A simplified correlation between vertebrate evolution and Paleozoic geomagnetism

Background. Despite a fifty-year failure of paleontologists to find a viable connection between geomagnetic polarity reversals and evolutionary patterns, recent paleobiology databases show that the early appearance, radiation, and diversification of Paleozoic vertebrates tends to occur during periods having frequent collapses of the Earth's geomagnetic field. The transition time during the collapse of the Earth's protective magnetic shield can last thousands of years, and the effects on biota are unknown. Solar and cosmic radiation, volcanism, climate alteration, low-frequency electromagnetic fields, depletion of ozone, the stripping of atmospheric oxygen, and increasing production of Carbon14 in the stratosphere have been proposed as possible causes, but previous studies have found no effects.

Methods. Using published databases, we compiled a spreadsheet showing the first appearance of 2210 age-dated genera with each genus assigned to one of eleven major taxonomic groups. From Gradstein's Geologic Time Scale 2012, we delineated 17 Paleozoic zones with either high or low levels of polarity reversals.

Results. From our compilation, 737 Paleozoic vertebrates represent the initial radiation and diversification of individual Paleozoic vertebrate clades. After compensating for sample-size and external geologic and sampling biases, the resulting Pearson's correlation coefficient between the 737 genera and geomagnetic polarity zones equals 0.89. These results suggest a strong relationship exists between Paleozoic vertebrates and geomagnetism.

Discussion. The question: is this apparent connection between geomagnetism and the evolution of Paleozoic vertebrate due to environmental or biologic factors. If biologic, why are vertebrates the only biota effected? And after an indeterminate period of time, how do vertebrates become immune to the ongoing effects of polarity reversals?

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Introduction

Geomagnetic polarity reversals occur randomly at a rate of about two or three times per million years (Gradstein, 2012). The transition between the collapse of the Earth's protective magnetic shield and its subsequent regeneration can last thousands of years, and any effects on biota during this interim are unknown.

In 1963, Uffen raised the possibility of polarity reversals increasing extinction rates due to harmful solar and cosmic radiation. Others pointed out the Earth's atmosphere is our primary shield despite a potential loss of ozone (Crutzen, 1975). Secular variations of a weakening geomagnetic field intensity show enhanced cosmic-ray production of ^{10}Be, ^{36}Cl, and ^{14}C in the stratosphere (McHargue, 2000). Reinforcing this view, age-dated Greenland ice cores show relatively high concentrations of these isotopes during polarity excursions (Raisbeck, 2006). Despite active repair mechanisms, DNA is susceptible to ^{14}C decay (Sassi, 2014), and Van Huizen (2019) showed weak magnetic fields can directly alter the regeneration of worms. Volcanism (Courtillow, 2007), climate alteration (Harrison, 1974), low-frequency electromagnetic fields (Liboff, 2013), depletion of ozone (Huang, 2017), and the stripping of atmospheric oxygen (Wei, 2014) have been proposed as possible culprits. But Glassmeier and Vogt in their review of *Magnetic Polarity Transitions and Biospheric effects*, after listing numerous causations, found no evidence of effects (Glassmeier, 2010). Pechersky's 2012 study found minimal correlation between biozones and geomagnetic polarity. And Sepkoski's 2002 marine fossil compendium shows virtually no alignment of biota and polarity reversals—with one exception, family-level Paleozoic vertebrates.

In our previous study (Staub 2018), we showed a strong connection between geomagnetic activity and the initial twenty-million-year evolution of 27 separate clades. In this study, for simplicity and reproducibility, we will compare only major phylogenetic groups. Instead of a twenty-million-year limit, we will use a replacement approach, where the early radiation of a clade's evolution ends at the intervention of a subsequent phylogenetic group. For example, Cambrian conodonts are considered early-phase, whereas Ordovician and later conodonts are late phase. The difference: the two phases are split by the appearance in the Early Ordovician of the pteraspidomorphs with their protective scales and armor. Likewise, the jawless fish are early-phase until the appearance of the gnathostomes; jawed fish until the osteichthyans; bony fish until the sarcopterygians; lobe-finned fish (including lung-fish and tetrapodomorphs) until the

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Upper Devonian tetrapods; the tetrapods until the amniota (Reptiliomorpha); followed by the reptiles and pelycosaurs until the therapsids. The early-phase genera represent the early evolution and radiation of their respective clades. They will be used to correlate vertebrate evolution to geomagnetism. See Figure 1.

Figure 1 Polarity Reversals and Distribution of Paleozoic vertebrates.

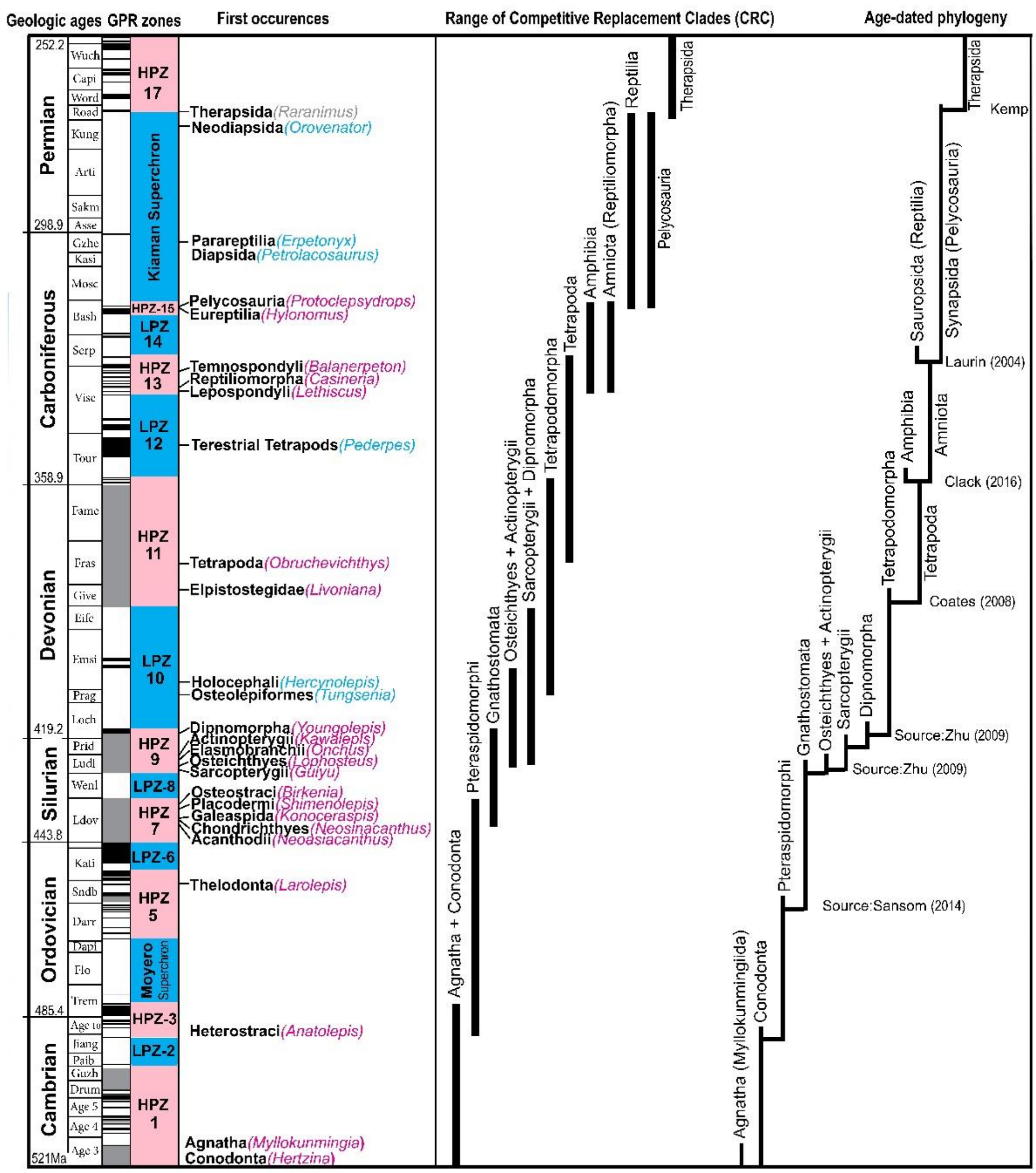

Figure 1: Columns (1) and (2): geologic periods and stages (Gradstein 2012). Column (3): geomagnetic polarity reversals from multiple sources (black is normal polarity; white is reversed; gray represents multiple reversals). Column (4): high (red) and low polarity (blue) zones. Column (5): FAD of originating genus of 28 clades. Column

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(6) shows the "early-phase" ranges of 11 major groups of Paleozoic vertebrates. Column (7): Possible age-dated phylogeny of Paleozoic vertebrates, with sources.

Methods

The Paleobiology database (paleobiodb.org), Benton's list of terrestrial vertebrates from the supplemental in *The first half of tetrapod evolution* (Benton, 2013), Zhao and Zhu's *Siluro-Devonian vertebrate biostratigraphy and biogeography of China* (Zhoa, 2009), and Sepkoski's 2002 marine compendium were the sources for our compilation of 2210 Paleozoic vertebrate genera. No other sources for genera were used.

Each genus was assigned to one of eleven major taxonomic groups: 1) Agnatha (jawless fish), including conodonts. 2) Pteraspidomorphs (armored and scaled fish). 3) Gnathostomata (jawed fish) including Chondrichthyes (fish with cartilage) and Placodermi. 4) Osteichthyes (bony fish) and Actinopterygii (ray-finned fish). 5) Sarcopterygii (lobe-finned fish) including the tetrapodomorphs and dipnoi (lungfish). 6) Basal tetrapods. 7) Amphibia, including lepospondyls and temnospondyls. 8) Amniota, including reptiliomorpha. 9) Reptiles, including Parareptilia, Eureptilia, and Diapsida. 10) Pelycosaurs. 11) Therapsids. See Table 2.

Paleozoic geomagnetic activity in the Paleozoic includes two polarity superchrons (the Kiaman and Moyero) plus six polarity chrons lasting more than 6 million years. Using Gradstein 2012, Ogg 2016, Hansma 2015, Lanci 2013, Hounslow 2016, and Opdyke 2009, we dated 303 individual geomagnetic polarity reversal to delineate 17 Paleozoic zones. The nine zones with high levels of polarity reversals (HPZ) lasted for 130.4 million years (Ma). The eight zones with low-levels (LPZ) lasted 138.4 ma. Note the time spans for the High and Low-Level polarity chrons are essentially equivalent, with a slight disadvantage to our hypothesis. See Figure 1.

The Paleobiology database lists 37,800 occurrences of Paleozoic chordata genera (September 7, 2019) with each occurrence listing geologic stage plus the "max_ma" and "min_ma" dates. From these occurrences, we found the earliest appearance of 1668 genera.

A genus is often dated entirely within the range of an LPZ or HPZ. But when the "max_ma" and "min_ma" are split by a dated polarity zone, we divided each genus proportionately. For example, the Lochkovian lasted from 419.2 to 410.8 Ma, but is split by a polarity zone at 416.5 Ma. Therefore, 32% of a Lochkovian genus is placed in the Upper Silurian HPZ10, and 68% in the Lower Devonian HPZ9. Proportionality is our only dating systematic.

Refer to the supplemental file for a full listing of our 2210 genera, proportionally placed in individual polarity zones. A complete color-coded dataset with references can be found at Dryad (doi:10.5061/dryad.1ns1m8q0).

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Table 1: Distribution of early phase genera assigned to clades and placed in individual polarity zones.

CLADES	HPZ-1 Early Cambrian	LPZ-2 Paiban Stage	HPZ-3 Upper Cambrian	Moyero Superchron	HPZ-5 Sandbian Stage	LPZ-6 Katian Stage	HPZ-7Early Silurian	LPZ-8 Wentlock Stage	HPZ-9 Late Silurian	LPZ-10 Early Devonian	HPZ-11 Late Devonian	LPZ-12 Tournaisian	HPZ-13 Late Visean	LPZ-14 Pendleian	HPZ-15 Westphalian A	Kiaman Superchron	HPZ-17 Late Paleozoic	TOTAL GENERA
Early Chordata	16.5	7.5	22	1.1														47.1
Pteraspidomorphs		0.4	0.6	3.1	7.8	1.1	22.1	0.7	0.2									36.0
Gnathastomata					1.8	0.2	5	1	32.5	13.8								54.3
Actinopterygii									4	1								5.0
Sarcopterygii									4.6	27.8	51.6							84.0
Basal tetrapods											15.1	9.3	5.2	0.4				30.0
Amphibia												1.3	7.2	3.9	15.4	10.2		38.0
Amniota												0.8	5.6	3.4	5.4	3.8		19.0
Reptilia															0.6	48.5	5.9	55.0
Pelycosauria															0.6	59.3	4.1	64.0
Therapsida																18	287	305.0

Table 1: The early-phase genera represent the early radiation of a clade, but an exact definition is needed. Using our replacement concept, the early-phase of a clade continues until it is replaced by a subsequent clade. The early phase of chordata and conodonts continues until the scales of Anatolepis are found in the Upper Cambrian (HPZ-3); the pteraspidomorphs (armored fish) until the appearance of fish with cartilage, (Areyonga or Dictyorhabdus), in the Upper Ordovician (HPZ-5); the Osteostraci and Galeaspida until the earliest placoderm (Shimenolepis) of the Early Silurian (HPZ-7); the shark-like Chondrichthyes until the earliest Osteichthyes (Andreolepis) of the Upper Silurian (HPZ-9); the bony fish until the first Sarcopterygian (Guiyu) of the Upper Silurian (HPZ-9); the lobe and lung fish until the early "tetrapods" (Livoniana, Tiktaalik, Acanthostega, Ichthyostega, Hynerpeton) of the Upper Devonian (HPZ-11); the basal tetrapods until the earliest Reptiliomorpha (Casineria) of the Upper Visean (HPZ-13); the egg-laying Amniota until the Reptilia (Hylonomus) of Westphalian A (HPZ-15), which is immediately prior to the Kiaman Superchron; the reptiles and pelycosaurs until the therapsids of the Upper Permian (HPZ-17). Note: had we used the geologic stage date instead of polarity zones as the end-point of these clades, Pearson's Correlation Coefficient would have dropped from 0.89 to 0.86.

Results

Using Paleobiology, Benton, Zhao, and Sepkoski, we compiled an Excel spreadsheet (see Table 3 in the Supplemental) with 2210 Paleozoic genera (an increase of over 400 genera from our previous 2018 study). As expected, only about 52.9% (1116/2110) of these genera originated

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in high polarity zones. We listed 737 early-phase genera. 520 of these genera (70.6%) were found in high-polarity zones. Marine genera were 168 of 226 (74.3%); terrestrial genera were 352 of 511 (68.9%).

Extrinsic biases such as outcrop area and accessibility are known to affect the distribution of fossils (Peters, 2001). Sample-size is a potential problem (for example, there are only four early-phase osteichthyes compared to over 200 therapsids). To normalize these biases, we divided the early-phase genera by the total genera within each polarity zone, and then correlated those percentages to the rate of polarity reversals per million years for each of our high and low polarity zones. Note columns (f) and (i) in Table 2 (*Geomagnetic polarity zones and Total Distribution of Paleozoic Vertebrates*).

The resulting Pearson's correlation coefficient equals 0.8885 with a P-value of <.00001. By definition, this is a strong positive correlation.

Table 2 | Distribution of Paleozoic vertebrates within polarity zones.

Polarity Zones		Duration		Reversals		Distribution of Genera		
Zone	**Geologic stages**	**Ma**	**Ma**	**GPRs**	**per Ma**	**EP genera**	**Total**	**%**
HPZ-17	Late Permian	270-252.2	17.8	21	**1.18**	297.0	514.4	**57.7**
LPZ-16	Kiaman Superchron	316-270	46	10	**0.22**	139.8	480.9	**29.1**
HPZ-15	Westphalian A	318.8-316	2.8	5	**1.79**	22.0	33.1	**66.5**
LPZ-14	Pendleian Stage	328.1-318.8	9.3	5	**0.54**	7.8	49.1	**15.8**
HPZ-13	Late Visean	337.5-328.1	9.4	20	**2.13**	18.0	38.4	**46.9**
LPZ-12	Romer's Gap	356.5-337.5	19	6	**0.32**	11.4	87.4	**13**
HPZ-11	Late Devonian	388.4-356.5	31.9	32	**1.00**	66.6	262.1	**25.4**
LPZ-10	Middle Devonian	416.5-388.4	28.1	5	**0.18**	42.7	250.3	**17.1**
HPZ-9	Late Silurian	427.4-416.5	10.9	20	**1.83**	41.0	109.0	**37.6**
LPZ-8	Wenlock Stage	433.4-427.4	6	0	**0.00**	1.7	27.0	**6.3**
HPZ-7	Early Silurian	443.8-433.4	10.4	22	**2.12**	27.1	49.7	**54.5**
LPZ-6	Katian Stage	452-443.8	8.2	2	**0.24**	1.3	22.4	**5.9**
HPZ-5	Middle Ordovician	466.8-452	14.8	20	**1.35**	9.5	52.3	**18.2**
LPZ-4	Moyero Superchron	482-466.8	15.2	2	**0.13**	4.3	69.0	**6.2**
HPZ-3	Late Cambrian	490.2-482	8.2	17	**2.07**	22.6	40.6	**55.7**
LPZ-2	Paiban Stage	496.8-490.2	6.6	3	**0.45**	7.8	7.8	**32.2**
HPZ-1	Early Cambrian	521-496.8	24.2	85	**3.51**	16.5	16.5	**100**

Table 2 shows the 17 high (red) and low polarity zones (blue), their range and duration (Ma), number of polarity reversals, reversals per million years, and distribution of total genera in each polarity zone showing early-phase genera (EP), total genera, and percentage found in each polarity zone. Note that the Reversals per million years and percentage of genera are used to calculate Pearson's correlation coefficient using Social Science Statistics.

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Discussion

Although the statistical evidence shows a strong connection exists between the fossil record of Paleozoic vertebrates and polarity reversals, it does not determine if the causation is extrinsic (geologic) or intrinsic (biologic).

Fossilization is dependent on positive environmental conditions such as rapid burial or anoxia. Poor environmental conditions can cause gaps in the fossil record. Romer's Gap (LPZ-12) of the Early Carboniferous is now thought to be a sampling artifact (Anderson, 2015; Clack, 2016), but other gaps exist. The Middle Carboniferous Namurian Stage (LPZ-14) has been called a gap in the tetrapod record (Clack, 2012). Olsen's gap runs between the last occurrence of pelycosaurs in North America until the earliest appearance of therapsids in the uppermost Kiaman superchron (LPZ-16). The Moyero Superchron (LPZ-4), shows active diversification of conodonts but limited occurrences of agnathan vertebrates. The Cambrian Paibian (LPZ-2) gap lists only two conodonts, while the Upper Ordovician LPZ-6 is void of vertebrates other than conodonts. That these gaps correlate with low-polarity zones implies the causation is environmental, not biologic.

Volcanic activity, climate change, and the depletion of ozone have been linked to geomagnetic polarity reversals. But if these external causations are the connection, then why are invertebrates essentially unaffected? And after an indeterminant period of time, how do vertebrate families become immune to the ongoing effects of polarity reversals? Are DNA repair mechanisms involved?

Conclusions

In reality, evolution is a continuum with natural groups and clades merely artificial tools useful for clarification. Nonetheless, this continuum does not keep mutation rates from increasing periodically, nor does it keep the pace of evolution from accelerating during geomagnetic polarity collapses.

Detailed Methodology

Originally, we compiled a list of over 2000 Paleozoic vertebrate genera taken from multiple sources, but this early compilation lacked repeatability. Therefore, we limited our sources to the Paleobiology Database (downloaded September 7, 2019 from paleobioDB.org), Sepkoski's 2002 marine compilation, Benton's 2013 compilation, plus Zhao and Zhu's 2010 report. A single source would be ideal, but the Paleobiology Database still lacks many marine and terrestrial vertebrates, and their Phylum/Class/Order/Family taxonomy is often inadequate. Fossilworks (paleoDB.org) and Benton were referenced when needed to clarify taxon classification.

Any genus not listed in the four main sources was ignored. With duplicate genera, Sepkoski had the lowest priority. Otherwise, we chose the earliest, most precise date (Zhao and Zhu's dating appears to be excellent). We removed synonyms and uncertain genera. Imprecise dating >20 Ma was ignored, unless those dates were placed entirely within a single LPZ or HPZ.

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Paleobiology's "max_ma" and "min_ma" dates were entered directly into our spreadsheet (in our previous report we used Gradstein and Ogg for dating purposes).

Dolichopareias, an early amphibian, is not Tournaisian. It is Upper Visean (the fossil, dated Visean, was discovered in 1927—a book written soon after made the dating error—see paleobioDB).

The paleobiology database does not divide the Visean into sub-stages, therefore, we used Benton's dating.

Xiushuiaspis, Changxingaspis, Meishanaspis, Sinogaleaspis, and Geraspis (Galeaspida) were recently placed by PaleobioDB into the Sheinwoodian Stage using data from Zhu and Wang in 2000. Instead, use Zhoa and Zhu's 2010 report for these fossils.

The Cambrian presents a unique problem. There are 15.74 genera in the Early Cambrian HPZ-1, followed by 7.88 genera in LPZ-2 (See Table 2). This distribution is positive to our hypothesis, but when we divide the 7.88 genera by the total (7.88), the results still equal 100%. To compensate, we add the 15.74 genera from HPZ-1 to the 7.88 genera from LPZ-2 and divide 7.88 by the total (23.62) to get 33.3%.

The majority of the dating of the Cambrian is unreliable. Of the 44 Cambrian Chordata only 33 have any certainty. 13 are Early Cambrian (HPZ-1); 2 are Paibian (LPZ-2); 18 in the Late Cambrian (HPZ-3).

Generating Geomagnetic Polarity Zones

Gradstein and Ogg 20122, with updated data from Hansma[18], Lanci[19], Hounslow[20], Ogg 201617 and Opdyke[21], was used to individually date 303 Paleozoic geomagnetic polarity reversals and to define 9 high-level and 8 low-level polarity zones. Post-Cambrian, 193 polarity reversals occurred in 233.4 million years (0.827 polarity reversals per million years). This 0.827 value was used as a guide to delineate polarity zones. We extended the high-polarity zones by .2 myr after the uppermost polarity reversal in a zone (excluding the Silurian). See a list of individual polarity reversals below.

Lanci used zircons in his 2013 report on the *Upper Permian magnetic stratigraphy of the lower Beaufort Group in the Karoo Basin of South Africa* to accurately date the base of the Illawara polarity zone (top of the Kiaman superchron) at ~270 mya. He correlates his N3 polarity chron with the Wordian normal, which would place the Eodicynodon AZ into the middle or late Capitanian.

Individual Paleozoic polarity reversals (reds are high polarity zones; blues are low polarity zones).

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HPZ-17 (Guadalupian to Lopingian, Upper Permian): 252.46[4], 252.83[4], 253.0[4], 253.36[4], 253.72[4], 254.11[4], 254.35[4], 255.21[4], 257.20[4], 257.98[4], 258.18[4], 258.82[4], 259.7[4], 264.10[4], 264.42[4], 264.86[4], 266.07[4], 266.63[3], 267.63[3], 268.69[3], 270.0[3].

LPZ-16 (Kiaman Superchron, Upper Carboniferous to Lower Permian): 286.3, 297.3, 299.1, 299.3, 300.4, 300.8, 304.4, 308.7, 310.7, 311.75.

HPZ-15 (Upper Bashkirian): 316.2[5], 317.0, 318.6[4], 318.7[4], 318.8[4].

LPZ-14 (Upper Serpukhovian to Lower Bashkirian): 319.45, 322.7, 324.3, 326.92[4], 327.43[4].

HPZ-13 (Middle Viséan to Lower Serpukhovian, Carboniferous): 328.3, 328.65, 330.6, 331.3, 331.8, 331.9, 332.2, 332.3, 333.2, 333.35, 334.05, 334.25, 334.75, 334.9, 335.2, 335.7, 336.6, 336.8, 337.3, 337.5.

LPZ-12 (Romer's Gap, Early Tournaisian to Middle Viséan, Carboniferous): 343.0, 343.7, 344.3, 346.0, 347.45, 352.35.

HPZ-11 (Givetian to Famennian, Upper Devonian, plus Early Tournaisian): 356.7, 356.85, 357.6, 357.75, 358.4, 358.75, 360[1], 363.6[1], 364.7[1], 365.2[1], 367.7[1], 370.4[1], 371.5[1], 372.8[1], 373.3[1], 373.8[1], 375[1], 376.1[1], 377.3[1], 378.3[1], 378.65[1], 378.9[1], 379.3[1], 380.3[1], 381.6, 382.5[2], 383.1[2], 384.3[2], 386.4[2], 387.1[2], 387.7[2].

LPZ-10 (Middle Lochkovian to Eifelian, Lower Devonian): 393.3, 400.24, 400.76, 401.6[2], 402.5[2].

HPZ-9 (Ludlow to Pridoli Stages, Upper Silurian; Lower Lochkovian): 416.7, 418.2, 418.9, 419, 419.4, 419.9, 420.4, 420.9, 421.4, 421.9, 422.4, 422.9, 423.4, 423.9, 424.4, 424.9, 425.4, 425.9, 426.4, 426.9, 427.4.

HPZ-8 (Wenlock Stage, Middle Silurian): None.

HPZ-7 (Llandovery, Lower Silurian): 433.5, 433.8, 434.3, 434.8, 435.3, 435.8, 436.3, 436.8, 437.3, 437.8, 438.3, 438.8, 439.3, 439.8, 440.3, 440.8, 441.3, 441.8, 442.3, 442.8, 443.3, 443.8.

LPZ-6 (Middle Katian to Hirnantian, Ordovician): 448.9, 450.7.

HPZ-5 (Darriwilian to Lower Katian): 452.2, 452.34, 453, 453.6, 454.0[4], 454.73[4], 457.26[4], 457.7[4], 458.26[4], 459.19[4], 459.68[4], 461.21[4], 461.73[4], 462.11[4], 462.32[4], 462.76[4], 463.56[4], 464.6[4], 466.0[4], 466.8[4].

LPZ-4 (Moyero Superchron, Upper Tremadocian to Lower Darriwilian): 479.95, 480.1.

HPZ-3 (Cambrian Age 10 to Lower Tremadocian): 482.2, 482.7, 482.9, 484.35, 484.6, 484.8, 485.3, 485.9, 486.75, 486.95, 487.1, 487.2, 487.3, 487.8, 488.1[4], 490.05[4], 490.2[4].

LPZ-2 (Paibian to Upper Jiangshanian): 492[4], 492.2[4], 495[4].

HPZ-1 (Lower Cambrian): 497[4], 497.4, 497.55, 497.7, 497.85, 498.0, 498.1, 498.2, 498.3, 498.75, 498.95, 499.0, 499.15, 499.45, 499.6, 499.68, 499.75, 499.83, 499.9, 500.65, 500.75, 500.8, 501.1, 501.25, 501.45, 501.55, 501.65, 501.75, 501.8, 502.1, 502.2, 502.35, 502.8, 503.13, 503.6, 503.75, 504.1, 504.75, 505.3, 505.55, 506.7, 507.2, 508.9, 509.2, 509.52, 509.7, 510.17, 510.32, 510.6, 510.8, 511.72, 511.95, 512.05, 512.25, 512.4, 512.9, 513.4, 513.9, 514.4, 514.9, 515.4, 515.9, 516.18, 516.35, 517, 517.5, 517.6, 517.75, 517.85, 518.25, 518.35, 518.6, 518.64, 518.7, 518.85, 519.25, 519.25, 519.4, 519.55. 519.7, 520.2, 520.35, 520.6, 520.75, 520.85, 520.95.

Superscripts: 1 is for Ogg (2016); 2 is for Hansma (2015); 3 is for Lanci (2013); 4 is for Hounslow (2016); 5 is for Opdyke (2014). Polarity reversals without superscripts are from Gradstein (2012).

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