentinite massif was created to reconstruct the migration of fluids responsible for serpentinization. The model was implemented using a produced in-house computer application. The isotope data employed in the model were derived from laboratory analysis of oriented serpentinite samples. isotopic analyses of hydrogen and oxygen from serpentinite, oxygen from magnetite, and carbon and oxygen from carbonates were obtained for 173 samples.

**GEOLOGICAL SETTING**

**Śleża Ophiolite Complex**

Mafic and ultramafic rocks in the vicinity of the Śleża Mt. form a nearly complete ophiolite association including serpentinized peridotites, a narrow zone of metamorphosed ultramafic cumulates, metagabbros and metabasalt volcanic suite accompanied by a sheeted dyke complex (Majerowicz, 1979, 1981, 1984; Majerowicz & Pin, 1989, 1994; Pin et al., 1988). The Śleża ophiolite is in tectonic contact with the low-grade metamorphosed phyllites, cherts and radiolarites that adjoin the ophiolite complex from the north. In the south, the Śleża ophiolite borders on the Góry Sowie gneiss being separated from one another by a Neogene E–W trending fault system. According to Majerowicz and Pin (1989), the geochemical data suggest (1) the co-magmatic origin for all the ophiolite segments, (2) the occurrence of mafic cumulates, and (3) the resemblance to magmas generated in a MOR or back-arc setting. The estimates of δD and δ18O point to sea-floor metamorphism of the ophiolite (Jędrysek & Halas, 1989). During obduction of the ophiolite the metagabbros recorded the younger metamorphic overprint under greenschist facies conditions (Majerowicz et al., 2000; Floyd et al., 2002). Floyd et al. (2002) suggest, in contrast to the earlier studies (e.g., Majerowicz & Pin, 1989, 1994), that the differences between volcanic and plutonic members of the Śleża ophiolite preclude their affiliation to one coherent ophiolitic suite.

The Śleża ophiolite has been originally interpreted as individual intrusions of mafic and ultramafic magmas in their present-day setting (Finch, 1928; Teissseyre et al., 1960; Obere, 1972). Since the beginning of the 1980s, a consensus has been achieved that the Śleża ophiolite represents a vestige of oceanic crust (Majerowicz, 1979, 1981; Narębski et al., 1982; Majerowicz & Pin, 1986). Consequently, the tectonic models postulating the allochthonous position of the ophiolite began to predominate (Znosko,
The principal aim of the field work was mesostructural analysis and collection of samples for chemical, X-ray, and isotopic analyses. Both chemical and isotopic analyses were aimed at estimating mutual relationships between isotopic composition of hydrogen and oxygen and the orientation of brittle structures. Oriented rock samples were collected manually from previously measured joint surfaces and slickensided surfaces. Samples for isotopic analyses were treated mechanically to obtain powdered material.

Vacuum isotopic preparation is used to obtain selected elements derived from the rock in a gaseous state. The common feature of these procedures is cryogenic cleaning of the gases that enables measuring isotopic composition of the latter in a mass spectrometer. For isotopic analysis it is necessary to obtain hydrogen and oxygen from silicates, and carbon dioxide from carbonates.

Analyses of isotopic composition of oxygen and hydrogen were made in the Department of Isotopic Geology and Geocology of the Institute of Geological Sciences, University of Wroclaw, in the Laboratory for Mass Spectrometry of the Faculty of Physics and Applied Informatics of the AGH University of Science and Technology, as well as in the Department of Geological Sciences, Indiana University, Bloomington, USA. The Finnigan Mat delta E, Finnigan MAT 252, and Varian Mat CH7 spectrometers were used. Determinations of the carbonate contents and isotopic analyses of carbon and oxygen derived from carbonates were conducted in the Department of Isotopic Geology and Geocology, Institute of Geological Sciences, University of Wroclaw, using the Finnigan Mat delta E mass spectrometer.

**Numerical modelling**

The principal aim of this work was to construct and implement a digital model portraying the intensity of metamorphic fluid migration, with the use of isotopic mass balance. The model is mainly aimed at estimating the scale and directions of migration of serpentinizing fluids, as well as at explaining the interaction of these fluids with ultramafic rocks using the process of Rayleigh distillation. The model is based on a basic assumption of channelized fluid migration in the rock. The presented model is a static homomorphic model. The input data were discretised and subdivided into calculation blocks of identical spatial dimensions.

The main source of input data are pieces of information comprised in the data base, such as orientation of joints, slickensides and tectonic straie, as well as isotopic analyses of oriented samples. Taking into account complicated geological structure and the lack of possibilities of determining principal tectonic directions in the field, a method of clustering planar structures was used (Mydlowski & Jędrysek, 2004). Orientation of a given fracture set was determined basing on the angle comprised between the selected pairs of readings, i.e. the angle between vectors perpendicular to the fractures plotted on the Schmidt’s net. The angle was calculated in the following way:

For each pair of angles: azimuth of the dip $\alpha_i$ and dip $\beta_i$, the coefficients $x_i$, $y_i$, $z_i$ were determined:

$$x_i = -\cos \alpha_i \cdot \sin \beta_i$$
$$y_i = -\sin \alpha_i \cdot \sin \beta_i$$
$$z_i = \cos \beta_i$$

The angle between the selected pairs of measurements is (Mydlowski & Jędrysek, 2004):
\[
\gamma = \arccos \frac{x_1 \cdot x_2 + y_1 \cdot y_2 + z_1 \cdot z_2}{\sqrt{x_1^2 + y_1^2 + z_1^2} \cdot \sqrt{x_2^2 + y_2^2 + z_2^2}}
\] (2)

Determination of the average value of angle \( \gamma \) between the selected measuring point and the remaining points provides a basis for distinguishing individual groups of measurements, their number and spatial orientation.

In order to visualise the input structural data and the effects of their clustering, a tool was devised to project selected structures on the Schmidt’s net, enabling the immediate overview of readings collected from a given exposure.

Computational procedures used for each of the exposures made it possible to collect a set of data which embraces both orientation of the structures and the results of isotopic and chemical analyses. The data obtained provided a basis for defining sets of potential paths of metamorphic fluids. The presence of such paths is based on an assumption that fluids migrated through the rock massif utilising fractures, which, in gross part have been continuous and open for fluid migration (Jędrysek, 1989; Jędrysek & Halas, 1989). Such fractures could have represented potential paths of serpentinizing fluids, and their spatial distribution was analysed qualitatively. To determine privileged orientations of tectonic principal stresses in the Gogołów–Jordanów Massif, techniques of palaeostress analysis were used. These orientations were associated with the tectonic regime that existed during serpentinization of the rocks, and became a reference point for the results of modelling of fluid migration paths based on isotopic composition of minerals.

Visualisation of the respective stress field was made for the NDA (Spang, 1972), inversion (Angelier & Goguel, 1979; Angelier, 1979), and right dihedral methods (Angelier & Mechlér, 1977). To obtain the expected stress pattern at every point of the study area, the axes of maximum compression calculated for every exposure were interpolated for the entire study area. The same procedure was applied in relation to the minimum and neutral stress axes.

For the sake of the model, a temperature calculator was constructed basing on curves of a isotopic fractionation, enabling fast conversion of the coefficient of a isotopic fractionation into the \( \Delta \) value and vice versa. It is also possible to read temperatures at a given value of \( \Delta \), i.e. the coefficient of isotopic fractionation basing on a selected curve for a known temperature. Interactive plot of \( \Delta \) vs. \( T \) portrays the trend of selected curves of isotopic fractionation in the required temperature range. Moreover, a possibility exists to select the required curve from the library of isotopic fractionation curves obtained from the SIFC (Stable Isotope Fractionation Calculator; Beaudoin & Therrien, 2004) and from other sources, what enhances the model flexibility and makes the choice of a given curve much more reliable (e.g., Wenner & Taylor, 1973; Sakai & Tsutsumi, 1978; Graham et al., 1980, 1987; Satake & Matsuo, 1984; Saccocia et al., 2001) at a stage of model construction. The temperature calculator is active in other tasks of the model, being then activated without the graphic part providing only the results of calculations.

Application of the Rayleigh distillation model made it possible to determine the extent and variability of \( \delta D \) and \( \delta^{18}O \) of the rock and fluid in respect to the temperature and advancement (F) of the reaction (Rayleigh, 1896; Hoefs, 1996; Valley & Cole, 2001). In order to determine the molar proportions of water/rock interactions, the geochemical and structural parts of the model were used. Both the initial isotopic composition, as well as the temperature and water-to-rock molar ratio of the solution entering the massif represent unknown values. The base of determination of the water-to-rock ratio is the set of values of \( \delta D \) and \( \delta^{18}O \) of the rock, arranged according to a given fluid migration path, i.e. in the order of the progressing reaction. There is a link between each pair of the \( \delta D \) – \( \delta^{18}O \) values of the rock and a given point on the surface of the study area. Using an iterative technique, the shape of curvature of the model variability of \( \delta D \) – \( \delta^{18}O \) was applied to the real course of \( \delta D \) – \( \delta^{18}O \) from a given migration path through the relevant change of temperature of reaction, the initial isotopic composition of the solution, and the water-to-rock ratio. The result is given together with the degree of fitness (Lomnicki, 1999) to the set of real values of \( \delta D \) and \( \delta^{18}O \), showing that fragment of the migration path which meets the assumed criteria of the goodness of fit. Visualisation marks the selected fragment of the fluid migration path in a 3D view of the study area.

The proposed model makes it possible to trace relationships between individual areas of the studied serpentine massif, the temperature of serpentinization, and mutual share of the given water types in shaping the recent isotopic composition of hydrogen and oxygen of the serpentinites. For each path occupying the known surface of the study area, it is possible to calculate the rock mass, which, together with the known water-to-rock molar ratio makes it possible to determine the minimal mass of serpentinizing fluid entering the massif. Moreover, knowing the remaining fraction of fluid, \( F \), at each point of the study area, it is possible to calculate the intensity of serpentinization and probable sites of fluid vanishing.

An application was constructed which enabled proper activity of the model calculating the isotopic mass balance of serpentinizing fluids. When constructing this application, the extreme programming was used (eXtreme Programming, XP), except the pair programming. The program in uncompiled version includes 16,120 code lines.

RESULTS AND DISCUSSION

In this paper, I used 511 measurements of fractures and slickensides, as well as 102 oriented samples collected from 37 exposures. Together with additional analyses, 76 isotopic analyses of hydrogen from the group OH, 52 oxygen analyses of silicates, 11 oxygen analyses from magnetite, and 34 isotopic analyses of carbon and oxygen from carbonates were made.

The results of hydrogen isotopic analyses (\( \delta D \)) of serpentinite rocks vary from −102.3 ‰ to −13.4 ‰, whereas those of the Ślęża gabbros bordering from the north the Gogołów–Jordanów Massif range between −49.6 ‰ and −2.9 ‰. The highest values of \( \delta^{18}O \) of serpentine attain 11.15 ‰, the lowest is 1.45 ‰. For the gabbros, the \( \delta^{18}O \)
values are 7.32 ‰ and 5.48 ‰, respectively. From some samples, it was possible to obtain magnetite, the d oxygen values of which ranged between 0.44 ‰ and 5.85 ‰. Differences of hydrogen \( \Delta (\delta_{\text{max}} - \delta_{\text{min}}) \) from serpentine between samples oriented in the scale of individual exposures, are remarkable (Fig. 2).

**The water-to-rock molar ratio in relation to the Rayleigh distillation**

Before incorporating hydrogen particles from the fluid into ultramafic rock during serpentinization, the water-to-rock molar ratio (W/R) should be close to infinity for the hydrogen, and after the reaction is finished it should approach zero (all hydrogen reacted with the rock). However, the hitherto used formula for the W/R ratio (Taylor, 1977), directly applied to the Rayleigh distillation model, implies that this ratio will never attain the entire range of values (\( \infty:0 \)).

Attempts at determining the W/R ratio, using the rule published by Taylor (1977) in relation to the Rayleigh distillation, were unsuccessful. According to the author, the W/R ratio at the onset of reaction of serpentinizing fluids is approximated best by the following formula (Mydłowski, 2006):

\[
\frac{W}{R} = \frac{(\delta_{\text{rrz}}' - \delta_{\text{rrz}})}{(\delta_{\text{rrz}} - \delta_{\text{rrz}}')} 
\]

where:

- \( \delta_{\text{rrz}}' \) and \( \delta_{\text{rrz}} \) are the initial and final, respectively, genuine isotopic composition of the rock measured in a sample,
- \( \delta_{\text{rrz}}' \) is the initial isotopic composition of the fluid = the final expected composition of the rock (the final isotopic rock composition resulting from the Rayleigh distillation model).

The water-to-rock molar ratio will attain values derived from a set of real positive values. Knowing W/R values before the isotope exchange reaction starts is of crucial importance in estimating the amount of fluid reacting with the rock and its further influence on metamorphism.

A summary characterizing potential possibilities of channelized fluid migration (Fyfe et al., 1978; Thompson, 1987) in the Gogół–Jordanyów Massif (Jędrzejek, 1989; Jędrzejek & Halas, 1989) is shown in Fig. 3.

A number of scenarios including different origin, their amounts and temperatures of reaction with the rock, which could have led to the present values of \( \delta_{D} \) and \( \delta^{18}O \) may be generated. Therefore, it was assumed that if recent isotopic composition of serpentinites of the Gogół–Jordanyów Massif can be achieved at the lowest possible number of fluids and at the greatest possible amounts of the latter. Hence, the modelling started with the most simple scenario, including one-stage serpentinization.

![Fig. 2. Comparison of \( \Delta (\delta_{\text{max}} - \delta_{\text{min}}) \) hydrogen and oxygen values in the serpentine between oriented samples at the single outcrop scale](image1)

![Fig. 3. 3D view of the migration path of serpentinized fluids from selected path’s group on the background of geological map. The squares explain the local orientation of joint surfaces. The black curves shows predictable direction of the migration paths through the Gogół-Jordanyów Massif. The selected outcrops are also marked](image2)
One-stage serpentinization

The aim of one-stage modelling of serpentinization of the Gogołów–Jordanów Massif is to explain isotopic variability of hydrogen and oxygen in the most simple, possible way. Should this model be true, it would contradict the results obtained by other authors, who applied different methods (Jędrysek & Sachanbiński, 1994). One stage of serpentinization means that the recent isotopic composition of the rock (\(\delta D\) and \(\delta^{18}O\)) originated in each migration path due to reaction with a defined amount of fluid, genetically associated with one source and of known temperature of reaction (Fig. 4).

Two-stage serpentinization

A two-stage model of serpentinization should enable the reaction of rock masses with two fluids of any isotopic composition (\(\delta D\), \(\delta^{18}O\)), temperature, and the amount of \((W/R_{H_2O})\). The fluid entering the massif in the second stage reacts with the rock of isotopic composition modified by a fluid of the first stage. The two-stage modelling should be preceded by verification whether the presence of two fluids is sufficient to change isotopic composition of ultramafic rock (\(\delta D\), \(\delta^{18}O\)) to the present-day state (reverse modelling), keeping the \(\delta D\) and \(\delta^{18}O\) values of delivery sources known from natural environment. This can be verified by using graphic construction shown in Fig. 5.

Multi-stage serpentinization

A model of multi-stage serpentinization should enable one to examine the vulnerability of isotopic composition of the rock (\(\delta D\), \(\delta^{18}O\)) to changes resulting from \(\delta D\) and \(\delta^{18}O\) of water, temperature of reaction, and molar ratios \((W/R_{H_2O})\) for several consecutive stages. It is associated with the influence, on the same rock mass, of several, consecutive serpentinizing fluids of variable isotopic composition (\(\delta D\), \(\delta^{18}O\)), different temperature, and the amount of \((W/R_{H_2O})\). Fluid of the following, younger stage modifies isotopic

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**Fig. 4.** Graphic interpretation of water-to-rock molar ratio in the \(\delta D - \delta^{18}O\) space with marked initial isotopic composition of the rock, variability \(\delta D\) and \(\delta^{18}O\) of rock from selected migration path, and adjusted to model \(\delta D\) and \(\delta^{18}O\) of the rock. Explanations: \(\delta_{w}^{18}O\), \(\delta_{w}^{18}D\) – initial and final real isotopic composition of rock, respectively – isotopic composition from the rock-sample measured; \(\delta_{rrz}^{18}O\), \(\delta_{rrz}^{18}D\) – initial isotopic composition of fluid = final expected isotopic composition of rock (final isotopic composition of rock according to Rayleigh distillation); \(\delta_{rocz}^{18}O\), \(\delta_{rocz}^{18}D\) – initial expected isotopic composition of rock; \(\delta_{roz}^{18}O\), \(\delta_{roz}^{18}D\) – final expected isotopic composition of the rock.
composition of the rock, already altered by fluids active during previous stages of serpentinization. In this sense, the molar ratio W/R(H2O) acquires a new meaning, constraining molar proportions of water from a given stage of serpentinization in respect to the rock altered by previous fluids.

The basic task preceding multi-stage modelling consists in verifying whether the presence of at least three fluids is sufficient for changing isotopic composition (δD, δ18O) of ultramafic rock to the present-day state (reverse modelling), maintaining at the same time the δD and δ18O values of delivery sources found in natural environment. Fig. 6 shows graphic interpretation of such a verification.

Each of three isotopic delivery sources A, B, C can be located at a point (δD, δ18O), whose deviation (ΔD, Δ18O) from the isotopic composition of the rock is inversely proportional to the W/R molar ratio (W/RW, W/RB, W/RC). The ΔD/Δ18O ratio is dependent on molar proportions between hydrogen and oxygen within the fluid and the rock. In case of pure distilled water, this proportion equals to 2. This figure may insignificantly shift depending on the solution’s pH: rising at low pH, and falling at high pH. The hydrogen/oxygen molar ratio for peridotite approaches zero, while for serpentine it is close to 2/7 (Taylor, 1974). Moreover, each of three isotopic delivery sources A, B, C is limited by environmental constraints. The pattern presented in Fig. 6 implies that contemporary isotopic composition (δ18O and δD) of serpentine, as a combined product of isotopic delivery sources, could have originated due to the influence of three sources: oceanic, magmatic, and meteoric. It was accepted that δ18O and δD values of meteoric water (source C) match those of the Wrocław water (Duliński et al., 2001). Water of magmatic origin has the greatest share in modelling variability of δ18O and δD in serpentine, owing to high W/RB ratio, while waters of oceanic and meteoric origin are of minor importance. Assuming that source B is compatible with isotopic composition of metamorphic or formation waters of lower δD and higher δ18O ranges, the W/R ratio of source B would be lower, and fractions of A and C sources should increase, to obtain the same joint product of δ18O and δD, typical for serpentine. The model shown in Fig. 6 is a general one, and does not take into account all factors controlling the real isotopic composition of

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**Fig. 5.** Arrangement of two fluid sources with respect to hypothetic fluid source determined in one-stage serpentinization model

**Fig. 6.** Test of possibility to obtain the present values of oxygen and hydrogen isotopic composition in serpentine through modification with alteration of three sources of serpentinizing fluids
the flu ids ac tive in serpentinization, like, for in stance, those of tem per a ture or vari abil ity of \( d^{18}O \) and \( d^D \) of the rock along fluid mi gra tion paths. \( d^D \) and \( d^{18}O \) val ues of t he se rpentinizing flu ids in a 3-stage m odel of serpe ntinization of a se lected mi gra tion path in the Gogo³ów–Jordanów Mas sif are plot ted in Fig. 7.

Tem per a tures of re ac tion and mo lar ra tios W/R cal cu lated with equa tion (3) are also given. The re sults are true for a migration path run ning from the south-eastern edge of the serpentinite massif towards its centre (Fig. 8).

Know ing mo lar re la tion ships of each stage of serpen tinization, it is pos si ble to cal cu late the to tal mass of fluid s active in meta mor phic al ter ing of the se lected frag ment of the Gogo³ów–Jorda–nów Mas sif.

INFLUENCE OF CO\(_2\)-BEARING FLUIDS ON THE CONTENT OF CARBONATES

Nu mer ous au thors tried to build mod els ex press ing the mode of rock-\( CO_2 \)-bear ing fluid in ter ac tion (Rye & Wil liams, 1981; Matsuhisa et al., 1985; Zheng, 1990). Some mod els as sume the bal anced re ac tions fluid-rock (Zheng & Hoefs, 1993), what is not the case in the Gogo³ów–Jordanów Massif. How ever, none of the solu tions known to the au thor ac cept dif fer en ti a tion of the iso to pic \( d^{13}C \) and \( d^{18}O \) com po si tion of the rock and fluid bas ing on the Ray leigh dis til la tion. Dur ing an at tempt of cal cu la tion of the mass of \( CO_2 \) and de ter mining their source of or i gin, the same rules were used which accompa nied mod el ling of the bulk fl ow of the fluid com posed of water. Since the well-calib rated curve for car bon for magnesite-\( CO_2 \) is not known, the curve of iso to pic frac tion ation, a, for of do lo mite-\( CO_2 \) (Sheppard & Schwarcz, 1970; Ohmoto & Rye, 1979) was used, due to close resem blance of both curves (Weber-Weller, 2000; Gartzos, 2004). Moreover, the amount of carbonates within the rock was taken into account. Comparing the amounts of
calcite and magnesite dispersed in the serpentine, it is likely to see that magnesite constitutes the main carbonate phase, particularly when the amount of carbonate minerals within serpentinite increases.

**PATTERN OF TECTONIC STRESSES IN THE GOGOŁÓW–JORDANÓW MASSIF**

The compressive stresses axis is oriented east-west and shows shallow plunge. Its orientation implies horizontal compression, oriented E–W to NE–SW in the SW part of the massif. The trajectories of $s_1$ stress mark the preferred strike orientation of extensional joints and faults, which are potential paths of fluid migration. Compression axes determined by the inversion method are, unlike those obtained from the NDA method, clearly deflected from the east-west orientation, and in the eastern part trend to parallel the serpentinite-gabbro boundary. On the other hand, the axis of tectonic stress is nearly vertical, pointing to small thickness of the overburden during deformation. High values of R coefficients for the NDA method and F coefficients for the inversion method indicate considerable elongation of stress ellipsoids.

**CONCLUSIONS**

Isotopic analyses of oriented samples collected from the Gogółów–Jordanów Massif, together with measurements of planar structures and a computer-generated model of the channelised isotopic fluid-rock interaction, allow calculation of the isotopic mass balance. Basing on the variability of $\delta^13D$ and $\delta^{18}O$ values for serpentinites along the paths of fluid migration it was found that serpinentization of peridotites was driven by fluids derived from at least three sources of different isotopic characteristics. The three following stages of serpinentization were distinguished that were assisted by oceanic, magmatic-hydrothermal and meteoritic waters.

1. The magmo-hydrothermal fluids played the dominant role in the serpinentization of peridotites since they constituted ca. 95% of the total mass of fluids, whereas the mass of oceanic water accounts to ca. 1% of the total mass of fluids.

2. To serpinitize 1 m$^3$ of rock, ca. $98 \cdot 10^4$ kg of fluid was necessary. The intensity of isotopic exchange between the fluid and the rock within a migration path, portrayed by the water-to-rock molar ratio, is strongly differentiated, and recalculated into the mass of fluid changes between $44 \cdot 10^3$ kg/m$^3$ to $56 \cdot 10^5$ kg/m$^3$ of the rock.

3. Strong differentiation in the intensity of isotopic exchange within a single migration path was observed: the activity of fluids diminishes with fluid migration along the path and sometimes drops to zero, leaving the rock unaltered.

4. Fluids bearing CO$_2$ most probably migrated vertically. The $\delta^{13}C$ values of dispersed magnesites point to a close relationship with endogenic sources. In the western part of the massif, $\delta^{13}C$ of dispersed magnesites attains a broader range of values compared to that of the eastern part, suggesting the influx of CO$_2$-bearing fluids from several feeding isotopic sources.

The compatibility of migration paths with the trajectories of compressive stresses in the Gogółów–Jordanów Massif points to a decisive role of fractures and faults in the infiltration of serpinentizing fluids.

The presented results do not directly imply a tectonic setting for serpinentization. Instead, they allow estimation of a source of fluid that was apparently dominated by hydrothermal waters. This corollary does not necessarily mean that serpinentization occurred in a continental setting. Hydrothermal waters could have potentially altered the earlier
isotopic composition of serpentine acquired during sea-floor metamorphism. In such a case, the present isotopic composition would represent a later stage of hydration that was active during and/or after obduction of the Ślęża ophiolite.

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