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How well do Precambrian paleomagnetic data agree with the Phanerozoic apparent polar wander path? A Baltica case study

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ABSTRACT

Precambrian paleomagnetic data are crucial for various tectonic and geophysical applications, the reconstructions of fusion and fission of supercontinents in particular. Due to many objective reasons, the variety of stability tests for these data are abridged in comparison to Phanerozoic results and is further hindered by the rather common refusal to consider the resemblance between Precambrian and younger poles. In this paper, we selected Precambrian paleomagnetic data with ages of <1.9 Ga from Fennoscandia, Ukraine and the Uralian margin of Baltica and compared them with Phanerozoic apparent polar wander path for this craton. Our most general finding is that there is a remarkable agreement between Precambrian data and younger segments of the Baltica APWP. We argue that this agreement is more than mere coincidence and may indicate that the remanence in the Precambrian rocks is not primary.

1. Introduction

In the mid-20th century, the first paleomagnetic data played the key role in demonstrating the existence of continental drift and providing the first insights into Phanerozoic paleogeography. Since then, there is a tendency to expand the paleomagnetic record both in terms of spatial and temporal coverage. The complexity of remnant acquisition in rocks is also recognized with the confirmation that the observed magnetizations may be much younger than the rocks. A second complication arises when attempting to provide age constraints on the magnetizations. It is far easier to ascertain the ages of magnetization components in relatively young objects. This is particularly true for rocks dating from the Mesozoic to present, in part, due to the existence of magnetic records on both land and on the seafloor. In contrast, Precambrian reconstructions are mostly based on paleomagnetic data, and the correct determination of magnetization origin and age becomes crucial, while the methods available to achieve these goals is reduced (i.e. no corresponding sea-floor records, no good fossil control and fewer outcrops).

Paleomagnetists have devised schemes that seek to formalize the procedure for evaluating the quality of a particular datum (see discussion in Van der Voo, 1990). In recent years, the most oft-used system for judging the merit of a particular pole is that of Van der Voo (1990), the so-called Q-factor. The "Q-factor", or quality factor is based on how many of the following criteria are met by a particular study. These include: (1) well-determined rock age and a presumption that magnetization is the same age; (2) sufficient statistics; (3) adequate demagnetization that demonstrably includes vector subtraction; (4) field tests that constrain the age of magnetization; (5) structural control and tectonic coherence with craton or block involved. (6) The presence of reversals; (7) no resemblance to paleopoles of younger age. In principle, the higher the Q-factor, the greater is the likelihood that the remanence correctly reflects the ancient geomagnetic field at a certain time within a certain block. As noted by Van der Voo, the Q-factor should not be used solely as a reason to reject a particular pole as high Q values do not guarantee a primary magnetization nor does a low Q-value indicate that a pole is incorrect.

It has been argued that the 7th point (i.e. resemblance to a younger paleopole) should be less important in evaluating Precambrian paleomagnetic data (see Veikkolainen et al., 2014). The rationale is simple in that the likelihood that a continent occupied the same latitude and orientation increases with the amount of time available (Veikkolainen et al., 2014). Although stated, rather matter-of-factly, this hypothesis has not been adequately tested

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in a statistically rigorous manner and there is no clearly defined statistical approach to determine the degree to which any two particular poles might overlap.

Generally speaking, it is the close agreement of paleomagnetic poles from older rocks with younger paleomagnetic poles that is used to argue for remagnetization. For example, results from the Ediacaran-aged Fen complex in southern Norway agrees well with the Permian pole for Baltica thus providing grounds for possible remagnetization during magmatism in the Oslo Graben nearby (Meert et al., 1998; Meert, 2014). There is a well-documented study of a limited area in southern Finland (Mertanen et al., 2008), where paleomagnetic signatures in deformed and non-deformed Mesoproterozoic rocks were compared with both Mesoproterozoic and Paleozoic records for Baltica and remagnetization was proposed as an explanation for similar directions. Yet, remagnetization is not always suspected when paleomagnetic poles from a younger unit match those of an older unit. One example is from the Harohalli region of India where two cross-cutting suites of dykes show overlapping paleomagnetic poles (one Early Paleoproterozoic and one Mesoproterozoic; Pradhan et al., 2008; Dawson and Hargraves, 1994; Halls et al., 2007; Belica et al., 2014).

The question posed by this paper is twofold: (1) how common is it for Precambrian paleomagnetic poles to match younger poles for the major cratons? and (2) is there a sound consistent basis for judging the degree to which those poles match? The initial impetus for writing this paper was triggered by a paleomagnetic study of Middle-Late Devonian minor intrusions on the northern coast of the Kola Peninsula, where most bodies proved to be completely, or nearly so, overprinted without clear evidence of remagnetization from geological data or rock-magnetic studies (Veselovskiy et al., 2013, 2016). Even more interesting is the fact that similar directions were identified in about twenty other studies with ages ranging from 500 Ma to >1.8 Ga throughout Fennoscandia. The authors attributed this commonality to a pervasive remagnetization in Early Jurassic time and triggered our interest to systematically compare Precambrian poles with the apparent polar wander paths (APWP's) for major cratons and provide some rationale for evaluating quality factor seven in the Van der Voo (1990) scheme.

The standard interpretation of a new paleomagnetic datum is to compare it with a reference; such as an apparent polar wander path for a particular tectonic unit (e.g., a craton). The difference between the pole and the reference path may further be used to evaluate relative tectonic motions (or the lack thereof), relative dating, and other purposes. The following terminology is used in this paper. A unit paleomagnetic pole (UPP) represents a time averaged magnetic pole that is assumed to coincide with the Geographic North or South pole. The UPP is calculated from the mean of virtual geomagnetic poles (VGP's) which are spot readings of the Earth's magnetic field. These spot readings (VGP's) may, or more likely, may not coincide with the Earth's geographic poles. A mean pole (MP) represents two or more UPP's averaged over a certain time window. The time ordered succession of UPP's or MP's constitute the apparent polar wander path (APWP). Hence, an UPP and a MP are of different statistical rank.

We think that two quite different questions can be answered with the same UPP and MP. The first (1) is the angular difference between these two poles (or directions) statistically significant? In this case, which is very common in tectonic interpretations, a direct comparison appears to be valid, despite the difference in statistical ranks. The second question is: Is the UPP in question drawn from the same population as the UPP's that are used for computing the reference MP? It is precisely this question that is to be answered if one wants to find whether an older UPP resembles (disagrees) some younger reference datum.

We argue that a valid procedure for the comparison in question #2 can be accomplished with the aid of Fisher statistics (Fisher, 1953) by calculating the radius of a confidence circle (B_p), which, on average, includes p% of reference UPP's. As is common in statistics, the p value of 95% is used. So if a new UPP falls inside the B_{95} circle, the possibility that the two directions are drawn from different populations is only 5%, thus making the pole comparison more definite. The kappa precision parameter (k; Fisher, 1953) gives a measure of the 'tightness' of data grouping. The higher the k-value, the tighter the grouping (see Van der Voo, 1990).

This method is illustrated (Fig. 1) with 280–300 Ma Baltic poles with Q-factor $\geqslant 5$ from a compilation by Torsvik et al. (2012). Seventeen Late Paleozoic UPP's are sufficiently well grouped ($K = 118$), and the MP is well defined ($A_{95} = 3.3°$). Our calculated B_{95} is 12.9°. Note that 5/17 of the Permo-Carboniferous UPP's (crosses) are significantly different from the coeval MP when using the A95 statistic. In other words, about 30% of the Early Permian UPP's would not be recognized as possible remagnetizations if the standard comparison was used. Fig. 1 also illustrates how the a95 statistic can yield conflicting results when comparing nearly identical poles to the MP. The arrow points to two nearly identical poles (one from the Alnwick Sill and the other from the Oslo volcanics). Because of the relatively small a95 around the Oslo Volcanics pole (1°), it falls outside the MP cone of confidence whereas the a95 for the Alnwick Sill (dashed black circle of 8.1° degrees) overlaps the MP.

Of course, two poles with disparate ages may also agree by chance. If there is a pole with a confidence circle of 10°, the probability of a second pole falling into this circle is about 1%, which is small, but not negligible. The common goal, however, is to test whether a UPP agrees with ANY reference MP for that craton. This agreement (or lack thereof) will be roughly proportional to the area occupied by the APWP and the confidence limits about the pole. A pole-by-pole comparison may be useful but does not properly serve the major goal of the paper, which is to systematically compare the Precambrian and Phanerozoic paleomagnetic data

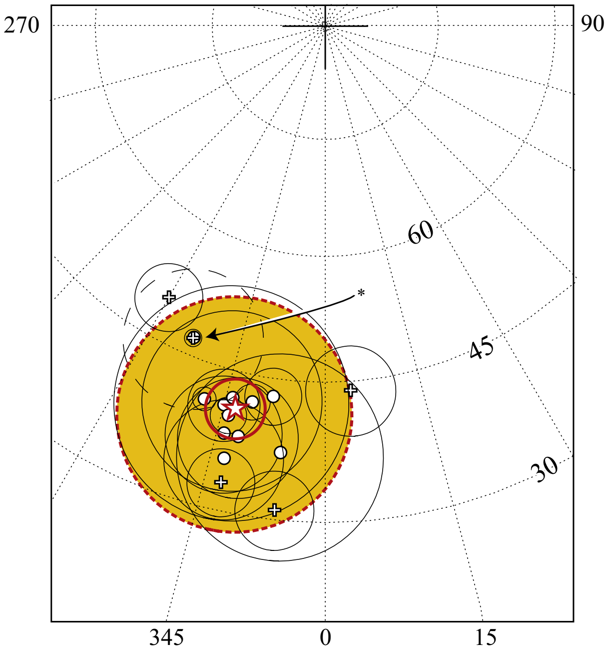

Fig. 1. Distribution of unit paleomagnetic poles with ages from 280 to 300 Ma from cratonic Baltica that were used by Torsvik et al. (2012) for calculation of the mean pole (star) with the confidence circles A_{95} and B_{95} (solid and dashed lines, respectively; see text for explanations). The unit poles that are statistically similar (different) to the mean pole are shown as open circles (crosses); confidence circles as shown as thin solid lines. The arrow points to two nearly identical poles (one from the Alnwick Sill and the other from the Oslo volcanics).