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Late burial dolomitization of the Devonian carbonates and a tectono-thermal evolution of the Holy Cross Mts area (Central Poland)

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Abstract: The Middle to lower Upper Devonian crystalline dolomites of the Holy Cross Mts were formed by a replacement of platform limestones and the recrystallization of eogenetic, facies-controlled dolomicrites. Stratigraphical data, petrological observations and the results of 1-D basin modelling are consistent with late burial dolomitization during the Carboniferous (340-305 Ma) predating the main phase of Variscan deformation.

Keywords: Holy Cross Mountains, Devonian, dolomitization, burial history

Introduction

The Devonian dolomites of the HCMts have been studied for more than a century (see the historical review in Narkiewicz 1991) but their origin is still disputable. According to the present author, the origin of dolomicritic and microdolosparitic varieties was controlled by depositional and early diagenetic (eogenetic) processes, whereas fine to coarse dolosparites were formed due to late burial (mesogenetic) replacement and recrystallization (Narkiewicz 1990, 1991, Narkiewicz et al. 2006). The alternative interpretation assumed synsedimentary, submarine hydrothermal origin for all the dolomite types (Migaszewski 1990, 1991). The present paper briefly summarizes previously reported- and unpublished data and interpretations contributing to the question of dolosparites origin. The new investigations included additional field observations, petrological studies (mostly stable isotopes, SEM and CL data), and 1-D basin modelling.

Regional and stratigraphic framework

During the Devonian and Carboniferous, the Holy Cross Mts were located in the foreland of the Variscan Orogen of Central and Western Europe (Narkiewicz 2007). Following the Late Carboniferous tectonic deformations and the ensuing Early Permian uplift, they were incorporated into the Late Permian-Mesozoic Mid-Polish Trough (Kutek & Głazek 1972), striking NW-SE along the margin of the East European Platform (Fig. 1). This depocentre was uplifted at the turn of Cretaceous and Paleocene, and the resultant erosion exposed the Palaeozoic core of the HCMts. Since then, the region has formed a part of an elevated area separating the northern Carpathian basins and the Carpathian Foredeep from the Eocene to Pliocene epicontinental basins of central-northern Europe.

The Palaeozoic core is subdivided by the WNW-ESE striking Holy Cross Fault (HCF) into southern and northern (Łysogóry) regions that differ in their Early Palaeozoic tectono-stratigraphic development (Dadlez et al. 1994). During the Devonian, the HCF was a distinct palaeogeographic boundary (Fig. 1). It separated the more stable Southern Region with lower subsidence and depositional rates from the northern one characterized by two to three times the thickness of sediment accumulation and generally more open and/or deeper marine facies. The development of a restricted shallow-marine carbonate shelf started in both regions near the Early-Middle Devonian boundary. This shelf soon evolved into a coral-stromatoporoid platform that was terminated in the north due to a deepening pulse and the related onlap of marly open-marine facies already in the late Eifelian. In the southern area, the carbonate platform persisted up to the earliest Frasnian when it became aerially limited to the Dyminy Reef complex developing through the middle Frasnian (Fig. 2). In the western HCMts, the Kostomłoty area (Fig. 1) displays a transitional development, with the main drowning episode in the Middle Givetian, probably related to the subsidence of a fault-controlled block (Fig. 2).

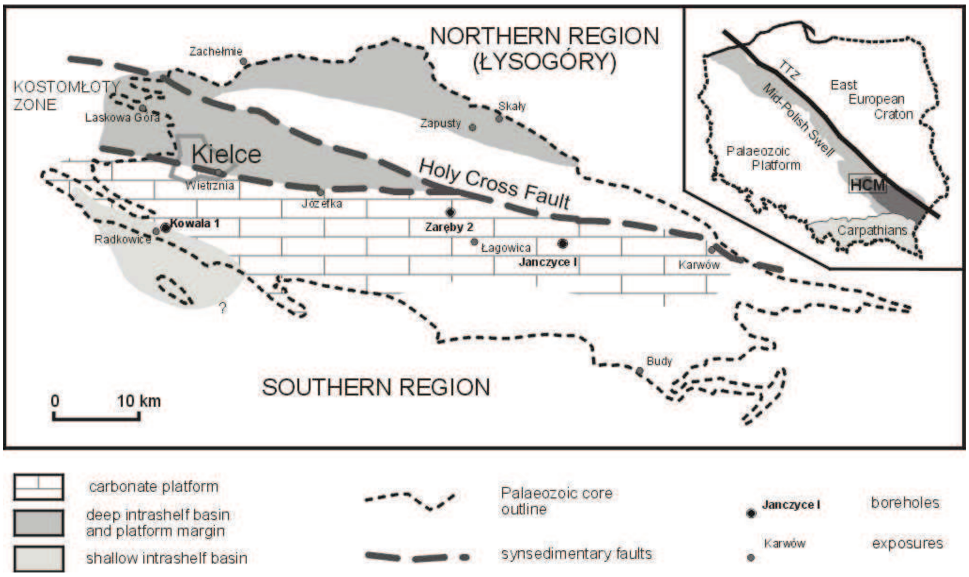

Fig. 1. Schematic palaeogeography of the Holy Cross Mts. during approximately Middle-Late Devonian transition. Indicated are key sections in which stable isotopic composition of the Devonian dolomites has been investigated. The inset map of Poland shows setting of the study area within the framework of major regional geological units.

The early stage of the Middle Devonian carbonate platform development corresponds roughly to the Eifelian in the south and to a lower part of the stage in the north. It is represented by well-bedded marly dolomicrites typically lacking open-marine fossils. The sediments are characterized by irregular microbial or parallel horizontal lamination, mud-cracked surfaces and erosional levels with intraclasts. It is overlain by the Kowala Fm. (Narkiewicz et al. 1990, Narkiewicz & Narkiewicz, in print) composed mostly of coral-stromatoporoid and other shallow-marine platform limestones or crystalline dolostones. The subordinate dolomicrites and dolomicrosparites mostly form the upper parts of lower-order shallowing-upwards cycles.. In the Southern Region, the crystalline dolostones display a characteristic regional geometry in a cross-section perpendicular to the HCF (Fig. 2). Their upper boundary cross-cuts the general pattern of the depositional architecture of the Givetian to Frasnian carbonate platform and the Dyminy Reef complex. It reaches its highest stratigraphic position along the norther margin of the region, ranging up to the lowermost Frasnian while the thickness of the complex attains 300-400 m. Its top is stratigraphically lower southwards, lying in the middle and, probably also, lower Givetian. In the Kostomłoty area, the entire upper part of the Middle Devonian carbonate platform succession is developed as crystalline dolomites. In the Łysogóry Region, the crystalline dolomites tend to form thick and continuous bodies in the lower part, whereas they are irregularly interspersed with dolomicrites and limestones upwards in the sections (e.g., Narkiewicz & Narkiewicz, in print; Skompski & Szulczewski 1994).

On a meter- to decimeter-scale, the dolosparites show a complex pattern of cross-cutting and replacive relationships along the horizontal or lateral contacts with the overlying limestones (Narkiewicz 1990, 1991). In this more or less gradual replacement zone, selectively dolomitized ramose stromatoporoid (*Amphipora*) biostromes, selectively replaced micritic matrix of stromatoporoids and corals, and relatively sharp horizontal contacts of dolosparite with overlying shaly/marly beds are common.

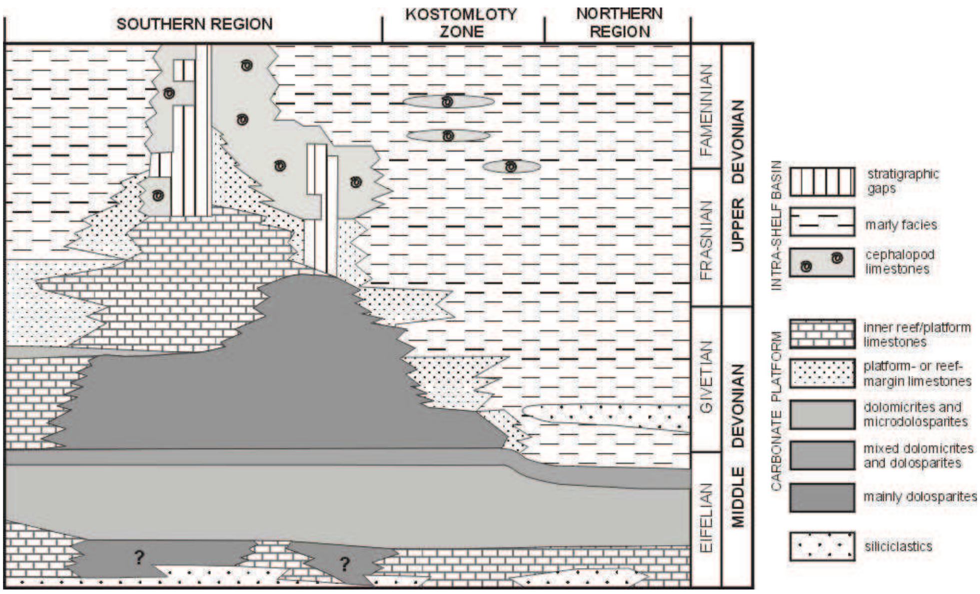

Fig. 2. Position of the crystalline dolomites within the stratigraphic-facies framework of the Middle to Upper Devonian in a schematic south-north cross-section (western Holy Cross Mts.).

Petrology of crystalline dolostones

The crystalline dolomites include both matrix mosaic- and drusy cement varieties. The former variety is generally composed of anhedral to subhedral fine- to medium-sized low-Fe dolomite crystals with a common range of 50-300 µm. In many cases, it shows minute ("dusty") inclusion patterns mimicking replaced limestone fabrics. This allows the recognition in thin-section of such features of replaced limestones as peloids, fossil remains or fenestral structures, as well as later structures, notably calcite veins. Matrix-type dolomite is typically non-luminescent or weakly luminescent. It is nearly stoichiometric containing 50-54 mol% $CaCO_3$; an average of 30 samples is 51.2 mol%. The trace elemental composition of a carbonate fraction shows enrichment in Fe and Mn relative to replaced limestones (based on ca 40 samples). The enrichment in silica (bulk composition) and in Fe, Mn, Sr and Na in a carbonate fraction is characteristic particularly for the upper part of the crystalline dolomites, transitional to the overlying limestones (Narkiewicz 1990; 1991).

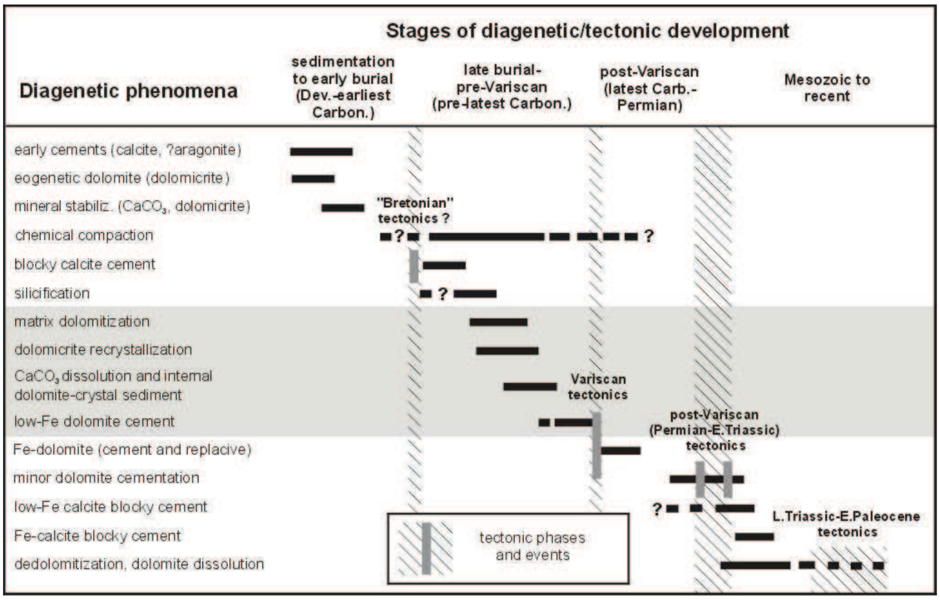

Fig. 3. Succession of most important diagenetic phenomena and tectonic events that affected the Middle Devonian to Frasnian carbonates in the Holy Cross Mts. Grey horizontal strip highlights processes related to the main phase of pervasive dolomitization.

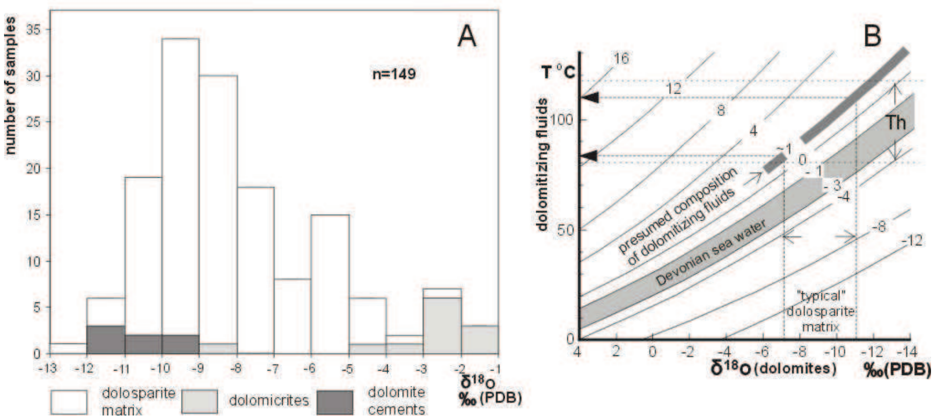

Fig. 4. Oxygen isotope compositions of the Middle Devonian to Frasnian dolomites in the Holy Cross Mts. (A), and interpretation of temperatures and isotopic compositions of dolomitizing fluids (B) after Land (1983). Th – range of fluid-inclusion homogenization temperatures in dolosparites. Range of $\delta^{18}O$ for a Devonian sea water – cf. van Geldern et al. (2006).

The dolosparites are commonly fractured and display irregular millimeter- to centimeter-sized vugs and, more rarely, intercrystalline porosity. The large pores can often be attributed to dissolved organic skeletons, mainly those of stromatoporoids and corals.

They are often filled with geopetal internal sediment composed of dolomite crystals, and by several generations of dolomite and calcite cements (Fig. 3). The dolomite cements include low-Fe types (mainly earlier generations) and Fe-dolomites (typically outer rims). The crystals are typically centimicron- to millimeter-sized, commonly saddle-shaped and with a complex pattern of CL zoning. Commonly, the oldest zones are non-luminescent or dull-luminescent and the intermediate zones show alternating bright and dull zones enveloped, in turn, by non-luminescent, high-Fe zones. CL studies also reveal subsequent generations of variably-luminescent original- or recrystallized cement, but their volumetric importance and regional distribution is limited.

Thin sections reveal a common recrystallization of dolomicrite which is irregularly replaced by a mosaic of fine- to medium crystalline dolomite difficult to distinguish from a product of $CaCO_3$ replacement. CL observations also document replacement or recrystallization of dolomite cements by later-phase irregular differently-luminescing dolomite which otherwise is not recognizable in thin section.

The dolomitization-related phenomena, outlined above, of replacement, dissolution, internal deposition, cementation and recrystallization have been related to other diagenetic and tectonic features in order to place them in the proper temporal context of the geological evolution of the Devonian strata. The paragenetic succession (Fig. 3) demonstrates that the matrix dolosparite development and dolomicrite recrystallization postdate carbonate mineral stabilization and the blocky calcite cements, including those filling tensional fractures of probable tectonic origin. They also postdate onset of chemical compaction processes as is demonstrated by a partial obliteration of horizontal residual clayey seams and stylolite sutures. On the other hand, matrix dolosparite is cross-cut by tectonic fractures attributable to Variscan (late Carboniferous) tectonism. This is consistent with the observation that geopetal dolomitic sediments in vugs are tectonically tilted together with enclosing dolosparite beds that are, in turn, truncated by a nearly horizontal Variscan unconformity in, e.g., Zachełmie Quarry (Narkiewicz & Narkiewicz, in print). Most of Fe-dolomite cements postdate the matrix dolomitization and ensuing tectonic features. Late calcite blocky cements and minor latest generations of dolomite cements are even younger. The post-Variscan tectonics (probably Permian to Early Triassic) is indicated by fractures, partly filled with late blocky Fe-calcite, that cross-cut late dolomite- and calcite cement generations. The widespread dedolomitization phenomena selectively affected mainly Fe-dolomite. They can be related to post-Variscan erosion and/or to Paleogene and later exhumation of the Palaeozoic core of the HCMts.

Oxygen and carbon isotopes have been studied in ca 150 samples from 13 sections covering broad stratigraphic intervals of Devonian dolomites throughout the entire HCMts. area (Fig. 1). In contrast to a narrow range (-1 to 1 ‰) of rather indistincive $\delta^{13}C$ signatures, three general dolomite categories are characterized by distinct $\delta^{18}O$ values. The dolomicrites (excepting a single sample) show values between -5 and -1 ‰, mostly -3 to -1 ‰ (Fig. 4A). Assuming a slightly negative $\delta^{18}O$ (-3 to -1 ‰) for Devonian sea-water (van Geldern et al. 2006), this gives a temperature range 25-45°C consistent with surface temperatures in the Devonian tropics (Fig. 4B). The $\delta^{18}O$ signature of the matrix dolosparite is predominantly between -11 and – 7 ‰ (Fig. 4A). Fluid inclusion homogenization measurements, based on 64 samples of the crystalline dolomite, gave a range of Th values between 80.5 and 117.5°C. Coupled with the above $\delta^{18}O$ range, this allows the $\delta^{18}O$ of the dolomitizing solutions to be estimated as ca 1 ‰, thus pointing to a slightly elevated salinity relative to the Devonian sea-water.

Although $\delta^{18}O$ in dolosparite matrix displays roughly normal distribution around median values of -10 to -8 ‰, a considerable proportion of the dolosparites shows elevated values in the range -7 to -4 ‰ (Fig. 4A). These dolomites are here interpreted as recrystallized dolomicrites with an isotopic signal partly preserving the memory of the original sediments.

The $\delta^{18}O$ signatures in a few (7) investigated dolomite cements show relatively low values between -12 and -9 ‰. Assuming $\delta^{18}O$ of the dolomitizing fluids as ca. 1 ‰, the temperatures of crystallization can be estimated to lie in the upper half of the determined Th range, i.e. 100-120 ^{o}C (Fig. 4B).

The strontium isotope data are fewer (about 20 analyses) and less conclusive than the oxygen investigations (Narkiewicz et al. 2006, and unpublished data). There seems to be a good negative correlation between $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ for dolosparite matrix. This would suggest a radiogenic strontium contribution increasing with increasing temperature of dolomitizing solutions. $^{87}Sr/^{86}Sr$ in two investigated dolomite cements was found to be higher than in any matrix dolosparite; this is consistent with the depleted $\delta^{18}O$ data. Nevertheless, micrites display a wide range from expected marine values close to 0.708 to elevated radiogenic signatures of ca. 0.71, the latter found in the Łysogóry Region.

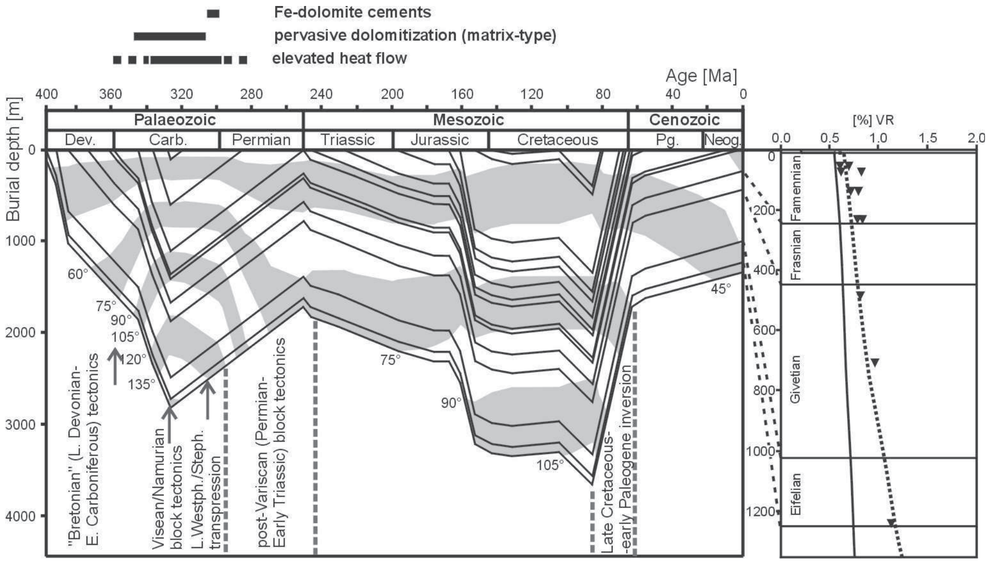

Fig. 5. Modelled burial-thermal history of the Devonian to recent time-interval based on the Janczyce I borehole section. Graph on the right shows calibration with the vitrinite reflectance (% VR) data and the best-fit curve (see the text for further explanations). Time scale after Gradstein et al. (2004).

Dolomitization and tectonothermal evolution of the area

The fluid inclusion homogenization temperatures and the palaeotemperatures derived from the oxygen-isotope composition of the crystalline dolomites were tested against an independently obtained model of the burial-thermal history for the Janczyce I borehole section (located in Fig. 1). The modelling was performed with Marta Resak and Ralf Littke in the RWTH Aachen using PetroMod 1-D software. The results of this study will be the subject of a separate publication.

The Permian to Cretaceous stratigraphic input for the modelling included sediment thickness reconstructed by Dadlez et al. (1998). The Carboniferous stratigraphy was reconstructed basing mainly on Żakowa & Migaszewski (1995). The Carboniferous evolution is particularly speculative as the existence and magnitude of tectonic phases is hypothetical due to the incompleteness of the sedimentary record. We assumed onset of uplift due to vertical block movements near the Early-Late Carboniferous boundary. The uplift continued into the Late Carboniferous, when major transpressional Variscan deformations occurred, and on through the Permian involving several phases of block movements. The modelling results are consistent with heat flow elevated to 70-80 mWm^{-2} during the Late Carboniferous and progressively decreasing in the Early Permian to recent values of ca. 50 mWm^{-2}. Elevated Variscan heat flow was earlier postulated based on the thermal maturity pattern in the Devonian (Belka 1990; Marynowski 1999). The alternative interpretation, assuming Mesozoic thermal events (Poprawa et al. 2005) was not confirmed.

The best-fit model for the Janczyce I section is presented in Fig. 5. According to the model, the Middle Devonian carbonates attained temperatures higher than 80°C at depths of ca. 1.5 km in the Early but not the earliest Carboniferous. This is consistent with the post-Bretonian (i.e., postdating the Devonian-Carboniferous boundary) onset of dolomitization (Fig. 3). The strata remained buried at depths of ca. 1.5-2.5 km at temperatures >80°C until the Early Permian when the temperatures started to decrease in line with uplift and erosion. Paragenetic studies have shown that the upper time limit for the regional pervasive dolomitization is imposed by the late Westphalian tectonics. The temporal relationship between the Viséan/Namurian movements and dolomitization has not been established yet. The 100-120°C temperature window defined above for late Fe-dolomite cements is limited to a narrow time interval in the latest Carboniferous, post-dating the terminal Variscan transpressive tectonism.

Conclusions: a genetic model

Sedimentological characteristics as well as petrological features and stable isotope geochemistry, confirm that the dolomicrites composing the bulk of the early Middle Devonian lithofacies were formed in shallow-marine, more or less restricted depositional environments, comprising vast carbonate mud-flats and lagoons. The source of Mg was normal or slightly altered sea-water at temperatures of 25-45°C.

The crystalline matrix-type dolomites were formed by replacement of diagenetically-mature Middle Devonian to lower Frasnian platform limestones and recrystallization of eogenetic dolomicrites. The temperature of the dolomitizing fluids was in the range 80-120°C based on fluid inclusion and oxygen isotope data. The relative enrichment in heavy O and Sr isotopes and in reduced Fe and Mn, suggests that the fluids were saline brines of reducing character. These were, presumably, formation waters evolved due to pressure solution processes and interactions with carbonates (including eogenetic dolostones), clay minerals and quartz. Results of 1-D basin modeling, coupled with the isotope data and reconstructed paragenetic susccession, allows constraining of the probable age of dolomitization to ca. Viséan – early Westphalian with burial depths in a range 1.5-2.5 km.

A regional subsurface fluid circulation pattern is required for a large-scale pervasive dolomitization in order to supply large amounts of Mg from relatively diluted water-solutions occurring in natural systems. Spatial correlation between the zone of elevated heat flow along the HCF on one hand, and the maximum range of dolomitization on the other, suggests thermal convection as a probable mechanism of circulation. An additional factor enhancing Mg supply could have been compaction-driven flow towards the buried northern margin of the Middle Devonian-Frasnian carbonate platform (Fig. 2). Both of these mechanisms were earlier proposed by the author (Narkiewicz 1990; 1991).

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