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The emergence of plate tectonics and the Kuhnian model of paradigm shift: a bibliometric case study based on the Anna Karenina principle

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Abstract How scientific progress functions in detail and what the specific prerequisites for scientific breakthroughs in a given research area are, is still unclear today. According to philosopher of science Thomas S. Kuhn, scientific advancement takes place via paradigm shift. As a principle supplementing Kuhn's theory, we proposed the Anna Karenina principle: a new paradigm can be successful only when several key prerequisites are fulfilled (e.g., verified by means of independent data and methods). If any one of these prerequisites is not fulfilled, the paradigm will not be successful. Aiming at investigating the schema of paradigm shift supplemented by the Anna Karenina principle with the aid of concrete examples from science, in this study we analyze one of the most important scientific revolutions: the shift from a fixed to a mobile worldview in geoscientific thinking. This paradigm shift will be explained based on key papers that played a decisive role, selected carefully from reviews in the literature. The account of the development will be complemented by empirical findings that were produced based on publication and citation data using the software Histcite.

Keywords Paradigms · Scientific revolutions · Plate tectonics · Bibliometrics · Anna Karenina principle

Introduction

It is still unclear today how scientific progress functions in detail and what the specific prerequisites for scientific breakthroughs in a given research area are. According to

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philosopher of science Kuhn (1962),[1] research takes place within paradigms. These are scientific findings that are recognized by the scientific community as the foundation for further work and that are summarized in textbooks. The development of science takes place in a cyclical pattern: Kuhn (1962) made a distinction between "normal science", which is guided by recognized paradigms, and scientific revolutions, which become necessary when deviations can no longer be explained by the existing paradigms. These deviations or anomalies lead to scientific crises, which is when the research community in a research area conducts "extraordinary science". The existing paradigms become blurred, and then the scientific community replaces them with new paradigms (paradigm shift). These scientific revolutions start up a new phase of normal science—without the research in a research area cumulatively approximating closer and closer any absolute truth.

Although Kuhn (1962) described a turn of the tide from normal science to scientific revolution, he did not describe what mechanism leads to a scientific revolution—what prerequisites must be given for a revolution to take place (see also Kuhn 1977). Approaches to supplement Kuhn's model seem to be needed all the more urgently, as most of the examples that were presented to develop and illustrate the change from phases of normal science to scientific revolutions were taken from the nineteenth century or the first half of the twentieth century. Modern science and especially the developments in the age of Big Science (starting circa 1960) are much more complex (see here Marx and Bornmann 2010) and cannot be sufficiently reflected upon on the basis of Kuhn's model (Kuhn 1962).

Bornmann and Marx (2012) brought in what they called the Anna Karenina principle (AKP) as a way of thinking about success in science. The first sentence of Leo Tolstoy's novel *Anna Karenina* is: "Happy families are all alike; every unhappy family is unhappy in its own way". Here Tolstoy means that for a family to be happy, several key aspects must be given (such as good health of all family members, acceptable financial security, and mutual affection). If there is a deficiency in any one or more of these key aspects, the family will be unhappy. Bornmann and Marx (2012) introduced the AKP as a way of thinking about scientific breakthroughs: a new paradigm can be successful only when several key prerequisites are fulfilled. If any one of these prerequisites is not fulfilled, the paradigm will not be successful.

The AKP does not contain any previously overlooked new conditions for scientific revolutions; rather, it delivers a certain view of, or organizing schema for, the things that lead to a breakthrough. Only when these prerequisites are fulfilled is there a "happy family" (in this case, a scientific revolution), which is like all other happy families in that all prerequisites are fulfilled (see here also Šešelja and Weber 2012). The key prerequisites are as follows: solid evidence in answer to basic questions must be presented (1); it is taken up by colleagues (2) and can be verified by means of independent data and methods (3). Especially important is the stating of verifiable predictions that can then be confirmed (4). This requires techniques for gathering data (5). Of decisive importance is a satisfactory and convincingly formulated theory that answers more questions than it raises (6). In demand in this connection are simplicity, elegance (aesthetic qualities) (7), and explanatory power of the new paradigm emerging from the new theory (8). For understanding of the paradigm, clear and plain language and the introduction of easy to remember labels are very helpful (9). Finally, what is needed is the particular last crucial step that leads to the definitive breakthrough and the establishment of a new paradigm (10). For a scientist making a crucial contribution to a scientific revolution, important stubbornness in thinking

[1] In this paper we used the 52 references for the 52 key papers upon which our analysis using the HistCite program was based (see below).

and good networking among colleagues in the field are important (11) (see also Bornmann and Marx 2012).

Our aim is to examine the paradigm shift schema supplemented by the AKP based on specific examples taken from modern science. In this paper we analyze one of the most important scientific revolutions in the natural sciences: the development from a fixed to a mobile worldview in the geosciences. Some philosophers and historians of science argued that this paradigm shift can be described with respect to Kuhn's terms of normal science and scientific revolutions (e.g., Šešelja and Weber 2012; Stewart 1990). For a long time, the continents and oceans were considered to be permanent, rigidly fixed and immobile. According to that view, vertical and not horizontal tectonic movements played the principal role in the development of the Earth's crust. In a complex process of scientific activities, this model (or theory; both model and theory are used here synonymously for a simplified picture of reality) of the Earth's crust as being fixed (the fixism paradigm) was replaced by the idea of the Earth's crust as being in motion (the plate tectonics paradigm).

The shift in paradigms from fixism to plate tectonics will be explained based on key papers that played a decisive role, selected carefully from reviews in the literature. The account of the development will be complemented by empirical findings that we produced based on publication and citation data using the software package Histcite developed by Eugene Garfield (http://garfield.library.upenn.edu/algorithmichistoriographyhistcite.html) (2004, 2009). We thus join ranks with the number of previous studies that used this kind of data to investigate diverse paradigm shifts in science. For an overview of older studies, see Tabah (1999). Small (2003) and Marx and Bornmann (2010) reviewed more recent studies.

The technique of bibliometric analysis

Citation-based indicators are now being used frequently as an additional criterion when evaluating research (this is called "informed peer review"). But this type of data can also be used in history of science investigations (for example, see Kragh 1987; Scharnhorst and Garfield 2010). By citing a work, authors of papers are normally showing that they conducted their research under the influence of the cited source. The database of the citation counts used in this study is Thomson Reuters' Science Citation Index (SCI), which is available through Web of Science (WoS) and covers the period back to 1900 (http://scientific.thomsonreuters.com/products/wos/).

Our starting assumption here is that the paradigm shift in the geosciences from fixism to plate tectonics can be understood with the aid of the citations that exist among the important key papers. We also assume that the importance of a key paper can be estimated via the total number of times that it has been cited: the higher the citation count for a paper, the more important the work was for the paradigm shift. However, it must be taken into consideration that an important part of the information flow in science is not documented in the form of publications and citations. First of all, there is the phenomenon of obliteration by incorporation (Merton 1965; Garfield 1975). This occurs when certain ideas are mentioned in a work but not attributed to a source in the form of a reference citation. In addition, besides the flow of information via publications, there is also informal exchange among scientists (mutual visits, conversations during conferences, and so on).

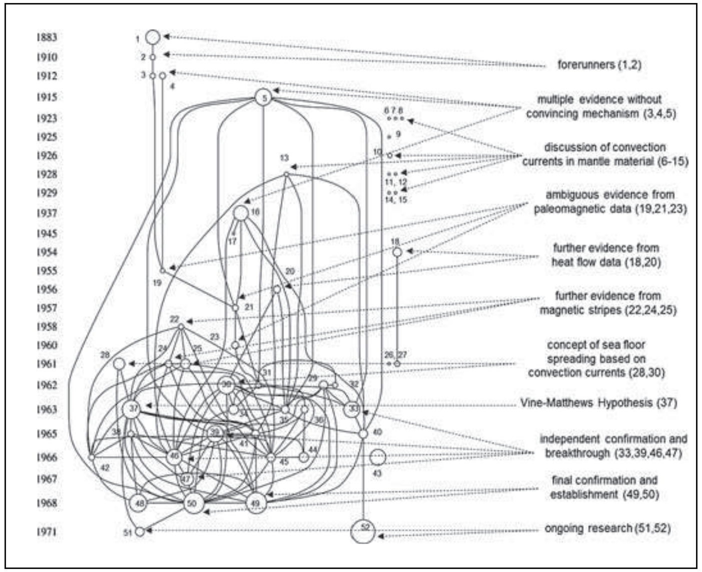
For the (bibliometric) investigation of the paradigm shift to plate tectonics, we selected a total of 52 key papers from reviews that described important contributions to the paradigm shift (see especially books by Anderson (1971) and by Oreskes (2003) but also numerous other reviews, such as Frisch and Meschede (2005)). These 52 key papers, which are listed in Fig. 1, contain the lowest common denominator of works that in the reviews were deemed especially important for the paradigm shift. Out of these 52 papers, 40 papers are WoS source records; 12 papers and books are not covered by the WoS.

We used the software HistCite (http://garfield.library.upenn.edu/algorithmichistoriographyhistcite.html) (Garfield 2004, 2009) to analyze the structure, history, and the relationship of the 52 key papers and books. The historiograph in Fig. 1 (the citation network) displays the linkages (citations) among these papers represented by circles. The diameters of the circles (nodes) are proportional to the Global Citation Score (GCS) of the 52 papers, which are numbered from 1 to 52. The GCS provides the citation counts based on the full WoS count from time of publication up to the end of 2010 (the data was downloaded on January 17, 2011). Between the nodes there are 113 connections (that is, there are approximately two connections per node on average); the pathway arrows indicate which later papers cited which earlier papers. The graph illustrates how the nodes are positioned on the pathways between the papers (this is called centrality). The interconnectedness helps to identifying central publications. The legend to the right of the figure provides in short form the contribution to the paradigm shift that can be ascribed to the individual papers.

In Fig. 1, some key bibliometric figures are provided for each of the 52 works (Suess and Waagen 1883; Taylor 1910; Wegener 1912a, b, 1915; Joly 1923a, b, c; Ampferer 1925; Daly 1926; Holmes 1928a, b, c; 1929; Du Toit 1929, 1937, 1945; Bullard 1954; Runcorn 1955; Bullard et al. 1956; Creer et al. 1957; Mason 1958; Collinson and Runcorn 1960; Mason and Raff 1961; Raff and Mason 1961; Bullard and Day 1961; Gaskell et al. 1961; Dietz 1961; Runcorn 1962a, b, c; Hess 1962; Wilson 1963a, b, c; Cox et al. 1963; Vine and Matthews 1963; Heirtzler and LePichon 1965; Wilson 1965a, b, 1966; Vine and Wilson 1965; Heirtzler et al. 1966; Opdyke et al. 1966; Pitman and Heirtzler 1966; Vine 1966; McKenzie and Parker 1967; Morgan 1968, 1971; Le Pichon 1968; Isacks et al. 1968; Elsaesser 1971) that indicate the work's importance in the network of the 52 works or in science generally. With regard to these figures, it is important to take into account that the bibliometric analysis of historical publications is particularly problematic due to citation errors and errors in databases (Marx et al. 2010; Marx 2011). The citations have to be searched manually via the cited reference search mode in WoS, so as to obtain a count of not only correct but also incorrect citations (reference mutations, which are found more frequently in historical papers) of a publication.

The Local Citation Score (LCS) provides the citation counts based only on the citation network presented in the historiograph (from time of publication up to the end of 1971—the year when the last paper in the network was published). The LCS can be seen as a measure of the impact of a given paper within the ensemble of the selected key papers. $LCS_{o/e}$ in Fig. 1 shows the ratio of the actual number of citations of a work (LCS observed: LCS_o) to the number of expected citations (LCS expected: LCS_e) in the citation network. LCS_e is the number of papers that were published 2 years or more after the paper in question. For each key paper in Fig. 1, it could be expected that all subsequent papers would refer to it—that is, cite it. Not included in the calculation of the expectation value are papers in the same publication year and the year thereafter, since a paper first has to be noticed and incorporated into new papers before it can be cited. For instance, Pitman and Heirtzler (1966) could have been cited in five later papers, but in fact the paper was cited in only two papers.

Based on the calculation of the LCS, QUO % is the percentage of subsequent papers that cited the paper in question; it is therefore a measure of the importance of a paper within the historiograph. For example, the QUO % for the Pitman paper (Pitman and Heirtzler 1966) is 40 %. That means 40 % of the subsequent papers cited Pitman's paper.



#	Key-Paper	$LCS_{o/e}$	$QUO_{\%}$	GCS	$GCP_{\%}$
1.	SUESS E, 1883, DAS ANTLITZ DER ERDE	1/51	2	404	68
2.	TAYLOR FB, 1910, BULLL GEOL SOC AM, V21, P179	1/50	2	62	13
3.	WEGENER A, 1912, GEOL RUNDSCHAU, V3, P276	1/48	2	62	13
4.	WEGENER A, 1912, PETERM GEOGRAPH MITT, V58, P185/253/305	1/48	2	89	19
5.	WEGENER A, 1915, DIE ENTSTEHUNG DER KONTINENTE	7/47	15	575	128
6.	JOLY J, 1923, NATURE, V111, P603	0/44	0	0	0
7.	JOLY J, 1923, PHILOS MAG, V45, P1167	0/44	0	8	2
8.	JOLY J, 1923, PHILOS MAG, V46, P170	0/44	0	1	0
9.	AMPFERER O, 1925, NATURWISS, V13, P669	0/42	0	6	1
10.	DALY RA, 1926, OUR MOBILE EARTH	0/42	0	36	9

#	Key-Paper	$LCS_{o/e}$	$QUO_{\%}$	GCS	$GCP_{\%}$
11.	HOLMES A, 1928, GEOL MAG, V65, P236	0/37	0	4	1
12.	HOLMES A, 1928, NATURE, V122, P431	0/37	0	4	1
13.	HOLMES A, 1928, T GEOL SOC GLASGOW, V18, P559	4/37	11	36	9
14.	DUTOIT AL, 1929, AM J SCI, V17, P179	0/37	0	0	0
15.	HOLMES A, 1929, MIN MAG, V40, P205/286/340	0/37	0	11	3
16.	DUTOIT AL, 1937, OUR WANDERING CONTINENTS	5/36	14	467	135
17.	DUTOIT AL, 1945, AMER J SCI, V243, P404	0/35	0	0	0
18.	BULLARD E, 1954, PROC R SOC LONDON SER A-MATH, V222, P408	1/33	3	150	56
19.	RUNCORN SK, 1955, ADVAN PHYS, V4, P244	1/32	3	43	16
20.	BULLARD EC, 1956, ADV GEOPHYS, V3, P153	2/31	6	95	37
21.	CREER KM, 1957, PHILOS TRANS R SOC SER-A, V250, P144	2/30	7	85	34
22.	MASON RG, 1958, GEOPHYS J ROY ASTRON SOC, V1, P320	6/30	20	64	26
23.	COLLINSON DW, 1960, GEOL SOC AMER BULL, V71, P915	1/24	4	102	43
24.	MASON RG, 1961, GEOL SOC AMER BULL, V72, P1259	6/20	30	106	45
25.	RAFF AD, 1961, GEOL SOC AMER BULL, V72, P1267	4/20	20	179	77
26.	BULLARD EC, 1961, GEOPHYS J ROYAL ASTR SOC, V4, P282	0/20	0	57	24
27.	GASKELL TF, 1961, GEOPHYS J ROY ASTRON SOC, V5, P80	0/20	0	0	0
28.	DIETZ RS, 1961, NATURE, V190, P854	2/20	10	264	113
29.	RUNCORN SK, 1962, CONTINENTAL DRIFT	6/15	40	167	73
30.	HESS HH, 1962, HISTORY OF OCEAN BASINS	8/15	53	595	260
31.	RUNCORN SK, 1962, NATURE, V193, P311	3/15	20	82	36
32.	RUNCORN SK, 1962, NATURE, V195, P1248	0/15	0	63	28
33.	WILSON JT, 1963, CAN J PHYS, V41, P863	1/15	7	488	217
34.	WILSON JT, 1963, NATURE, V197, P536	3/15	20	186	83
35.	WILSON JT, 1963, NATURE, V198, P925	2/15	13	141	63
36.	COX A, 1963, NATURE, V198, P1049	4/15	27	108	48
37.	VINE FJ, 1963, NATURE, V199, P947	9/15	60	677	302
38.	HEIRTZLE.JR, 1965, J GEOPHYS RES, V70, P4013	5/6	83	74	34
39.	WILSON JT, 1965, NATURE, V207, P343	6/6	100	588	273
40.	WILSON JT, 1965, PHILOS TRANS R SOC SER-A, V258, P145	2/6	33	166	77
41.	VINE FJ, 1965, SCIENCE, V150, P485	4/6	67	125	58
42.	HEIRTZLER JR, 1966, DEAP SEA RES, V13, P427	3/5	60	89	42
43.	WILSON JT, 1966, NATURE, V211, P676	0/5	0	507	241
44.	OPDYKE ND, 1966, SCIENCE, V154, P349	2/5	40	192	91
45.	PITMAN WC, 1966, SCIENCE, V154, P1164	2/5	40	166	79
46.	VINE FJ, 1966, SCIENCE, V154, P1405	3/5	60	517	246
47.	MCKENZIE DP, 1967, NATURE, V216, P1276	1/2	50	374	182
48.	MORGAN WJ, 1968, J GEOPHYS RES, V73, P1959	2/2	100	641	319
49.	LEPICHON X, 1968, J GEOPHYS RES, V73, P3661	1/2	50	890	443
50.	ISACKS B, 1968, J GEOPHYS RES, V73, P5855	1/2	50	888	442
51.	ELSASSER WM, 1971, J GEOPHYS RES, V76, P1101	0/0	–	176	94
52.	MORGAN WJ, 1971, NATURE, V230, P42	0/0	–	1112	595

Fig. 1 Historiograph on the paradigm shift from fixism to plate tectonics in the geosciences based on 52 selected key papers (two early works (Suess and Waagen 1883) and (Taylor 1910) were not included). The diameter of the nodes is proportional to the value of the GCS. The time scale is not linear (that is, there are gaps in time)

The higher the QUO %, the more important the paper is in the network. As Fig. 1 shows, there are several papers that were never cited by other key papers. The authors of subsequent papers were not familiar with these papers, or they did not use these papers as a basis in their research, or there is a case of obliteration by incorporation (Merton 1965; Garfield 1975), meaning that the papers were used but not cited.

To determine the total impact of each paper as compared to the other 51 papers in the citation network, for each paper we calculated the annual average citation rate (based on the GCS), and for all 52 papers we calculated the average of all annual average citation rates ($m = 4.7$). GCP % indicates how many percentage points of the GCS of a paper lie above the average of 4.7 (% value > 100) or lie below the average (% value < 100). For example, the impact of a paper by Du Toit (1937) is 35 percentage points above the average, and the impact of a paper by Suess and Waagen (1883) is 32 percentage points below the average (100–68).

Results of the bibliometric analysis and application of the AKP

The transition from a fixist to a dynamic view of the earth

Shortly before his death, Albert Einstein wrote the foreword to a book by Hapgood (1958) that was published in 1958. In the foreword, Einstein dismissed the notion of continental drift—the movement of Earth's continents relative to each other—as a naive idea. As would be shown soon afterwards, Einstein had this time backed the wrong horse.

Forerunners

Already in the mid 1800s, the similarity between fossil plants in North America and Europe was discovered. At the end of the nineteenth century, Austrian geologist Eduard Suess discussed for the first time the specific similarity between geological formations in Africa and Brazil and postulated the supercontinent "Gondwanaland". Suess published a summary of his ideas in *Das Antlitz der Erde* in 1883. In 1910 Frank Bursley Taylor, an American amateur geologist, proposed that mountains had formed as a result of continental drift caused by the tidal pull of the moon. Another forerunner was Austrian Alpine geologist Otto Ampferer, who developed ideas about the forces that had formed the mountains; Ampferer developed his hypotheses already at the start of the twentieth century but published them only later (Ampferer 1925).

The first approaches that moved away from the prevailing fixist point of view (fixism) and towards a dynamic view of the Earth did not yet trigger any continuing and comprehensive research activity. Up to the early 1900s there was no convincing evidence, and there were no technical means available to verify the new theories. At this point, the theories were more of a scientific curiosity than a serious matter for science.

According to the historiograph in Fig. 1, the works by Suess and Waagen (1883) and Taylor (1910) are linked with only one single later paper (Runcorn 1955) (QUO % = 2). This means that for the subsequent works that contributed substantially to the paradigm shift, the two works are not very important. Although Suess's book (1883) has a high GCS of 404, it nevertheless lies 32 % below the average (GCP % = 68).

Serious discussion on whether the form and location of the continents changed over the course of geological time only began with Alfred Wegener. In 1912 Wegener published an essay in *Geologische Rundschau* and another in *Petermanns Geographische Mitteilungen*.

Wegener's (1915) well-known book, *Der Ursprung der Kontinente und Ozeane* (*The Origins of Continents and Oceans*), was published in 1915 (with revised editions in 1920, 1922, and 1929, and an English translation in 1924). The book outlined Wegener's theory that the continents had formed a single large mass, which rifted, or split, millions of years ago, its pieces drifting into their current position over time. Wegener was the first to present all evidence that supported continental drift systematically (Wegener 1912a, b; 1915).

First, Wegener pointed out that the continents fit together like the pieces of a puzzle—especially if one looked not at today's coastlines but at the submerged, seaward edges of the continental shelves. Geological findings and fossils supported this insight. The rock formations on continents opposite of one another are very similar, and also the distribution areas of fossil plants and animals provide evidence of the existence of a former single land mass, which Wegener called Pangaea ("all lands"). What is more, coal deposits in cold regions must have been formed in tropical regions and then drifted into their current position. However, Wegener could not offer any plausible mechanism for *how* the continents move through the Earth's crust. He assumed that tides generated by lunar pull and centrifugal forces played a role, which was hardly believable. At the time, it was not possible to imagine any forces that could be responsible for continents plowing through the Earth's crust and drifting over the Earth's mantle.

Although Wegener's works had some important key aspects or conditions for scientific success (which is why his book was cited with above-average frequency), they did not fulfill many other prerequisites of a scientific breakthrough according to the AKP: There was only relatively little evidence supporting the theory, technical options for verification were still underdeveloped (there was not yet any sea research as we know it today, and there were no geophysical probes), and most of all, there was no convincing mechanism, no well-founded notion of the driving force, in sight. Wegener's theory stood at first on shaky ground. It also did not help that Wegener was not by training a geologist; he was a meteorologist, and in the eyes of the geological community, the fervor of the "outsider" seemed suspect.

Still, Wegener's theory certainly received attention and was not rejected out of hand. Criticism came from England and mainly from the United States after publication of *The Origins of Continents and Oceans* in English. The critical reactions were so polemical and contemptuous that the term "drift" became discredited and was hardly used for 30 years [an overview on the critical reactions is given by Šešelja and Weber (2012)]. Not until the 1960s were discoveries made that delivered unambiguous and convincing evidence that continents do in fact move. The resulting paradigm of plate tectonics goes beyond Wegener's original theory in many respects, however.

The relative impact within the network of Wegener's book (1915) on the origin of the continents is only 15 % (QUO % = 15); however, a value higher than that is achieved by another paper (Mason 1958) not before 1958. But Wegener's book shows a high total impact (GCS = 575). The citation impact of the book is 28 % higher than the average of all publications that contributed to the paradigm shift (GCP % = 128). Up to the early 1960s, only one other work (Du Toit 1937) had a similarly high total impact. In this connection it should be taken into account that Wegener's name is frequently mentioned in the titles of scientific papers without specific citations of Wegener's book [implicit or informal citations (Marx and Cardona 2009)].

As early as in the 1920s Irish physicist John Joly postulated a drift theory that was based on convection currents caused by the Earth's internal heat generated by radioactive decay (Joly 1923a, b, c). Still during Wegener's lifetime (Wegener died in 1930 on an expedition in Greenland), Alpine geologists Otto Ampferer and Robert Schwinner developed a theory of mountain formation that was based on convective heat transport in the Earth's interior (Ampferer 1925). In America, Reginald A. Daly (a professor at Harvard University) published *Our Mobile Earth* in 1926. Arthur Holmes of Scotland was the first earth scientist to grasp the implications of mantle convection, which was a major contribution already in the 1920s to the modern view of the mechanism of continental drift (Holmes 1928a, b, c; 1929). The close resemblance of geological phenomena and fossil plants and animals on the continents in the Southern Hemisphere led South African geologist Alexander Du Toit to accept and follow up Wegener's theory of continental drift (Du Toit 1929, 1945), and after Wegener's death Du Toit published *Our Wandering Continents* in 1937.

As Fig. 1 shows, there are hardly any connections among all of these works (except for Du Toit's book 1937) and hardly any connections with later works. The values of QUO % are correspondingly low. Total impact in GCP % is also very low. The fixist point of view blocked the formation of a theory of the Earth that could answer fundamental questions in the geosciences: how did continents and oceans, mountains and valleys, and volcanoes come into being? The theory was developed only later, starting in about 1960, in the form of the paradigm of plate tectonics.

Magnetism in ancient rocks

In the early 1950s English researcher Patrick Blackett (Imperial College London) and his student Keith Runcorn (Cambridge University and Newcastle University) (Collinson and Runcorn 2002) became interested in remanent magnetization in rock. Like little compasses, tiny crystals of ferric oxide (mainly magnetite = Fe_3O_4) in basalt are oriented in the direction of the Earth's prevailing magnetic field and remain frozen in that position after cooling. That is, remanent magnetization provides a record of the orientation of Earth's magnetic poles at the time of the rock's formation. Blackett and Runcorn discovered that the orientation of the remanent magnetization of many rocks did not correspond to the current orientation of the Earth's magnetic field (Runcorn 1955; Creer et al. 1957; Collinson and Runcorn 1960). The orientation of magnetization in dependency upon the age of rocks yielded coherent polar wandering curves. The question was now whether the Earth's magnetic poles had wandered relative to the Earth's crust or the continents had moved relative to one another.

As was soon discovered, the orientation of rocks was too varied for the entire crust of the Earth to have moved. Runcorn's studies showed that England, or Europe, and America must have changed their orientation and position relative to one another greatly (Creer et al. 1957). By the end of the 1950s at the latest, Runcorn was convinced that the paleomagnetic data was evidence of continental drift. In 1962 Runcorn published two works on convection currents as the possible mechanism of continental drift as well as a book, *Continental Drift*, summarizing the findings (Runcorn 1962a, b, c).

However, the evidence was questionable, for there was room for different interpretations. The different magnetic orientation of rocks could have other causes, such as chemical and structural changes in the time after their formation. Some rocks reversed their polarity after heating. It was therefore not certain whether the Earth's magnetic field had in fact reversed its polarity and also whether rocks in fact retained their record of the direction of the Earth's magnetic field across millions of years. There was also a certain problem of one-sidedness with the magnetic measurements: all the data came from one group of researchers and were produced using one measurement method and were all land-based.

The technical options for further verification were limited and there was still no convincing mechanism or notion of the driving force that moved the continents.

Runcorn's works on remanent magnetism (Runcorn 1955; Creer et al. 1957; Collinson and Runcorn 1960) delivered the first conclusive evidence of large horizontal movements of the Earth's crust, and Runcorn was also one of the first to suspect that the driving force was convection currents within the Earth (Runcorn 1962). But the far-reaching significance of his papers was not recognized at first, so that the research direction that Runcorn opened up (based on the magnetic direction of continental rocks) became stuck. Except for the magnetic data, there was little evidence at the time supporting continental drift. The picture was therefore not clear, and there were alternatives to the idea of continental drift.

Although without doubt groundbreaking, the total impact of Runcorn's works is low, far below the average in fact (GCP % = 16–43). His early works (Runcorn 1955; Creer et al. 1957; Collinson and Runcorn 1960) were cited by only a few subsequent papers (QUO % = 3–7) and thus have very low importance within the citation network. The same holds for his later papers (Runcorn 1962b, c). Only Runcorn's book (Runcorn 1962a) was cited by almost half of all of the subsequent works (QUO % = 40), but the total impact of the book is also below the average (GCP % = 73).

A turn to the ocean

In the early 1950s the U.S. Navy became interested in locating submarines and thus in underwater geomagnetism. British geophysicist Ronald Mason was invited to participate in a joint research expedition of Scripps Institution of Oceanography and the U.S. Navy and Atomic Energy Commission. In the summer of 1955 Mason and his assistant Arthur Raff began measuring the magnetism of the sea floor off the coast of the Pacific Northwest. To his surprise, Mason found a zebra-striped pattern, running north/south, of normal magnetism (pointing north) und magnetic anomalies of the sea floor. As was later recognized, these anomalies apparently had something to do with the magnetic reversals of the Earth's field, already known about at the time. In August 1961 Mason and Raff (both of them at the time at Scripps Institution of Oceanography) published the final map of their zebra-striped magnetic pattern (Raff and Mason 1961) (they had published initial findings in 1958). There existed no plausible explanations as to why the magnetic striping existed.

After Runcorn's land-based data, this brought the first sea-based evidence of the large-scale shifting of the Earth's crust, but it was not recognized as such and was not connected with the land data. Mason and Raff had identified patterns of magnetic anomalies that they had not looked for and could not interpret (magnetic reversal of the Earth's field had not yet been discussed). Even though their discovery was the first decisive piece of evidence of movement of the ocean floor and thus of large-scale horizontal movements, according to the AKP a key prerequisite for the scientific success of their papers was lacking: the interpretation of the data based on a satisfactory and convincingly formulated issue or theory.

As Fig. 1 shows, all three papers by Mason and Raff have relatively high importance for the works in the network: they are cited by 20–30 % of all key papers (QUO % = 20–30) and are thus quite well networked with later works. However, the overall impact of the two earlier papers (Mason 1958; Mason and Raff 1961) is below average (GCP % = 26–45). Only the slightly later work (Raff and Mason 1961) almost reaches the average across all papers, with GCP % = 77.

The formulation of the paradigm of a mobile crust of the Earth was introduced in the 1950s and is closely connected with American geologist Harry Hess (at Princeton

University). Hess used the echo sounder for scientific investigations and became amazed at the marked structuring of the ocean floor in the area of the mid-oceanic ridges (also called the mid-oceanic crests), which belong to an enormous, single, global mid-oceanic ridge system. Instead of thick sediment layers similar to those in the coastal areas, Hess found trenches and gorges covered with volcanic craters. In this area the ocean floor was apparently astonishingly young. Hess eventually found an explanation of his observations: new oceanic crust is formed continuously on either side of the mid-oceanic ridges, spreading away from the ridge in opposite directions like on two conveyor belts as it is pushed to the side by new material rising from chambers below. Hess assumed that the entire crust of the Earth moves, not just the continents, and estimated the rate of motion to be approximately the same as the rate of fingernail growth (a few centimeters per year).

As early as 1939 Hess had already speculated that the driving force of this spreading of the sea floor could be the convection cells in the Earth's mantle (considering, among other things, the discovery of sea floor gravity anomalies in Pacific deep-sea ditches by Felix Vening-Meinesz of the Netherlands). In the mid 1950s, British geophysicist Sir Edward Bullard (Cambridge University) showed that there is much higher than expected heat flow along the mid-oceanic crests (Bullard 1954; Bullard et al. 1956). Both of these points gave excellent support to Hess's model. However, the impact of Bullard's papers within the network of papers is extremely low (QUO % = 0–6). In 1944 British geologist Arthur Holmes had presented a theory of continental drift based on this mechanism in *Principles of Physical Geology*. In 1960 Hess then wrote a report based on his findings [*Report to the Office of Naval Research*; as this report was supported by contract, it did not appear in the open literature (Oreskes 2003 p. 79)]; it was published in 1961 only as a preprint and then published in 1962 as a book chapter. In the introduction Hess (1962, pp. 599–600) wrote with caution: "I shall consider this paper an essay in geopoetry. In order not to travel any further into the realm of fantasy than is absolutely necessary I shall hold as closely as possible to an uniformitarian approach". The total impact of Hess's "History of Ocean Basins" (1962) is high, and it was cited considerably more often than the average of other works in the network (GCP % = 260). More than half of the later works cited Hess's paper (QUO % = 53).

According to Hess (1962), the ocean floor does not come from volcanoes but instead is formed on a large scale and constantly at the mid-oceanic ridges (evidence: earthquakes, heat flow, central arrangement) and falls back into the deep-sea trenches. As the mechanism for this, Hess proposed convection cells in the Earth's mantle. The model explains: (1) the uniform thickness of the basalt layer under the ocean, (2) the young age of the ocean floor (thin sedimentation, few volcanoes), (3) the mountain formation; folding as a consequence of the horizontal movement, and (4) the approximate current amount of water in the seas. With the rate of formation of 1 cm per year, the sea floor would nowhere be any older than 250 million years old. This was a verifiable prediction that was later confirmed.

Independently of Hess, Robert Dietz (at Scripps Institution of Oceanography) developed a very similar model and in the title of a paper in 1961 coined the pertinent term "sea-floor spreading", which came into frequent use in the literature. The paper by Dietz (1961) was cited by only 10 % of the later works, but it also had above-average total impact (GCP % = 113).

Simplicity and elegance play an important role in the acceptance of theories. However, these features of the model initially aroused suspicion. But the ground for discussion of continental drift had been prepared once again. Hess (1962) had put forward a satisfying and elegant explanatory model for answering important fundamental questions in the geosciences. But it was still being rejected in the early 1960s by the vast majority of the community of geoscientists. This was because only relatively few independent measurements existed (only from Bullard 1954; Runcorn 1955; Bullard et al. 1956; Creer et al. 1957; Collinson and Runcorn 1960) that also pointed to large-scale movement of the Earth's crust.

Synthesis as hypothesis

One year later, British geophysicist Drummond Matthews (Cambridge University) discovered magnetic anomalies in the Indian Ocean, this time across part of a mid-oceanic ridge. In 1962 Fred Vine met Matthews, who became his PhD supervisor. After analyzing Matthew's raw data, Vine discovered a striped pattern similar to that found by Mason and Raff (1961; Mason 1958; Raff and Mason 1961). As a result of this, Vine made the crucial step, seeing a direct causal connection between the zebra-striped pattern of normal and reversed magnetism and the spreading of the sea floor: at the mid-oceanic ridges, as the rising hot magnum formed new crust and cooled, the magnetite in the rock aligned itself with the prevailing magnetic field at the time. As the crust formed and moved away from the ridges, periodic reversals in the Earth's magnetic polarity would result in just precisely this striped pattern of magnetism.

Vine had previously attended a lecture by O. J. Jones (at Cambridge University in January 1962) on the formation of the North Atlantic basin. One of the core points of the lecture was that rock from a quarry in Wales was exactly like rock from a quarry in the Appalachian Mountains. At the same conference, Vine attended a lecture by Hess, who reported on (1) findings on in his hypothesis on crustal motions, and (2) the strange striped magnetic pattern in the northeastern Pacific.

Vine now combined Hess's (1962) model of sea floor spreading with the magnetic polarity reversals: the result was the Vine–Matthews hypothesis (VMH). The VMH was based on three hypotheses, each of which was still doubted, however: remanent magnetism, geomagnetic field reversal, and sea floor spreading. In addition, the timescale of the geomagnetic reversal was still uncertain. There was also the question as to whether the different widths of the striping were caused by a non constant rate of spreading or a changing rhythm of the magnetic reversals. Vine and Matthews published their hypothesis in the fall of 1963 in *Nature*. At first, the VMH met with a low response. Later, however, as the numbers in Fig. 1 show, this paper was cited extremely frequently—both in the local and global environment (QUO % = 60, GCP % = 302). The very high interconnectedness in connection with the also high total impact indicates that the paper is one of the central works for the paradigm shift.

Canadian geophysicist Lawrence Morley (Geological Survey of Canada, Ottawa) independently arrived at the same hypothesis as Vine und Matthews (1963) (Morley referred to land-based data but also knew of Masons' sea-based data). Here, remembering the paper by Dietz (1961) played a crucial role. Morley submitted his paper to *Nature* in February 1963 and received a rejection 2 months later; the reason stated for the rejection was that the paper was too long. In April Morley submitted the paper to the *Journal of Geophysical Research* and waited a long time for an answer. In August he received a rejection letter, in which the editor wrote that an anonymous reviewer had stated: "Such speculation makes interesting talk at cocktail parties, but it is not the sort of thing that ought to be published in the *Journal of Geophysical Research*". Morley was frustrated in September when the Vine and Matthews paper (1963) came into his hands, for now he could not submit his own paper without appearing to plagiarize their work. Oreskes (2003,

p. xx) wrote: “In retrospect, the Vine and Mathews presentation was much more developed, including a sophisticated analysis of existing sea floor magnetic data”.

At almost the same time and independently of one another, Hess (and also Dietz) had combined convection in the Earth’s mantle with sea floor spreading, and Vine and Mathews (and also Morley) had combined sea floor magnetic stripes with sea floor spreading. With this, previously separate lines of research became connected in the interplay of theory and experiment. This prepared the way for fruitful discussion and the later paradigm shift. Regarding the ability for synthesis, there is a strong analogy here to Wegener: Wegener’s strength was not his profound geological knowledge but rather his scientific comprehension. Vine, too, did not need to have been a long active and experienced researcher in order to arrive at his pioneering outcome.

But the facts available were still inconsistent. The significant elements of the new theory—sea floor spreading and the global magnetic polarity reversals—were not generally recognized at the time, as they were not conclusively indisputable. And the expected symmetry of the magnetic striping on either side of the mid-oceanic ridge as the definitive evidence of continental drift (see below) had not yet been found. The majority of American scientists were supporters of fixism. Some researchers gradually began to doubt the fixist point of view, but that did not yet suffice for a change in perspectives.

Confirmation

In 1965, with no knowledge of Vine and Matthews, James Heirtzler (Lamont Geological Observatory, Columbia University) conducted aeromagnetic surveys and found a symmetrical striped pattern on either side of the mid-Atlantic ridge between England and Greenland (Heirtzler and LePichon 1965; Heirtzler et al. 1966). It is interesting that both of these papers by Heirtzler were cited more often in the local citation environment (QUO % = 83, 60) than in the global citation environment (GCP % = 34, 42). In retrospect, the same symmetrical pattern was also found in Mason and Raff’s data on the northeastern Pacific (see below).

In the meantime, magnetic polarity reversal had been proved and a geomagnetic polarity time scale (GPTS) constructed on the basis of age determination. What is more, the time sequences of spreading and polarity reversals matched astonishingly well. The time points of the reversals at different locations were in agreement and now produced a consistent picture. In 1963, determining the age of rock using the potassium-argon dating method, Cox et al. 1963 (United States Geological Survey in Menlo Park, California) constructed a polarity time scale going back ~4 million years (land-based). They named the main epochs after the pioneers of geomagnetism (Brunhes, Matuyama, Gauss, Gilbert). They called the shorter periods of several 10,000 of years to several 100,000 of years “events” and named them after the locations on land where the rock samples were found. The youngest event is the Jaramillo event, a reversal of the Earth’s magnetic field that occurred 900,000 years ago and is found worldwide as a characteristic narrow magnetic stripe.

In 1965 and 1966, the ocean floor spreading hypothesis received confirmation through another independent piece of evidence: core samples of ocean sediments, which provide a record, as a vertical pattern, of the sequence of the different magnetic polarity at different times. The horizontal and vertical magnetic patterns match exactly. Here, independently of Cox et al. (1963), the Jaramillo event was also found by Opdyke et al. (1966) (Lamont Geological Observatory, *Eltanin* mission) and by Pitman and Heirtzler (1966) (Lamont Geological Observatory). Pitman and Heirtzler’s (1966) paper in particular is very well connected with the other papers, as Fig. 1 shows. In a paper published in *Science* in 1966, Vine put all the new findings together in a convincing way. This paper—also a highly connected paper in Fig. 1—can be considered a turning point on the way to acceptance of the VMH (Anderson 1971).

In a dissertation (1965/1966) Xavier Le Pichon supported convection without sea floor spreading, although in his research area sea floor spreading was already coming to be accepted. At the time it was still dangerous for young researchers to base their careers on a new theory. But in 1968 Le Pichon wrote one of the most highly cited papers in the area of sea floor spreading, drawing upon many important works mainly from the 1960s (see Fig. 1).

Confirmation and corroboration through independent data, methods, sub-disciplines, and researchers dramatically increased the probability that continental drift was a valid theory. In this situation a sense of excitement arose, a scientific gold rush, that accelerated the development enormously. The new comprehensive theory delivered a simple and elegant explanation for the many previously unresolved basic questions in the geosciences. It answered more questions than it raised, which is very important for scientific advancement. Nevertheless, the scientific community was still opposed to it or undecided; what was missing was the final crucial step that leads to the definitive breakthrough and the establishment of a new paradigm.

Canadian geophysicist J. Tuzo Wilson (University of Toronto) had suspected that the age of the Hawaii Islands increases the further the islands are from the mid-oceanic ridge called the East Pacific Rise. A stationary hot spot produced magma that had apparently risen to produce one volcanic island after another; continuing plate movement eventually shifts the islands away from the hotspot, cutting them off from the magma source, and volcanism ceases. Wilson's hypothesis was confirmed entirely by radiometric dating of the rocks. In addition to the magnetic data, this was further, independent evidence of the spreading of the ocean floor. Wilson (a, b) published his findings in 1963 in the *Canadian Journal of Physics* and as a summary in *Nature*. Taken together, these two papers show a high degree of connection with the other key papers and also a far above-average total impact.

In the meantime, deep sea soundings had revealed that the mid-oceanic ridge was cut through with deep fracture zones. Wilson saw in these a new form of geological faults—which he called transform faults—that explain exactly what happens at the mid-oceanic ridge during seafloor spreading (Wilson 1965). Already in 1967, 2 years after the publication of Wilson's theory (1965), seismological data confirmed conclusively that the great faults in the area of the mid-oceanic ridge are transform faults as described by Wilson. Wilson was right on target for the second time.

The theory of transform faults provided further confirmation of the VMH. In the stripes of normal and reversed polarity in the maps and magnetic surveys by Mason and Raff, Wilson identified an oceanic ridge off Vancouver Island from which the sea floor spread in either direction. His concept of the transform faults had predicted the existence of a ridge in this location. Wilson named it the Juan de Fuca Ridge (Wilson 1965). This paper delivered crucial pieces of evidence providing a firm foundation for the VMH. Wilson's paper (1965) is one of the works in Fig. 1 with the highest impact, both regarding the works within the network (QUO % = 100) and also with regard to the total impact (GCP % = 273). Thus, also the bibliometric data substantiates and quantifies the tremendous importance of Wilson's work in connection with the paradigm shift from fixism to plate tectonics.

Wilson delivered new evidence, completely independently of the magnetic data, and expanded the scope of the theory considerably. Land and sea-based data now fit together without any problems. Together with the magnetic surveys, the findings from volcanism in connection with the age determination as well as the supported model of the transform faults yielded a comprehensive picture. Vine and Wilson published a model of sea floor spreading in the north Pacific in October of 1965. Already in 1963 Wilson had also brought the convection currents into it (Vine and Wilson 1965), and in 1966 Wilson discussed the history of the development of the Atlantic. Walter Elsaesser (1971) played a significant role in the further clarification of the connection between convection and sea floor spreading.

This put the mid-oceanic ridges and trenches spanning the oceans in a different light. When Wilson published his paper on transform faults in 1965, he was the first to call the masses of rock moving in relation to one another and meeting at boundaries “plates”. Wilson divided the Earth’s surface into at the minimum six large and several smaller movable plates, which are kept in motion by the convection currents in the Earth’s mantle. It was in this paper (Wilson 1965) that the new paradigm got a new and easy to remember name. Wilson became the father of plate tectonics.

Over geological periods of time, the rock of the plates behaves like thick syrup; it is soft but not quite melted. Changes occur along the mid-oceanic ridges and trenches, while the inner areas of the plates remain undisturbed. The lighter continents ride on top of these plates. When two plates crash together, one plate is pushed below the other into the mantle and is melted. When a continent lies at the margin of a melting zone, mountains are pushed up. The engine of these movements are enormous convection currents in the Earth’s mantle in the form of rotational movements, which are driven by the heat generated from the radioactive decay of unstable elements deep in the Earth’s interior.

The papers in Fig. 1 starting in 1962 (relatively many of them by Wilson) make up the main phase in the development of the paradigm shift; they contain the main prerequisites for the last crucial step that leads to the definitive breakthrough. Among these papers there is mostly a very high interconnectedness—that is, these works refer to many previous papers in the network and are cited frequently by papers that followed (see the high QUO % values). The GCS % values are mostly high or even far above average.

The shift to the plate tectonics paradigm did not occur due to one paper or one person at a specific point in time but instead over the course of a long process and at first in different lines of research (quite similar to the development of the Big Bang theory in modern cosmology (Marx and Bornmann 2010)). The paradigm shift could only take place after all essential prerequisites were given. Due to the long and complex prehistory, which following Kuhn (1962) can be called a phase of normal science (up to 1962), and its great importance for the paradigm shift, we can not only focus on the main phase starting in 1962 but also must view the two phases in close connection. In the phase up to the end of the 1950s, serious doubts about fixism had already been raised. Then in the early 1960s, extraordinary science was conducted, and in this phase the new paradigm emerged in the geosciences and replaced the old paradigm.

Final breakthrough

After the Second World War, seismology was promoted, as it was important for the monitoring of atomic test ban treaties. And so it was not long before extensive testing of the plate tectonics paradigm was conducted. It was soon shown that (as expected) the earthquake zones are concentrated along the seams of the Earth’s mantle, which provided final and convincing evidence for the new paradigm. Three American seismologists (Bryan Isacks, Jack Oliver, and Lynn R. Sykes) published a summary of findings in 1968, in which plate tectonics and seismology became joined in marriage, so to speak. As Fig. 1 shows, this paper cites very many previous works in the network, and it has a far above-average total impact. However, the absolute number of citations received in the network (LCS_o) by this and also the other, later papers is low, as with time (that is, towards the bottom of the figure), there are fewer and fewer potential citing papers. About 2 years after publication of the paper by Isacks et al. (1968) the term subduction was coined. Subduction refers to the process by which one plate is forced to slide under the other plate when two plate boundaries collide. Here, as one plate sinks into the Earth's mantle and melts, crust is destroyed and recycled back into the interior of the Earth, offsetting the material rising at the mid-oceanic ridges.

Seismology delivered further independent evidence and expanded the scope of the paradigm. For the first time, there was a complete picture of the processes and forces shaping the earth. Putting seismology together with the geophysical sub-disciplines previously important for the new model brought about the final, definitive, and irrefutable establishment of plate tectonics. One could not expect to find more and better evidence to support the new paradigm. And with this, all prerequisites for paradigm shift as outlined by the AKP were fulfilled.

If we consider 1965 to be the year in which plate tectonics was born [when Wilson coined the term "plates" Wilson (1965)], then it took at least another 2 years for the paradigm shift to be completed and for plate tectonics to become accepted by the research community. In the interplay of theory and experiment, which marks the advancement of knowledge in the natural sciences, what ultimately matters is clear and convincing proof. Once there was proof, in the form of paleomagnetic and seismological data in connection with age determination, the majority of scientists accepted the new paradigm in an astonishingly short time: "In 1930 perhaps 2 % of all geologists believed in continental drift; by 1967 the figure was more like 50 %, with more converts joining every day" (Anderson 1971, p. 154); "Despite the flurry of new finds during the early and mid-1960's, most people knew virtually nothing of what was happening. Not until the end of the decade did the enormousness of what was happening begin to filter through to the general public" (Anderson 1971, p. 181).

Although many researchers took part in collecting the data that delivered the most important pieces of the mosaic for the new paradigm, the crucial concepts came from a modest number of researchers. In their accounts, the crucial prerequisites for the paradigm shift were the good scientific supervision, the enthusiastic work environments at Cambridge University and Princeton University, and not least the overarching, wider interests of the successful participants. However, as many of the researchers were not equally well-versed in geology and physics and viewed the connections from too narrow a perspective, some decisive publications were at first hardly noted: "The many other disciplines properly associated with the study of the earth—geomagnetism, seismology, petrology, geophysics—had always been fragmented. The new theory of continental drift has brought them together" (Anderson 1971, p. 187).

Working independently, McKenzie and Parker (1967) (at Scripps Institution) and Morgan (1968) (at Princeton University) developed a plate tectonic model based on geometry in 1967/1968. Both papers have a far above-average impact in the local and global environment. McKenzie (Oreskes 2003, p. 169) wrote later: "But this sociological side of scientific discovery has (rightly) become recognized as of great importance by those, such as Thomas Kuhn, who write about the history of science, even though the formalism that they have generated seems to me at least strange and somewhat artificial." The expeditions of the research ship *Glomar Challenger* starting in 1968 securely established the evidence from drilling core samples conclusively and irrefutably. During expedition Leg 3, from Dakar to Rio de Janeiro, the age profile of the ocean floor along the Mid-Atlantic Ridge was determined systematically and fully using core samples. The results showed that the age of the sea floor increased symmetrically with distance away from the ridge to the west and east, in the expected manner: "It's fortunate that the project came just now because we are riding the crest of a breaking wave. The events which led up to it happened over a century, but the crest has formed in the last 4 or 5 years" (Anderson 1971, p. 169; here Anderson quotes Melvin Peterson at Scripps).

Discussion

The metaphor of science (and technology) mapping has been used for quite different concepts: co-word analysis, co-citation analysis, and historiography. Callon et al. (1986) can be seen as one of the founders of the co-word method based on text analysis. He coined terms like "actor-net" or "actor-world" as part of his theoretical vocabulary and established co-word maps. Small (1973) introduced the concept of co-citation analysis based on previews work on bibliographic coupling. Co-citation occurs when two works reference a common third work in their bibliographies. Based on co-citation analysis the concept of research fronts emerged and in 1980 the ISI (Institute for Scientific Information, Philadelphia) published the ISI Atlas of Science (Garfield 1981). This Atlas contained cluster maps showing the connectedness among core papers of given sub-specialties. The distance between the papers is inversely proportional to their co-citation strength. The historiography enabled by the HistCite software is a completely different approach of mapping. In contrast to the methods of co-word and the co-citation analysis, HistCite based maps reveal the citation network of the key publications most important for a given research topic. Once these basic structural elements (papers and books) of the topic are identified, they are presented graphically as an interconnected historiograph: a chronologic map or flow diagram which identifies both the bibliographic antecedents and descendents of its principal papers and authors (Garfield et al. 2003).

In this paper we followed two different aims. For one, we wanted to refine the method of historiography, so as to investigate scientific progress that can be called a scientific revolution following Kuhn (1962), empirically—based on publication and citation data. Previously we published a first bibliometric and history of science study on cosmology (Marx and Bornmann 2010), in which we examined the paradigm shift from a static to a dynamic universe. In this study, as a further example, we chose plate tectonics, because it has often been discussed in connection with the theory of paradigm shift. For instance, Peter Molnar, a geophysicist, wrote (Oreskes 2003, p. 325): "Plate Tectonics was a revolution less because it guillotined existing fixed ideas, and more because it affected the way earth scientists approach the study of the earth. Its impact has been both more gradual and more subtle than most active scientists realized at the time." In a paper titles, "What kind of revolution occurred in geology?," Michael Ruse stated (1978, p. 259): "My claim is that the revolution in geology was less abrupt than a Kuhnian would have it; more so than an evolutionist would have it … I may have highlighted a few of the salient features of the geological revolution and perhaps have pointed in the direction of finding an acceptable philosophical analysis".

On the basis of a historiograph, we showed that the entire network of papers that were decisive for the paradigm shift was published over the course of a century. But the main occurrences are concentrated in the 1960s and 1970s. The very early works are connected with the later, most decisive papers, whereby mainly two books, by Wegener (1915) and Du Toit (1937), played an important role in the later research. The high interconnectedness of the papers by Hess (1962) on sea floor spreading, by Vine and Matthews (1963) on the VMH, and by Wilson (1963) on the age of the Hawaiian Islands and on the transform faults Wilson (1965) with introduction of the term "plate tectonics" indicates that they had a central role in the paradigm shift from fixism to plate tectonics. The phase prior to the paradigm shift, during which these papers were published, could also be called Armageddon in the geosciences. According to the Book of Revelations in the Bible, Armageddon is the (symbolic) site of a battle during the end times before the beginning of a new world. In the geosciences, it was the last great debate, in which extraordinary science was conducted and in which it was decided that the new paradigm would gain acceptance, replacing the old. With the papers by Le Pichon (1968) and Isacks et al. (1968), the debate was concluded and the new paradigm established once and for all: the papers not only fully confirmed plate tectonics based on seismology but also contained a summary of many central, earlier works in the network.

In addition to refining the bibliometric methods, we also aimed to examine the AKP, an extension of Kuhn's (1962) theory that we proposed (Bornmann and Marx 2012), taking a concrete example from science. Looking at the geosciences, we showed that a scientific revolution becomes highly likely only once certain prerequisites (see introduction above) are fulfilled. For the paradigm shift in the geosciences, there were many starts and attempts and various lines of research that were brought together step by step. The initial starts (forerunners) were not taken up by the scientific community at first, since, for one, the consequences for the foundations of the geosciences were far-reaching and revolutionary, and, for another, the indications stood on shaky ground. It took the courage of unbiased, young researchers and support from some older leading figures in the geosciences (such as Bullard, Hess, and Matthews) to get broad discussion of the existing and the new paradigms going. The fragmentation of fields in the geosciences made it difficult to be aware of all of the relevant factors that spoke for the new paradigm. There were too few researchers working across the sub-disciplines or having overarching interests. It took a critical mass of convincing data in combination with the synthesis of the pieces in a satisfactory overall picture, which was finally accepted by the scientific community in the geosciences.

We attempted to trace this overall picture on the basis of bibliometrics and the AKP. With this, we brought a pattern into a number of events that were often neither planned nor foreseeable. In retrospect, paths that the paradigm shift took from fixism to plate tectonics can be reconstructed, but in the events of the time these paths were hardly foreseeable, and they probably often resulted by chance. Merton and Barber (1958) coined the term "serendipity" to describe this familiar phenomenon of accidental discovery. The discovery of the magnetic striping by Mason and Raff (1961; Mason 1958; Raff and Mason 1961) was unexpected. No one had been looking systematically for the striped pattern in connection with the discussion on whether the Earth's crust was fixed or moving. And the impetus from Hess and Vine pointing towards the connection between the convection in the Earth's mantle (Hess), the magnetic striping (Vine) and the spreading of the sea floor resulted from chance encounters at various conferences. But the coincidences happened, and it then took open-mindedness in the face of the unexpected. There is an old saying the lucky coincidences come to those who work hard. Science cannot be planned down to the last detail, but it also does not advance purely by chance. The knowledge gained arises in the interplay of hypothesis/theory and experiment. The individual events in the course of this process are not foreseeable but are not by chance in the sense that any other constellation of the circumstances would also have been conceivable and would have led to the same success.

This study thus has importance not only for bibliometrics and history of science but also has implications for science policy: science requires a certain amount of freedom so as to provide room for accidental discoveries.

References

Ampferer, O. (1925). On continental drift. *Naturwissenschaften, 13*, 669–675.

Anderson, A.H. (1971). *The drifting continents.* New York: G. P. Putman's Sons. ISBN: 3-7653-0263-5.

Bornmann, L., & Marx, W. (2012). The Anna Karenina principle: A way of thinking about success in science (in press). *Journal of the American Society of Information Science and Technology* (to be published).

Bullard, E. (1954). The flow of heat through the floor of the Atlantic Ocean. *Proceedings of the Royal Society of London A, 222*(1150), 408–429.

Bullard, E. C., & Day, A. (1961). The flow of heat through the floor of the Atlantic Ocean. *Geophysical Journal of the Royal Astronomical Society, 4*, 282–292.

Bullard, E. C., Maxwell, A. E., & Revelle, R. (1956). Heat flow through deep sea floor. In: *Advances in Geophysics 3*, 153–181.

Callon, M., Law, J., & Rip, A. (Eds.). (1986). *Mapping the dynamics of science and technology: Sociology of science in the real world*. London: MacMillan Press.

Collinson, D. W., & Runcorn, S. K. (1960). Polar wandering and continental drift—evidence from paleomagnetic observations in the United States. *Bulletin of the Geological Society of America, 71*(7), 915–958.

Collinson, D. W., & Runcorn, S. K. (2002). *Biographical memoirs of fellows of the Royal Society, 48*, 391–403.

Cox, A., Doell, R. R., & Dalrymple, G. B. (1963). Geomagnetic polarity epochs and pleistocene geochronometry. *Nature, 198*(488), 1049–1051.

Creer, K. M., Irving, E., & Runcorn, S. K. (1957). Geophysical interpretation of paleomagnetic directions from Great-Britain. *Philosophical Transactions of the Royal Society of London A, 250*(974), 144–156.

Daly, R. A. (1926). *Our mobile earth*. New York: Charles Scribner's Sons.

Dietz, R. S. (1961). Continent and ocean basin evolution by spreading of the sea floor. *Nature, 190*(477), 854–857.

Du Toit, A. L. (1929). The continental displacement hypothesis as viewed. *American Journal of Science, 17*(98), 179–183.

Du Toit, A. L. (1937). *Our wandering continents—an hypothesis of continental drifting*. London: Oliver & Boyd.

Du Toit, A. L. (1945). Further remarks on continental drift—discussion. *American Journal of Science, 243*(7), 404–408.

Elsaesser, W. M. (1971). Sea-floor spreading as thermal convection. *Journal of Geophysical Research, 76*(5), 1101–1112.

Frisch, W., & Meschede, M. (2005). *Plattentektonik—Kontinentalverschiebung und Gebirgsbildung*. Darmstadt: Wissenschaftliche Buchgesellschaft. ISBN 3-534-15834-2.

Garfield, E. (1975). The 'Obliteration phenomenon' in science—and the advantage of being obliterated! *Current Contents, 51*(52), 5–7.

Garfield, E. (1981). Introducing the ISI Atlas of Science: Biochemistry and Molecular Biology, 1978/80. *Current Contents, 42*, 279–287.

Garfield, E. (2004). Historiographic mapping of knowledge domains literature. *Journal of Information Science, 30*(2), 119–145.

Garfield, E. (2009). From the science of science to scientometrics: Visualizing the history of science with HistCite software. *Journal of Informetrics, 3*(3), 173–179.

Garfield, E., Pudovkin, A. I., & Istomin, V. S. (2003). Why do we need algorithmic historiography? *Journal of the American Society for Information Science and Technology, 54*(5), 400–412.

Gaskell, T. F., et al. (1961). The structure of the ocean floor. *Geophysical Journal of the Royal Astronomical Society, 5*(1), 80–84.

Hapgood, C. (1958). *Earth's shifting crust: A key to some basic problems of earth science*. New York: Pantheon Books.

Heirtzler, J. R., & LePichon, X. (1965). Crustal structure of mid-ocean ridges, 3. Magnetic anomalies over mid-Atlantic ridge. *Journal of Geophysical Research, 70*(16), 4013–4033.

Heirtzler, J. R., LePichon, X., & Barron, J. G. (1966). Magnetic anomalies over the Reykjanes ridge. *Deep Sea Research, 13*, 427–432.

Hess, H. H. (1962). History of ocean basins (p. 599–620). In: *Petrologic studies*: *a volume in Honor of A. F. Buddington*. Boulder: Geological Society of America.

Holmes, A. (1928a). Radioactivity and continental drift. *Geological Magazine, 65*, 236–238.

Holmes, A. (1928b). Continental drift. *Nature, I22*, 431–433.

Holmes, A. (1928c). Radioactivity and earth movements. *Transactions of the Geological Society of Glasgow, 18*, 559–606.

Holmes, A. (1929). A review of the continental drift hypothesis. *Minaral/Mining Magazine 40*, 205–209, 286–288, 340–347.

Holmes, A. (1944). *Principles of physical geology*. London: Nelson and Sons.

http://garfield.library.upenn.edu/algorithmichistoriographyhistcite.html.

http://scientific.thomsonreuters.com/products/wos/.

Isacks, B., Oliver, J., & Sykes, L. R. (1968). Seismology and new global tectonics. *Journal of Geophysical Research, 73*(18), 5855–5899.

Joly, J. (1923a). The surface movements of the earth's crust. *Nature, 111*, 603–606.

Joly, J. (1923b). The movements of the earth's surface crust. *Philosophical Magazine, 45*(270), 1167–1188.

Joly, J. (1923c). Movements of the earth's surface crust, II. *Philosophical Magazine, 46*(271), 170–176.

Kragh, H. (1987). *An introduction to the historiography of science*. Cambridge: Cambridge University Press.

Kuhn, T. S. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Kuhn, T. S. (1977). *Die Entstehung des Neuen—Studien zur Struktur der Wissenschaftsgeschichte*. Hrsg. von Lorenz Krüger. Suhrkamp Taschenbuch Wissenschaft, Suhrkamp Verlag, Frankfurt. ISBN: 3-518-07447-4.

Le Pichon, X. (1968). Sea-floor spreading and continental drift. *Journal of Geophysical Research, 73*(12), 3661–3697.

Marx, W. (2011). Special features of historical papers from the viewpoint of bibliometrics. *Journal of the American Society for Information Science and Technology, 62*(3), 433–439.

Marx, W., & Bornmann, L. (2010). How accurately does Thomas Kuhn's model of paradigm change describe the transition from a static to a dynamic universe in cosmology? A historical reconstruction and citation analysis. *Scientometrics, 84*(2), 441–464.

Marx, W., Bornmann, L., & Cardona, M. (2010). Reference standards and reference multipliers for the comparison of the citation impact of papers published in different time periods. *Journal of the American Society for Information Science and Technology, 61*(10), 2061–2069.

Marx, W., & Cardona, M. (2009). The citation impact outside references—formal versus informal citations. *Scientometrics, 80*(1), 1–21.

Mason, R. G. (1958). A magnetic survey off the west coast of the United States between latitudes 32-degrees-N and 36-degrees-N, longitudes 121-degrees-W and 128-degrees-W. *Geophysical Journal of the Royal Astronomical Society, 1*(4), 320–329.

Mason, R. G., & Raff, A. D. (1961). Magnetic survey off the west coast of North America, 32-degrees-N latitude to 42-degrees-N latitude. *Geological Society of America Bulletin, 72*(8), 1259–1266.

McKenzie, D. P., & Parker, R. L. (1967). North Pacific—an example of tectonics on a sphere. *Nature, 216*(5122), 1276–1280.

Merton, R. K. (1965). *On the shoulders of giants*. New York: Free Press.

Merton, R. K., & Barber, E. G. (1958). *The travels and adventures of serendipity: A study in historical semantics and the sociology of science*. Princeton: Princeton University Press.

Morgan, W. J. (1968). Rises, trenches, great faults, and crustal blocks. *Journal of Geophysical Research, 73*(6), 1959–1982.

Morgan, W. J. (1971). Convection plumes in lower mantle. *Nature, 230*(5288), 42–43.

Opdyke, N. D., et al. (1966). Paleomagnetic study of Antarctic deep-sea cores. *Science, 154*(3747), 349–357.

Oreskes, N. (Ed.). (2003). *Plate Tectonics—an insider's history of the modern theory of the earth*. Cambridge, MA: Westview Press. ISBN 0-8133-4132-9.

Pitman, W. C., & Heirtzler, J. R. (1966). Magnetic anomalies over Pacific-Antarctic ridge. *Science, 154*(3753), 1164–1166.

Raff, A. D., & Mason, R. G. (1961). Magnetic survey off the west coast of North America, 40-degrees-N latitude to 52-degrees-N latitude. *Geological Society of America Bulletin, 72*(8), 1267–1271.

Runcorn, S. K. (1955). Rock magnetism—geophysical aspects. *Advances in Physics, 4*(14), 244–291.

Runcorn, S. K. (1962a). *Continental drift*. New York: Academic Press.

Runcorn, S. K. (1962b). Towards a theory of continental drift. *Nature, 193*(4813), 311–314.

Runcorn, S. K. (1962c). Convection currents in the earth's mantle. *Nature, 195*(4848), 1248–1249.

Ruse, M. (1978). What kind of revolution occurred in geology? *PSA*: *Proceedings of the Biennial Meeting of the Philosophy of Science Association*, pp. 240–273.
Scharnhorst, A., & Garfield, E. (2010). Tracing scientific influence. http://arxiv.org/abs/1010.3525v1.
Šešelja, D., & Weber, E. (2012). Rationality and irrationality in the history of continental drift: Was the hypothesis of continental drift worthy of pursuit? *Studies In History and Philosophy of Science A, 43*(1), 147–159.
Small, H. G. (1973). Co-citation in the scientific literature: A new measure of the relationship between two documents. *Journal of the American Society for Information Science, 24*, 265–269.
Small, H. (2003). Paradigms, citations, and maps of science: A personal history. *Journal of the American Society for Information Science and Technology, 54*(5), 394–399.
Stewart, J. A. (1990). *Drifting continents & colliding paradigms: Perspectives on the geoscience revolution*. Bloomington: Indiana University Press.
Suess, E., & Waagen, L. (1883–1901). *Das Antlitz der Erde* (Vol. 3, Vol. 3:2 parts). Tempsky, VF., Wien, SE. (1904–1924). *The face of the earth* (Vol. 5). Oxford: Clarendon Press. Suess, E. (1918). *La face de la terre*. A. Colin, Paris.
Tabah, A. N. (1999). Literature dynamics: Studies on growth, diffusion, and epidemics. *Annual Review of Information Science and Technology, 34*, 249–286.
Taylor, F. (1910). Bearing of the tertiary mountain belt on origin of the earth's plan. *Bulletin of the Geological Society of America, 21*, 179–226.
Vine, F. J. (1966). Spreading of ocean floor—new evidence. *Science, 154*(3755), 1405–1415.
Vine, F. J., & Matthews, D. H. (1963). Magnetic anomalies over ocean ridges. *Nature, 199*(489), 947–949.
Vine, F. J., & Wilson, J. T. (1965). Magnetic anomalies over a young ocean ridge off Vancouver Island. *Science, 150*(3695), 485–489.
Wegener, A. (1912a). Die Entstehung der Kontinente. *Geologische Rundschau, 3*, 276–292.
Wegener, A. (1912b). Die Entstehung der Kontinente. *Petermanns Geographische Mitteilungen 58*, 185–195, 253–256, 305–309.
Wegener, A. (1915). *Die Entstehung der Kontinente und Ozeane*. Braunschweig: Vieweg Verlag.
Wilson, J. T. (1963a). A possible origin of Hawaiian Islands. *Canadian Journal of Physics, 41*(6), 863–870.
Wilson, J. T. (1963b). Evidence from islands on spreading of ocean floors. *Nature, 197*(486), 536–538.
Wilson, J. T. (1963c). Hypothesis of earth's behaviour. *Nature, 198*(488), 925–929.
Wilson, J. T. (1965a). A new class of faults and their bearing on continental drift. *Nature, 207*(4995), 343–347.
Wilson, J. T. (1965b). Convection currents and continental drift-13. Evidence from ocean islands suggesting movement in earth. *Philosophical Transactions of the Royal Society of London A, 258*(1088), 145–167.
Wilson, J. T. (1966). Did Atlantic close and then re-open? *Nature, 211*(5050), 676–681.