Summary of Professional Accomplishments

1. Name

   Marcin Dąbrowski

2. Diplomas, degrees conferred in specific areas of science or arts, including the name of the institution which conferred the degree, year of degree conferment, title of the PhD dissertation

2008	PhD degree in the specialization field of geophysics conferred by the Department of Physics at the Faculty of Mathematics and Natural Sciences, University of Oslo Title of dissertation: "Anisotropy and heterogeneity in finite deformation - resolving vs. upscaling", supervisors: Prof. Yuri Y. Podladchikov, Dr Daniel W. Schmid, opponents: Prof. Neil Mancktelow, Prof. Viggo Tvergaard.
2004	MSc degree in Physics (specialization field: geophysics), Institute of Geophysics, University of Warsaw Master thesis title: "*Numeryczne modelowanie tekstur deformacyjnych*" ["Numerical modelling of deformation textures"], supervisor: Prof. Dr hab. Leszek Czechowski.
2002	MSc degree in Geology (specialization field: prospecting geology), Institute of Geological Science, University of Wrocław Master thesis title: "PT and structural constraints on Variscan exhumation of eclogites in Śnieżnik Massif", supervisor: Prof. Dr hab. Stanisław Mazur.

3. Information on employment in research institutes or faculties/departments or school of arts

2013 – rec	chief specialist, Polish Geological Institute – National Research Institute
2015 – 2019	researcher (20 %), Department of Geology, University of Oslo
2012 – 2014	researcher, Centre of Excellence (until 2013) Physics of Geological Processes, University of Oslo
2008 – 2012	postdoctoral fellowship, Centre of Excellence Physics of Geological Processes, University of Oslo

4. As the achievements, set out in art. 219 para 1 point 2 of the Act, I present a cycle of six scientific articles related thematically.

a) title

Numerical modelling of the development of selected ductile deformation structures under simple, pure and combined shear

b) list of publications in the presented cycle

The presented cycle comprises six thematically related scientific papers published in journals belonging to the list A of the Polish Ministry of Science and Higher Education

A1. Exner U., **Dabrowski M.** Monoclinic and triclinic 3D flanking structures around elliptical cracks (2010) *Journal of Structural Geology*, 32 (12), 2009-2021

Citation count: 17(12)*	Impact Factor: 1,911**	MNSiW points: 32(100)***

* citation count, excl. autocitations in brackets
** 5-year IF in the publication year
*** MNSiW points in the publication year, in brackets points according to the 2019 point list

My contribution to the publication included:

(1) designing numerical simulations, (2) deriving analytical expressions describing the velocity field around an elliptical slip surface, (3) implementing and optimizing the numerical code capable of simulating the development of three dimensional deformation structures around rotating slip surfaces in shear zones, (4) deriving novel analytical expressions, including the evolution of the relative offset along the slip surface in the limiting 2D case, (5) performing numerical simulations and selecting and analysing their results, (6) presenting numerical results in graphical form, (7) discussing the results, (8) participating in manuscript preparations, (9) participating in the revision and final editing of the article

A2. **Dabrowski M.**, Grasemann B. Domino boudinage under layer-parallel simple shear (2014) *Journal of Structural Geology*, 68, 58-65

Citation count : 20(18)	Impact Factor: 2,884	MNSiW points: 30(100)

My contribution to the publication included:

(1) conception of the work and design of the methodology, (2) adjusting own numerical codes based on the finite element method to periodic models, (3) performing systematic numerical simulations, (4) numerical result analysis, (5) presenting numerical results in graphical form, (6) discussion and interpretation of the results, particularly in the context of the kinematic analysis of shear strain magnitude, (7) preparing the manuscript (excluding the chapter on natural examples), (8) revision of the article and final editing.

A3. Grasemann B., **Dabrowski M.** Winged inclusions: Pinch-and-swell objects during high-strain simple shear (2015) *Journal of Structural Geology*, 70, 78-94

Citation count: 13(12)	Impact Factor: 2,084	MNSiW points: 35(100)

My contribution to the publication included:

(1) participation in conceptual work and design of the methodology, (2) adjusting own numerical codes based on the finite element method to non-linear materials, (3) performing systematic numerical simulations, (4) designing and implementing tools to automatically analyse numerical results, (5) numerical result analysis, (6) presenting numerical results in graphical form (figures and animations), (7) participation in discussion of the results, (8 preparing some parts of the manuscript and commenting on the rest of the manuscript, (9) participation in the revision of the article

A4. Adamuszek M., **Dabrowski M.** Sheath fold development in monoclinic shear zones (2017) *Terra Nova*, 29 (6), 356-362

Citation count: 2(1)	Impact Factor: 2,229	MNSiW points: 35(100)

My contribution to the publication included:

(1) research concept of studying the impact of general shear on the morphology of sheath fold developing around slip surfaces, (2) participation in literature study, (3) numerical code preparation and optimization for calculating structure evolution around slip surfaces under general shear, (4) participation in the development of unique initial model configurations for general shear conditions, (5) result analysis and discussion, (6) participation in the preparation of the manuscript and the final revision of the article

A5. Grasemann B., **Dabrowski M.**, Schöpfer M.P.J. Sense and non-sense of shear reloaded (2019) *Journal of Structural Geology,* 125, 20-28

Citation count: 4(3)	Impact Factor: 3,128	MNSiW points: 100(100)

My contribution to the publication included:

(1) participation in discussions on the conception of work, (2) numerical code preparation and performing numerical simulations, (3) preparing numerical result presentation in graphical form, including supplementary animations, (4) participation in result analysis and discussion, (5) preparing the manuscript fragment about finite element modelling, (6) commenting on the manuscript, (7) participation in the revision of the article

A6. **Dabrowski M.**, Grasemann B. Numerical modelling of boudinage under pure shear: implications for estimating viscosity ratios and finite strain from natural examples (2019) *Journal of Structural Geology,* 126, 109-128

Citation count: 1(1)	Impact Factor: 3,128	MNSiW points: 100(100)

My contribution to the publication included:

(1) conception of the work and design of the methodology, (2) literature study, (3) preparation of numerical tools, (4) performing systematic numerical simulations, (5) numerical results analysis and selection, (6) designing the method of estimating strain and rheological parameters based on the detailed geometric analysis of boudins, bow-tie veins, and scar-folds, (7) preparing numerical result presentation in graphical form, (8) discussing the results in the light of the previous research, (9) preparing the manuscript (excluding the chapter on natural examples), (10) revision of the article and final editing

Net Impact Factor of the cycle *	15,364
Net MNSiW points of the cycle**	332 (600)

* 5-year IF from the publication year
** MNSiW points from the publication year, in brackets points from 2019 rating

c) author's commentary on the presented publication cycle

Introduction

Quantitative analysis of rock deformation is one of the basic tasks of tectonics and structural geology. Both brittle and ductile deformation structures carry a lot of information about the deformation path, and the results of micro- and mesostructural analyzes are a valuable contribution to recognizing the history of large-scale tectonic movements. The Curie principle, which postulates symmetry of causes and effects, forms the foundation of quantitative structural analysis. According to it, the spatial symmetry of deformation structures reflects the symmetry of the causative factors, allowing for deciphering the kinematics of deformation (Sander, 1930; Paterson & Weiss, 1961). Research on the symmetry of deformation structures in rocks, as well as their orientation towards geographical directions, have become deeply rooted in structural analysis and still constitutes one of its basic research tools.

In the next stage, the kinematic analysis tailored to the large deformation regime, which is characteristic of ductilely deformed rocks, were leading the way. Quantitative assessment of strain magnitude proved extremely fruitful and was at that stage the "driving wheel" of structural research. The theoretical foundations of kinematic analysis applied to structural geology were laid out in the textbook "Folding and fracturing of rocks" (Ramsay, 1967), which, having been updated in the form of several successive editions, had a huge impact on the environment of structural geologists. The classical kinematic analysis in structural geology owed its success to a relatively simple formulation. One of its important simplifying assumptions was the adoption of a homogeneous medium model, which allowed the use of analyses based on a constant field of deformation, without the need to solve differential equations of the continuum mechanics.

Parallel to the development of the kinematic analysis, as early as in the 1950s, there appeared publications describing theoretical works (e.g. Biot, 1957), analogue modelling (e.g. Ramberg, 1955), and a little later also pioneering numerical studies (e.g. Strömgård, 1973), whose aim was to explain the physical mechanisms of the formation of tectonic structures such as folds, or boudinage, which develop in unquestionably heterogeneous geological media. Over time, a growing gap could be observed between the supporters of classical kinematic models and the advocates of more complex, but with solid physical bases, mechanical models. In the following years many of the disputed issues were agreed upon, but the echoes of these discussions have returned to this day (Fletcher and Pollard, 1999), sometimes taking a rather turbulent form (e.g. Passchier et al., 1992).

The period when structural analysis flourished was the end of the 1970s and 1980s. At that time, based on numerous field observations of ductile deformation structures occurring within the shear zones, a systematic classification of kinematic shear sense indicators was developed (Berthé et al., 1979; Simpson & Schmid, 1983; Passchier & Simpson, 1986). This concept, on the one hand, combined the achievements of kinematic analysis, especially in the area of progressive non-coaxial deformation such as simple shear, and on the other included the then knowledge about the behaviour of heterogeneous objects in high shear zones, which at that time was based primarily on theoretical analyzes (e.g. Ghosh and Ramberg, 1976) and analogue models (e.g. Van Den Driessche and Brun 1987). In the follwing decades, mechanical models for the evolution of ductile tectonic structures in shear zones were theoretically established, and also strongly developed due to increasingly accurate numerical simulations (Bjørnerud & Zhang, 1995; Bons et al., 1997; Ježek et al., 1999; Mandal et al., 2000; Schmid & Podladchikov, 2004; Marques et al., 2005; Dabrowski & Schmid, 2011; Griera et al., 2013). After entering the new millennium, modern techniques of three-dimensional imaging of structures, such as computer microtomography (Fusseis et al., 2014), as well as high-resolution, efficient and precise methods of measuring the local orientation of the crystallographic network of minerals based on electron microscopy became a great support for structural analysis (Prior et al., et al., 2009).

Modern microtectonic analysis has emerged from synergies between field observations, supported by modern imaging methods, theoretical models and numerical and analogue simulations (Passchier and Trouw, 2005). In the arsenal of its tools, in addition to the already classic, qualitative techniques of assessing the direction and sense of shear, there are also quantitative methods for estimating the magnitude of deformation, including its degree of non-coaxiality (Xypolias, 2010). The recent achievements in the field of analysis of classical tectonic structures such as buckling folds are worth noting (Schmalholz and Podladchikov, 2000; Adamuszek et al., 2013; Schmalholz and Mancktelow, 2016). Modern quantitative analysis of fold morphology allows a reliable assessment of the shortening amount in the deformed medium. It is also inseparably associated with the estimation of viscosity ratios between the materials forming the layer and its surrounding, may in effect act as natural rheometers (Schmalholz & Podladchikov, 2001; Adamuszek et al., 2011). It should be emphasized that the viscosity ratios deciphered in this way reflect the relationships between the non-linear parameters of rock flow under natural conditions of usually an extremely low rate of deformation, which for practical reasons is unattainable during laboratory tests.

Before describing the main research objectives of the work, the results of which constitute the scientific achievement discussed, the author of this paper will be tempted to briefly present his own perspective on contemporary challenges and open problems of analysis of ductile deformation structures. Cylindrical buckling folds or numerous varieties of boudinages are characterized by fairly well-shaped translational symmetry and as a result, with good approximation, they can be treated as two-dimensional structures. However, many other types of tectonic structures, such as typical for shear zones σ- and δ-clasts, or sheath folds, are undeniably characterized by three-dimensional morphology. This poses a number of research challenges, particularly in terms of their description in the field, where only their two-dimensional cross-sections are usually available for direct observation. Despite the huge development of modern 3D imaging techniques, their use in structural analysis is still rare, in part due to their high cost. Numerical simulations of complex three-dimensional deformation structures are still a technical challenge, despite the constant increase in the power of modern computing servers. Both the appropriate representation of the complex geometry of evolving three-dimensional structures and the need to use computational grids with a huge number of computational nodes are the problem in this case. Additionally, numerical solution of systems of linear equations associated with the discretization of 3D problems is, for strictly algebraic reasons, a more difficult task compared to solving 2D problems. All these factors mean that 3D modelling often requires reaching for quite complex, although strongly developing, techniques of parallel and distributed computing on large server clusters. As a result, many problems in structural geology have still not been systematically studied using three-dimensional numerical simulations. Thus, the deformation paths of some groups of tectonic structures are still quite poorly recognized, and their analysis is limited to the use of basic theoretical models, which most often only cover the regime of small deformations. An attractive alternative to numerical models may be the analogue modelling technique, but it is often associated with difficulties in reproducing proper deformation conditions, selecting appropriate materials, and also in eliminating a number of undesirable factors such as boundary effects. In addition, in the case of analogue 3D models, the technical challenge is to depict the development of structures in time and space. All these difficulties sometimes result in a retreat from mechanical models and development of heuristic kinematic models in their place (eg Bastida et al., 2005).

The technical difficulties discussed above are most likely temporary and can be expected to be gradually overcome with the further development of numerical methods, an increase of computing power and improvement of analogue modelling methods. Another major challenge we are currently facing is the need to properly capture the complex microscopic mechanisms of dislocation and diffusion creep, along with a number of associated processes such as dynamic recrystallization. Macroscopic models of rock deformation nowadays used in structural geology are often based on fairly elementary isotropic rheological laws for either linear or non-linear fluids. It is natural that each model is a deliberate simplification of reality and its usefulness should be primarily determined by its ability to produce predictions consistent with field observations or experimental results. Hydrodynamic models based on simple isotropic fluids have undoubtedly been a great success in structural geology, explaining the physical mechanisms behind the development of many ductile tectonic structures (e.g. Johnson and Fletcher, 1994). In the opinion of the author, it is an incorrect approach to completely negate dynamic models using an excuse that they do not take into account the full spectrum of the complexities observed in nature (e.g. Aerden, 2005). However, one should agree with the opinions indicating that rock deformation may differ from simple hydrodynamic flows, and factors such as rheological non-linearity, multi-level heterogeneity of rock media, as well as mechanical anisotropy associated with both the macroscopic texture such as layering as well as the crystallographic fabric (microtexture) may play an important role. All this suggests that ductily deforming rocks should be treated as non-linear and anisotropic fluids with memory. In the opinion of the author, the 21st century will be a period of further proliferation of computer simulations of deformation processes using realistic rheological models for rocks, as well as taking into account the coupling between mechanical processes and chemical reactions. Improved models of ductile deformation structures may lead to highlighting their importance as natural rheometers and, in effect, help determine the mechanical parameters of rocks, such as viscosity, which due to the time scale of their natural creep are not directly verifiable under laboratory conditions.

The systematic recognition of the evolution of selected ductile deformation structures developing in a broad spectrum of background shear conditions was the main research goal of the presented scientific achievement. Particular attention was paid to their usefulness for shear sense analysis, strain magnitude and type estimation, as well as the assessment of viscosity ratios. In the course of conducted works, the development of deformation structures forming around slip surfaces was analyzed, including two-dimensional flanking structures, extensional crenulation cleavages, and three-dimensional sheath folds in rocks subjected to general shearing. Winged inclusions, which belong to the category of rotating tectonic inclusions that develop in highly non-coaxial shear zones, as well as torn boudinage structures reworked under simple or pure shear were also studied. Computer simulations performed using own, tailored numerical tools, supported by analytical solutions and theoretical analyses were the basic research method. The conducted research was developed based on selected field observations. The presented results are an original scientific achievement and broaden and systematize our knowledge about the mechanisms of development of ductile deformation structures. As a result of the work carried out, i.a., new models for the development of sheath folds and winged inclusions in shear zones have been proposed, and the development of a new class of structures of the ductilely reworked budinage has been theoretically envisaged. The results described in the presented publication suite will be discussed after a brief description of the ductile deformation structures relevant to this work, as well as after a brief presentation of the methodology used.

Ductile deformation structures

Ductile deformation structures, including the crystallographic fabric, provide an observational foundation for structural analysis of metamorphic rocks. The issues related to the development of ductile structures have been addressed in a number of works including specialized textbooks (e.g., Passchier and Trouw, 2005), review articles (Goscombe et al, 2004; Mukherjee, 2014a; Zhang and Fossen, 2020), and albums with field and microscopic observations (Mukherjee, 2014b; Vernon, 2018). They are also extensively discussed in modern textbooks on structural geology (Pollard and Fletcher, 2005; Fossen, 2016). It is worth recalling that the analysis of ductile micro- and meso-tectonic structures provides valuable clues and keys to understanding the origin of large-scale structures, where more complex, brittle-ductile deformation mechanisms, sometimes involving elasticity as well as gravity, may play an important role. At the turn of the 1980s and 1990s, review studies reflecting the then state of knowledge about microstructural kinematic analysis and evolution of ductile deformation structures appeared in the Polish literature (Cymerman, 1989; Achramowicz and Cymerman 1992; Aleksandrowski, 1992). Selected issues related to microstructural analysis are also briefly discussed in Polish textbooks on structural geology (Kuzak and Żaba, 2011) and tectonics (Dadlez and Jaroszewski, 1994), as well as in scripts and online materials related to tectonics courses. Nevertheless, in the authors' view, there is a noticeable lack of a modern textbook in the Polish language, which would comprehensively discuss the state-of-the-art of ductile deformation structures, and in particular systematize their terminology. Below, only a brief discussion of structures relevant to the presented scientific achievement will be presented.

Flanking structures

Flanking structures are a highly differentiated group of structures, which occur within ductile shear zones. They typically take the form of gentle deflections, which may, however, develop into more tightly folded shapes. The development of flanking structures has been connected with the activity of slip surfaces (Grasemann and Stüwe, 2001; Passchier, 2001), whose role may be played, among others, by reactivated crack surfaces or mineral veins filled with material of reduced viscosity with respect to the host shear zone. The initial orientation of the slip surface and the degree of non-coaxiality of background deformations, which is conventionally characterized by kinematic vorticity number (Truesdell, 1953), have a major influence on the initial stage of development of flanking structures. The orientation of the slip surface with respect to the eigenvectors of the rate of deformation tensor determines the current sense of slip, and in particular its relation to the background shear sense. In the case of simple shear, the slip on surfaces inclined to the shear direction at an angle between 45° and 135° is antithetical, while it is synthetic in the case of the remaining orientations. These sectors always have a total range of 90° and their exact span depends on the orientation of the principal axes of the rate of deformation tensor, which, in turn, depend on the proportion between pure and simple shear in the background flow.

Under large strain deformation, the slip surface is also subject to deformed. The concept of rotating and stretching or shortening slip surfaces was already developed in the 1980s in application to faults (Means, 1989). In a homogeneous medium, the deformation of the slip surface is passive, similarly to the behaviour of material surfaces. The bisector lines of the previously discussed sectors of antithetical and synthetic slip separate subdomains in which the slip surface is under either instantaneous shortening or stretching. The distribution of the synthetic and antithetical sectors of slip surface rotation is slightly more complex. In the case of simple shear, all slip surfaces, regardless of their orientation, rotate synthetically. On the other hand, a complementary sector of antithetic rotation may occur in the case of general shear. The extent of this sector increases with an increasing pure shear component in the background deformation. The sectors of synthetic and antithetical rotation of the slip surface are delimited by the eigenvectors the velocity gradient tensor, which are generally oblique to each other. These eigenvectors have been named repulsor and attractor because they represent directions of "repulsion" (repulsor) and "attraction" (attractor) of the flow lines due to the background flow.

The rotation of the slip surface may change the sense of slip, which is a key factor responsible for a rich morphology of flanking structures. For a typical initial orientation of the slip surface, which corresponds to the direction of mode I fractures, a transition from initially antithetic to late-stage synthetic slip is observed for background simple shear. With a less inclined initial orientation, an additional phase of synthetic slip may appear in the initial stage, leading in effect to a three-stage structure development. Based on the relation between the sense of total offset on the slip surface and the background shear sense, antithetic and synthetic types of flanking structures were distinguished (Wiesmayr and Grasemann, 2005). It should be stressed that the observed final sense of offset is a cumulative result of its several-stage evolution and does not necessarily reflect the slip sense in the last stage of structure development. In analogy to the classification of faults, the analysis of displacement on the slip surface allows for distinguishing extensional and compressional flanking structures. Both normal and reverse drag can be observed in the vicinity of the slip surface, which is another important classification criterion for flanking structures (Wiesmayr and Grasemann, 2005). Contrary to common views, it is more typical for reverse drag than normal drag to develop in the initial stage of structure evolution. However, it should be stressed that the curvature sense may vary along the slip surface (Grasemann et al., 2005). As in the case of the offset, the final deflections of the foliation in the vicinity of the slip surface are the effect of a multistage evolution of the structure, which may lead to the development of quite complex morphologies at a late stage of their development (Exner et al., 2004).

Grasemann et al. (2003) proposed a mechanism of formation for synthetic structures of the extensional crenulation cleavage (shear bands) type based on the model of development of flanking structures under general shear conditions. Synthetic offsets of significant amplitude may develop due to slow rotation of slip surfaces with initial orientation close to the repulsor direction. The usefulness of flanking structures for the shear sense analysis, the determination of kinematic vorticity number and finite strain estimation has been analyzed in several publications (Grasemann and Stüwe, 2001; Grasemann et al., 2003; Kocher and Mancktelow, 2005; Gomez-Rivas et al., 2007). Similarities and differences between ductile flanking structures growing around strongly rotating and stretching slip surfaces in shear zones and fault-related folds that develop in shallower, more brittle sedimentary basin environments were also discussed (Wiesmayr and Grasemann, 2005).

Sheath folds

Due to intensive studies of shear zones carried out at the turn of the 1970s and 1980s, the occurrences of strongly non-cylindrical folds, whose axis often took the direction parallel to the mineral stretching lineation, have been widely documented (Carreras et al., 1977). Both the size and geometry of sheath folds vary greatly (Alsop and Holdsworth, 2004), and later studies have shown that their growth can occur in a wide range of geological environments, from shear zones in metamorphic rocks, to strongly deformed salt diapirs and slamps in unconsolidated sediments (Alsop et al., 2007). Sheath folds have been described in Poland, among others, in metamorphic formations of the Góry Sowie (Owl Mts) Massif (Cymerman, 1990) and the Śnieżnik Massif (Cymerman, 1992) in the SW Poland, as well as within salt diapirs in the Polish Lowlands (Burliga, 2014) and in the rocks of the Upper Silesian Coal Basin (Teper, 1998).

The development of sheath folds is primarily associated with zones of intensive, non-coaxial shearing (Cobbold and Quinquis, 1980). The occurrence of eye structures in cross-sections perpendicular to their elongation is the diagnostic feature of sheath folds. Based on the geometric features of the contours forming the eyes, Alsop and Holdsworth (2006) proposed a quantitative method of shear fold classification. The method was based on the ratio between the aspect ratios of the external and internal contours in the eyes. They presented a summary of measurements of the proposed geometric indicator and correlated them with the Flinn parameter K of the strain ellipsoids that were determined by independent methods for the examined shear zones.

Early models of sheath folds development emphasized the role of passive amplification of initial perturbations of the foliation, as well as perturbations of the deformation field itself due to the presence of rigid, corrugated walls of shear zones (Cobbold and Quinquis, 1980). In later years, a model of sheath fold developing as a result of a perturbed flow field around a rotating rigid inclusion in a shear zone was proposed (Marques and Cobbold, 1995). In A1, which belongs to the presented suite of research papers, the possibility of sheath fold development around elliptical slip surfaces was suggested. This model was developed and systematically studied for the simple shear case in later publications (Reber et al., 2012; Reber et al., 2013a; Adamuszek and Dabrowski, 2017). In particular, a link was sought between the geometric parameters of the sheath folds, which were determined according to the classification framework presented by Alsop and Holdsworth (2006), and finite strain, and also other parameters such as the initial orientation of the slip surface or its elongation. All the previously mentioned analyses of sheath fold formation are based on the model of passive folding, without the activity of buckle folding. The process of sheath fold development in a mechanically layered medium, effectively exhibiting viscous anisotropy, was studied in numerical (Kocher and Mancktelow, 2006) and analogue experiments (Reber et al., 2013b).

Tectonic inclusions in shear zones

A number of interesting ductile tectonic structures are associated with isolated porphyroclasts or more generally tectonic inclusions deformed within shear zones. These objects can be subject to both rotation and internal deformation and their behaviour depends largely on their rheological contrast with respect to the surrounding medium. Numerous theoretical studies as well as numerical simulations and analogue experiments have allowed for the quantitative analysis of deformation paths of ductilily deforming tectonic inclusions depending on their initial shape and background deformation (e.g. Mancktelow, 2013). In the case of objects with high relative viscosity, their dynamics is largely limited to synthetic rotation, whose instantaneous rate depends on their elongation and current orientation to the shear direction (Ghosh and Ramberg, 1976). Under general shear conditions, the inclusions can stabilize and develop a steady-state orientation, which depends on their orientation. As a result, statistical analysis of the orientation of large populations of rigid, rotating clasts can be used to determine the kinematic vorticity number in shear zones (Simpson and De Paor, 1993; Jessup et al., 2007). In the case of objects with monoclinic symmetry, such as mica fish, antithetic rotation and subsequent stabilization may occur even in the case of simple shear (e.g. Ceriani et al., 2003).

The perturbation of the velocity field around rotating inclusions in shear zones leads to the development of characteristic asymmetrical structures, referred to as the rolling structures, whose importance for the kinematic analysis of shear sense was already recognized in the 1980s (Van Den Driessche and Brun, 1987). The rotation of porphyroclasts is often accompanied by dynamic recrystallization of their rims, which results in a progressive "erosion" of the inclusion core and the introduction of a low viscosity recrystallized material into the surrounding matrix. The progressive rotation of clasts results in the formation of strongly asymmetrical δ-clast structures at a low rate of recrystallization, while σ-clasts develop when the rate of recrystallization is high (Passchier and Simpson, 1986). These structures are among the flagship kinematic shear sense indicators and have been repeatedly used to reconstruct the kinematics of shear zones, including those occurring in Poland (e.g. Mazury and Puziewicz, 1994). It is worth mentioning that the recrystallizing rim with low relative viscosity can influence the rotation rate of the clasts, often leading to their stabilization (Schmid and Podladchikov, 2004). Complex types of asymmetric structures may occasionally be observed around porphyroclasts, including the so-called pressure shadows, which develop due to the activity of pressure solution and reprecipitation in a deforming rock. Detailed classification of recrystallizing and deforming porphyroclasts in shear zones, and related structures, together with a discussion of the mechanisms of their formation, has been presented in the textbook "Microtectonics" by Passchier and Trouw (2005).

Reworked torn boudinage

Tectonic boudinage occurs in a very wide range of length scales, ranging from single mineral grains to typical outcrop scale occurrences to large crustal-scale structures. The initial development of boudinage is most often associated with the process of fracturing and fragmentation of competent rock layers under the influence of compression oriented at a high angle to their elongation (Ramberg, 1955). The related layer-parallel stretching leads to a gradual separation of the boudins together with a ductile deformation of the surrounding medium, which is sometimes accompanied by filling the inter-boudin space with the products of metamorphic segregation or even rock melting (Ghosh and Sengupta, 1999). At this stage of structure development, the boudins themselves may also be subject to deformation and this type of ductilily reworked boudinage has been the subject of research work carried out within the framework of this scientific achievement. Previous experiments (e.g. Ramberg, 1955; Mandal and Khan, 1991) and numerical simulations (Lloyd and Ferguson, 1981; Samanta and Deb, 2014; Samanta et al., 2017) revealed the influence of a number of factors on the degree of separation, orientation and final shape of reworked boudins. Effects related to initial fracture orientation and density, the initial orientation of the layer, non-coaxiality of background deformation and rheological contrast between the layer and its surroundings were analysed. Despite such complex effects, reworked boudins have been used as shear sense indicators finite strain gauges, and to infer the kinematic vorticity number (e.g. Mandal et al., 2007; Maeder et al., 2009), as well as rheological contrast (Treagus et al., 1996; Samanta et al., 2017).

Based on a detailed analysis of the boudin morphology from numerous natural occurrences of boudinage, Goscombe et al. (2004) constructed an extensive classification scheme of boudinage structures, including boudinage reworked under the influence of progressive or later imposed deformations. It should be stressed that the number of conditioning factors and the complexity of the mechanisms active during boudinage reworking cause considerable difficulties in attempts to develop a coherent classification scheme. Torn boudinage develops under the conditions of brittle layer fragmentation, as opposed to drawn boudinage, which is produced under a strong component of ductile deformation already in the initial stage. With progressive stretching of the boudinaged layer, under ductile deformation, torn boudinage, which is initially angular, takes on barrel shapes (Ramberg, 1955). The barrels exhibit concave inner faces, which separate the adjacent boudins, and convex outer ones. Depending on the rheological contrast and the amount of the stretch, a wide spectrum of boudin morphology is observed (Samanta and Deb, 2014), including fish-mouth and lensoidal boudins.

During the progressive ductile reworking of the boudinage layer, slip may occur at the inner faces between the adjacent boudins. The slip sense compared to the background shear sense is the basis for distinguishing two genetic variants of asymmetric boudinages: shear band boudinage and domino boudinage. It should be noted that the boudin asymmetry can be related both to the reworking of the boudinaged layer under the influence of non-coaxial deformation and to the initially oblique fractures between the boudins. The initial fracture orientation, in addition to the elongation of the boudins and the viscosity contrast, is an important factor influencing the rotation and deformation of the boudins. For the opposite initial fracture orientations, asymmetrical structures with different rotation and slip sense may develop, effectively mirroring each other. Additional complications may arise due to the initially oblique layer orientation with respect to the principal flow directions, resulting in boudin rotation even under pure shear. Thus, great caution is needed when using asymmetrical boudinage for shear sense analysis (Passchier and Druguet, 2002; Goscombe and Passchier, 2003).

Research methodology

The basic research method used during the realization of the discussed works were computer simulations, which were performed with the use of own numerical tools, implemented in the computing environment of MATLAB. Closed-form analytical expressions were used to calculate the velocity field, which was used for analyzing the development of flanking structure. The closed-form expressions were obtained using a triple limit of an analytical solution describing the displacement field in an isotropic elastic medium around an ellipsoidal heterogeneity (Eshelby, 1959). In the first step, the solution was adapted to the case of an incompressible medium by taking the Poisson's coefficient in the limit of ½. According to the so-called correspondence principle (Biot, 1954), the obtained elastic solution directly corresponds to the solution for a viscous medium by interpreting the displacement field as the velocity field. Subsequently, the obtained expressions were adjusted to the case of an elliptical rather than ellipsoidal inclusion (in the limit of a vanishing length of one of its principal axis) with negligible viscosity (the limit of zeroing the viscosity ratio between the inclusion and the matrix), which corresponds to the case of a friction-less slip surface. The discussed derivations were described in detail in the appendix to work A1.

The conducted numerical simulations of three-dimensional flanking structures are based on a combination of a code for calculating the rotation and deformation of the slip surface and a code for determining the velocity field in its surroundings. Calculation of the velocity field requires taking into account the current shape of the slip surface and its orientation towards the background flow directions. The passive evolution of the slip surface ensures that it maintains its elliptical character, which allows for a successive calculation of the velocity field based on the derived analytical expressions. The analysis of the development of deformation structures was carried out with the use of adaptive integration of the trajectories of points located around the slip surface. Due to the three-dimensional nature of the structure and the related large size of data, as well as the presence of quite computationally complex operations, a number of optimizations were applied, which allowed for a significant reduction of calculation time.

Analytical methods cannot be directly applied to modelling the evolution of complex, heterogeneous structures such as winged inclusions or boudinage reworking. To analyze their development, systematic, two-dimensional computer simulations based on the so-called mixed formulation of the finite element method for the incompressible Stokes flows (e.g. Elman et al., 2014) were conducted. Numerical research was carried out using own codes implemented in the MATLAB environment, based on the optimized MILAMIN code, which has been developed since 2006 (Dabrowski et al., 2008; www.milamin.org). Due to the development of quite complex shapes of the studied deformation structures, the conducted simulations required the use of highly adaptive computational grids, which were refined in the immediate vicinity of the analyzed objects. The applied approach allowed for using computational domains of large relative size and, as a result, to avoid undesirable boundary effects. The simulations were often conducted until very large finite strain was achieved, which was one of the most serious numerical challenges during the research. On the one hand, the increasing complexity of the shape of structures during the simulation resulted in a progressive increase in the number of computational elements. On the other hand, achieving large deformations in computer simulations, while maintaining an appropriate level of numerical accuracy, required the use of very numerous time steps, which was particularly challenging for materials with non-linear rheology, requiring numerical iterations for each time step. Thanks to the use of strongly optimized MILAMIN code, as well as efficient, multithreaded methods of solving systems of linear equations and quickly convergent iterative methods for non-linear problems, it was possible to carry out systematic simulations of the analyzed structures. This allowed for recognizing in detail the impact of a number of parameters on the development of the studied deformation structures. Some simulation runs were conducted in parallel series with the use of Neptun computational cluster in the Polish Geological Institute-PIB.

<u>Discussion of the publications comprising the presented scientific achievement</u>

The results of the research work contained in the publications constituting the presented scientific achievement will be discussed below. In the first section, the results on the development of flanking structures will be discussed. Publications A1 and A4 and, in part, A5 were entirely devoted to this topic. In the next section, the mechanical model of winged inclusion development will be discussed. The model was presented in detail in publication A3, and in publication A5 it was mentioned in the context of shear sense kinematic analysis. The last section of the discussion will be devoted to the research related to ductilily reworked boudinage, which was presented in A2 and A5 and A6.

Flanking structures, including sheath folds, developing around slip surfaces in shear zones (publications A1, A4 and A5)

Publication A1 presented the results of research work aimed at recognizing the effect of three-dimensional deformation on the development of flanking structures. The development of structures around an isolated, elliptical, frictionless slip surface embedded in an isotropic linear fluid was analysed. Mechanical effects related to rock layering, which, in strongly sheared rocks, can result in anisotropic viscosity, were not considered. The initial aspect ratio of the slip surface was an important geometrical parameter, and its influence on structure development was systematically examined during both theoretical analyses and numerical simulations. Away from the slip surface, which was locally perturbing the flow, the background velocity field was a two-dimensional pure or simple shear in the XZ plane. In most analyzed cases, one of the principal axes of the elliptical slip surface was parallel according to the Y-axis, which led to the development of monoclinic structures. For a few selected systems, the development of triclinic structures was modelled for initially oblique slip surface with respect to the principal flow directions (XYZ).

Several analytical results were developed during this research, and they were presented and discussed in details in publication A1. The analysis included the dependence of the velocity jump across the slip surface on its elongation, the slip direction as a function of the applied far-field shear direction as well as the rotation and deformation of the slip surface with background strain. A detailed analysis of the evolution of the offset along the slip surface was also carried out, and for the limiting two-dimensional cases, closed-form analytical expressions were obtained, which described the normalized displacement of the central marker for both pure and simple shear. The effects related to the variation of the initial aspect ratio of the slip surface were quantified using systematic numerical simulations. It is worth mentioning that the morphology of flanking structures observed in the central XZ plane did not show significant differences when the initial elongation of the slip surface towards the Y-axis was increased past the initially circular slip surface case.

At large strain, the development of eye structures in YZ sections perpendicular to the shear direction was observed. This observation allowed for proposing a hypothesis in article A1 about the possibility of sheath fold development around elliptical slip surfaces active in simple shear zones. This concept was later strongly developed and presented in a number of publications, including the A4 publication belonging to the presented series. The publication A1 also discusses the morphology of triclinic flanking structures developing around to slip surfaces that were initially oblique to the principal flow directions. Triclinic slip surfaces were observed in the field (examples from the Greek island of Serifos are presented in A1) and their characteristic features include lineation bending within the XY plane of foliation in the vicinity of the slip surface. Thanks to the numerical simulations carried out, it was possible to directly demonstrate that triclinic flanking structures can develop under the conditions of plane-strain, two-dimensional background deformation, without the need to refer to complex, triclinic flow states. The analysis of triclinic flanking structures may be helpful in determining the kinematics of deformation as well as in estimating strain magnitude in shear zones.

Due to their widespread occurrences, flanking structures are often used in shear sense analysis. Unfortunately, these structures are quite problematic from the point of view of kinematic analysis. Extensive crenulation cleavage is one of the most frequently used shear sense indicators. It was already mentioned in the introduction that structures with the geometry of the extensive crenulation cleavage can develop under general shear conditions around a slip surface with an orientation close to the metastable repulsor direction. Such surfaces experience antithetical rotation, or even stagnation, while constantly accumulating synthetic slip, which, together with the progressive deformation in the background, may lead to the development of a large offset and related strong deflections of the surrounding foliation (Fig. 1a). A transition from reverse to normal deflections along the slip surface is a characteristic feature of this type of structures. Similar in appearance, extensional flanking structures (Fig. 1b) may develop around typical, synthetically rotating surfaces that

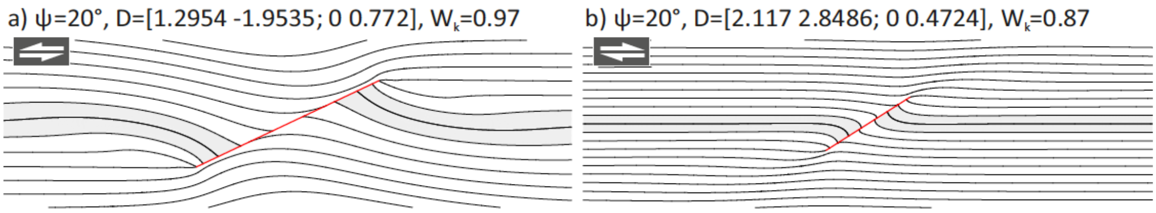


Fig. 1
a) Extensional crenulation cleavage formed around a slip surface under background sinsistral shear. b) Flanking structure developed under dextral shear. The initial orientation of the slip surface ψ, the deformation gradient tensor D and kinematic vorticity number W_k are given.

accumulate an antithetic slip up to a certain stage before the transition to a synthetic slip and the development of characteristic, hooked, overturned folds. Compared to the extensional crenulation cleavage, such structures are characterized by a smaller foliation offset and a less-developed transition from reverse to normal drag. Unfortunately, these features are not very diagnostic and in the field, with often an incomplete picture of the structure, this may lead to erroneous interpretations and wrong shear sense determination. A detailed discussion of this issue is presented in publication A5.

In publication A4, the development of sheath folds forming around elliptical slip surfaces under monoclinic shear conditions is investigated. The study focused on the case of shear-reactivated tensile cracks of initially circular shape. The initial foliation orientation was taken parallel to the XY plane, which corresponds to its asymptotic position in simple shear. Under these assumptions, seven significantly different initial configurations were obtained out of twelve general cases of monoclinic flows, in which a three-dimensional pure shear component is combined with simple shear (Tikoff and Fossen, 1999). The development of sheath folds was analysed using numerical simulations for a systematically increasing contribution of the pure shear component. The structure evolution was discussed in detail for the three important types of background deformation: constriction, plane-strain simple shear and flattening (Fig. 2). In the medium subject to a far-field constriction, the development of a strongly elongated, tubular sheath fold was observed. In this case, the eye structures observed in the YZ sections showed almost perfectly circular contours. For the reference case of simple shear, a typical morphology of the eye structure was observed, which is characterized by a set of non-concentric, asymmetric contours similar in shape to ellipses, and in cross-sections intercepting the slip surface showing a very indicative anvil type of geometry. Under flattening conditions superimposed perpendicularly to the shear plane, the eye structures, as expected, were characterized by a strong elongation in the Y direction. In the cross-sections intercepting the slip surface, an excessive flattening of the structure was observed in its immediate vicinity, and the structure appeared as bivergent flanking fold. It should be noted that the flattening resulted in the development of a non-cylindrical fold with quite a gentle curvature of the fold axis, with an opening angle greater than 90°, which makes the analyzed structure not belong *sensu stricto* to the class of sheath folds.

In the course of the research, a quantitative geometric analysis of the eye structures was performed. The focus was on the study of the aspect ratio of the outermost contours within

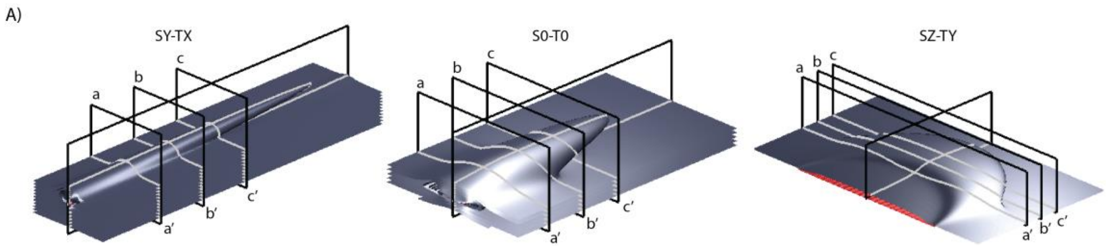


Fig. 2
The morphology of sheath folds developed around slip surfaces under general shear conditions: A) constrictional flow, B) plane strain C) flattening.

the eye. The analysis of the simulation results allowed for observing and characterizing a decreasing trend between the eye elongation and the Flinn parameter of the finite strain tensor (Green strain tensor), which is consistent with the results obtained in the field (Alsop and Holdsworth, 2006). For the particular types of the studied background deformation (constriction, flattening, flattening), indicative ranges of the eye elongation were also determined. Detailed analyses showed that the elongation of the outermost contour in the eye structure can be quite well correlated with the ratio of the deformation tensor component in the Y direction to the smaller of its components measured in the XZ plane.

The study confirmed the postulated hypothesis of the development of strongly non-cylindrical folds as late-stage flanking structures around the slip surface active in the simple shear dominated shear zones. However, even a small contribution of pure shear may have a clear influence on the morphology of the sheath folds, and especially on the aspect ratio of the eye structures. The transpression associated with juxtaposed stretching towards the kinematic Y-axis results in the development of non-cylindrical folds with mild fold axis curvature, which cannot be classified as strictly sheath folds. Moreover, the eye structures may take on the character of coupled, bivergent flanking folds, which may lead to incorrect determination of shear direction in the field. The eye structure elongation observed in the YZ planes may be used to assess strain magnitude and, in particular, to estimate the contribution of either the extension or shortening in the out-of-plane Y direction.

Winged inclusions (Publications A3 and A5)

The aim of the study was to develop and analyze a mechanical model of winged inclusions, a particular type of rotating tectonic inclusions in simple shear zones, and to evaluate their usefulness in the kinematic analysis of shear sense and finite strain magnitude. The conducted research was based on the concept of winged inclusion development due to ductile deformation of non-recrystallizing objects with initial φ-clast geometry under non-coaxial background shear. Drawn boudins, which are late-stage reworked pinch-and-swell objects (Goscombe et al., 2004), are a good example of the original structure for winged inclusion. The shape evolution of isolated, initially φ-shaped inclusions with homogeneous internal structure embedded in a medium subject to background simple shear was systematically studied using numerical simulations. An isotropic fluid model in its either Newtonian or power-law variant (Carreau model) was used to model the deformation of the inclusion and the matrix. The effective viscosity ratio between the inclusion and the matrix was an important parameter characterizing the investigated system. The initial geometry of the φ-shaped inclusion was represented by mirroring and stitching a truncated Gaussian curve, whose width (standard deviation) parameterized the initial elongation of the inclusion. To improve the quantitative analysis of the simulation results, a semi-automatic method of partitioning the deformed object into the core and the wings was developed. After testing a number of procedures, it was decided to perform the partitioning using the approach of the α-shapes (Edelsbrunner et al., 1983).

The results of the performed simulations and their analysis, together with field observations that motivated the research, as well as examples of model applications are presented in publication A3. The publication is supplemented with animations showing the evolution of winged inclusions for the analysed range of the inclusion to matrix viscosity ratio and the initial inclusion elongation. A number of regularities governing the development of winged inclusions were demonstrated in the course numerical simulations. Already in the early stage, a clear separation of the central part of the inclusion was observed, which at later stages formed a fairly compact core subject to deformation and rotation in a manner similar to the behaviour of elliptical inclusions in shear zones (Mancktelow, 2013). In particular, a markedly increased instantaneous rotation rate of the elongated core part of the inclusion was recorded when it was oriented perpendicular to the shear direction. In all the analyzed cases, a synthetic core rotation was observed, without any clear tendency for stabilization. The lower core elongation the higher mean rate of rotation was observed. Already in the early stage of deformation, the inclusion wings were subject to significantly stronger stretching, as well as slower rotation, compared to the core part, which led to their progressive differentiation. For the low viscosity ratio cases, this process produced extremely thinned inclusion wings, and their slower rotation resulted in the development of a spiral-arm structure (Fig. 3; upper row). With increasing strain, multiple spirals of strongly stretched wings around the stable rotating core of the inclusion were observed. In simulations with increased contrast of viscosity, this mechanism was inefficient and the wing rotation was only periodically delayed in relation to the rotation of the core (Fig. 3; lower row). In this regime, the episodic development of folds within the inclusion wings was

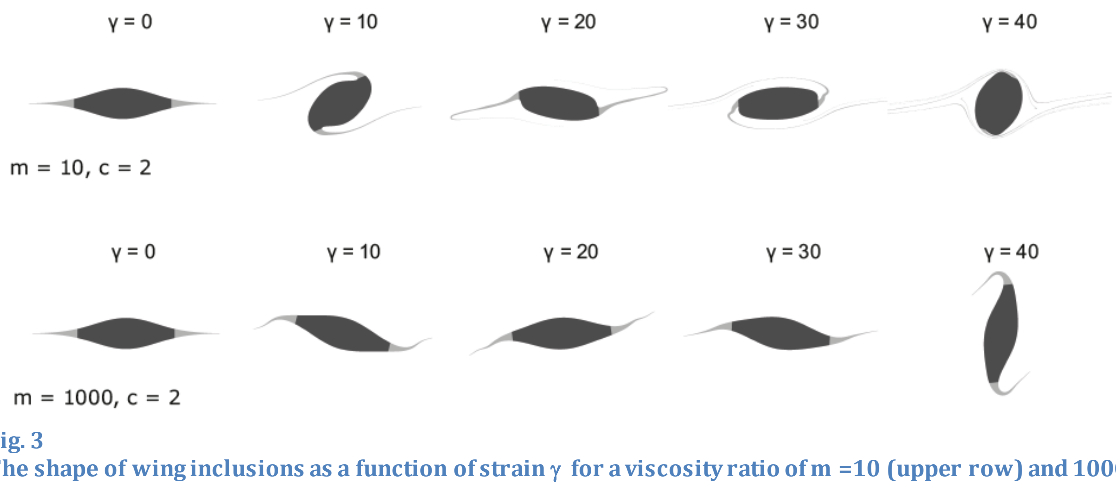


Fig. 3
The shape of wing inclusions as a function of strain γ for a viscosity ratio of m =10 (upper row) and 1000 (lower row). The normalized standard deviation c determining the initial width of the ϕ–shaped inclusion is set to 2.

recorded.

The observed regular deformation of the inclusion core became an encouragement to try to compare it directly with the deformation paths of perfectly elliptical objects (Bilby and Kolbuszewski, 1977). For comparison purposes, a match was sought between the observed and theoretical rotation curves for ellipses. It should be stressed that the degree of matching was in many cases, unfortunately, quite low, and the obtained aspect ratios of the equivalent ellipses were often visibly greater than those obtained from the direct geometric analysis of the simulation results. This allowed for drawing a conclusion that the core of the winged inclusion rotates much slower than suggested by solely its shape, which indicates an important role of wings in determining the rotation rate of such objects. It is also worth noting the small but systematic decreasing trend in the elongation of the inclusion core, which contrasts with the expected periodical evolution of high viscosity elliptical inclusions. The described behaviour may be associated with a weak but still active transfer of material from the core part to the wings.

The conducted research allowed for a detailed and systematic recognition of the evolution of φ-clast type of tectonic inclusions deformed under the background simple shear. In all analyzed cases, a monotonic, synthetic rotation of the inclusion core was observed, which led to the development of a clearly asymmetrical, and in the case of low viscosity contrast, even spiral structure. At first glance, the asymmetry of the emerging structures seems to reinforce the role of winged inclusions as shear sense kinematic indicators. In this respect, the usefulness of winged inclusions with spiral arms is undisputed. Moreover, one could even be tempted to assess finite strain based on analyzing the multiplicity of the spiral arms of the inclusion, which reflects the number of its revolutions. Unfortunately, no natural examples of strongly spiral winged inclusions have been found, which may be r elated to the low preservation potential of the extremely thinned inclusion wings under the conditions of dynamic recrystallization in shear zones. In the case of high viscosity contrast, the cyclic evolution of winged incluions was observed in numerical simulations, including the development of asymmetric structures of mildly spiral character, which in the course of progressing deformation became almost fully extended, and with further rotation of the core, the asymmetric twisting was repeated. On the one hand, this limits the potential for the use of such winged inclusions in the shear sense analysis, and on the other hand, it fully disqualifies them as finite strain gauges. However, the documented stage of structure development, in which, with a slight synthetic rotation of its long axis from the shear direction, the structure takes on an appearance strikingly similar to sigmoid tectonic inclusions of recrystallizing σ_a- and σ_b-clasts, turned out to be the biggest problem. In such a case, an erroneous interpretation unfortunately leads to a wrong determination of the shear sense.

In principle, there should not be a problem in the field with distinguishing recrystallizing σ-clasts from winged inclusions, which result due to ductile reworking of non-recrystallizing φ-clasts originating from pinch-and-swell structures in shear zones. However, the analysis of published kinematic interpretations for ductile shear zones indicates that such interpretation errors may be quite widespread. This problem is addressed in publication A5, which belongs to the scientific achievement under discussion. This paper also presents suggestions for reinterpretation of published shear sense determinations based on the analysis of asymmetric tectonic inclusions. The simulation results described in detail in Publication A3 indicate that the analysis of associated fold structures can be helpful in distinguishing winged inclusions from σ- or δ-clasts and other related structures. The results of the study also allowed for drawing an additional conclusion about the possibility of producing rootless folds in simple shear in the course of the evolution of winged inclusions, which allows for a different than standard interpretation of their role in kinematic analysis.

Ductile reworking of torn boudinage under pure and simple shear conditions (Publications A2, A5 and A6)

The research goal was to identify factors influencing the ductile reworking of boudinaged rock layer, as well as to assess the usefulness of such structures for kinematic analysis. Special attention was paid to the evolution of boudin shape and orientation and the process of their separation. The development of internal deformation structures within the boudins as well as in their neighbourhood was analysed. Systematic numerical simulations were carried out to establish the deformation patterns depending on the viscosity ratio between the boudins and the surrounding matrix, as well as on the initial elongation and separation of the torn boudins.

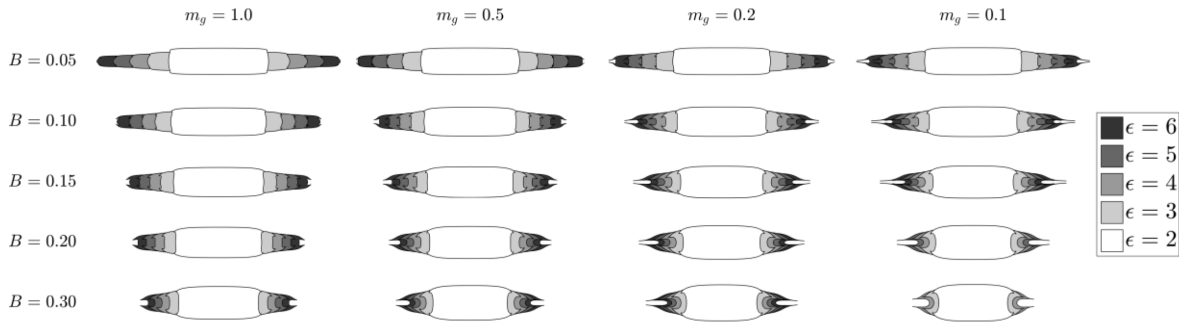
The A2 publication presents the results of numerical simulations of ductile reworking of a periodically boudinaged layer under layer-parallel simple shear. Torn boudins with initially rectangular cross-sections and viscosity 10 times higher than the matrix viscosity exhibited synthetic rotation accompanied by strong internal deformation. Rhomboidal boudins, which were observed in the early phase, became clearly sigmoidal at strains exceeding $\gamma=20$. Boudins with a much higher viscosity than the matrix showed a clear reorientation depending on their initial elongation and were only slightly subject to internal deformation. Due to the model assumptions related to periodicity, no further separation of the boudins was admissible in the phase of their ductile reworking. In this case, boudin rotation could only be accommodated by their internal deformation and slippage along the boundaries separating them. As a consequence, increasing the parameter of the initial separation favoured boudin rotation, and a detailed analysis of the results of the numerical simulations allowed to quantify this effect.

Classical hydrodynamic models indicate that isolated objects elongated into the shearing direction rotate with a slower rate than isometric objects, which is also reflected in the early phases of rotation of periodically arranged torn boudins. However, it can be expected that sustaining the rotation of isometric objects in a periodical sequence requires the activation of their internal deformation due to a clear tendency to close the narrow apertures separating them. This hypothesis was confirmed by the analysis of the results of computer simulations, which showed a systematic decrease in the rotation rate of square-shaped torn boudins. In the case of initially elongated objects, the rotation rate was maintained or even increased after reaching a critical level of reorientation leading to a loss of close contact between the inner faces of adjacent boudins. It should be noted that the rotation rate of weakly separated boudins was many times lower than that of the corresponding isolated objects.

The modelling work described in publication A2 also included the process of ductile reworking of finite-length torn boudinage under simple shear. The results of the simulations showed that the boudins located in the extreme sectors of the torn layer rotate faster, which is accompanied by their separation from the rest of the boudin array and their migration perpendicular to the shearing direction. As a result of these processes, the boudin array developed an overall sigmoid shape, with strongly twisted end parts. At shear strains of $\gamma>20$, a rather chaotic system of boudins was observed, within which objects originally located in the extreme sectors of the layer are particularly strongly redistributed. Natural examples of sigmoid and chaotic boudin arrays occurring within strongly sheared marbles were shown in publication A2. The development of these structures can be explained within the framework of the scheme proposed above, and it could be related to the large deformation evidenced in the analysed marbles.

The A6 publication presented the results of numerical simulations of ductile reworking of torn boudinage under progressive layer-parallel stretching. The research focused on objects with an initially rectangular cross-section, but the case of initially asymmetrical rhomboidal boudins was also considered. Additionally, the effects related to filling the initial boudin gaps with a material of a reduced viscosity were analysed. Particularly interesting results were obtained for the so far poorly studied regime of small initial boudin separation, down to only a few per cent of the layer thickness. In this regime, pronounced ductile reworking was observed even in the case of a very high viscosity ratio. The development of atypical boudin shapes, characterized by convex inner faces and flat or slightly concave outer faces, was noticed in the numerical simulations. With the initial separation exceeding 20-30% of the layer thickness, a typical development of the barrel geometry of a building with concave internal faces and slightly convex external faces was observed, in agreement to previously published results of numerical simulations (e.g. Samanta and Deb, 2014). At a high stretch, boudins with 10 times higher viscosity than the matrix exhibited C-shaped internal faces with a characteristic claw-like appearance of their corners, and at a slightly lower viscosity ratio, strongly stretched structures of the "fish mouth" type developed. For intermediate initial separations, the simulations showed the development of previously unrecognized complex structures characterized by the occurrence of a central convexity within the generally concave inner faces. The conducted systematic numerical simulations allowed for characterizing a wide spectrum of boudin shapes depending on their initial separation, viscosity ratio and the degree of reworking (stretch). For the selected cases, analyses of the development of deformation structures within and around the reworked boudins were also carried out. A particular attention was paid to the strongly thinning region corresponding to the original gap fill, which forms characteristic bow-tie veins and the so-called scar folds in the adjacent area.

No significant influence of rheological nonlinearity and initial boudin elongation on their later development was observed. On the other hand, introducing a gap infill material with a reduced viscosity caused noticeable changes in the boudin shape evolution (Fig. 4). For a



Ryc. 4
The shape of reworked torn boudins as a function of layer ε. The initial ratio B between the width of the inter-boudin gap and the layer height is varied in rows, while the viscosity ratio m_g between the gap in-fill material and the matrix is varied in columns. The viscosity ratio between the budin and the matrix is set to 5.

small initial separation, the already twice lower viscosity of the gap in fill material with respect to the matrix suppressed the previously observed tendency to develop a central convexity within the internal boudin faces. With further decreasing of the gap in-fill viscosity, the central bulge did not develop at any stage of deformation. Reducing the viscosity of the gap in-fill material was accompanied by strong stretching of boudin corners, resulting in the development of quite untypical structures of the "fish mouth" type, which looked like a "marlin head".

The recognition of a clear tendency to create a central bulge within the internal boudin faces for an initial separation not exceeding 20% of the layer thickness was an important result of the carried out work. Natural examples of such structures were presented in the A6 publication, but they are admittedly rather rare. The inhibition of the central bulging in the case of naturally reworked boudin may be related, for example, to their initial shape, which could be slightly different from that assumed in the studied model due the activity of plastic deformation during crack propagation. However, above all, it seems to indicate the activity of the processes of material dissolution, mobilization and reprecipitation within the boudin gaps, which may lead to their large initial width, without the involvement of truly viscous deformation at this initial stage. Moreover, the results of computer simulations have shown that with a reduced viscosity of the gap in-fill material, no bulging within the internal boudin faces was observed even in the case of small initial separations. Strongly localized deformation in the inter-boudin region may cause structural changes, e.g. reduction of grain size, or textural changes such as the development of the crystallographic fabric, which may additionally lead to effectively reduced viscosity in this area.

The initial boudin separation has a clear impact on the evolution of their shape during ductile reworking. Boudins with a small initial separation developed strong elongation even at high viscosity ratios. Based on the simulation results, sets of curves were developed to show boudin elongation and their normalized separation depending on the initial values of these parameters and the viscosity ratio between the boudins and the matrix. In practice, these results can be useful for determining the amount of stretch due to ductile reworking. The method relies on key parameters such as the initial separation and the viscosity ratio, which can be determined based on a detailed analysis of the boudin shapes. In the A6 publication, an example of stretch factor reconstruction based on the analysis of the geometry of the boudinaged and viscously reworked amphibolite layer is presented. The analysis took into account the presence of the in-fill material with a reduced viscosity as well as the geometry of the scar folds. As a result, not only the estimated value of the stretch factor was obtained, but also the initial boudin separation and the effective viscosity ratios between the amphibolite, biotite schist and gap in-filling quartz were estimated.

The conducted research works also included the case of initially rhomboidal boudins. Such oblique shaped boudins in consistently asymmetrical, periodical arrangements rotate synthetically in relation to the slope of their internal faces. Boudin rotation occurs despite the fact that there is no simple shear component active along the stretched layer. In the carried out numerical simulations, the reorientation of rigid rhomboidal boudins took place until their longer diagonal is placed along the stretching direction. It was shown that with a small initial separation, the kinematic reorientation model of the "bookshelf" type (Mandl, 1987) is a very good approximation of the evolution of their orientation. The use of a non-linear viscosity for the matrix material had little influence on the reorientation process, but it resulted in the development of strongly asymmetrical folds around rotating square-shaped torn boudins.

The evolution of shape and orientation of low viscosity rhomboidal boudins was also analysed. The development of the central convexity on the inner faces disappeared with decreasing their initial slope. The development of inverted drag of the boudin layering in the vicinity of the inner faces was observed, which indicates the activity of a localized slip in this area. Strongly oblique rhomboidal boudins, whose inner faces were initially inclined at an angle of 60^{o}, transformed into sigmoidal structures, which was accompanied by a clear reduction in their separation. As in the case of the extensive crenulation cleavage discussed earlier, the transition from inverted to normal deflections of the internal layering along the deformed inner boudin faces was observed. The reorientation of the boudins is reflected in the asymmetric development of adjacent structures. The oblique character of the deformation structures was exhibited both by the bow-tie veins and the scar folds.

The results of the simulations presented in publications A2 and A5 indicate problems with the use of asymmetric reworked boudins as kinematic shear sense indicators. The main difficulty is related to the correct recognition between antithetically rotating shear boudins and synthetically rotating domino boudinage. Layering deflections observed in the vicinity of the internal faces of domino boudins are unexpectedly normal. This makes these structures clearly similar to shear boudins, however, developed under simple shear with an opposite sense. The development of asymmetrical boudin shapes as a result of ductile reworking of initially rhomboidal boudins under coaxial stretching constitutes an additional problem. In these cases, the indicative barrel shape of the boudins can sometimes help to recognize the contribution of the pure shear component. On the other hand, the style of internal layering deflections at the contact with internal faces may reflect their initial obliquity, which in the case of deformed boudins is unfortunately difficult to reproduce.

Summary

The systematic computer simulations carried out allowed for examining mechanical models of selected ductile deformation structures. The obtained results facilitate the recognition of their usefulness for kinematic shear sense analysis, as well as for rheometric analysis and finite strain estimates.

The mechanical model of sheath fold formation around elliptical slip surfaces in shear zones is among the most important achievements of the presented series of publications. The presented interpretation of sheath folds as three-dimensional ductile flanking structures also allows for a deeper understanding of the role and activity of slip surfaces in shear zones. Owing to systematic computer simulations, a great morphological richness of three-dimensional flanking structures, including sheath folds in the strict sense of the term, has been recognized, which may help structural geologists to identify and interpret them correctly.

I consider the recognition of the finite strain deformation path of φ-shaped tectonic inclusions to be another valuable achievement. Due to the complexity of the shape of such structures, proper investigation of their evolution required the use of high-resolution numerical modelling. The obtained results may encourage geologists to take into account in their analyses of shear zones deformation structures associated with non-recrystallizing, rotating tectonic inclusions.

The conducted research also allowed for systematic recognition of ductile reworking of torn boudinage under simple and pure. As a result, it was possible to reproduce a wide spectrum of boudin shapes already described in the literature, but also to document structures not yet recognized. It can be expected that the published results will allow field geologists to look in a new way at the reworked boudinage and, in particular. to pay more attention to the relationship between the shape of the boudins and the degree of their separation. Detailed field observations may have valuable implications for general considerations concerning the role of pressure solution during ductile deformation.

Recognizing the evolution of the studied structures for a wide range of background shear conditions was another important achievement. In the case of reworked boudinage, the deformation patterns were analysed for both simple and pure shear conditions. In the case of flanking structures, however, it was possible to recognize their evolution under general (triclinic) three-dimensional shear. The results of the morphology analysis of the modelled structures can be used to determine kinematic conditions in natural shear zones, including the degree of its non-coaxiality.

Special attention was paid to the role that ductile deformation structures can play in the kinematic shear sense analysis. The presented interpretation ambiguities, which also concern recognized and widely used kinematic indicators, show that caution needs to be exercised. The developed methodological guidelines may contribute to changing the view on the role of the discussed ductile deformation structures as shear sense indicators, as well as to the necessity of reinterpreting shear sense determinations and, in some cases, modifying local or even regional tectonic solutions.

Quantifying the tools for reconstructing finite strain based on the morphology of the studied structures was another important achievement. A great potential in this respect can be associated with torn boudinage reworked under progressive stretching. As part of this scientific achievement, it was proposed to quantitatively assess the background stretch factor based on a detailed analysis of the boudin shape, their separation, as well as the morphology of the associated bow-tie veins. During the analysis, the viscosity ratio between the boudins and the matrix is also determined, which suggests that these structures may also play the role of natural rheometers. It should be stressed, however, that similarly to other tectonic structures, this type of analysis gives rather little possibilities to determine the power law exponents of the involved materials.

The computer simulations carried out and the detailed analyses of their results allowed for achieving the intended research objective. It was possible to analyze a number of problems, the solutions to which were sometimes quite surprising, but there are still interesting issues to explore, and in the course of the analyses new questions also appeared. Within the framework of the discussed series of publications, a simplified two-dimensional analysis of the evolution of φ-shaped tectonic inclusions was presented. In the future, with the development of computational capabilities, a full three-dimensional analysis of this problem may be tempted. An interesting supplement to the presented research would be to analyze the process of ductile reworking of torn boudinage, including rhomboidal shapes, under general shear conditions. In the opinion of the author, the most interesting development of the discussed research would be the systematic recognition of the role of mechanical anisotropy in the development of ductile deformation structures in shear zones. Mechanical models based on isotropic constitutive compounds in many cases provide results consistent with the observations. This is quite an intriguing observation, considering that strongly deformed rocks in shear zones have clearly anisotropic textures. The author of this paper has already initiated research on this issue.

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5. Presentation of significant scientific or artistic activity carried out at more than one university, scientific or cultural institution, especially at foreign institutions

After starting my work in 2013 at the Lower Silesian Branch (LSB) of the Polish Geological Institute-NRI (PGI-NRI), I maintained close cooperation with the Physics of Geological Processes Centre (PGP), renamed The Njord Center in 2018, at the University of Oslo. During this period I promoted two PhD theses (Mr. Kjetil Thøgersen, thesis title: "Statistical properties of sheared suspensions" and Mr. Jan Stanislas Cornet, thesis title: "Analytical and numerical modeling of cavity closure in rock salt") carried out at PGP, and I continued my research collaboration with Dr. Alban Souch and Dr. Marcin Krotkiewski. As a result of this cooperation, 9 joint publications were published in, among others, Journal of Fluid Mechanics, Rock Mechanics and Rock Engineering, Tectonophysics and Parallel Computing.

I was in the initiative group of the project entitled "Physico-chemical effects of sequestration of CO2 in the gas-bearing shales in Pomerania: ShaleSeq", in which PGP played the role of a Norwegian partner and PGI-NRI was the leading organization on the Polish side. The ShaleSeq project was financed from the Norway Grants, within the Polish-Norwegian Research Cooperation Programme implemented by the National Centre for Research and Development (NCBiR). In the course of the project, we cooperated with Dr Anne Pluymakers from PGP, and a joint publication in The Photogrammetric Record is the result of this cooperation.

Since 2017 I have been conducting joint research with Dr. Xin Zhong, who at that time started his postdoctoral internship at PGP. Our research collaboration focuses on the mechanical aspects of a novel method of reconstructing pressure and temperature of metamorphism, which is based on measurements of residual stresses in mineral inclusions using Raman spectroscopic analysis. So far, 2 publications, in Geophysical Journal International and Contributions to Mineralogy and Petrology, an approved manuscript in American Mineralogist, and three more manuscripts submitted to the editorial offices of the journals have been the result of this collaboration. Within the framework of this and related scientific activities I also cooperate with Prof. Jacek Szczepański from the Institute of Geological Sciences of the University of Wrocław (IGS UWr). I have also developed a research study on mechanical effects in application to petrological systems together with Prof. Yuri Podladchikov from the University of Lausanne and Prof. Roger Powell from the University of Melbourne (joint publication in the Journal of Metamorphic Geology).

Since 2009 I have been developing a research collaboration with the Structural Processes Group at the University of Vienna, headed by Prof. Bernhard Grasemann. The research topics are centered around issues related to the evolution of ductile deformation structures in rocks under large strain conditions in shear zones, and in my contribution I focus on mechanical and tectonic analyses based on analytical and numerical models. The first article in my research collaboration with the Vienna Group was published in 2010 in the Journal of Structural Geology. Since 2013, the cooperation has been further intensified (every year I spend about a week in Vienna visiting Prof. Grasemann's group), and it produces a series of 4 joint articles in the Journal of Structural Geology, which constitute a large part of this scientific achievement.

In the years 2011-15 I was a secondary supervisor of the doctoral thesis carried out at the University of Potsdam (Mrs. Elvira Mulyukova, thesis title: "Stability of the large low shear velocity provinces: numerical modeling of thermochemical mantle convection"). I am also a co-author of a publication in the Journal of Geophysical Research B: Solid Earth, which was based on the results obtained during the above smentioned doctoral dissertation.

6. Presentation of teaching and organizational achievements as well as achievements in popularization of science or art

Teaching achievements:

After obtaining my doctoral degree I was a secondary supervisor of 7 defended doctoral theses, 5 of which were carried out at the University of Oslo, and one each at the University of Potsdam and the Institute of Geophysics of the Polish Academy of Sciences in Warsaw. I also supervised and co-supervised 6 MSc theses (University of Oslo, University of Wrocław, and AGH University of Science and Technology in Kraków).

In 2009 I delivered a block of 4 lectures and exercises on flow in porous media and numerical methods of solving the Stokes equation. Classes were conducted at the University of Oslo as part of a semester course entitled "Methods in Physics of Geological Processes".

(FYS-GEO4300). I also took part as one of the course leaders in a week-long field work related to this course.

In the summer semesters of 2010-12, I gave lectures and exercises entitled "Introduction to mechanical geomodelling" (FYS-GEO4510; 6 hours a week) for master's students and PhD students at PGP at the University of Oslo.

In the period 2013-16 I organized internal workshops in the field of numerical solution of partial differential equations for employees of the Computational Geology Laboratory in the Lower Silesian Branch of the Polish Geological Institute of Geology (PIG-PIB).

In 2015 I gave lectures on "Micromechanics and effective material parameters" and "Effective viscosity" to the researchers participating in the ShaleMech project as part of the ShaleMech Summer School in Srebrna Góra.

In the first half of 2017 I regularly conducted optional classes called "Modelling of Geological Processes" for a group of several studenents, and in July 2017 I run a 3-day "Summer Numerical Workshop". In the beginning of 2020 I run optional classes called "Modelling of Thermal Processes" for a group of several students from IGS UWr.

Organisational achievements:

In 2009, I co-organized a workshop called "Numerical modeling in Earth sciences" at the 33rd International Geological Congress (IGC) in Oslo.

In 2009 I was the coordinator of the "Geodynamics group" and in 2010-2012 I was the coordinator of the "Earth Materials group" at PGP at the University of Oslo. My duties included reporting of the group's research activity during regular meetings of the Centre's Scientific Board and as part of annual reports.

Since 2011 I have been a co-organizer of the oral sessions during EGU meetings in Vienna. In 2011 I co-organized a session entitled "Recent advances in modelling of tectonic processes", in 2012-14 "Recent advances in computational geodynamics", in 2016-2018 "Recent advances in Geodynamics: Computational methods and applications" and in 2019 "Quantitative structural geology: 3D characterization, analysis and modelling".

Since 2013 I have been developing from scratch the Computational Geology Laboratory (CGL) in the Lower Silesian Branch of PGI-NRI, which was attached to the Centre for Geological Processes Modelling (CMPG). In the following years, I coordinated the substantive work of the Wrocław part of the CMPG team (4-8 people), which took part in the implementation of a number of projects financed by NCBiR, NCN, MNiSW and the Ministry of Environment. One of my organisational achievements were preparatory activities and configuration works related to the purchase and systematic development of the Neptun computing cluster. Neptun cluster is currently composed of 33 high-performance servers, which are used to perform serial numerical simulations in CMPG.

Since 2015 I co-organized cyclic workshops in the field of computational fluid mechanics (CFD in Wrocław; http://www.ift.uni.wroc.pl/~maq/cfdwroclaw/ ; main organizer: Dr hab.

Maciej Matyka from ITF UWr.). So far, 6 meetings have been held, during which 29 presentations have been delivered.

As part of the ShaleMech project, I co-organized in 2015 a week-long Summer Meeting in Srebrna Góra, in which 45 project participants took part, and the 5th General Meeting of the project in Wrocław ("Geomechanical Soulshots") in 2016, in which, apart from all the researchers, numerous representatives of the Polish Oil and Gas Company (PGNiG) - the industrial leader in the project - took part. In 2016 I also organized the final meeting of the international project ShaleSeq, which gathered all the researchers involved in Wrocław.

Since 2018 I have conducted scientific seminars in the Lower Silesian Branch of PGI-NRI. In the years 2018-19, 44 presentations were delivered as part of scientific meetings in LSB PGI-NRI.

Achievements to promote science:

I delivered a lecture popularizing issues related to rock folding processes during the workshop entitled "Analogue and numerical modeling of folds", which I co-organized as part of the III Polish Geological Congress in Wrocław in 2016.

I prepared and presented a number of presentations aimed at making the results of research work carried out at the CMPG more accessible to a wide audience, among others, at the forum of the student science club at IGS UWr, as part of a faculty seminar at the Faculty of Physics and Astronomy of the University of Warsaw, at KGHM Cuprum in Wrocław, during lectures of the Polish Geological Society and during jubilee celebrations at LBS PGI-NRI.

7. Apart from information set out in 1-6 above, the applicant may include other information about his/her professional career, which he/she deems important.

Discussion of other scientific research achievements (not related to the doctoral thesis)

Other research in the field of modelling ductile deformation structures

At this point, I will discuss my other work related to the development of ductile deformation structures, in which my participation was small or which have not yet been completed. As part of my supervision of Ms. Jacqueline Reber's doctoral thesis at PGP, I was involved in research on the development of sheath folds under simple shear. In this work, a three-dimensional mechanical model of structure evolution around elliptical slip surfaces was used. The model was described in detail in the A1 publication, which belongs to this scientific achievement. Reber et al. (2012) studied the development of sheath folds around the slip surface initiated within the ductile simple shear zone. The modelling results were compared with examples of natural occurrence of sheath folds, confirming the hypothesis put forward earlier in the A1 publication. In another work, Reber et al. (2013) presented the results of systematic numerical simulations, which allowed for recognizing the impact of the initial orientation of the slip surface and finite strain magnitude on the characteristics of the developing sheath folds. Later, the study of the morphology of sheath folds forming under simple shear was further refined (Adamuszek and Dąbrowski, 2017). Currently, I am involved in the project aimed at analyzing the development of tectonic structures around and within heterogeneous inclusions subject to a background simple shear. In this study, the analytical model of flow perturbation is used in its general formulation, which includes the case of an ellipsoidal inclusion.

In the years 2008-2012 I was a secondary supervisor of the doctoral thesis of Ms Marta Adamuszek, which was carried out in PGP. The doctoral research was focused on the process of buckle folding. Automated analysis of fold geometry and mechanical models of single layer folding were used to assess the degree of layer shortening and the viscosity ratio between the folded layer and the surroundings (Adamuszek et al., 2011). In Adamuszek et al. (2013a), a new theoretical model of large strain, finite-amplitude single layer folding was proposed. The model was verified based on the results of systematic numerical simulations. In the next study, the process of folding of a composite layer comprising high concentrations of strong clasts was simulated and the influence of the folding process on the effective viscosity of the medium was analysed (Adamuszek et al., 2013b).

After obtaining my doctoral degree I was involved in research work, which is a continuation of the research activities initiated during my doctoral thesis, on the influence of the evolving texture of heterogeneous rock on its effective viscosity under large deformation. In my approach, I emphasized the need of using high-resolution numerical schemes for this type of analysis. I have shown that the use of standard advection schemes to analyse the development of deformation textures in heterogeneous media may result in numerical artefacts, especially under non-coaxial simple shear conditions. Unfortunately, these artefacts sometimes resemble naturally occurring structures. I have also performed systematic simulations of texture evolution in a non-homogeneous and non-linear viscous medium subjected to stretching. In particular, I analysed the development of the anisotropic effective viscosity and related mechanical instability processes taking the form of internal boudinage. The results of this work have so far been presented at international conferences (Dabrowski, 2012; Dabrowski, 2014a; Dabrowski, 2014b).

In recent years, I have conducted methodological work aimed at verifying the performance of the so-called Fry's method, which can be used to estimate finite strain based on the analysis of the so-called vacancy field in the diagram of the relative positions of some anti-clustered rock elements. I focused on assessing the usefulness of the method for the case of rocks with porphyroclasts, whose spatial redistribution during deformation may be disturbed by the effects due to local mechanical interactions. As a result of my research work, I was able to propose a technical improvement for identifying and analysing the anisotropic of the central vacancy field. The developed variant of the Fry's method was tested in application to the date quartzite from Krzywina (Strzelin massif) in cooperation with Prof. Jacek Szczepański from IGS UWr, and the obtained strain magnitudes were compared with the predictions of an independent method. The results of these works were presented several times at international conferences (Dabrowski et al., 2016, Dabrowski, 2016). Currently, I am working on a manuscript describing the results of numerical simulations of porphyroclast dynamics under pure and simple shear.

Adamuszek M., Schmid D.W., Dabrowski M. (2011) Fold geometry toolbox - Automated determination of fold shape, shortening, and material properties. *Journal of Structural Geology*, 33(9), 1406-1416

Adamuszek M., Schmid D.W., Dabrowski M. (2013a) Theoretical analysis of large amplitude folding of a single viscous layer. *Journal of Structural Geology*, 48, 137-152.
Adamuszek M., Dabrowski M., Schmid D.W. (2013b) Interplay between metamorphic strengthening and structural softening in inclusion-bearing layered rocks. *Terra Nova*, 25(5), 381-386
Adamuszek M., Dabrowski M. (2017) Sheath folds as a strain gauge in simple shear. *Journal of Structural Geology*, 102, 21-36
Dabrowski M. (2012) Analytical and numerical modeling of ductile deformation in anisotropic rocks. *GeoMod 2012*, Lausanne, Switzerland
Dabrowski M. (2014a) Mechanical instability and effective anisotropic properties in two-phase rocks under pure and simple shear. *Kachanov Symposium*, Wiedeń, Austria
Dabrowski M. (2014b) Can we understand rocks without anisotropy?. *EGU General Assembly Conference Abstracts 16*
Dabrowski M., Szczepański J., Grasemann B., Rogowitz A. (2016) The Jegłowa metaconglomerate ("Dattelquarzit", SW Poland): a source of conflicting microstructural interpretations since the advent of modern fabric analysis by Bruno Sander. *GeoTirol*, Innsbruck, Austria
Dabrowski M. (2016) The evolution of spatial distribution patterns of rigid porphyroclasts under pure and simple shear. *EGU General Assembly Conference Abstracts 18*
Reber J.E., Dabrowski M., Galland O., Schmid D.W. (2013) Sheath fold morphology in simple shear. *Journal of Structural Geology*, 53, 15-26
Reber J.E., Dabrowski M., Schmid D.W. (2012) Sheath fold formation around slip surfaces. *Terra Nova*, 24(5), 417-421

Research in the field of geodynamics, tectonics and geomechanics

After obtaining my PhD degree, I became interested in mechanical modelling in application to tectonic large-scale geodynamic problems, and in the following years I also took part in research on geomechanics. During the supervision of the master's thesis (University of Oslo) and later doctoral thesis (University of Potsdam) of Mrs. Elvira Mulyukova, I was involved in modelling the thermomechanical convection process in the Earth's mantle, taking into account the presence of zones with anomalous chemistry in its lower parts (Large Low Shear Velocity Provinces). Mulyukov et al. (2015) presented a systematic analysis aimed at assessing the impact of convective movements on the stability of anomalously heavy material segregations in the lower Earth's mantle.

I was also interested in the problem of lithospheric folding during this period. I focused my work on developing an analytical model of large-scale fold development, taking into account non-linear and temperature dependent rheology of the stratified lithospheric medium as well as gravitational effects. The results of this work were presented during international conferences (e.g. Dąbrowski and Jarosiński, 2011). In the following years, I studied fold structures formed over a basement fault, looking for connections between the evolutions of fault-related folds and flanking structures in shear zones. I conducted numerical simulations to identify the stress state within a stratified sedimentary basin over a fault in a rigid basement and to assess potential fault propagation paths based on the analysis of the stress field. The obtained results were presented during the international CETEG conference (Dąbrowski and Badura, 2014). In the following years, in cooperation with Prof. Ray Fletcher, I also developed a new analytical solution for the problem of a half-space subjected to a displacement (velocity) jump at its boundary, taking into account the anisotropy of elastic parameters.

In the years 2014-18 I acted as a supervisor of Mr. Jan Cornet's doctoral thesis at PGP. The research was mainly concerned with the problem of rock salt deposits hosting closing cavities such as boreholes or caverns formed as a result of the technological process of salt leaching. An analytical mechanical model of cylindrical cavity closure with circular cross-section has been developed taking into account the complex rheological response of rock salt, including high stress nonlinear dislocation creep regime and grain size dependent diffusion creep regime (Cornet et al., 2017). Cavity closure was analysed for the lithostatic pressure load but also under non-zero differential stress conditions (Cornet et al., 2018). The publication by Cornet and Dabrowski (2018) presented a model development for the challenging case of nonlinear viscoelastic medium.

In the years 2014-17 I coordinated the work of the research team carrying out the task entitled "Stress and flow modelling in shale complexes" in the project "Integrated geomechanical research to intensify gas production from shale formations of Pomerania: ShaleMech" financed by the BlueGas - Polish Shale Gas programme by NCBiR. In the ShaleMech project, I participated in, among others, theoretical and numerical analyses of anisotropy of effective elastic parameters of shale rocks, taking into account the role of microfracturing and stress-induced anisotropy; analytical and numerical modeling of three-dimensional stress perturbation around hydraulic fractures in anisotropic media; numerical analysis of the reactivation potential of a natural fracture network under the influence of hydraulic fracturing treatment and differential stress conditions in the medium. The results of these studies were presented during general project meeting, which also hosted representatives of PGNiG - the project leader. Currently, in cooperation with Prof. Marek Jarosiński from PGI-NRI, I am preparing a manuscript describing the results of three-dimensional stress state modelling in mechanically anisotropic medium disturbed by multistage hydraulic fracturing. As a secondary supervisor, I was also involved in the research carried out in Mr. Maciej Trzeciak's doctoral thesis, which was performed within the ShaleMech project. Trzeciak et al. (2018) presented the results of laboratory measurements, which were used to develop a viscoelastic constitutive model of the creep process in shale. In the next publication, the influence of viscoelastic creep of shale horizons on the evolution of stress state in a sedimentary basin subjected to tectonic and glacial loads was analysed (Trzeciak et al., 2020).

In the last few years I have also studied the impact of topographical loads on the state of stress in the Earth's crust. The aim of my research was, i.a., to assess the connections between the relief producing processes and the state of stress in the rock mass, as well as to recognize the degree of tectonic stress perturbation by the topographic factor, which is a valuable indication for potential in situ stress measurements. Preliminary results of these works, applied to the Sudetes (Lower Silesia, Poland), were presented in the form of an oral presentation during an international conference (Dabrowski et al., 2015). As part of my involvement in the implementation of the Polish Geological Survey project entitled "4D Cartography in the coastal zone of the southern Baltic Sea - Stage I", I also conducted research on the application of the finite element method to the analysis of mechanical stability of slopes, including the assessment of the impact of in situ stress on the development of mass movements. The results of these activities were presented during the GEOST II conference (Dąbrowski et al., 2016) and will also be developed as a publication.

In 2018-19 I was also involved in research work related to salt tectonics and tectonic phenomena accompanying volcanic processes. The publication by Adamuszek and Dąbrowski (2019) presented the results of numerical simulations and a theoretical model describing the process of anhydrite boudin sinking within the rock salt. The paper focused on processes related to mechanical interaction between adjacent blocks of sinking anhydrite. In turn, the work by Souche et al. (2019) analysed the initial phase of elastic-plastic deformation of layered sedimentary rocks under the influence of magma injections in the form of an expanding finger-shaped intrusion.

Adamuszek M., Dabrowski M. (2019) Sinking of a fragmented anhydrite layer in rock salt. *Tectonophysics*, 766, 40-59

Cornet J., Dabrowski M., Schmid D.W. (2017) Long term cavity closure in non-linear rocks. *Geophysical Journal International*, 210(2), 1231-1243

Cornet J., Dabrowski M., Schmid D. W. (2018) Long term creep closure of salt cavities. *International Journal of Rock Mechanics and Mining Sciences*, 103, 96-106

Cornet J.S., Dabrowski M. (2018) Nonlinear Viscoelastic Closure of Salt Cavities. *Rock Mechanics and Rock Engineering,* 51(10), 3091-3109

Dąbrowski M., Jarosiński M. (2011) Lithospheric folding - to fold or not to fold? *Kongsberg Seminar*, Kongsberg Norway

Dąbrowski M., & Badura J. (2014) Finite element modeling of fault-propagation folding above a rigid basement: A case study of the Nysa Kłodzka Graben (Sudetes, SW Poland). *Geologia Sudetica*, *42*

Dąbrowski M., Badura J., Aleksandrowski P. (2015) Rock failure due to topographic stress in the Sudetes Mts: towards a three-dimensional numerical model. 16th Workshop On Recent Geodynamics of the Sudety Mts. and Adjacent Areas, Srebrna Góra

Dąbrowski M., Badura J., Pacuła J. (2016) Modelowanie procesów geologicznych aktywnych w pasie brzegu klifowego. *„Procesy geologiczne w strefie brzegowej morza - GEOST II"* Jastrzębia Góra

Mulyukova E., Steinberger B., Dabrowski M., Sobolev S.V. (2015) Survival of LLSVPs for billions of years in a vigorously convecting mantle: Replenishment and destruction of chemical anomaly. *Journal of Geophysical Research B: Solid Earth*, 120(5), 3824-3847

Souche A., Galland O., Haug Ø.T., Dabrowski M. (2019) Impact of host rock heterogeneity on failure around pressurized conduits: Implications for finger-shaped magmatic intrusions. *Tectonophysics,* 765, 52-63

Trzeciak M., Sone H., Dabrowski M. (2018) Long-term creep tests and viscoelastic constitutive modeling of lower Paleozoic shales from the Baltic Basin, N Poland *International Journal of Rock Mechanics and Mining Sciences,* 112, 139-157

Trzeciak M., Dabrowski M., Jarosiński M. (2020) Stress distribution models in layered, viscoelastic sedimentary basins under tectonic and glacial loads. *Geophysical Journal International*, 220(2), 768–793

Mechanical modelling applied to petrology

My interest in the issue of stress variations in rocks and the related petrological implications, including the impact on the thermodynamic equilibrium of mineral phases, dates back to my undergraduate studies. Various geological processes can cause long-term local overpressures in mineral inclusions and grains, or even in isolated rock units on a larger scale. Petrological effects related to the development of local overpressure in metamorphosed rocks may have significant consequences for regional tectonic and geodynamic reconstructions. Allowing for the possibility of a non-lithostatic pressure profile in the earth's crust makes conventional techniques of assessing the burial depth and the magnitude of rock exhumation problematic. I had an opportunity to come into contact with the issue of exhumation of high pressure metamorphic rocks during my master's thesis focused on the occurrences of high pressure rocks in the Lądek and Śnieżnik Metamorphic Unit, as well as during subsequent field work in Norway (Western Gneiss Region) and Greenland (Liverpool Land). In connection with the latter works, I took part in the development of a theoretical model of overpressure development within migmatized metamorphic complexes (Hartz et al., 2007).

Since 2013 I have focused on the problem of overpressure development on the scale of mineral inclusions and grains. Dąbrowski et al. (2015) developed a mechanical model of viscous relaxation of a localized overpressure in a material with power fluid rheology, which is widely used to describe the process of ductile flow of rocks and minerals. The analyses carried out showed a fundamental influence of rheological non-linearity on the characteristic time scale of the relaxation process, which may have its expression in the development of mineral paragenesis in metamorphic rocks. In the following years, I continued to study the relaxation of local overpressure in the rocks, which allowed to take into account the effects associated with viscoelasticity, as well as the complex viscosity model of Carreau type fluid, corresponding to the rheology of a medium characterized by the simultaneous activity of dislocation and diffusion creep (Dabrowski et al., 2016).

Since 2017, I have been conducting joint research with Dr. Xin Zhong (now the Free University of Berlin; formerly PGP, University of Oslo) on Raman elastothermobarometry. This is a novel method, independent of the assumptions and complications of equilibrium thermodynamics of mineral phases, for the reconstruction of metamorphism conditions, which has been flourishing in recent years thanks to the significant development of the Raman micro-spectroscopy. Thanks to the high accuracy of measurements allowing for the detailed analysis of the Raman spectra shifts and based on experimental calibrations and theoretical models, it is possible to determine the pressure and sometimes even the full stress state within the analysed mineral grains. Raman's measurements in quartz inclusions in garnets occurring in rocks subjected to high pressure metamorphism in their history shows quite common presence of residual pressure ("overpressure") reaching the level of several hundred MPa. Incomplete stress relaxation of quartz inclusions occurring in exhumed rocks is associated with their distinctly different thermomechanical parameters in relation to the garnet grains covering them. The knowledge of the thermomechanical parameters of the studied minerals allows, based on the predictions of the mechanical model and the measurement of the residual pressure, to determine the original pressure at which the surrounding grain has overgrown the inclusion. A number of factors influence the behaviour of residual stress in the mineral inclusions, and in addition to the significant viscous relaxation under high temperature conditions, the formation of micro-cracks is an important process leading to a decrease in residual stress. Cutting of the inclusions through the surface of the thin section leads to a full relaxation of the normal stress component and such grains are not suitable for elastothermobarometric analysis. Therefore, it is even recommended to use thin section with a non-standard, increased thickness. In the methodical work of Zhong et al. (2019a) we analyzed the degree of reduction of residual pressure in the inclusion depending on its distance from the thin section. Recently, we have also conducted research on the influence of elastic anisotropy of the inclusion phase on induced residual stresses. The results of our research show that in the case of quartz the influence of its mechanical anisotropy is largely compensated by the effects related to thermal expansion anisotropy for typical thermal gradient values. On the other hand, the anisotropy of thermomechanical parameters may play an important role e.g. in case of rutile inclusions. Zhong et al. (2019b) presented the use of zircon inclusions in garnets as an elastothermometer. The comparison of the results of elastothermobarometry with the results of classical geothermobarometry carried out for eclogites from the Bergen area in western Norway showed a high degree of consistency between the different methods. Together with Prof. Jacek Szczepański from IGS UWr and Dr. Xin Zhong I am also involved in a research project, in which the method of quartz in garnet elastobarometry has been applied to rocks from the Kamieniec Metamorphic Unit in the Sudetes.

Hartz E. H., Podladchikov Y. Y., Dabrowski M. (2007) Tectonic and reaction overpressures: theoretical models and natural examples. *EGU General Assembly Conference Abstracts 9*

Dabrowski, M., Powell, R., Podladchikov, Y. (2015) Viscous relaxation of grain-scale pressure variations. *Journal of Metamorphic Geology*, 33 (8), 859-868

Dabrowski M., Powell R., Podladchikov Y. (2016) Grain-scale pressure variations: build-up and viscoelastic relaxation. *EGU General Assembly Conference Abstracts 18*

Zhong X., Dabrowski M., Jamtveit B. (2019a) Analytical solution for the stress field in elastic half space with a spherical pressurized cavity or inclusion containing eigenstrain. *Geophysical Journal International,* 216(2), 1100-1115

Zhong X., Andersen, N.H. Dabrowski M., Jamtveit B. (2019b) Zircon and quartz inclusions in garnet used for complementary Raman thermobarometry: application to the Holsnøy eclogite, Bergen Arcs, Western Norway. *Contributions to Mineralogy and Petrology,* 174, 50

Porous and fracture flows

After my doctorate, I became interested in porous flows. Initially, I was mainly concerned with computational models of single-phase flow in the pore space of synthetic granular media. At that time, I was interested in the comparison between the numerically determined effective permeability and the predictions of empirical and theoretical models (effective media approximations). Pore scale flow modelling requires numerical simulations of incompressible Stokes flow in complex, three-dimensional domains. The analyzed examples were used to test the iterative approach of solving three-dimensional Stokes problems using finite element method formulations for unstructured (tetrahedral) computational grids. I was also interested in numerical modeling of three-dimensional porous flow convection using the upscaled Darcy model. In the following years, I was also involved in a commercial project on multiphase porous flows (hydrocarbon migration). In the years 2009-12, I acted as a secondary supervisor for Mr. Alban Souche's doctoral thesis at PGP at the University of Oslo. Souche et al. (2014) analyzed the process of fluid convection within a sedimentary basin located in the hanging wall of a low-angle normal fault. The results of numerical simulations allowed for recognizing transient thermal anomalies of quite considerable amplitudes, which were associated with convection plumes over a strongly heated exhumed basement.

In the years 2014-2017 I coordinated the work of a research team carrying out the task "Multiphase flow in fractured shale rocks" in the project "Physico-chemical effects of sequestration of CO2 in the gas-bearing shales in Pomerania: ShaleSeq", which was financed from Norwegian Grants under the Polish-Norwegian Research Cooperation Programme operated by NCBiR. The main objective of the project task was to identify the characteristics of single- and two-phase flows in fractures with roughness and/or contacts. For the analyzed class of flows, a new up-scaled 2.5D model based on the Stokes-Brinkman equation was proposed, whose main advantage is the possibility to impose the Dirichlet type boundary condition on the edges of contacts between the fracture walls. Based on the results of direct, three-dimensional simulations of the Stokes flow, the proposed up-scaled model has been verified by Mr. Piotr Olkiewicz for a wide range of fracture wall roughness types and for a different degree of its closure. The results of these studies were presented during international conferences (e.g., Olkiewicz and Dabrowski, 2017). I also took part in a related research work aimed at developing a photogrammetric method for reconstruction of fracture wall roughness in shale rock. An innovative photogrammetric method, adapted to measure roughness characterized by an amplitude of several tens of micrometers, was described in a publication by Olkowicz et al. (2019). Together with Dr Michał Dzikowski and Dr Łukasz Jasiński, we presented a systematic comparison of numerical simulation reults carried out with the Boltzmann network gas method and the finite element method for single-phase flow in a plane-walled aperture with cylindrical obstacles of a circular cross-section (Dzikowski et al., 2018). The analyzed geometry is an idealised equivalent of a hydraulic fracture supported by the proppant grains. The results of three-dimensional numerical simulations were also compared with the 2.5D predictions of the Stokes-Brinkman up-scaled model. The up-scaled model was also the subject of detailed analyses described in the publication of Jasiński and Dąbrowski (2018). Comparisons with three-dimensional Stokes simulations showed a clear advantage of the Stokes-Brinkman model over the conventional Reynolds model. The 2.5D up-scaled model was also used to construct and test effective media approximations for the permeability of a fracture with obstacles. The effective permeability modeling was based on i.a. an analytical solution of the elementary Stokes-Brinkman flow around a single cylindrical circular obstacle in a plane-walled aperture. Later, the Stokes-Brinkman model was generalized to the case of multi-phase flows, including surface tension effects at the phase boundary. During the ShaleSeq project and in the following years, together with Dr. Dzikowski, I was involved in research work aimed at systematic analysis of the performance of the Stokes-Brinkman model for two-phase flows in a fracture with obstacles.

Dzikowski M., Jasinski L., Dabrowski M. (2018) Depth-averaged Lattice Boltzmann and Finite Element methods for single-phase flows in fractures with obstacles. *Computers & Mathematics with Applications,* 75(10), 3453-3470

Jasinski L., Dabrowski M. (2018) The effective transmissivity of a plane-walled fracture with circular cylindrical obstacles. *Journal of Geophysical Research: Solid Earth*, 123, 242-263

Olkiewicz P., & Dabrowski M. (2017) Numerical modelling of single-phase flow in rough fractures with contacts. *EGU General Assembly Conference Abstracts* 19

Olkowicz M., Dabrowski M., Pluymakers A. (2019) Focus stacking photogrammetry for micro-scale roughness reconstruction: a methodological study. *The Photogrammetric Record,* 34, 11-35

Souche A., Dabrowski M., Andersen T.B. (2014) Modeling thermal convection in supradetachment basins: Example from western Norway. *Geofluids*, 14(1), 58-74

Suspension dynamics

In my doctoral thesis, I analyzed the development of deformation structures around a rigid, rotating inclusion in a layered, anisotropic medium subjected to background simple shear. During this period, I was also interested in the more general issue of collective dynamics of rigid clasts in shear zones. Later, I was focused on the influence of inclusion concentration and their shape on the development of shape preferred orientation and the evolution of the effective viscosity of the whole system. I presented the preliminary results of my research at several international conferences (e.g. Dabrowski, 2009; Dabrowski, 2010). In the following years, I was developing and adapting numerical tools to analyze the dynamics of rigid inclusions under simple and pure shear, taking into account the periodic symmetry of the system. The formulation allowed for a great deal of flexibility in the selection of numerical integration methods for inclusion trajectories, which facilitated performance comparisons, especially in the context of close contact development between inclusions (the research was carried out in the hydrodynamic limit, without introducing artificial interactions that would limit the development of small apertures between inclusions).

Later, issues related to the suspension dynamics were the subject of research carried out as part of Mr. Kjetil Thøgersen's doctoral thesis, which I supervised. This research required integrating inclusion trajectories, the number of which in some models reached several thousand, in a regime of very large deformations (simple shearing with deformation exceeding $\gamma>100$). In his work, Mr. Thøgersen studied, i.a., the phenomena of self-diffusion and clustering of inclusions in suspension, which he analysed in detail using statistical physics methods (Thøgersen et al., 2016). In the publication by Thøgersen and Dąbrowski (2017), the influence of inclusion rotation on the effectiveness of the liquid mixing process was analysed. Simulations were also carried out to assess the fluctuation of the effective viscosity anisotropy of the suspension in relation to the evolution of its microstructure, and the results of these studies are described in one of the chapters of Mr. Thøgersen's dissertation. An interesting phenomenon observed in suspensions, including crystal-melt systems studied by volcanologists, is the migration of inclusions (clasts) associated with the gradient of their concentration and shear rate gradient (the so-called Bagnolds effect). Our pilot studies indicated that direct numerical analysis of the Bagnolds effect requires studying systems subjected to much higher deformations ($\gamma>1000$) and with much higher number of inclusions ($N>10000$) than were available at that time.

Dabrowski M. (2010) Crystal-bearing melts – a perplexing rheological enigma. *22th Kongsberg Seminar*, Kongsberg, Norwegia

Dabrowski M. & Schmid D.W. (2009) Effective mechanical properties of composite rocks. *Deformation, Rheology & Tectonics*, Liverpool, UK

Thøgersen K., Dabrowski M., Malthe-Sørenssen A. (2016) Transient cluster formation in sheared non-Brownian suspensions. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics,* 93 (2), 022611

Thøgersen K., Dabrowski M. (2017) Mixing of the fluid phase in slowly sheared particle suspensions of cylinders. *Journal of Fluid Mechanics*, 818, 807-837

Numerical methods and their implementation

An important area of my research activity is the development, implementation, and optimization of numerical tools, including primarily the Finite Element Method (FEM) in application to thermo-mechanical problems discretized using unstructured computational grids. After obtaining my PhD degree, I took part in research works aimed at performance optimization of the parallel implementation of the sparse matrix vector multiplication, which forms the core of iterative methods of solving systems of linear equations related to unstructured FEM discretizations (Krotkiewski and Dabrowski, 2010). Krotkiewski and

Dabrowski (2013) presented a high-performance, GPU-tailored implementation of a computational stencil for three-dimensional, regular data grid. This procedure is an important computational kernel during solving differential equations discretized by the method of finite elements or differences on structured grids. Later, I also worked on the procedure of sparse matrix vector multiplication for unstructured FEM discretizations in a variant allowing for no explicit matrix assembly. This type of approach allows for significant memory savings, with acceptable computational overheads.

After my PhD, I was involved in research and implementation work aimed at improving and developing the MILAMIN (www.milamin.org) computational package, the original version of which was published as part of my PhD thesis. These activities developed in many ways. I have developed and implemented procedures to apply the code to non-linear materials. The implementation adapted to nonlinear viscous materials (Carreau fluid) was used, i.a., in the FOLDER package (Adamuszek et al., 2016), which is a tool for analyzing folds and boudinage. The code variant for elastic-plastic materials using the von Mises' criterion was described in a joint publication by Yarushina et al. (2010). Later, I also worked on a formulation covering the Drucker-Prager plasticity case. I have also developed several improvements to the original version of the code, including the calculation of the so-called stiffness matrix in FEM and the application of boundary conditions. I was also involved in programming work aimed at imlementing and optimizing a number of auxiliary tools, including those in the area of computational geometry. I also participated in numerous discussions concerning optimization and implementation works conducted by Dr Marcin Krotkiewski, which resulted in a package of highly efficient MUTILS numerical procedures supporting FEM calculations for unstructured grids.

Adamuszek M., Dabrowski M., Schmid D.W. (2016) Folder: A numerical tool to simulate the development of structures in layered media. *Journal of Structural Geology*, 84, 85-101

Krotkiewski M., Dabrowski M. (2010) Parallel symmetric sparse matrix-vector product on scalar multi-core CPUs. *Parallel Computing*, 36(4), 181-198

Krotkiewski M., Dabrowski M. (2013) Efficient 3D stencil computations using CUDA. *Parallel Computing*, 39(10), 533-548

Yarushina V.M., Dabrowski M., Podladchikov Y.Y. (2010) An analytical benchmark with combined pressure and shear loading for elastoplastic numerical models. *Geochemistry, Geophysics, Geosystems*, 11(8)

Summary of my research record

My publication record includes 40 papers indexed in the Web of Science (WoS) database, of which 6 are part of the presented publication cycle and 5 are related to my doctorate thesis. The IF index of the publications included in the cycle is 15.364, of papers related to my doctorate thesis is 12.415, and the total IF index of all my publications is 105.361. According to the WoS database (as of 06.04.2020), the papers constituting the presented scientific achievement were cited 57 times in total (47 without self-citations), the papers related to my PhD project 187 (151 without self-citations), and the total citation count of all my publications is 453 (377 without self-citations). My publication record also includes 9 papers that are not indexed in the WoS database and a chapter in a monograph. My Hirsh index according to the WoS database is 13.

I have authored and co-authored 187 conference abstracts in total, presented mainly during international conferences. After obtaining my doctoral degree, I gave 15 oral presentations, including 6 invited talks. I personally presented 25 posters, 16 of them after obtaining my PhD degree. I have co-authored 40 oral presentations (35 after obtaining my PhD) and 105 posters (100 after obtaining my PhD).

I was a task leader in ShaleSeq and ShaleMech projects financed by NCBiR. I participated in research projects financed by NCBiR, NCN and ERC.

In the years 2008-2020 I prepared 36 reviews of scientific works, including 8 times for Journal of Structural Geology. I also prepared a review of a doctoral dissertation conducted at ETH Zurich.

After obtaining my doctoral degree, I acted as a secondary supervisor of 7 defended PhD theses and I supervised 6 MSc theses.

I received His Majesty the King's gold medal for the PhD thesis. After obtaining my doctoral degree, I received an award for my teaching activity at PGP at the University of Oslo. I received three times special awards from the Director of PGI-NRI, including for an award for overall scientific achievements in 2019. I received Commendation in the Academic Achievements category of the "Geologia 2019" Award organized by the Ministry of Environment in Poland.

Marcin Dąbrowski

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(Applicant's signature)