Anisotropy of Magnetic Susceptibility: Application to Tectonics and Basin Evolution

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Abstract

The anisotropy of magnetic susceptibility (AMS) was proposed over half a century ago and has earned tremendous popularity. The AMS method is a powerful quantitative tool for fabric analysis, especially in fine-grained sedimentary rocks that lack macroscopically observable paleocurrent indicators. In addition, the AMS has proven as an extremely sensitive indicator to record 'invisible' deformational fabrics. Thus, the AMS is increasingly used to characterize the preferred orientation of magnetic minerals from depositional to tectonic setting within a given basin, with the benefit of potentially recording weak upper-crustal strains. The AMS was tested in a sequential geological setting along the northern edge of Gondwana during the Neoproterozoic–Cambrian. The objective of this research is to find the timing and mechanism operated on the northern margin of Gondwana during active-pasive margin transition. In the Cadomian terranes, after the active Cadomian orogeny ceased, several diverse compositional plutons intruded the Teplá–Barrandian unit of the Bohemian Massif. The AMS data are able to differentiate the pre-, syn-, and post-plutonism structures (The Kdyně pluton, the Czech Republic). The possible geodynamic causes of this event were interpreted as a result of a slab break-off. Following this plutonism, the crust at the surface evolved as a graben-type structure of the Příbram–Jince basin (the Czech Republic). The AMS has successfully revealed the paleocurrent direction changes in this sedimentary basin, which was related to the change of tectonic regime.

Keywords: Anisotropy of Magnetic Susceptibility, Gondwana, Cadomian, Teplá–Barrandian unit,,tectonics.

1. Introduction

Rock texture can be used to infer deformational history and geological setting, and records the mechanisms of deformation, orientation and magnitude of principal stresses. The complexities of internal structure of rocks are indiscernible. The anisotropy of magnetic susceptibility (AMS) is a technique in defining the physical properties of a rock which is useful for petrofabric and structural studies (e.g., Borradaile, 1997; Hrouda, 1982). The AMS method is used to define the preferred orientation of magnetic minerals by measuring the crystallographic axes. The AMS technique is applicable to any rock and soft sediment type and able to determine invisible fabrics in rocks such as paleocurrent, flow of a magma, and weak deformation. Moreover, the AMS measurement in laboratory is quick (about 2 minutes per specimen) and easy to operate, allowing statistical and structural arangement in fabric investigation, especially useful to map the complex structures related to depositional and tectonic.

This study is designed to unravel the timing and mechanism between active to passive margin transformation. The AMS method were tested in a transitional zone during the late Ediacaran to early Cambrian within the Cadomian orogenic belt, the Bohemian Massif, the Czech Republic (Fig. 1). These locations represent key information about crucial structural styles transformation, from compressional to extensional regimes, involving a shallow plutonic bodies (Kdyně plutons) and sedimentary basin (The Příbram–Jince basin). The Cadomian subduction terminated ca. 540 Ma in the Armorican massif and Saxothuringia but keep subducting in the Iberian and Bohemian Massifs at least until the early-middle Cambrian (Hajná et al., 2018). As a result, some of plutonic events still arose in the Bohemian Massif ca. 524–522 Ma, represented by the Kdyně plutons. On the surface, the Příbram–Jince sedimentary basin was deposited ca. 515–499 Ma with a domination of fluvial deposits that interrupted by a brief marine transgression and accompanied by periodic volcanic activity.

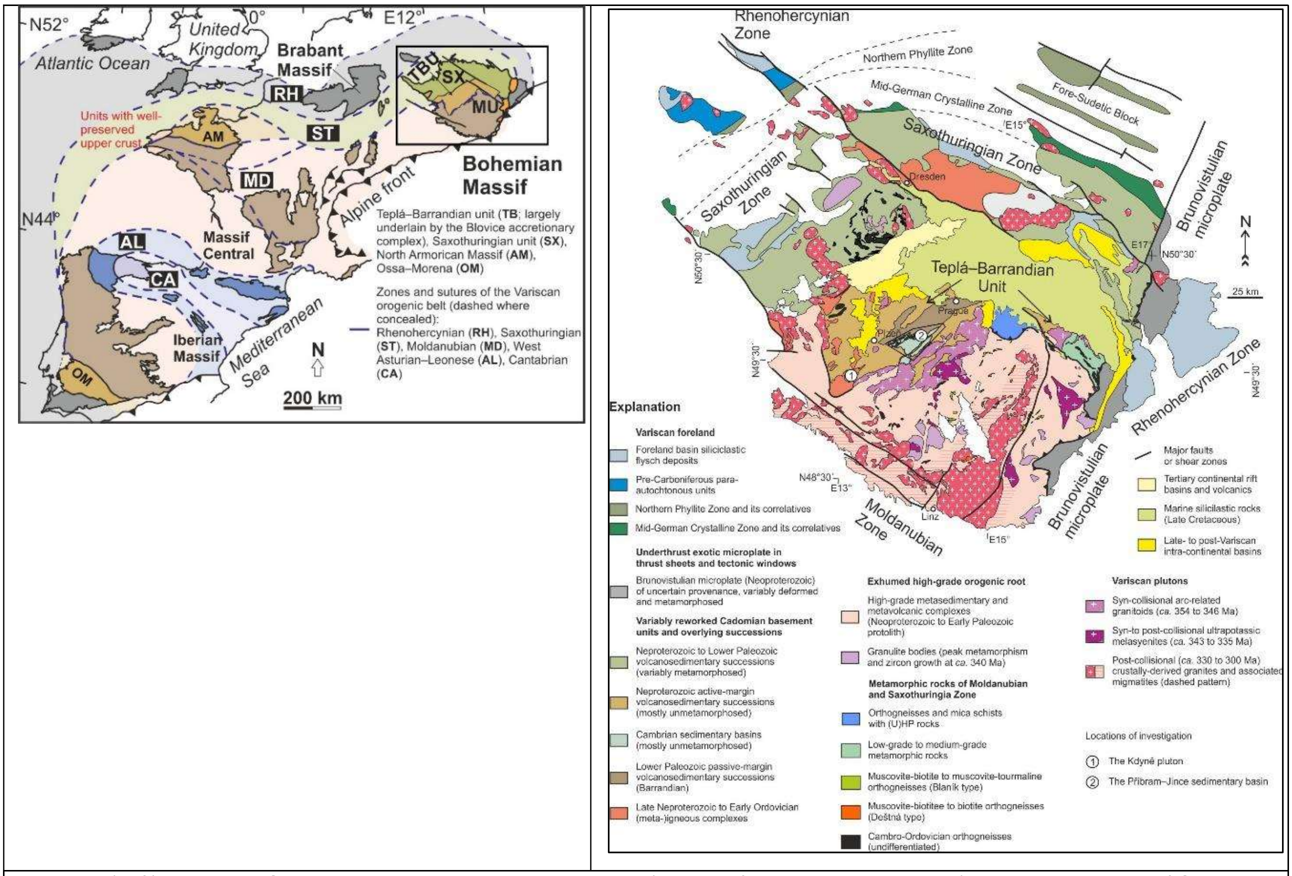


Figure 1. (Left) Avalonian-Cadomian terranes in the late Paleozoic (redrawn from Nance et al., 2002), with the overview of Cadomian crustal fragments within the Variscan orogenic belts of Europe (compiled from Martínez Catalán, 2011); (Right) simplified geologic map of the Bohemian Massif (background geology based on Chábet al. 2007)

The kinematic analysis was supported by a detail field structural record both in Kdyně pluton and the Příbram–Jince basin. An oriented thin section was provided to support this analysis. Combination of field observation and rock magnetic (AMS) analyses are designed to examine the depositional processes through internal characteristic of rocks, to evaluate the tectonic controls on fluvial deposit and magmatic flow systems in plutonic setting, and to establish general conceptual model during Gondwana's active to passive margin transition.

2. Data and Methods

The methods used in this research are integrated between macro and micro structural analysis. Field mapping was performed to record macro-structures such as structural, stratigraphic and sedimentology features. To assist some field interpretation, micro structural analysis through anisotropy of magnetic susceptibility (AMS) was conducted in the laboratory of Rock Magnetism at the Institute of Geology and Paleontology, Charles University, Prague. The AMS samples were drilled from 6 plutonic, 14 meta-graywacke, and 18 sedimentary rocks using hand-held drill. The core samples are cut into more than 500 standard cylindrical specimens (2.1 cm high and 2.5 cm in diameter).

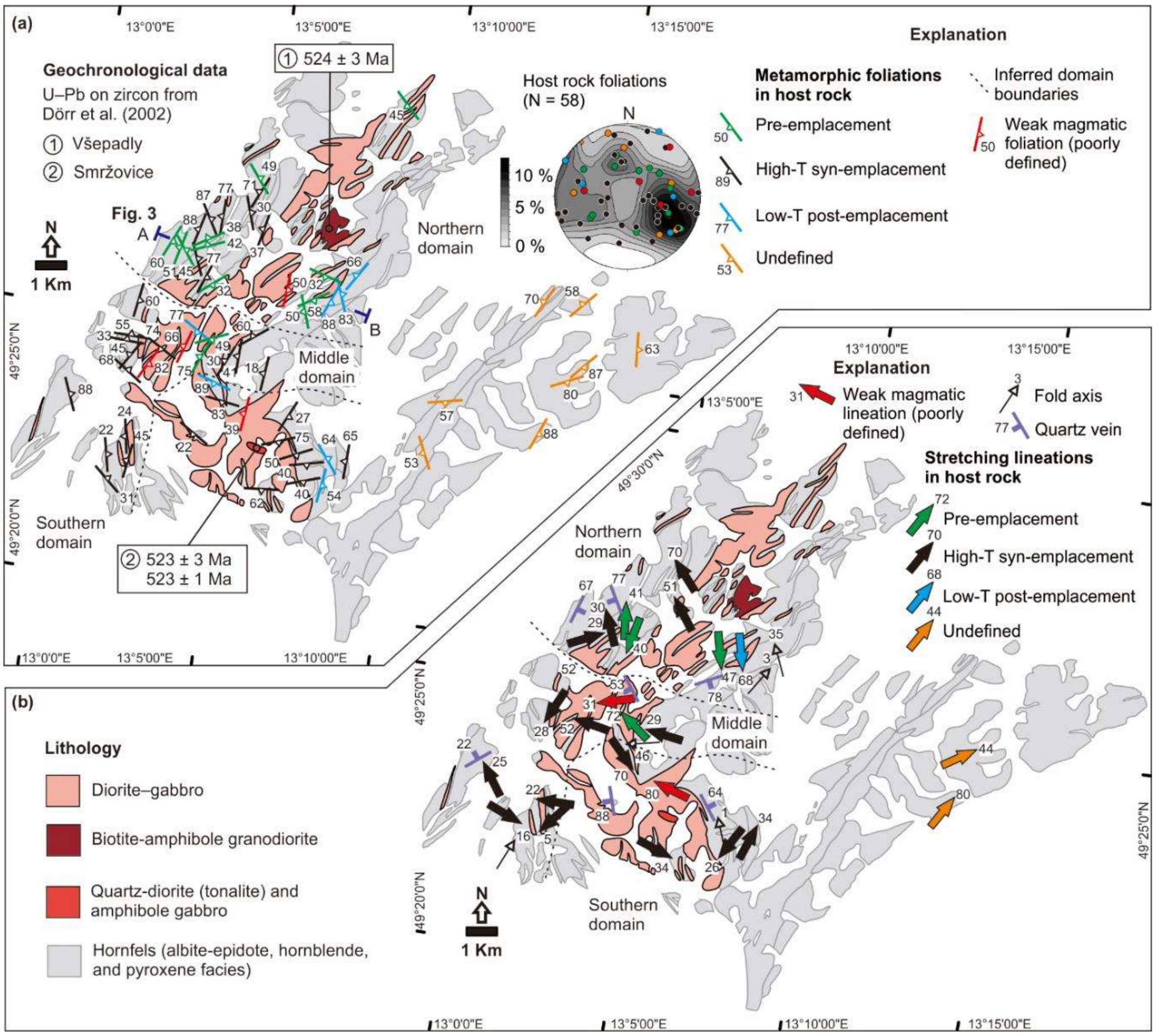


Figure 2. Field data observation from Kdyně pluton. (a) distribution of metamorphic foliations, color coded based on the orientation between its foliation to the pluton contacts with the host rock (b) various stretching lineations direction in pluton bodies and its host rock.

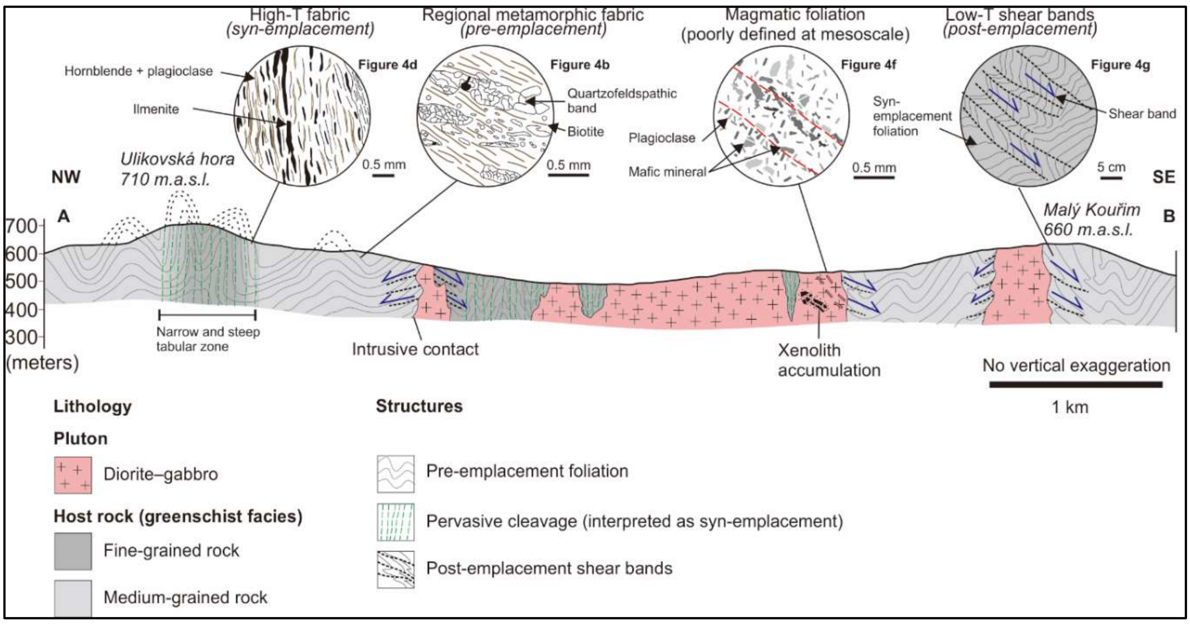


Figure 3. Cross section of Kdyně pluton that shows various emplacement fabrics of host rock intruded by diorite to gabbro plutons.

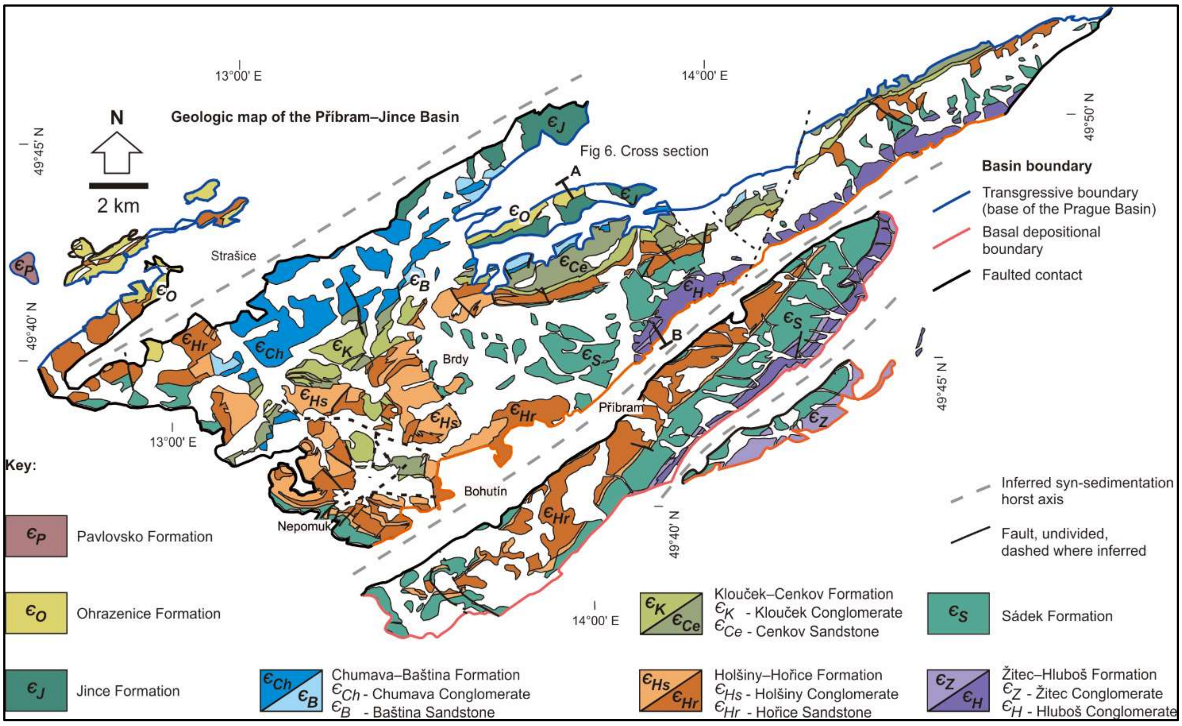


Figure 4. Simplified geologic map of the Příbram–Jince basin.

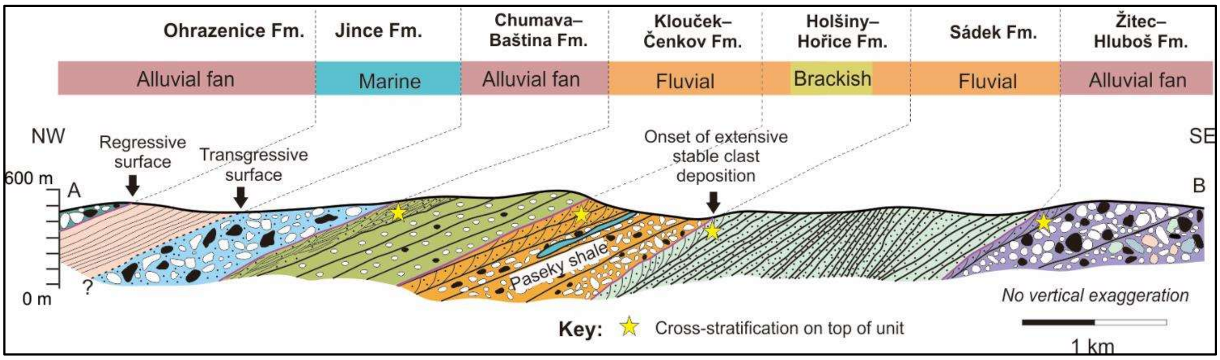


Figure 5. Cross section of the Pribram-Jince basin, fluvial-dominated with short-lived marine transgression.

Anisotropy of Magnetic Susceptibility (AMS)

Magnetic susceptibility is the ability of a substance to be magnetized by an applied magnetic field (k). The magnetic susceptibility involved the ratio between magnetization (M) within the material and the applied magnetic field strength (H), or expressed as (SI unit are used here):

$$k = \frac{M}{H} \quad 1)$$

Low field anisotropy of magnetic susceptibility (AMS, e.g., Borradaile and Jackson, 2004, 2010; Tarling and Hrouda, 1993) was chosen to quantify the symmetry, intensity, and orientation of magnetic fabric from selected samples. Each of minerals inside a rock has a distinguish magnetic property. Therefore, the magnetic property in a rock is anisotropy and divided into three groups.

The magnetic minerals which have higher susceptibility value (from 1×10^{-3} to 1×10^{-2}) are called ferromagnetic (i.e., magnetite, maghemite, and other iron oxides), while smaller magnetic susceptibility (from 1×10^{-5} to 1×10^{-4}) are termed paramagnetic mineral (i.e., olivine, amphibole, biotite, muscovite). On the contrary of above types, the magnetic minerals which have different orientation than the applied magnetic field, hence, have a negative magnetic susceptibility (-1×10^{-5}), are called diamagnetic (e.g., quartz, calcite).

The mineral contribution to the bulk susceptibility of rock may vary significantly, depending on their intrinsic susceptibility as well as on their concentration; for instance, if a rock contains paramagnetic minerals as the mineral constituents (ca. 10%) with mean susceptibility range from 1×10^{-4} to 1×10^{-3}, its susceptibility and anisotropy are affected by the paramagnetic and ferromagnetic fractions.

AMS is easier to be visualized by its ellipsoid with three orthogonal principal axes, which are the longest, intermediate, and shortest axis corresponding to maximum (k_1), intermediate (k_2), and minimum (k_3) principal susceptibilities, respectively (e.g., Hrouda, 1982; Tarling and Hrouda, 1993). In petrofabric analysis, k_1 represents magnetic lineation, and k_3 is the normal (pole) to the magnetic foliation.

There are three parameters used to characterize the magnetic fabrics (e.g., Hrouda, 1982):

(1) the bulk susceptibility represents the proportion and composition of diamagnetic, paramagnetic, and ferromagnetic minerals in a measured specimen,

$$k_m = \frac{k_1 + k_2 + k_3}{3} \qquad 2)$$

(Nagata, 1961; Janák, 1965)

(2) the degree of anisotropy reflects the eccentricity of the AMS ellipsoid and thus may indicate the intensity of the preferred orientation of the magnetic minerals,

$$P = \frac{k_1}{k_3} \qquad 3)$$

(Nagata, 1961)

(3) and the shape parameter indicates the shape of the AMS ellipsoid. For $-1 \leq T < 0$, the ellipsoid is prolate; for $T = 0$ it is triaxial or transitional between linear and planar magnetic fabric; for $1 \geq T > 0$ it is oblate.

$$T = \frac{2ln\left(\frac{k_2}{k_3}\right)}{ln\left(\frac{k_1}{k_3}\right)} - 1 \qquad 4)$$

(Jelínek, 1981)

3. Results and Discussion

A. Field Observation

The northern domain of Kdyně pluton shows an alternating and irregular sheet-like pluton bodies with host rock, while the southern domain is more homogenous (Fig. 2). Most of the outcrops is isotropic and the foliation and lineation are macroscopically rare to be discovered, except few of plagioclase and mafic minerals (amphibole and/or pyroxene) that show shape-preferred orientation. Magmatic foliation is oriented NNE–SSW to NE–SW with various dip, and the plunges of magmatic lineation are oriented to the WSW (azimuth 31◦) or the NW (azimuth 80◦). Kdyně pluton intruded the Neoproterozoic host rock, hence, resulting the pre-, syn-, and post-emplacement fabrics (Fig. 3). The pre-emplacement fabrics show an alternating mica-rich and quartzofeldspathic bands, and a metagraywackes and phyllitic shales foliation, mostly present in the northern and middle structural domains (Fig. 2 and 3). The foliation dips moderately to steeply and its strike is sub-parallel to almost perpendicular to the NE–SW pluton axis. The syn-emplacement fabrics are related to high-temperature and low-pressure metamorphic event and sub-parallel to intrusive contact and pluton axis. This syn-emplacement fabrics is widely distributed around the pluton as well as in the host rock interior. The post-emplacement fabrics are characterized by shear bands and space cleavage parallel to fold axial planes, resemble a cascading fold associated with normal kinematics in a metamorphic core complex.

On contrary, the Příbram–Jince basin (Fig. 4) is composed of eight fluvial and marine rock formations, which are the Žitec–Hluboš, the Sádek, the Holšiny–Hořice, the Klouček–Čenkov, the Chumava–Baština, the Jince, Ohrazenice and Pavlovsko formations (Havlíček, 1971; Kukal, 1971). This basin is dominated by monomictic quartz and polymictic conglomerates and few fine-grained sedimentary rocks. A significant grain changing from boulders to fine-grained sediment occurred at the lower part of the basin between the polymictic conglomerate of the Žitec–Hluboš formation ca. 515 Ma (various clast of quartz, granite, plagio-granite, chert, rhyolite), the Sádek ca. 512 ± 5 Ma (sandstone and siltstone), and the monomictic conglomerate of the Holšiny–Hořice formations ca. 511 ± 3 Ma (quartz sandstone conglomerate). Paleocurrent analysis shows that the Žitec–Hluboš and the Sádek formations flow toward the NW and NE or oblique, while the Holšiny–Hořice formation toward the ENE or parallel to the basin.

B. Microstructure analyses

The samples from Kdyně pluton are divided into host rock and pluton. 18 oriented and 4 non oriented samples were collected and sliced into thin section.

In the host rock, the pre-emplacement samples are dominated by metagraywacke consist of quartzofeldspatic bands, alternating with mica bands (composed of biotite and fine-grained chlorite–muscovite matrix). The quartz-plagioclase bands are fine-grained (0.1–0.5 mm) and could be folded into asymmetric folds (Fig. 6b). The syn-emplacement microstructure has a steep foliation. The fine-grained hornblende–plagioclase bands are alternating with coarse-grained plagioclase and pyroxene-rich aggregates (Fig. 6d). The post-emplacement is characterized by metabasic lithologies (Fig. 6g). The shear planes cut obliquely and locally the pre-existing syn-emplacement foliation defined by bands and lenses of recrystallized plagioclase.

The pluton is dominated by diorite to gabbro with 0.1 to more than 1 mm crystal size. Biotite–clinopyroxene–hornblende diorite composed of plagioclase (andesine), tschermakite (tschermakitic hornblende to actinolitic hornblende), clinopyroxene (augite), orthopyroxene (hypersthene), biotite, opaque minerals (ilmenite, apatite, pyrrhotite), and some quartz.

The samples from the Příbram–Jince basin were derived from 18 fluvial and marine sedimentary rocks. Most samples show a dynamic recrystallization with frequent volcanic fragments occurrence. In the basal part (the Žitec–Hluboš Formation), the quartz grains are generally uniform in size (ca. 0.5–0.7 mm) and has an undulose extinction, while the volcanic fragments (lava, tuff, and volcanic glass) are highly variable in size, ranging from 0.1 to 1 mm (Fig. 7b).

The Sádek Formation is represented by 100–250 µm angular to sub-angular quartz grains and mostly lack undulose extinction. The quartz grains are embedded in a clay-rich matrix, containing abundant clastic grains of chlorite.

Other quartz-pebble conglomerate samples are composed fine to medium-grained, sub-angular to sub- rounded quartz clasts with size ranging from 0.5 to 2 mm (Fig. 7d). Most of the quartz grains within the clasts exhibit undulose extinction and show low- to high-temperature dynamic recrystallization. The only different with the basal part is that these conglomerates are monomictic (polycrystalline quartz aggregates) and show small amount of volcanic fragments.

C. Anisotropy of Magnetic Susceptibility (AMS) Analysis

Rock magnetic response in pluton and sedimentary basin are different. The mean magnetic susceptibility of Kdyně pluton ranges between -10^{-6} and 10^{-3}, however, it is dominated by 10^{-4} and 10^{-3}, representing the combination of paramagnetic and ferromagnetic minerals. Meanwhile, the sedimentary rocks in the Příbram–Jince basin ranges from -10^{-3} and 10^{-2}, with the most frequent values between -10^{-5} and 10^{-4}, corresponding to paramagnetic minerals.

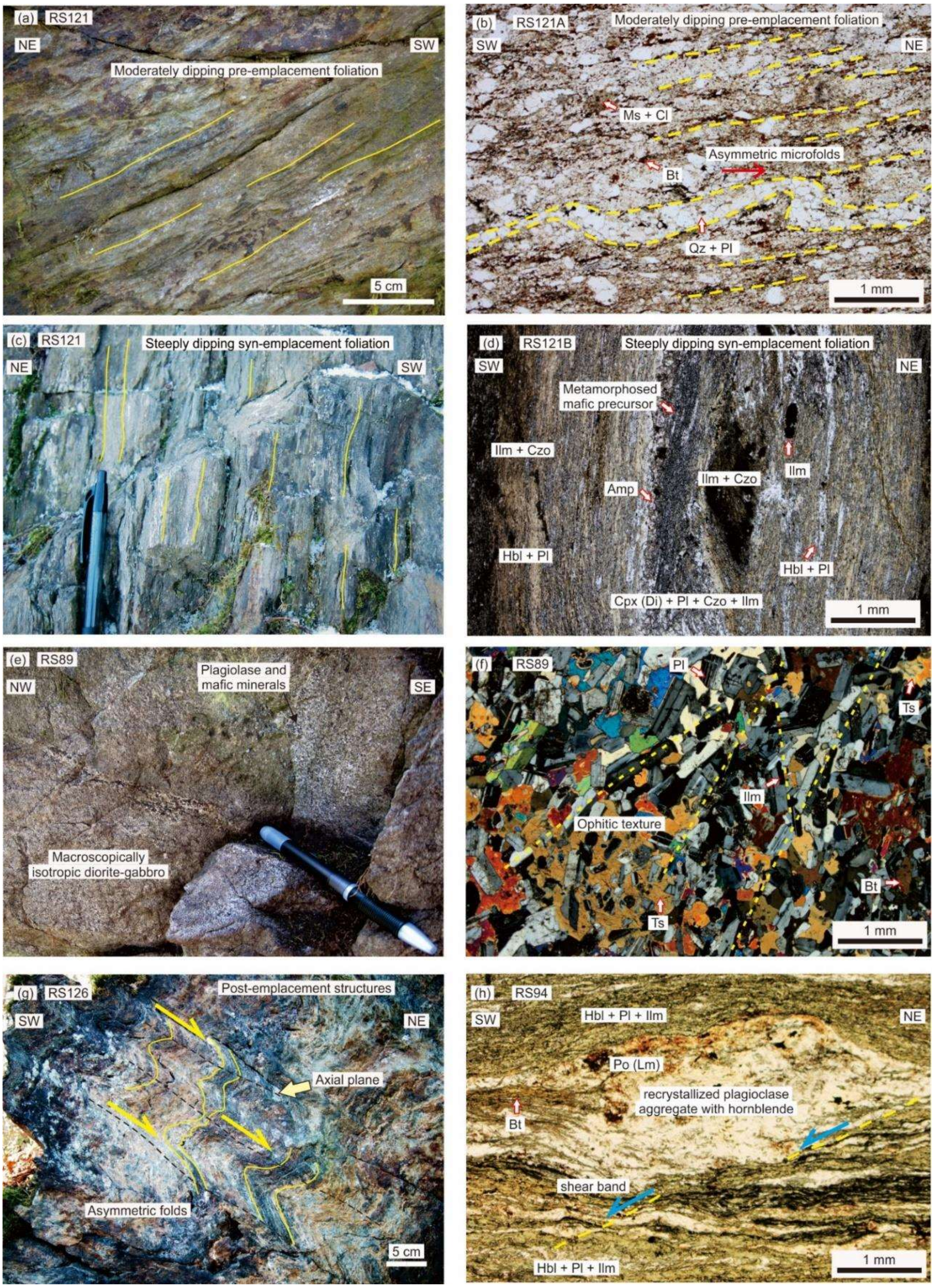


Figure 6. Outcrops of Kdyne host rock and pluton (left panel) and its microstructure. Most of thin section are oriented parallel to stretching lineation, except for the granite. Mineral abbreviations: Amp = amphibole, Bt = biotite, Cl = chlorite, Cpx = clinopyroxene, Czo = clinozoisite, Di = diopside, Hbl = hornblende, Ilm = ilmenite, Lm = limonite, Ms = muscovite, Pl = plagioclase, Po = pyrrhotite, Px = pyroxene, Qz = quartz, Ts = tschermakite.

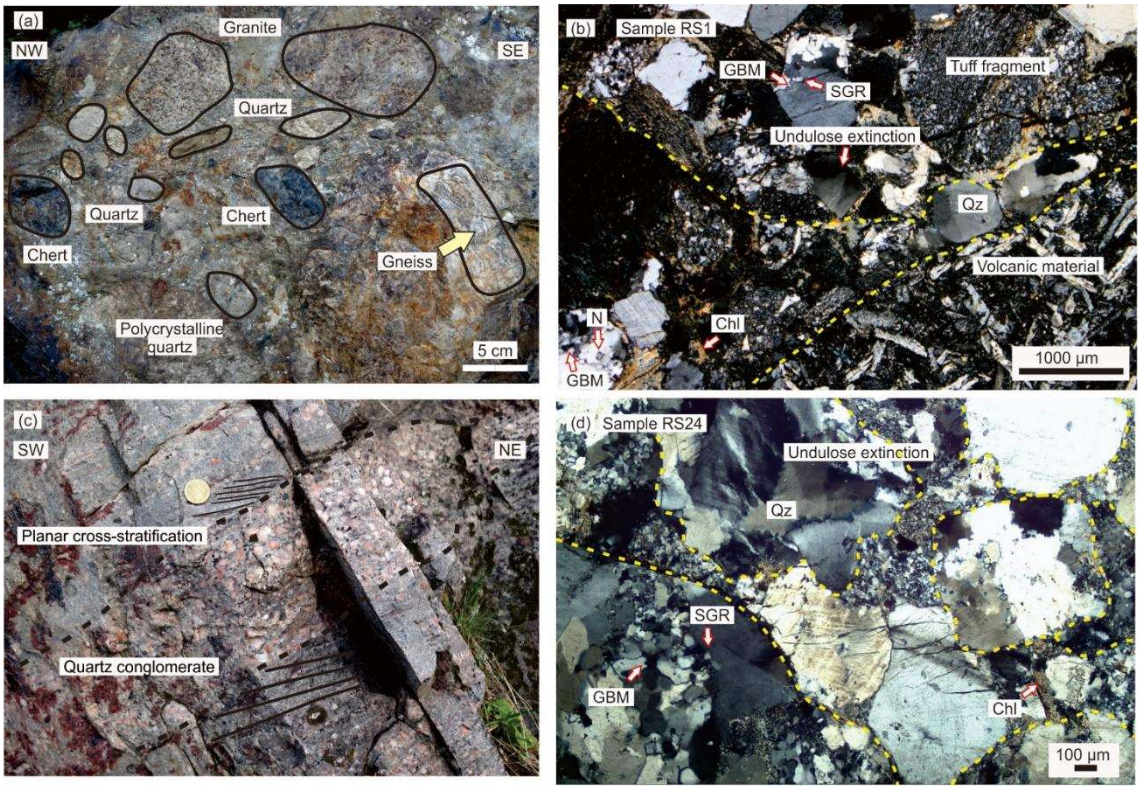


Figure 7. Representative outcrops of the Příbram–Jince basin with its microstructures. a and b: The basal part of this basin (Žitec–Hluboš Formation) consists of volcanic and metamorphic grains. c:Cross-stratification structure in a conglomeratic sandstone. d: Most quartz has been subjected to dynamic recrystallization. Abbreviation: New grain (N) emerged as the result of progressive subgrain rotation (SGR). Grain boundary migration (GBM). Chl = chlorite, Ms = muscovite, Pl = plagioclase, Qz = quartz.

The characterization of AMS fabrics in Kdyně pluton is grouped based on measured orientation distribution and its relation to angular relationships between the principal susceptibilities of magnetic minerals and the mesoscopic fabric measured on the outcrop (Fig. 8). AMS fabric in Kdyně pluton and its host rock is divided into three types: (1) Type 1 is characterized by invisible mesoscale foliation, (2) Type 2 is marked by a small angle (15° to 25°) between magnetic to the measured mesoscopic foliations, and (3) Type 3 is comprised by high angular relationship (>30°) between the mesoscale and magnetic foliations.

Magnetic fabrics of the Příbram–Jince basin is classified according to their angular relationship between bedding and/or cross-stratification to principal susceptibilities of magnetic minerals (Fig. 9). The classification is managed to differentiate four end-member types. Type I is characterized by highly clustered principal susceptibilities and its maximum principal susceptibilities (k_1) is parallel to sub-parallel to bedding or cross-stratification planes, suggesting a depositional fabric. Type II fabric is marked by sub-parallel magnetic foliation to bedding or cross-stratification, while magnetic lineations are disperse broadly within or close to the bedding or cross-stratification plane. AMS ellipsoids in Type II are oblate ($0.06 < T < 0.9$) and low – moderate degrees of anisotropy ($1.0 < P < 1.7$) and are associated with compactional fabric during burial. The Type III fabric is marked by steep striking magnetic foliations, creating a high angle to the bedding with subhorizontal magnetic lineations close to the bedding plane. The shape parameter and degree of anisotropy show no specific characteristic, suggesting that Type III is a tectonic fabric. Type IV shows a high angle of magnetic foliations and lineation to the bedding, high degree of anisotropy, and oblate to prolate shape parameters. This Type IV represents an inverse magnetic fabric. Therefore, only Type I, which shows a depositional record used for further analysis.

D. Tectonic implication

The structures in the Kdyně pluton show an orthogonal features between foliation and lineation (metamorphic and magmatic). These features occurred due to shallow intrusion that pushed a more brittle host rock upward (Fig. 10b). The post emplacement is then affected by shear structures, indicating that the Kdyně pluton was located between a major strike-slip zone, and thus influenced the sickle-shaped pluton bodies.

On another hand, the Příbram–Jince basin is highly probable experienced tectonic transformations. This can be inferred from a changing of tectonic quiescence during 512 Ma to a sediment resupply from different direction with a dextral transtension influence (Fig. 8a).

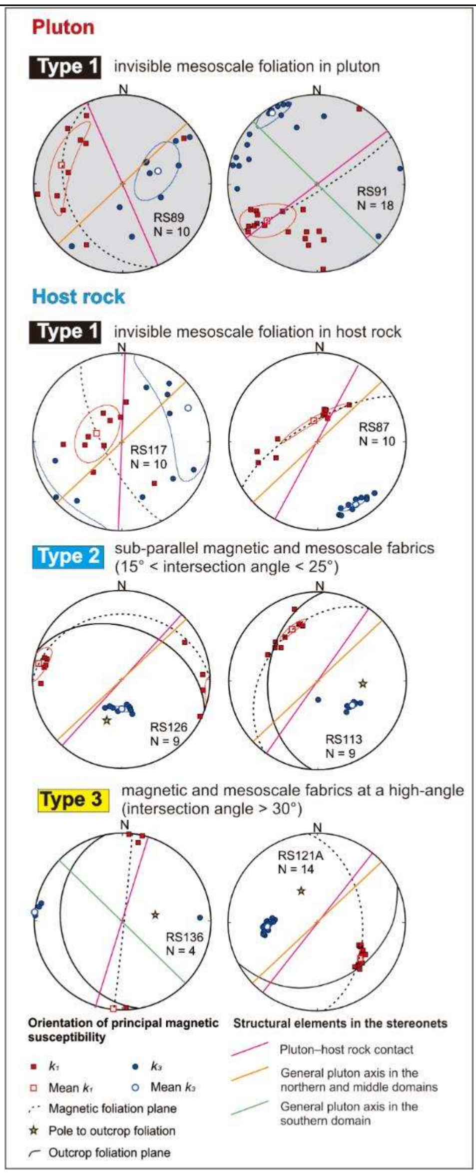


Figure 8. Representative AMS fabric in the Kdyně pluton and host rock. The AMS fabric is classified based on the orientation of pluton-host rock contact, pluton axis, and magnetic foliation and lineation.

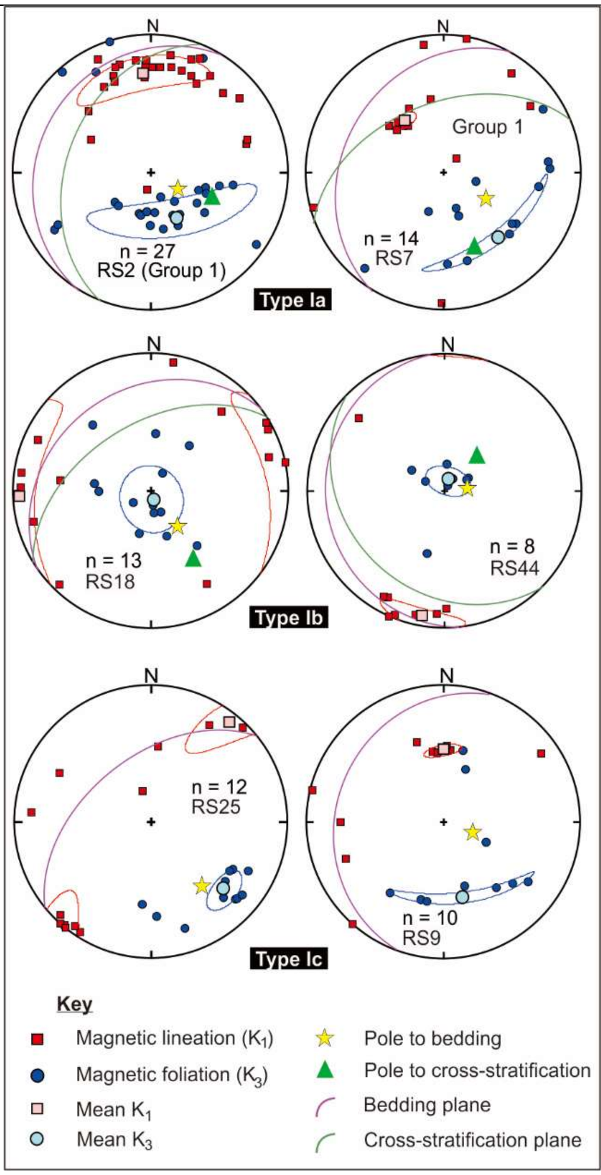
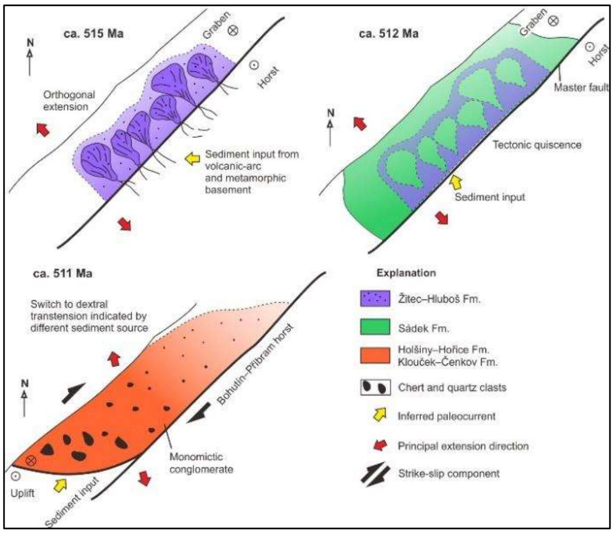


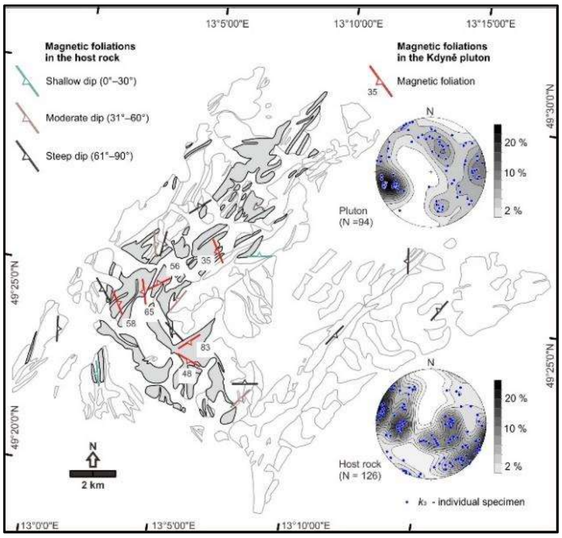
Figure 9. Type I of AMS fabric in the Příbram–Jince basin shows sub-parallel plane between bedding, sedimentary structure, and magnetic lineation and foliation, suggesting a depositional record during active sedimentation.

D. Conclusion

Magnetic fabrics in a rock record important features related to dynamic processes. Magmatic activity in Kdyně pluton is a key feature that act as a driving force and promote an active rifting mode after the Cadomian subduction (524–522 Ma). This active rifting may possibly be substituted by a passive rifting mode in the Příbram–Jince basin due to another paleo-ocean subduction (Iapetus Ocean) and caused slab-pull force operated on Gondwana margin from ca. 510 Ma onwards.



(a)



(b)

Figure 10. (a) evolution of lower Příbram–Jince basin demonstrates the change in sedimentary provenance from oblique to parallel basin axis, indicating a tectonic switching. (b) Distribution of magnetic foliations in the host rock shows that the mineral grains tend to follow Kdyně pluton-host rock contact, suggesting a similar condition in a magma flow and emplacement.

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References

Borradaile, G., Henry, B., 1997. Tectonic applications of magnetic susceptibility and its anisotropy. Earth Sci. Rev. 42, 49–93.

Borradaile, G.J., Jackson, M., 2004. Anisotropy of magnetic susceptibility (AMS): magnetic petrofabrics of deformed rocks. Geol. Soc. London, Special Publications 238, 299–360.

Borradaile, G.J., Jackson, M., 2010. Structural geology, petrofabrics and magnetic fabrics (AMS, AARM, AIRM). J. Struct. Geol. 32, 1519–1551.

Cháb, J., Stráník, Z., and Eliáš, M., 2007. Geological map of the Czech Republic 1:500,000: Czech Geological Survey.

Hajná, J., Žák, J., Dörr, W., Kachlík, V., Sláma, J., 2018. New constraints from detrital zircon ages on prolonged, multiphase transition from the Cadomian accretionary orogen to a passive margin of Gondwana. Precambr. Res. 317, 159–178.

Havlíček, V., 1971. Stratigraphy of the Cambrian of Central Bohemia. J. Geol. Sci. Geol. 20, 7–52.

Hrouda, F., 1982. Magnetic anisotropy of rocks and its application in geology and geophysics. Geophys. Surveys 5, 37–82.

Janák, F. 1965. Determination of anisotropy of magnetic susceptibility of rocks. Stud. Geophys. Geod. 9, 290–301.

Jelinek, V. 1981. Characterization of the magnetic fabric or rocks. Tectonophysics 79, 63–7.

Kukal, Z., 1971. Sedimentology of Cambrian deposits of the Barrandian area (Central Bohemia). J. Geol. Sci., Geol. 20, 53–100.

Nagata, T., 1961. Rock Magnetism. Maruzen, Tokyo, 350.

Nance, R.D., Gutierréz-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A., Woodcock, N.H., 2010.

Evolution of the Rheic Ocean. Gondwana Research 17, 194–222.

Nance, R.D., Murphy, J.B., Keppie, J.D., 2002. A Cordilleran model for the evolution of Avalonia. Tectonophysics 352, 11–31.

Tarling, D. and Hrouda, F., 1993. Magnetic anisotropy of rocks. Chapman & Hall, London.Boggs, S. (2014).