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Review of the PhD thesis
'Mechanisms and time scales of formation of ribbon continents'
submitted by Reza Syahputra

There is no conflict of interest between the author of the present thesis and the referee.
The thesis submitted by Reza Syahputra is focusing on the interaction between late Neoproterozoic to Ordovician deformation, magmatic activity, and sedimentation affecting the central part of the Bohemian Massif. This period was characterized by the transition from an Andean-type active margin, related to the Cadomian orogeny at the northern margin of Gondwana, to rifting and development of a passive margin during the opening of the Rheic ocean. The age and type of magmatic activity were studied in the Kdyně pluton of the Teplá-Barrandian Unit, which represents the upper crustal level, and in Moldanubian metagranitoids of the Pardubice and Vysočina area, which display deeper structural levels. The type of sedimentation was investigated in the Příbram–Jince basin, which largely consists of Cambrian sedimentary and volcanic rocks.
The new data and results were attained using a combination of various field and analytical methods, which include optical microscopy, anisotropy of magnetic susceptibility (AMS), and U–Pb zircon geochronology. The most important results can be summarized as follows: (1) The Kdyně pluton was an apical part of a domal structure in the upper crust and was primarily controlled by magma buoyancy rather than tectonic deformation through rapid and multiple emplacement processes. The deformation during the pluton emplacement was partitioned into simple shear-dominated zones that delimited pure shear-dominated belts. This rapid heat input

into the former accretionary complex of Blovice was perhaps due to slab break-off, indicating the initial stage of extension in the Teplá–Barrandian unit. (2) The Příbram–Jince basin was formed by synsedimentary normal faulting during the separation of the Avalonian– Cadomian belt from the northern Gondwana margin. The tectonic setting evolved from pure shear to a pull-apart dextral transtension with its source coming from the local material of the Blovice accretionary complex. (3) The slab break-off in the Teplá–Barrandian unit was followed by lithospheric thinning that caused emplacement of granitic magma in the Moldanubian zone due to basalt underplating in the extended crust. This event was coeval with the Avalonia ribbon terrane's rift–drift transition and opening of the Rheic Ocean (at ca. 485 Ma).

The thesis is clearly organized and well written. One major part of it that is dealing with the AMS data of the Příbram–Jince basin has already been published in Gondwana Research, 105, 492–513, with the candidate of the thesis as first author. Most of the data are presented in form of figures and tables, which are also clear and well explained in the captions. Nevertheless, when going through the text, some shortcomings and a number of questions arose that should be addressed during the defence of the thesis. They are listed in the following paragraph.

- P. 1. Gondwana is referred to as a supercontinent. Is this correct? To my knowledge, a supercontinent is a landmass made up of most or all of Earth's land. The supercontinent cycle includes supercontinents such as Rodinia and Pangaea. In the present case, instead of Gondwana, I suggest using the term Pannotia, which describes the short-lived ‘supercontinent’ in Vendian times.
- Did a supercontinent really exist when the so-called ribbon continent was formed? This question is very important as the heat bulge below such a supercontinent might have supported the break-up of the large landmass and the separation of ribbon continents along its margins.
- It is stated that the evolution of ribbon continents typically includes four main stages: (1) rifting and rift–drift transition, (2) drift, (3) collision and reworking, and (4) late-stage oroclinal rotation and/or strike-slip slicing. We know a similar sequence of geodynamic stages described by the Wilson cycle, which, however, has not been mentioned at all
- Section 4 “Data and Results” includes many published data, which should have been presented either earlier in the “Introduction”/“Regional Geology” sections or later in the “Discussion” section. It is important for the reader of the present thesis to know the emplacement depth and the cooling history of the Kdyně plutons, which are well known but have not been addressed in the thesis. For example, the Všepadly granodiorite and the Smržovice diorite intruded at shallow crustal levels (<ca. 7 km depth) and K–Ar age dating yielded 547 ±7 and 549 ±7 Ma for hornblende and 495 ±6 Ma for biotite of the Smržovice diorite, suggesting that this pluton has remained at shallow crustal levels (T <ca. 350 °C) since its Cambrian emplacement (Bues et al., 2002, and references therein).
- In section 4.1., the change in melt composition from the Stod to the Neukirchen pluton has been described. However, the depth of intrusion, which is well constrained for the Stod pluton (Zulauf et al., 1997, Fig. 6), and the cooling ages of amphibole and micas have not been considered, although these are important for the interpretation of the new data obtained in the frame of the present thesis.

Moreover, the model of a layered intrusion, as described by Vejnar (1986) should also be considered here.

- AMS data are interesting. However, foliation and lineation derived from macroscopic and microscopic investigations of the constituent minerals are more reliable for constraining the kinematics and structural evolution of ad deformed rock. What type of lineation is present? Stretching lineation? Mineral lineation? The host rock of the Kdyňe pluton underwent polyphase ductile Cadomian deformation (at least two deformation phases in the Domažlice crystalline complex and the area of Stod; Zulauf, 1995, 1997; Zulauf et al., 1997). Close to the contact with the pluton, this primary strain fabric was overprinted by emplacement-related fabrics or even by more or less static contact metamorphism and related annealing (pyroxene hornfels zone). For this reason, the AMS foliation and lineation obtained from the host rock are difficult to interpret. This problem should be addressed at least in the 'Discussion' section.
- The Žitec–Hluboš Formation as the stratigraphically deepest member of the Příbram–Jince basin is part of the present study and thus was described in detail concerning composition and components. It should be noted that a granite boulder of a conglomerate of this sequence collected near the Tuškovský mill has been investigated in detail by Dörr et al. (2002). The major element composition points to a peraluminous granite. In the diagrams Nb+Y/Rb and Y/Nb of Pearce et al. (1984), the granite plots within the volcanic-arc field. In the Concordia diagram, three zircon fractions define an upper intercept at ca. 600 Ma and a lower intercept at ca. 275 Ma with a large uncertainty, because they plot close together. The upper intercept is interpreted as intrusion age of the granite (Dörr et al., 2002). These data should be important for unravelling the geodynamic setting in late Neoproterozoic to Cambrian times.
- P. 72: The description of the microfabrics of the Cambrian sediments is a bit confusing as we are dealing with inherited structures of the clastic grains and pebbles on the one hand, and with structures obtained during the Variscan folding and shearing, which affected all of the components and the matrix, on the other hand. It has been stated that clastic grains of chlorite are frequent along contacts between the quartz grains of the Žitec–Hluboš Formation, occasionally accompanied by new growth of muscovite. Thus, fluids were important during deformation. What about the role of fluids during deformation? Peak stresses should have been present along grain-grain contacts particularly between pebbles of conglomerates, supporting pressure solution and formation of pitted pebbles. Pressure solution of quartz is particularly strong at contacts to micas. The Cambrian strata were deformed during the Variscan cycle, which should have led to solution precipitation creep, particularly in the fine-grained rocks.
- P. 74: In caption of Fig. 22. I don't like describing processes in the microphotographs, such as annealing, grain-boundary migration recrystallization or subgrain-rotation recrystallization. The photographs show microfabrics, which should be described. Based on these microfabrics, the

deformation mechanisms can be inferred. Moreover, annealing resulting from grain boundary area reduction? It should be the other way round. GBAR results from annealing.

- What is a recrystallized tuff? In material science and in structural geology, recrystallization is a thermally activated process related to the slip and climb of dislocations. It implies the formation of new grains with a low amount of dislocations at the expense of older deformed grains with a high amount of dislocations. A tuff, however, includes different mineral phases and probably also volcanic glass. Deformation of these took place at relatively low temperature, where dislocation creep did probably not occur.
- In the sediments of the Příbram–Jince basin, the Type III of magnetic fabrics is interpreted as a tectonic fabric closely corresponding to the regional Variscan cleavage and stretching lineation in ductile deformed domains (Casas and Murphy, 2018; Stephan et al., 2016; Žák et al., 2013). What does this mean? Fabric in which rocks? The citations listed above seem to be not or only partly appropriate. Note that ductile Variscan fabrics in the Teplá-Barrandian Unit have been described from the Cadomian basement exposed near Domažlice, Stod and Teplá. (Zulauf, 1995, 1997, 2001; Zulauf et al., 1997). This Cadomian basement is resting below the sediments of the Příbram–Jince basin. Close to the Cambrian plutons, Cadomian and Variscan imprints can be well distinguished because of static contact metamorphism. Why not comparing the magnetic fabrics of the sediments (inferred to be of tectonic origin) with these fabrics? What is the Variscan fabric in the sediments described in the present thesis? What is the Variscan metamorphic grade in the sediments? As I remember right, there should be no or at least a very low grade metamorphism in these sediments. A distinct cleavage is therefore lacking in these rocks. What was the dominant deformation mechanism in the Cambrian sediments? I guess it was cataclasis and solution-precipitation creep. Thus, in order to interpret the AMS data of the sediments, their fabric and strain related to the Variscan deformation has to be analysed and described.
- It has been emphasized that the AMS-derived palaeocurrent directions must be interpreted with caution. I agree with this statement. Does it really make sense to carry out AMS studies in conglomerates, where each pebble has its own inherited AMS memory?
- P. 108. An age progression of the Kdyňe plutons is highly speculative as the U-Pb ages of both plutons are the same within the uncertainties (Smržovice 523 ±3 Ma; Všepadly granodiorite 524 ±3 Ma). Note, even the Orlovice gabbro and the Tešovice granite of the Stod pluton yielded these ages.
- The emplacement mechanisms of plutons are strongly dependent on the intrusion depth. For this reason, I am wondering why the intrusion depths of the studied granitoids of the Kdyňe pluton have not been addressed, not in the ‘Introduction’ nor in the ‘Results’ or ‘Discussion’ section of the present thesis. In the NE part of the investigated area, all plutons including the the Tešovice biotite granite, the Všepadly granodiorite and the Smržovice diorite, intruded at shallow crustal levels (<ca. 7 km depth, Zulauf et al., 1997; Bues et al., 2002). As a shallow emplacement is assumed in the emplacement model of the Kdyně pluton presented by the candidate, why not mention these data?

- Similar steep syn-emplacement hornfelsic foliation and steep fold axes as described from the plutons of the Kdyňe area have been described from the contact aureole of the Stod pluton (Zulauf, 1995, 1997; Zulauf et al., 1997). To unravel the geodynamic evolution of the Tepla-Barrandian Unit in Cambrian times, all these observations are significant and should be considered at least in the 'Discussion' section.
- P. 110. The syn- to late-emplacement dextral shearing in the Domažlice crystalline complex (ca. 522 Ma) was not directed NNE-SSW as stated in the present thesis, but was directed ENE-WSW (Fig. 4a in Zulauf et al., 1997, Fig. 2 in Zulauf and Helferich, 1997). However, the pre-plutonic Cadomian S2-foliation is trending NNE-SSW (Fig. 4b in Zulauf et al., 1997). Thus, this pre-plutonic Cadomian S2-foliation could have controlled the orientation of the fabric observed by the candidate in the northern part of the studied pluton.
- P. 111. It has been stated that the whole structure of the Kdyně pluton geometrically resembles a combination of the "b-type" and "a-type" domes described in metamorphic core complexes in the Aegean Sea and Alaska with two orthogonal principal extension directions and normal low angle detachments accommodating exhumation of the hot, magma-bearing domains in the footwall. Based on the very shallow intrusion depth (< 7 km) obtained by Zualuf et al. (1997) and Bues et al. (2002), this model seems to be not appropriate. Moreover, the cooling ages of hornblende and biotite of the study area between Kdyně and Stod are Cambrian meaning that rocks situated at structural levels where T > ca. 300°C have not been exhumed since Cambrian times. Thus, we are not dealing with metamorphic core complex in the study area.
- P. 111 and 131.The Cadomian P-T loop shows a phase of HT-LP metamorphism, which post-dates Barrovian metamorphism. This HT-LP metamorphism is older than the intrusion of the ca. 522 Ma old plutons (Zulauf, 1997; Zulauf et al., 1997). For this reason, the statement that significant rapid heat input occurred through the 522 Ma old plutons into an otherwise cold accretionary/forearc setting is questionable.
- P. 125. It is stated that ophiolites along the Tepla-Barrandian/Moldanubian boundary, that might indicate a spreading ridge and significant separation of the two units, are lacking. This, however, is not the case. Serpentinite and peridotite of the Bohemian shear zone have been described by Vejnar (1966, 1977). Moreover, large bodies of ultramafic rocks are also present along the Hoher-Bogen shear zone (Bues and Zulauf, 2000; Bues et al., 2002).
- P. 131. The Kdyně pluton was interpreted by Vejnar (1986) as a tectonically layered intrusion. I am wondering that this interpretation has not been considered in the 'Discussion' section.
- P. 133. It is argued that the Moldanubian and the Teplá-Barrandian unit belong to one and the same crustal unit. However, the emplacement of arc-related plutons in the Teplá-Barrandian unit migrated from S (ca. 522) to N (ca. 511). For this reason, I would expect even older plutons in the Moldanubinan crust situated today south of the TBU. Why are the lower to middle Cambrian plutons, which are

widespread in the TBU, largely lacking in the Moldanubian crust and why are the plutons of the Moldanubian crust even younger (Cambrian/Ordovician boundary)?

- Citations in the text are not always correct. For example, U-Pb age of Mračnice trondhjemite (U–Pb on zircon, 523 + 4/–5 Ma) has been published by Zulauf et al. (1997) but not by Zulauf and Helferich (1997). References in the reference list are partly lacking or not acceptable: The following citation is listed twice but with different year:

Zulauf, G., Schitter, F., Riegler, G., Finger, F., Fiala, J., Vejnar, Z., 2000. Age constraints on the Cadomian evolution of the Teplá Barrandian unit (Bohemian Massif) through electron microprobe dating of metamorphic monazite. Zeitschrift der deutschen geologischen Gesellschaft, 627–639.

Zulauf, G., Schitter, F., Riegler, G., Finger, F., Fiala, J., Vejnar, Z., 1999. Age constraints on the Cadomian evolution of the Teplá–Barrandian unit (Bohemian Massif) through electron microprobe dating of metamorphic monazite. Z. Dtsch. geol. Gesell. 150, 627–639.

The following publications are important for the Cadomian deformation of the study area and for the evolution of the Kdyňe Massif in particular:

Bues, C. and Zulauf, G., 2000. Microstructural evolution and geologic significance of garnet pyriclasites in the Hoher-Bogen shear zone (Bohemian massif, Germany). Int. J. Earth Sci., 88, 803-813.

Vejnar, Z., 1966. Peridotites and serpentinites of the Česky les mountains. Krystalinikum, 4, 163-170.

Vejnar, Z. 1977. Mica peridotites of western Bohemia. Krystalinikum, 13, 115-128.

Vejnar, Z., 1986. The Kdyňe massif, South-West Bohemia—a tectonically modified basic layered intrusion. Sb. Geol. Věd, Geol. 41, 9 – 67.

Zulauf, G., 1995. Cadomian and Variscan tectonothermal events in the SW part of the Teplá-Barrandian Unit (Bohemian Massif, Czech Republic). Zbl. Geol. Paläont. Teil I, 1993 H.9/10: 1516-1528.

Despite the above mentioned shortcomings and open questions, I conclude that the PhD thesis submitted by Reza Syahputra is a significant step forward, which helps to unravel and understand the geodynamic evolution of the Bohemian Massif during the final stage of the Cadomian orogenic cycle and during subsequent opening of the Rheic ocean. When taking the above recommendations into account, including the consideration of all published data, I suggest also publication of those data of the present thesis, which have yet not been published.

I recommend the thesis for its defense without reservations.

Frankfurt a.M., 19.02.2023

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