New late Paleozoic paleopoles from the Donbas Foldbelt (Ukraine): Implications for the Pangea A vs. B controversy

Maud J.M. Meijers a,b,⁎, Maartje F. Hamers a, Douwe J.J. van Hinsbergen a,c, Douwe G. van der Meer d, Alexander Kitchka e, Cor G. Langereis b, Randell A. Stephenson f

a Paleomagnetic Laboratory Fort Hoofddijk, Dept. of Earth Sciences, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands
b Dept. of Tectonics and Structural Geology, Faculty of Earth and Life Sciences, VU University Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands
c Physics of Geological Processes (PGP), University of Oslo, Physics Building, Sem Sælands vei 24, 0316 Oslo, Norway
d Shell International Exploration and Production B.V., Kessler Park 1, 2288 GS Rijswijk, The Netherlands
e Dept. of Earth Sciences, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands
f Department of Earth Sciences, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands

⁎ E-mail address: meijers@geo.uu.nl (M.J.M. Meijers).

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ABSTRACT

The Carboniferous to early Permian apparent polar wander (APW) path for Eurasia is not well constrained, because of the paucity of reliable paleomagnetic poles. This is at least partly responsible for the Pangea A vs. B controversy in the early Permian: is the overlap between the northern and southern continents during the early Permian caused by a lack of reliable paleomagnetic data (Pangea A) or must a large displacement along a mega-shear zone be invoked (Pangea B)? Here, we present results from six paleomagnetic sampling sites ranging in age from the early Carboniferous to the early Permian from sedimentary rocks in the Donbas Foldbelt (Ukraine) to improve the Carboniferous–early Permian APW path for Eurasia and to contribute to solving the Pangea A vs. B controversy. Six time intervals were sampled in the Donbas Foldbelt (eastern Ukraine), which was filled with sediments and volcanic units during the late Devonian to Permian syn- and post-rift subsidence phases. We present results from sediments that were corrected for inclination shallowing with the elongation/inclination (E/I) method. We conclude that there is a general northerly movement of the Donbas Foldbelt: the resulting paleolatitudes are slightly but generally significantly higher than expected from existing APW paths. The late Carboniferous to early Permian data provide three new reliable paleopoles for Eurasia. The early Permian pole does not necessarily require a Pangea B reconstruction. It results in higher paleolatitudes for Laurussia in the early Permian and removes the overlap between Gondwana and Pangea. We also reconstructed the position of Laurussia based on Carboniferous Laurentian poles recently corrected for inclination shallowing, which clearly favours a Pangea B configuration. It seems that the Pangea A vs. B debate is as lively as before. The three early Carboniferous paleopoles give reliable paleolatitudes, but declinations significantly deviate from the expected directions. We argue that the southernmost part of the Donbas Foldbelt underwent a counterclockwise rotation, related to Mesozoic compressional events that are recognised in paleostress analyses.

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1. Introduction

Pangea is the youngest in a series of postulated supercontinents that assembled most of the Earth's continents. The reconstruction of Pangea stems from Wegener's recognition (1915) that the modern Atlantic margins may once have fit together. Subsequently, this assemblage was further constrained by linking similar palaeontological and lithostratigraphical palaeogeographic domains (Köppen and Wegener, 1924; Du Toit, 1937). The identification of Pangea formed a crucial basis for the concept of plate tectonics, one of the most fundamental discoveries in Earth Sciences. Pangea existed from the late Paleozoic to early Mesozoic, and broke up since the Jurassic, finally leading to the present-day configuration of oceans and continents. For the break-up history an array of geological and geophysical techniques is available, including reconstruction of seafloor spreading through marine magnetic anomalies (Heezen, 1960; Dietz, 1961), hotspot tracks (Richards et al., 1989; Müller et al., 1993; Norton, 2000) and paleomagnetically constrained apparent polar wander (APW) paths (Creer et al., 1954; Besse and Courtillot, 2002; Torsvik et al., 2008a).

The history of assembly as well as the final configuration and subsequent break-up of Pangea is essential to constrain the starting point of our present-day plate tectonic configuration and to define rates and dimensions of plate tectonic motion. The break-up history
can well be constrained through the record of marine magnetic anomalies, but constraining of Pangea’s assembly largely relies on APW path reconstructions. Hence, we need more reliable and accurate paleomagnetic poles, because their scarcity leaves room for the ongoing controversy on the position of northern Pangea (Laurussia) with respect to southern Pangea (Gondwana) during the Permo-Carboniferous. In particular, paleomagnetic data provide paleolatitudes and rotations of continents, but no paleolongitude constraints. Depending on the selection of paleomagnetic data, a paleolatitudinal overlap exists between the northern and southern continents in the equatorial realm during the late Carboniferous and Permian, that can be as large as 15° (or ~1650 km). The first recognition of this overlap by Irving (1977) led him to propose a so-called Pangea B configuration (Fig. 1a), in which a shear zone with a mainly longitudinal displacement of ~3500 km during the Permo-Triassic places Gondwana east of Laurussia in the early Permian. On the basis of a new compilation of paleomagnetic data, Morel and Irving (1981) propose a transition from Pangea B to Pangea A to occur mainly in the Permian and Triassic, whereas Torcq et al. (1997) suggest a Triassic transformation. More recently, Muttoni et al. (1996, 2003, 2009) argued for the necessity of a Pangea B type reconstruction on the basis of paleomagnetic data from Adria, as a part of the African plate (Fig. 1a) and propose a transition from Pangea B to Pangea A in the Permian. The Triassic overlap between the northern and southern continents has disappeared, since more paleomagnetic data have become available. Other authors, however, question the necessity for Pangea B, and suggest that the overlap is caused by a lack of sufficient high quality paleomagnetic data (e.g. inclination shallowing due to compaction) (Rochette and Vandamme, 2001; Van der Voo and Torsvik, 2004) or to an octupolar contribution to the Earth’s magnetic field (Kent and Smethurst, 1998; Van der Voo and Torsvik, 2001; Torsvik and Cocks, 2004). Most studies (e.g. Van der Voo and Torsvik (2004)) also question the quality of assigned ages.

Numerous authors have attempted solving the Pangea controversy that was identified in paleomagnetic data, by researching independent lines of evidence. Evidence for a shear zone that may have accommodated the Pangea B to Pangea A transformation was first proposed in the late-70s by Arthaud and Matte (1977). Based on their data review on rifts that extend from the Appalachians to the Urals, they conclude that the Pangea transformation occurred in the late Paleozoic. Later studies, by e.g. Schaltegger and Brack (2007) on magmatism related to shearing, seem to confirm the scenario of a Permian Pangea B to A transition. However, a number of rift basins that are possibly associated with Pangea transformation, have been

![Fig. 1. Pangea reconstructions (in white) at a) 282 Ma after Muttoni et al. (2003), where the overlap between the northern and southern continents is removed by introducing a large shear zone (in red); b) in white, reconstruction at 300 Ma following Torsvik and Van der Voo (2002); c) in white, reconstruction at 300 Ma following Torsvik et al. (2008a). b) and c) in grey: Laurussia reconstruction on the basis of our site LP2 (299 Ma). All reconstructions in b) and c) require no overlap between the northern and southern continents. Eurasian (Laurussian) poles are calculated from Laurentian (Eurasian) poles using a Bullard fit (Bullard et al., 1965), with an Euler pole at 88°N, 27°E (angle = 38°). Iberia was not included in the reconstructions.]
Fig. 2. a) Tectonic map of the southern part of the East European Craton, showing the late Devonian Pripyat–Dniepr–Donets rift basin, and the inverted Donbas Foldbelt. Rectangle indicates the location of panel b. b) Cenozoic subcrop map of the Donbas Foldbelt around Donets (modified after Stovba and Stephenson, 1999), indicating the paleomagnetic sampling sites (LC3&4, LC1&2, MC, UC, and LP). D, Middle Devonian–Upper Devonian; C1, Tournaisian; C2, Visean; C3, Serpukhovian; C4, Bashkirian; C5, Moscovian; C6, Kazimovian–Gzhelian; P1, Asselian; P2, Sakmarian; T, Triassic; J, Jurassic; K, Upper Cretaceous; cMA, central Main Anticline. The red dotted lines indicate the major faults that would have possibly caused ∼15° counterclockwise rotation of sites LC4, LC3 and LC1_2, as modeled in the study by Saintot et al. (2003b). Y = east–west trending Yujni Fault and V = east–west trending Vassiliev Fault.
explained differently by Gutierrez-Alonso et al. (2008). They explain the shear zone in the central part of the Pangea A world and rift basins that are radially positioned in the outer part of Pangea by introducing a novel model of ‘self-subduction’ of the Pangean plate.

Lines of evidences from climatic reconstructions, based on paleo- nology were investigated by e.g. Angiolini et al. (2007). By coupling palynology, ocean circulation patterns and paleomagnetic data, they reconstruct the early Permian landmasses to a Pangea B configuration. Geophysical data were used by Torsvik et al. (2008b) to develop a hybrid plate motion reference frame that places reconstructed large igneous provinces of the past 300 Myr above the edges of large low shear wave velocity provinces, enabling correlation of surface processes to the deep mantle. In their reconstructions, a Pangea A assemblage of the continents is favoured. Recently, van der Meer et al. (2010) have shown that topography constrains the paleolatitude of subducted slabs, but this approach unfortunately only has the required resolution until the late Permian (260 Ma), showing a Pangea A configuration at that time. Decades after introduction of the Pangea B configuration, the Pangea controversy remains a matter of debate. The solution could come from enlarging the paleomagnetic database, by supplying well-dated paleomagnetic data from the stable continents.

Only very few Carboniferous paleomagnetic poles exist for Laurussia, which formed the major constituent of northern Pangea. Laurussia included the late Devonian and younger Dniepr–Donets basin in present-day Ukraine (Fig. 2). Here, we present paleomagnetic results of six age intervals from lower Carboniferous to lower Permian sediments in the Donbas Foldbelt, a mildly compressively deformed segment of the Dniepr–Donets basin, and we discuss the results within the context of the Pangea A vs. B controversy.

2. Geological setting

The Donbas Foldbelt is the inverted southeasternmost segment of the NW–SE trending Pripyat–Dniepr–Donets Basin (DDB), which formed since the middle-late Devonian (Stephenson et al., 2006). It is located in the southern part of the East European Craton (EEC) (Fig. 2). The EEC was part of Baltica until the early Paleozoic, after which it amalgamated with Laurentia to form Laurussia. The DDB extends from Belarus to southern Russia, linking with the Karpinsky Swell further to the southeast (Fig. 2a). To the north it is bounded by the (Archean-) Paleoproterozoic Voronezh Massif, to the south by the (Archean-) Paleoproterozoic Shield, also of (Archean-) Paleoproterozoic age. The EEC was part of Baltica until the early Paleozoic, after which it amalgamated with Laurentia to form Laurussia. The DDB extends from Belarus to southern Russia, linking with the Karpinsky Swell further to the southeast (Fig. 2a). To the north it is bounded by the (Archean-) Paleoproterozoic Voronezh Massif, to the south by the (Archean-) Paleoproterozoic Shield, also of (Archean-) Paleoproterozoic age. The DDB deepens towards the southeast, with sediments having a maximum thickness of ∼2 km in the Pripyat Through in the northwest and ∼22 km in the Donbas Foldbelt (Chekunov et al., 1993; Stovba et al., 1996). In middle-late Devonian times pre- and syn-rift sedimentary and volcanic units were deposited on top of the crystalline basement of the EEC followed by the deposition of Carboniferous and Permian post-rift sequences as a result of thermal subsidence in the Permo-Carboniferous (Van Wees et al., 1996). Relatively thin units of Tournaisian and lower Visean carbonates and thick upper Visean to upper Carboniferous successions of dominantly paralic clastic sediments were deposited unconformably on top of the basement and the Devonian sediments (Stovba et al., 1996). Permian sediments are scarce in the Donbas Foldbelt, and confined to the north of the basin.

Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>Age (Ma)</th>
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<th>D</th>
<th>I</th>
<th>K</th>
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<td>38.2</td>
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<td>117</td>
<td>117</td>
<td>200.2</td>
<td>23.9</td>
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ml = marker limestone.
(Stovba and Stephenson, 1999). Reactivation of the rift occurred during the end of the late Visean and during latest Carboniferous–earliest Permian times (Stovba et al., 2003; Stephenson et al., 2006).

After the Paleozoic, the Donbas basin was deformed by large-scale WNW to ESE striking faults and folds, of which the central Main Anticline is the most dominant feature (Fig. 2b). The origin of these folds and faults were long enough to provide two or more specimens. In total, 749 samples were collected were mostly large enough to provide two or more specimens. In total, 749 samples were collected and 907 specimens were demagnetised.

### Table 3.1. Sampling and Preparation of Samples

<table>
<thead>
<tr>
<th>Site</th>
<th>Age</th>
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<td>Permian</td>
<td>Limestone</td>
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<tr>
<td>Donets</td>
<td>Carboniferous</td>
<td>Sandstone</td>
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<tr>
<td>Saintot</td>
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<td>Basalt</td>
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<tr>
<td>Popov</td>
<td>Carboniferous</td>
<td>Claystone</td>
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#### 3. Paleomagnetic sampling, methods and results

3.1. Sampling procedure and age of sampled formations

For the purpose of constructing a late Paleozoic APW path from the Donbas Foldbelt, we collected 724 samples from eleven sites at five localities, covering six time intervals, north and south of the city of Donets (Table 1, Fig 2b). The Carboniferous lithostratigraphy of the Donbas Foldbelt is in the former Soviet Union traditionally subdivided into suites (Popov, 1965). These suites have been correlated to the regional stratigraphic substages and to the global stratigraphic scales; for the most recent overview and compilation we refer to Menning et al. (2006). Recently, Davydov et al. (2010) have provided new results on U–Pb ages and Milankovitch cyclicity in the Donets Basin, and calibrated the regional time scale to the global time scale, essentially confirming the earlier correlation of Menning et al. (2006). We indicated the ages of the sampled marker limestones and horizons, according to Menning et al. (2006) and Davydov et al. (2010) in Table 1. To allow comparison of our data to the APW paths, we correlated the regional substages to the latest version of the Geologic Time Scale, GTS2008 (Ogg et al., 2008) Those ages are indicated in Table 1 and Fig. 3.

3.2. Methods

The anisotropy of magnetic susceptibility (AMS) was measured (Fig. 4) to determine the magnetic fabric of the sediments and to
assess whether they have a mainly sedimentary fabric or a tectonic fabric that may be indicative of the amount of strain that the rocks underwent since their deformation (Hrouda, 1982). During deformation, the maximum axis of the AMS tensor \(k_{\text{max}}\) will gradually align with the direction of maximum extension and become perpendicular to the direction of maximum compression. For calculations Jelinek (Jelinek, 1981, 1984) statistics were used.

Thermomagnetic runs to determine magnetic carriers were carried out in air (Fig. 5), using a modified horizontal translation type Curie balance, with a sensitivity of \(5 \times 10^{-9} \text{ Am}^2\) (Mullender et al., 1993). Approximately 30–65 mg of powdered rock samples was put into a quartz glass sample holder and was held in place by quartz wool. Heating and cooling rates were 10 °C/min. Temperatures were increased to a maximum of 700 °C.

The samples were demagnetised using alternating field (AF) and thermal (TH) progressive stepwise demagnetisation. Samples were thermally demagnetised in a magnetically shielded oven, with steps of 10 °C–100 °C up to a maximum of 645 °C. The AF demagnetisation was carried out with increments of 3–20 mT, up to a maximum of 80 or 100 mT. The natural remanent magnetisation (NRM) of all samples was measured on a 2G Enterprises horizontal 2G DC SQUID cryogenic magnetometer (noise level \(3 \times 10^{-12} \text{ Am}^2\)). For AF demagnetisation, we used an in-house developed robot assisted and fully automated 2G DC SQUID cryogenic magnetometer.

Demagnetisation diagrams of the NRM were plotted as orthogonal vector diagrams (Zijderveld, 1967) (Fig. 6). To determine characteristic remanent magnetisation (ChRM) directions, results from generally five to eight successive temperature or AF steps were analysed by principal component analysis (Kirschvink, 1980). In several cases, samples with a direction that deviated from the general NRM behaviour were analysed using the great-circle approach (McFadden and McElhinny, 1988) (Fig. 6c). This method was developed to identify

Fig. 3. Paleomagnetic directions, correlated to the GTS2008 (Ogg et al., 2008), see Section 3.1 for explanation. Vertical bars denote age errors. Blue closed squares indicate the mean formation directions (declination, latitude) and their errors (blue horizontal bars, \(\Delta \Omega_x, \Delta \lambda \) (calculated from \(\Delta I_x\)) from the present study (Table 1). Black closed circles in the right panel indicate paleolatitude resulting from inclination correction with the TK03.CAD model (Tauxe and Kent, 2004), and horizontal bars shows the 95% bootstrap error range. Green star indicates data points from Iosifidi et al. (2010) (one late Carboniferous and two Permian data points). Grey shaded area shows the \(\Delta I_x, \Delta \lambda \) error envelope of the Eurasian APW path from Torsvik et al. (2008a) for 310–260 Ma and the Laurussia polepath from Torsvik and Cocks (2005) for 360–320 Ma, calculated for the city of Donets (48°N, 37.8°E). Red diamonds are the raw data entries from Eurasia and North America used to construct these APW paths. Purple arrows and diamonds show the effect of correction for inclination error and improvement of dating of North American poles by Kodama (2009) and Bilardello and Kodama (2010) on the declination/latitude calculations for the Donbas. Dev. = Devonian, Fam. = Famennian, Bashk. = Bashkirian, Mosc. = Moscovian, Kas. = Kasimovian, Gzh. = Gzhelian, Ass. = Asselian, Kung. = Kungurian, Roa. = Roadian, Wor. = Wordian, Capit. = Capitanian, and GPTS = geomagnetic polarity time scale.
the direction on the great circle that lies closest to the average direction obtained from well-determined NRM directions. Samples yielding maximum angular deviation (MAD) $>15^\circ$ were rejected from further analysis. A total of 907 specimens was demagnetised, from 749 samples. Of these, the results of 503 demagnetisations were used to calculate the final paleomagnetic poles (Table 1).

Fisher statistics (Fisher, 1953) were used to calculate site-means and virtual geomagnetic pole (VGP) means. Because scatter of paleomagnetic directions induced by secular variation of the Earth’s magnetic field is circular at the poles, but gradually becomes more ellipsoid towards the equator (Tauxe and Kent, 2004), we calculated the VGPs from all directions. Successively, a variable cut-off (Vandamme, 1994) was applied and the error in declination ($\Delta D_x$) and the error in inclination ($\Delta I_x$) of the site were calculated following Butler (1992).

To determine whether two distributions have a common true mean direction (ctmd), we used the reversal test developed by McFadden and McElhinny (1990) and their classifications (A, B, C, indeterminate). The classifications are based on the critical angle $\gamma_c$ and the angle $\gamma$ between the means. Because we use their test with simulation, the test is equivalent to using the $V_w$ statistical parameter of Watson (1983).

To correct for a possible shallowing of inclination in sediments caused by compaction during burial, we used the elongation/inclination ($E/I$) method (Tauxe and Kent, 2004; Tauxe et al., 2008). A large number of individual directions are required to apply the model successfully (preferably $N>100$). Since the number of individual directions from our sites varies from 50 to 118, we will discuss the validity of using this correction per locality.

3.3. Paleomagnetic results

The AMS measurements of sites LP and MC2 (Fig. 4a and b) show an alignment of the $k_{\max}$ axis, which may have been caused by an ENE–WSW extensional or a NNW–SSE compressional episode, or by transport current directions during the time of deposition. The AMS measurements of all other sites revealed random directions, with very large error ellipses (e.g. Fig. 4c) (Jelinek, 1981, 1984), and cannot be interpreted in terms of an AMS fabric. Flinn diagrams of the AMS measurements (Fig. 4d) show that MC2 is strongly oblate, likely because of more compaction of these clays than of the limestones, while the reds of site LP show a mixture of oblate and prolate fabrics.

The dominant prolate fabric of site MC1 has little meaning of a random AMS fabric (Fig. 4c), likely caused by the low intensities of the limestones and a relatively large diamagnetic contribution.

From all sites, test sets of samples were demagnetised both thermally and using AF demagnetisation, to allow comparison of both techniques (Fig. 6), similar to the procedures in Gong et al. (2008b). This implies that all AF demagnetised samples were first heated to 150 °C to remove possible stress in magnetite grains caused by surface oxidation at low temperatures (Van Velzen and Zijderveld, 1995), except for the clays of site MC2. Our tests showed that the limestones of site UC should be pre-heated to higher temperatures, until 250 °C or 300 °C before AF demagnetisation. In general, this pre-heating technique appeared very successful, since the overprint direction could already be removed at significantly lower AF fields. The lower Permian (LP) sites were not demagnetised using AF treatment, since
the maximum applicable alternating field (100 mT) was not high enough to fully demagnetise the hematite-bearing samples.

From most sites, a low temperature/low coercive force component could be isolated, that is indistinguishable from the GAD field at the present latitude (Fig. 7a) and is therefore a recent overprint. Only in site LP, we did not observe this low temperature GAD field, because nearly all samples were pre-heated until 200 °C.

Fig. 6. Orthogonal vector diagrams (Zijderveld, 1967), showing characteristic demagnetisation diagrams for all sampled sites in tilt corrected coordinates. Closed (open) circles indicate the projection on the horizontal (vertical) plane. Dashed lines in a) (LP1.45A and LP1.80A) indicate the steps that were used for great-circle analysis (McFadden and McElhinny, 1988). In Fig. 5a), c) and d), the remaining magnetisation after thermal or AF demagnetisation can be seen (LP1.80A, MC1.27A, MC1.67A and LC2.7A). These components are also displayed in Fig. 7b)–d). The demagnetisation diagram of specimen MC1.67A is shown twice, to display the three distinct directions: the low temperature component that resembles the present-day GAD direction, the medium coercive force component (interpreted as the primary ChRM) and the remaining high coercive force component after full AF demagnetisation, that is close to the present-day GAD direction. An equal area plot of a demagnetisation diagram that was interpreted using great-circle analysis is shown in a) (LP2.49A): dashed (solid) line denotes projection on lower (upper) hemisphere.
In samples from sites LP, we observed a high temperature component between 580 °C and ∼640 °C (Fig. 6a, LP1.18A and LP1.80A). This component, although not very often observed, yields a direction that seems to be resulting from a present-day overprint (Fig. 7b).

Samples from sites MC1, MC2 and LC1_2 could in ∼40% of the samples not be demagnetised to the origin using AF demagnetisation techniques (cf. Fig. 6c and d). Using thermal demagnetisation techniques, we could not isolate this component (e.g. Fig. 6c and d), because of magnetite generation and random natural remanent magnetisation (NRM) behaviour at temperatures above ∼400–450 °C. This indicates that there is a remaining hematite component in the samples. When interpreting this remaining component towards the origin, it is indistinguishable from the GAD field for sites MC1 and LC1_2 (Fig. 7c and d). This component has both normal and reversed polarities in site LC1_2, which indicates that it results from a recent overprint that at least in part predates the Brunhes Chron.

In site MC, this component is more disperse (Fig. 7c), particularly in the clays of site MC2, but most directions of the limestones of MC1 are close to the GAD field direction (Fig. 7d).
to the present-day GAD field. This may indicate that the remagnetisation is of chemical origin, possibly resulting from circulating fluids. In this case, clays would function as an aquitard, being more resistant to fluid circulation than the directly underlying limestones (MC1). A similar process has then likely occurred in the limestones of sites LC1_2. The fluids likely derive from burial and pressure dissolution of calcite, with the lithological effect that limestones are more prone to remagnetisation than marls. It is less likely that externally derived fluids have played an important role (Gong et al., 2008a).

3.3.1. Tournaisian
Site LC4 was sampled in lower Carboniferous (Tournaisian B) limestones. The stratigraphic thickness of the sampled interval is 23 m. It comprises 139 demagnetised specimens, from which 8 were demagnetised thermally and 131 using combined thermal and AF demagnetisation (Fig. 6f). Initial intensities range from ∼50 to 500 µA/m. Curie temperatures are between 520 °C and 580 °C (Fig. 5i), indicating that the main magnetic carrier is (Ti-poor) magnetite. For many specimens, we could not reliably determine the ChRM, caused by very low intensities between 550 °C and 600 °C. The resulting mean ChRM (N = 76), corrected for bedding tilt is D = 203.6 and I = −20.5 (Table 1, Fig. 7). Correction for inclination shallowing yields a not significant correction to I = −10.3 (Fig. 7k). The correction for inclination shallowing is statistically significant (I = −20.5, although the number of samples is quite low (N = 76). The samples of the combined sites MC1 and MC2 (sampled stratigraphy interval 1–1.5 m, respectively) were taken from upper Carboniferous (Bashkirian) limestones and claystones. Locality MC provided 193 demagnetised specimens; 17 specimens were fully remagnetised than marls. It is less likely that externally derived fluids likely derive from burial and pressure dissolution of calcite, with the lithological effect that limestones are more prone to remagnetisation than marls. It is less likely that externally derived fluids have played an important role (Gong et al., 2008a).

3.3.2. Visean
The fossiliferous and locally sandy limestones of the combined sites LC1_2 are early Carboniferous (late Serpukhovian) in age. The stratigraphic thickness of the sampled interval is several meters thick. Site LC1_2 consists of 118 demagnetised specimens, of which 12 specimens were demagnetised thermally, 106 using combined thermal and AF demagnetisation (Fig. 6d). Initial intensities range from ∼1 to 5 mA/m. Curie temperatures are between 560 °C and 570 °C (Fig. 5g and h). In some samples, an inflection around 300 °C may indicate an inversion of maghemite (Fig. 5g). The resulting ChRM (N = 89) after correction for bedding tilt is D = 197.2, I = −10.3 (Fig. 7k). The correction for inclination shallowing is statistically significant (I = −20.5, although the number of samples is quite low (N = 89).

3.3.3. Serpukhovian
The fossiliferous and locally sandy limestones of the combined sites LC1_2 are early Carboniferous (late Serpukhovian) in age. The stratigraphic thickness of the sampled interval is several meters thick. Site LC1_2 consists of 118 demagnetised specimens, of which 12 specimens were demagnetised thermally, 106 using combined thermal and AF demagnetisation (Fig. 6d). Initial intensities range from ∼1 to 5 mA/m. Curie temperatures are between 560 °C and 570 °C (Fig. 5g and h). In some samples, an inflection around 300 °C may indicate an inversion of maghemite (Fig. 5g). The resulting ChRM (N = 89) after correction for bedding tilt is D = 197.2, I = −10.3 (Fig. 7k). The correction for inclination shallowing is statistically significant (I = −20.5, although the number of samples is quite low (N = 89).

3.3.4. Bashkirian
The samples of the combined sites MC1 and MC2 (sampled stratigraphy interval 1–1.5 m, respectively) were taken from upper Carboniferous (Bashkirian) limestones and claystones. Locality MC provided 193 demagnetised specimens; 17 specimens were fully remagnetised than marls. It is less likely that externally derived fluids likely derive from burial and pressure dissolution of calcite, with the lithological effect that limestones are more prone to remagnetisation than marls. It is less likely that externally derived fluids have played an important role (Gong et al., 2008a).
from 10 to 200 µA/m, with some exceptions that have initial intensities up to 15,000 µA/m. Curie temperatures for the limestone samples are 570 °C–580 °C (Fig. 5e), so the magnetic carrier in the samples is magnetite. Thermal and AF demagnetisation yield identical results.

Initial intensities of the claystones (MC2) range 200–5000 µA/m. Thermomagnetic treatment shows a mainly paramagnetic decay (Fig. 5f), but a drop in intensity around 300 °C suggests either an iron sulfide as main carrier, or points to an inversion of maghemite.

The medium temperature/medium coercivity component in specimens from site MC1 was interpreted as the ChRM direction (Figs. 6c and 7j). Thermal demagnetisation of the claystone specimens of MC2 gave three components: a low temperature (~20 °C–270 °C) direction (Fig. 7c), a high temperature (~400 °C) and high coercive force component (~100 mT) that directs the present-day geocentric axial dipole (GAD) direction (Fig. 7a), and a medium temperature component (~300 °C–400 °C) that yields directions similar to those obtained in the AF demagnetised claystone and limestone samples (Figs. 6c, 7j and 9e–f). Because this medium temperature component was largely overprinted by the high temperature component (Fig. 7c), these results could not be used for further analysis.

AF demagnetisation diagrams of the claystones of MC2 yield three components: a low coercive force component (~0–20 mT) (Fig. 7a), a medium coercive force component (~20–60 mT) (Fig. 7j) and a high coercive force component (~60 mT) (Fig. 7c), that in general do not trend towards the origin, with some exceptions of the middle coercive force component. This medium coercive force component is similar to the directions in the other Carboniferous sites, although in a part of the samples it is heavily affected by a high coercive force component (~60 mT) (Fig. 9c). To discriminate between samples that were heavily affected by this high coercive force component and samples that could be used for determining ChRM directions, decay curves of the specimens were plotted and compared (Fig. 9b, d and g). In Fig. 9g, a clear difference between the samples that were significantly affected by the high coercive force component and samples that still yield a Carboniferous direction is clearly visible. The former were rejected from further analysis.

The mean directions of the limestones (MC1) and claystones (MC2) have a common true mean direction (ctmd) (~4.0°, χ = 56, classification B). The mean ChRM direction for MC1 and MC2 (corrected for tilt, N = 84) is: D = 223.4 and I = −15.0 (Table 1, Fig. 7j). Correction for inclination error would possibly give rather different results for limestones and claystones. Therefore we applied the E/I method to sites MC1 and MC2 separately, before applying the method to the combined data sets in order to check for differences in correction. We must take into account that the number of individual directions per data set is possibly too low to apply the E/I method, but corrections for both data sets separately are very similar (Table 1). Therefore, we decided to combine both data sets for E/I correction, resulting in a significantly steeper inclination of I = −22.4.

3.3.5. Kasimovian/Gzelian

Site UC was drilled in upper Carboniferous limestones (upper Kasimovian or lower Gzelian, marker limestone 0-61 of Popov (1965)). The marker limestone was sampled at two locations (several tens of meters apart), each in ~2 m of stratigraphy, covering the entire thickness of the limestone bed (see Table 1). The total number of demagnetised specimens is 114, out of which 18 specimens were demagnetised thermally (Fig. 6b). The remaining specimens were demagnetised using AF treatment, after thermal treatment until 250 °C or 300 °C. Initial intensities range from ~100 to 600 µA/m. We found a Curie temperature of 570 °C (Fig. 5d), indicating that the magnetic carrier is magnetite. An additional inclination point between ~300 and 350 °C could indicate an inversion of some maghemite. The ChRM direction that was corrected for bedding tilt (N = 86) is: D = 215.5 and I = −24.3 (Table 1, Fig. 7j). Correction for inclination error yields I = −33.0, which is statistically significant (Fig. 8, Table 1).

3.3.6. Asselian

Sites LP1, LP2 and LP3 were drilled in lower Permian (Asselian) red beds, only several tens of meters apart. The red beds in site LP3 are coarser than the red beds of sites LP1 and LP2. Each of the three sites was sampled within ~2 stratigraphic meters: the total stratigraphic thickness of the sites together is ~6 m. The total number of thermally demagnetised specimens is 208. Initial intensities range from ~3 to 7 mA/m in LP1 and LP2, and from ~7 to 10 mA/m in LP3. Néel temperatures of 660°–675 °C (Fig. 5a–c), and additional inflections in the thermomagnetic curves of LP1 and LP3 (Fig. 5a and c) representing Curie temperatures of 580 °C suggest that both hematite and magnetite are the magnetic carriers. We interpreted the magnetite component as the ChRM direction (Fig. 6a).

Since LP1, LP2 and LP3 were sampled from similar lithologies and within the same formation, and only several tens of meters apart, similar ChRM directions were expected. However, LP3 yields a direction very different from LP1 and LP2 (Table 1). Because the mean direction of LP3 plots on a great circle between the mean directions of LP1 and LP2 and the GAD field in the Donbas area (Fig. 7e–h), we interpret this as a remagnetisation that is transitional direction between the primary, early Permian direction and the GAD field. This is likely related to the slightly coarser nature of the LP3 sediments, and we therefore exclude LP3 from further analysis. The ChRM directions of LP1 and LP2 do not pass a ctmd test (McFadden and Lowes, 1981). From Fig. 7h, it can be seen that LP1 was also partly influenced by a later overprint. Only LP2 is used for further analysis.

Out of the 50 specimens from LP2 that were used for final calculation of the ChRM, 10 specimens have a ChRM direction derived from great-circle analysis (McFadden and McElhinny, 1988). The mean ChRM direction (bedding tilted corrected) is D = 212.0 and I = −29.5 (Table 1, Fig. 7f). If directions using great-circle analysis are excluded from analysis, the resulting ChRM is identical the same within error: D = 211.0 and I = −29.0. Correction for inclination error was not applied, since the number of specimens does not approach the minimum required number (N = 100).

4. Discussion

The ChRM directions from the lower Carboniferous to lower Permian limestones, claystones and red beds presented here are very consistent within each site (Fig. 7), they differ significantly per site, and all sites recorded reversed polarities. A fold test could not be applied to our datasets since we sampled the different time intervals at a single location, with only a small variation in bedding tilt. Iosifidi and Krhmanov (2002) did apply a fold test with a positive result to their lower Permian samples from the Donbas basin, which were collected from the same formation as our lower Permian samples.

The reversed polarity of the ChRM directions is in line with the age of MC, UC and LP, which were sampled within rocks that were deposited during the Permo-Carboniferous Reversed Superchron (PCRS), which lasted from ~317 to ~265 Ma (Opydko et al., 2000; Menning et al., 2006). During the Carboniferous period preceding the PCRS, several normal polarity chron's are known (Davydov et al., 2004). Although the Carboniferous polarity time scale is not well-determined, the normal polarity chron's reported by Davydov et al. (2004) in the time scale of Gradstein et al. (2004) cover only ~31% of the period preceding the PCRS. This implies that in the age range of our sites the probability is 70% that we sampled reversed polarity intervals. A Permian thermal event, recognised in fission track analysis and vitrinite-reflectance studies (Sachsenhofer et al., 2002; Spiegel et al., 2004), possibly related to a magmatic episode in the Donbas Foldbelt during the early Permian (Alexandre et al., 2004), could have caused a partial reversed polarity remagnetisation of the magnetic signal. However, the low inclinations we find here show a trend toward steeper inclinations with time, which is inconsistent with a remagnetisation event influencing our sites (Fig. 3). Indeed, several
sites, recorded a present-day or recent GAD field direction (Fig. 7a–d),
but it is clearly distinct from the component that we interpret as a
ChRM. The statistically significant directional difference between the
sites of different age intervals also implies that the ChRM in all sites
older than Permian cannot represent a Permian remagnetisation. We
therefore believe that our ChRM directions represent an original
magnetisation acquired at the time the rocks were formed.

The E/I method gives a significant change in inclination for sites
LC1_2, MC and UC. This is an indication that the NRM was acquired
before compaction. Correction with the E/I model for sites LC3 and LC4
produces a small but not significant change. There are several possible
explanations for this. It may imply that NRM acquisition was slightly
delayed, and acquired after early dewatering and compaction of the
sediments, possibly during early diagenesis (e.g. Van Hoof and
Langereis (1991)). A more likely explanation is that, because the
sediments of sites LC3 and LC4 were deposited nearest to the equator,
inclination shallowing is not significant, because of the low magnetic
field inclination.

Therefore, we conclude that the observed inclination/paleolatitude
and declination trends of the sampled time interval (Table 1, Fig. 3)
are the result of plate tectonics and/or local tectonic rotations. We
must now consider whether the Donbas region formed part of stable
Europe, so that corresponding paleopoles can be used for the APW
path for this time interval.

The only AMS results that did not give random directions are from
sites LP and MC2. Those results (Fig. 4) either reflect NNW–SSE
compression or the direction of currents during deposition of the
sediments. A paleocurrent direction is generally only recorded in
coarser grained sediments and high-energy sedimentary environ-
ments, which could be the case for the red beds of site LP. Paleoflow
directions are however absent for this region, and therefore we can
only speculate that the AMS orientation of both sites is a reflection of
NNW–SSE compression. This is in very good agreement with
paleostress data from Saintot et al. (2003a), that indicate an Eq-
Alpine strike–slip regime with NNW–SSE trending σ1.

Outside Scandinavia, there are no Carboniferous and early Permian
datasets from Baltica that are incorporated into the APW paths
(Torsvik and Cocks, 2005; Torsvik et al., 2008a). To discuss our data in
the large-scale framework of global plate movements, the
APW paths and to the youngest, northern three sites, suggesting a
rotation of ~20°. This rotation difference could imply that in the time
span between deposition of the sediments of sites LC1_2 and MC
(~ 8 Ma), the region rotated ~20°, which is not recognised in the APW
path (Torsvik and Cocks, 2005). Here, we must again take into account
however, that no Baltic poles outside Scandinavia are incorporated in
the Carboniferous APW path. Another way to explain the rotation
difference between the youngest sites and oldest sites is by
introducing a local rotation effect between the northern and central
part of the Donbas Foldbelt and its southern part, which has a
diverging strike from the general trend in the region. This strike
difference corresponds both in sense and magnitude to the declina-
tion deviation of our oldest sites from the published APW paths.
Anomalous N–S trending thrusts and folds in the sampling area of LC4
and LC3 were recognised by Saintot et al. (2003b), which they
mentioned to the Pliocene (late Triassic to Jurassic) and Alpine
(Cretaceous/Tertiary boundary) reactivation of shallow inherited
structures at the southern margin of the basin. Numerical models in
their study that calculate stress axis trends, predict a counter-clock-
wise rotation of ~15° with respect to the surrounding area for the area
between the Yujni and Vassiliev Faults (Fig. 2b). This is in good
agreement with our relative paleomagnetic rotations of sites LC4
and LC3. Site LC1_2 was sampled in the vicinity of a N–S trending
thrust fault, which could have possibly caused a similar effect. We therefore
suggest that the deviation is likely the result of local CCW vertical-axis
rotations in the southern part, implying that we cannot use the
directions of these sites for determining pole positions for further
analysis of the APW path. The sites are also situated in the region
where Arthaud and Matte (1977) proposed the shear zone that
accommodated Pangea transformation. The shear zone however,
would cause clockwise rotations, which is opposite to the counter-
clockwise (CCW) rotations of our oldest three sites.

In Fig. 1b–c, we compare a continent reconstruction at 300 Ma
based on our data from LP2, with those of Torsvik et al. (2008a) and
Van der Voo and Torsvik (2004) at 300 Ma. Laurussia is displayed in
grey, according to the pole from site LP2. Because Laurentia and
Eurasia were part of the same tectonic plate (called Laurussia) in
Pangean times, usage of Laurientian poles is allowed for Laurentia.
Comparing our data to the Gondwana reconstructions, there is no
overlap between the northern and southern continents. The same
holds for a reconstruction using the latest Carboniferous pole UC (not
displayed here). Therefore, these two datasets, would not require a
Pangea B type reconstruction. As mentioned above, Van der Voo and
Torsvik (2004) partly solve the overlap problem in the early Permian

Fig. 9. a) c) and e) Demagnetisation diagrams of characteristic samples of the claystones of site MC. b) d) and f) NRM intensity upon AF demagnetisation normalised by initial NRM
intensity. Grey rectangle indicates AF/temperature steps that were used for calculation of the ChRM directions. g) NRM intensity upon AF demagnetisation normalised by initial NRM
intensity of all individual samples of site MC2 normalised (total intensity). Highest AF/temperature step intensity was set to zero for display purposes. Grey (light-coloured) curves
decide the curves of the samples that were rejected and blue (dark-coloured) curves decide the samples that were used for calculation of the mean ChRM direction of site MC. The
ChRM directions belonging to the grey (light-coloured) curves were typically affected by a later acquired NRM component.
by considering only the highest quality European poles. They selected these on the basis of paleomagnetic quality, age control and also rock type (volcanics) to avoid the possibility of inclination shallowing in sediments (Van der Voo, 1990). In this way, Eurasia is located almost 10° further north at 280 Ma. If we compare our Permian data to Van der Voo and Torsvik’s (2004) presented polepath at 300 Ma, our data plot even ~5° further to the north (Fig. 1b). Moreover, our Carboniferous data points (Fig. 3) show a very general and gentle northward motion of Laurussia (at Donets) from near-equatorial position (3–5°N) to ~18°N, which strengthens the interpretation of a more northerly position of Laurussia during Pangean times, in line with Van der Voo and Torsvik (2004). Because of the juxtaposition of Laurentia and Eurasia, this means that, in the early Permian, our data from the Donbas Foldbelt would place Laurussia at a more northerly position, explaining the Pangea misfit without a need to introduce an octupole contribution to the Earth's magnetic field (e.g. Torsvik and Cocks, 2004).

Recently, Kodama (2009) and Bilardello and Kodama (2010) reassessed ages and corrected Carboniferous poles from the present-day eastern part of North America that likely occupied a position just south of the equator in the Pangea configuration for inclination error, using the inclination-shallowing correction method developed by Tan and Kodama (2003). The effect of an inclination correction for Laurentian paleolatitudes is of course inverse: following their data, Laurussia was positioned more southward rather than our more northward latitudes obtained from Ukraine. We illustrated this effect for the Donbas region in Fig. 3 (purple arrows) for the corrected results from the Glenshaw, Shepody and Maringouin Formations. More southerly positions of southwestern Laurussia would significantly increase the overlap of Gondwana and Laurussia, clearly requiring a Pangea B configuration. However, combining their results with ours would not only imply the necessity for a major shear zone to come from a Pangea B to a Pangea A configuration in the Triassic (Fig. 1), but also implies major stretching and subsequent shortening of Laurentia. This would make the Pangea controversy quite different than known so far. More important, the Carboniferous poles from Gondwana are largely based on poles from sediments (Torsvik and Van der Voo, 2004). Because of the juxtaposition of Laurentia and Eurasia, this means that, in the early Permian, our data from the Donbas Foldbelt would place Laurussia at a more northerly position, explaining the Pangea misfit without a need to introduce an octupole contribution to the Earth's magnetic field (e.g. Torsvik and Cocks, 2004).

Summarising, we present new Eurasian Carboniferous and early Permian paleomagnetic data that can be used to construct a more reliable paleogeography. These pole data are derived from southern France, with reliable age control, and we reinterpreted the pole data for the Donbas Foldbelt. The main contribution of this work is to allow an explanation of the Pangea configuration in the Triassic, in line with the results of Torsvik and Cocks (2004). However, we note that the Carboniferous poles from Gondwana and Laurussia, clear indications of a Pangea B configuration. Therefore, application of a method to correct for shallowing would result in a more southerly position of Gondwana, (partly) removing the overlap between the northern and southern continents. The strongly contrasting results of our study and those of Bilardello and Kodama (2010) and Kodama (2009) show that the Carboniferous paleomagnetic data still contain enough grounds for a Pangea controversy. Furthermore, data should cover and be representative for an entire continent, which is not the case for the Carboniferous and early Permian Eurasian polepaths, since no reliable eastern European and Asian data entries are available. In the late Permian pole path, many poles from southern France have been included, mainly from sediments (red beds). It was recently pointed out by Bazhenov and Shatsillo (2010) that at least during the late Permian, the French group of poles shows a significant deviation with respect to the late Permian poles of the remaining part of the continent. The authors suggest that this is caused by a hitherto unrecognized rotation of southern France. A similar effect of Carboniferous and early Permian groups of poles on the Eurasian polepath, would obviously have large implications for Pangea reconstructions. Paleomagnetic data were at the basis of the Pangea controversy, and although more and better data became available, the controversy remains.

5. Conclusions

Summarising, we present new Eurasian Carboniferous and early Permian sedimentary paleomagnetic datasets from sediments, and the only ones that are large enough to enable E/I correction for inclination shallowing in sediments (Tauxe and Kent, 2004), thereby improving the quality of these paleopoles. This allows us to constrain the Pangeo-Carboniferous paleolatitude of Laurussia at the position of the Donbas Foldbelt.

In general, our results yield similar or higher values for paleolatitude than those previously used to construct the APW path. Unfortunately, our lower and middle Carboniferous poles are most likely affected by a tectonic rotation, and therefore can only indicate reliable paleolatitudes.

Our upper Carboniferous and lower Permian data do not require a Pangea B type reconstruction. The paleolatitudes of Laurussia calculated from our poles enable a Pangea A reconstruction, and do not require an overlap of northern and southern Pangea terranes. However, a recent correction and reassessment of North American (Laurentian) paleomagnetic data from recent studies suggest quite the opposite and even require changes in the dimensions of Laurussia through time. Therefore, the Pangea A vs. B controversy is as lively as during the past 30+ yr. since Irving (1977).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2010.05.028.

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