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Analysis of paleomagnetic data: a tribute to Hans Zijderveld. Introduction

M.J. Dekkers[1], C.G. Langereis[1] & R. Van der Voo[2]
[1]*Paleomagnetic Laboratory 'Fort Hoofddijk', Faculty of Earth Sciences, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, the Netherlands;* [2]*Department of Geological Sciences, the University of Michigan, AnnArbor, MI 48109-1063, USA*

Introduction

This special issue of 'Geologie en Mijnbouw' is dedicated to Professor Hans Zijderveld, head of the paleomagnetic laboratory 'Fort Hoofddijk' of Utrecht University until March 1995. Hans was among the founders of this laboratory and he guided the paleomagnetic group at Utrecht throughout his career. The value of his many contributions to the field of paleomagnetism are best seen in the perspective of the development of paleomagnetism, which will be presented first.

Early developments in rock, paleo- and marine magnetism

In the early fifties, paleomagnetism emerged as a new and important discipline in the Earth Sciences because sensitive magnetometers became available. These astatic instruments enabled the measurement of the remanent magnetization of a number of rock types, especially volcanic rocks and red beds. In particular, Blackett's astatic magnetometer must be mentioned. Drawing upon work of Schuster, Sutherland and Wilson, Prof. Blackett (1947) argued for a theory, based on the magnetic fields of the Earth, Sun and the star 78 Virginis, that magnetism was an inherent property of massive rotating bodies. His hypothesis implied that a magnetic field generated by such a body would increase with distance away from its center. By performing magnetic field measurements in mines, Runcorn et al. (1951) showed that Blackett's hypothesis was untenable, at least for the field of the Earth.

However, wishing to test his hypothesis also by measuring the magnetic effects of a spinning body, Blackett had worked on the construction of a quite sensitive astatic magnetometer. According to his theory, a gold sphere of 10 cm diameter at rest with respect to the measuring system (thus rotating with the Earth), should produce a field of approximately 10^{-8} Gauss, but no magnetometer in those days could measure, even within several orders of magnitude, such a small field. Blackett (1952) described the design of his magnetometer that could reliably measure small magnetic fields (10^{-9} to 10^{-10} Gauss) but also had to report that the gold sphere did not produce any field. Clearly the hypothesis was to be abandoned, but Blackett realized that his instrument was well suited for the measurement of the weak remanent magnetization of rock samples and he made his instrument available for this purpose.

With this instrument or simplified copies, and with rudimentary versions of spinner magnetometers, it was soon discovered that some 'old' rocks, but certainly not all, had paleomagnetic directions oblique to the north. For a single locality this could be explained by movement of the magnetic pole with respect to the whole Earth (nowadays called 'true polar wander'). However, the magnetic poles of coeval rocks from different continents were found to be located at different spots on the globe implying several 'North poles' for the same period. This extremely enigmatic result called for a method to assess the statistical significance of comparisons between two or more sets of directions measured at different places. The spherical statistics developed by Fisher (1953) provided a way to compare directions measured in sets of rock samples and to put confidence limits around calculated means.

It quickly became common practice in paleomagnetism to use Fisher statistics, with the important outcome that coeval rocks from different continents had magnetic poles that were significantly different if the continents were kept in their current position. However, when the positions of the continents were restored according to Wegener's hypothesis of continental drift, they would yield a single magnetic pole. In retrospect, this confirmation of continental movements with respect to the Earth's rotation axis ('apparent polar wander') and with respect to each other, may now seem old hat to every earth sciences student, but in the early to mid-fifties this idea was not at all accepted; it was thought that this simply could not be true, although the fits were gradually supported better and better by independent climatic and geological information. Paleomagnetism gained enormous momentum after the publication of the articles by Runcorn (1956) and Irving (1956), which showed that the fit of Europe and North America after closure of the Atlantic Ocean was supported by their apparent polar wander paths, indicating that Wegener's hypothesis of continental drift had to be fact rather than fiction. This bewildered the scientists with fixist views in those days, as the drifting of continents was far beyond any geotectonic concept then accepted, mainly because a mechanism was lacking for 'rafting' continents through solid ocean floor. As a result, the scientific community was reluctant to accept the outcome of paleomagnetic research initially. But things were afoot in a different branch of geomagnetism, involving better definitions of normal and reversed periods of the geomagnetic field. The historical paper of Vine & Matthews (1963) in 'Nature' could thus argue for seafloor spreading to explain the symmetric pattern of magnetic anomalies centered around mid-ocean ridges, by calling upon the now better understood geomagnetic reversal patterns recorded sequentially in ocean-floor basalts. Even though this now provided a mechanism (or at least plausible kinematics) for continental drift, the community was slow to accept the theory of Wegener. Finally, however, continental drift and seafloor spreading were put together, and the concept of plate tectonics, the cornerstone of modern earth sciences, was developed. Plate tectonics became increasingly accepted from the mid-sixties onward, reaching nearly full acceptance as the basis for earth sciences in the early seventies. Readers interested in these early days may wish to consult Irving (1988) and LeGrand (1988), who give excellent accounts of the paleomagnetic and marine magnetic confirmations of continental drift in the fifties and early sixties. In addition, Frankel's review (1988) of how seafloor spreading and continental drift were put together to form the concept of plate tectonics is fascinating reading. A special issue of 'Scientific American' (1991) on science in the 20^{th} century ranked plate tectonics among the five greatest scientific breakthroughs of this century, together with the structure of matter, the expanding universe, the discovery of the molecules of life, and the physics of computing and communications.

The intriguing possibility that the continents had drifted, and that paleomagnetism could detect and quantify the movements, led many universities and governmental research organizations to set up paleomagnetic laboratories from the mid-fifties onward. The Netherlands were involved from the beginning. Profs. Van Bemmelen and Nieuwenkamp (Utrecht University, structural geology and mineralogy, respectively), suggested to Jan Hospers, then a graduate student from Groningen University, that he join a British expedition to Iceland in 1950 where he sampled sequences of lava flows for the measurement of remanent magnetization. He returned to Iceland in 1951 and 1952 for further collection of samples and showed that the geomagnetic field was axial irrespective of its sign. He advocated field-reversals which had until then been believed to be artifacts (Hospers 1953, 1954). Hospers measured his rock samples in the United Kingdom in close cooperation with Prof. Runcorn, who later in 1970 became 'doctor honoris causa' of Utrecht University for his outstanding contributions to the fields of geomagnetism and paleomagnetism.

Zijderveld's influence in paleomagnetism and tectonics at Utrecht University (1957–1980)

Jan Veldkamp, professor of geophysics, got together with Martin Rutten, professor of geology, in the late 1950s, to decide that Utrecht University should also have a paleomagnetic laboratory and they appointed Jo As and Hans Zijderveld as scientific assistents. Zijderveld, who had finished his MSc studies at Utrecht University, was about to leave for Canada to assume a position in an ore-prospecting company, when he was offered the job as daily manager of the laboratory. As we all know, he took the job. The laboratory was first housed at the Royal Netherlands Meteorological Institute in De Bilt. An important accomplishment in the early days was the paper by As & Zijderveld (1958) on the necessity of progressive stepwise demagnetization to reduce the scatter in paleomagnetic data. Rocks were as a rule not demagnetized at that time. Néel (1949) showed that for single-domain (SD) grains the relaxation time, a measure of (paleo)magnetic stability, is related to their volume. He termed grains with short relaxation times 'magnetically viscous', meaning that they easily and continuously align their magnetization direction according to the present-day direction of the geomagnetic field. Such viscous grains contaminate the 'old' or primary natural remanent magnetization (NRM) of rocks which contain grains with a continuum of relaxation times. As & Zijderveld (1958) showed that alternating-field demagnetization was effective in removing present-day field overprints from the original NRM signal, thus providing the early foundation for reliable determinations of ancient magnetic field directions and paleopole positions.

From 1962 onward, the paleomagnetic laboratory has been housed in 'Fort Hoofddijk', today located in the middle of the Utrecht University campus east of the city. The 'Fort Hoofddijk' building is inside the botanical gardens of the university. It is the oldest building of this campus, as well as the first building to be arranged as a laboratory. 'Fort Hoofddijk' is an old military fortress, built in 1879, which belonged to the 'Nieuwe Hollandse Waterlinie', a defense line designed in mid-19th century to protect the western part of the Netherlands from military invasion. Protection would be created by the flooding of a strip of land between the Rhine river and Amsterdam. The elevation of the city of Utrecht is too high to be flooded, but it could be protected by a ring of approximately 15 fortresses on its eastern side. The 'waterlinie' (water defense line) was never used for military purposes, because the arrival of airplanes made this static strategic concept outdated. 'Fort Hoofddijk' is very appropriate for magnetic measurements of rocks, because no iron was used in its construction. This guarantees a quiet ambient magnetic field only subject to natural variations, essential to high-quality data acquired by means of astatic magnetometers. Even today, when astatic magnetometers are no longer used, a quiet ambient magnetic field is an important asset.

In the sixties, the main research goal of the paleomagnetic laboratory was to provide quantitative data on the wandering of continents throughout geological time, providing paleogeographic reconstructions and analyses of global plate movements. Zijderveld was heavily involved in supervising a series of MSc and PhD theses, with the unfortunate result that he could hardly find time to work on his own PhD dissertation. However, his thesis, entitled 'Paleomagnetism of the Esterel rocks' was finally finished in 1975. In the department of geology, Wensink also carried out paleomagnetic research sharing students and working together with Zijderveld. The PhD theses produced at the paleomagnetic laboratory are listed in the Appendix.

Zijderveld was particularly dedicated to improve (and document) the quality of the demagnetization data produced in his laboratory. In 1967, he described a method to analyse demagnetization diagrams, which takes into account the intensity information in addition to the directional information (Zijderveld 1967). This method consists of an orthogonal projection of the vector endpoints of each demagnetization level onto the horizontal and vertical planes, either N-S or E-W directed (Figure 1). This projection technique provides a much better visualization of the paleomagnetic directions, and allows a better estimate of their quality, than could be achieved with the more conventional stereographic projections. Orthogonal demagnetisation diagrams now are often referred to as 'Zijderveld diagrams'. His classic 1967 paper 'AC demagnetization of rocks: Analysis of results' is one of the most frequently cited articles in paleomagnetism; a survey of the science citation index (available in Utrecht on line from 1992 onward) indicates 219 citations (including only 8 'self-citations') for the period 1992–1996.

Tectonic paleomagnetic studies were initially concentrated on Italy and the Iberian peninsula, not in the least because Profs. Rutten and Van Bemmelen, who directed many geological mapping projects of PhD students in these areas, urged every one of them to collect paleomagnetic samples. This fortuitous synergism led to the discovery of deviating declinations in these areas, different from what would be predicted if the areas had always belonged to 'Stable Europe'. The article by Zijderveld & Van der Voo (1973), describing the rotations with respect to stable Europe of Iberia, Corsica, Sardinia and the Southern Alps in Italy, summarizes this pioneering type of work and introduced the concept of microplates.

Subsequent work logically extended the geographic coverage farther east through the Alpine Mediterranean-Iranian-Himalayan-Indonesian orogenic system, leading to many publications of Fort Hoofddijk students and staff (e.g. Gregor, Klootwijk, VandenBerg, Van der Voo, Van Dongen, Wensink and Zijderveld).

New directions for Zijderveld's group: rock magnetism and magnetostratigraphy (1980–1997)

Until the mid seventies the research emphasis had remained focused on tectonic paleomagnetism. Zijderveld recognized, however, that the ancient NRM component appeared to post-date the age of the rock

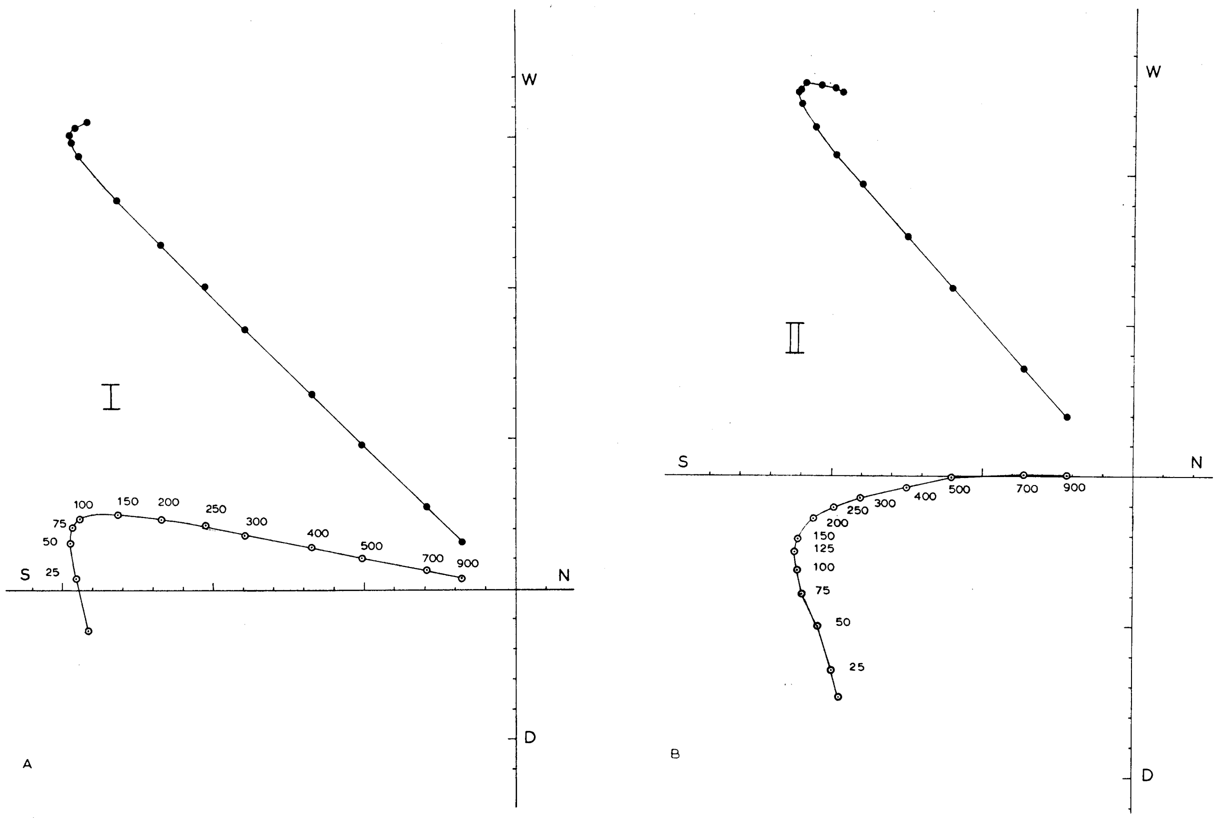

Figure 1. Examples of progressive demagnetization diagrams or ‘Zijderveld diagrams’ of two Permian basalt flows from a single outcrop in the Esterel before tectonic correction (from Zijderveld 1967). Projection of the vector endpoints at each demagnetization level onto the horizontal plane (declination) is indicated with full symbols, and that onto the vertical plane (N-S plane in the present case) with open symbols. Peak alternating fields indicated by numbers (in Oersted). The directions in the horizontal plane are N, W and S (E of course opposite of W), directions in the vertical plane are D (down, ‘up’ of course opposite down), N and S. Both projections share the N-S line. Units on both axes represent $112*10^{-6}$ Gauss in A) and $115*10^{-6}$ Gauss in B). Apart from nicely showing the NRM behaviour during stepwise progressive demagnetization, the figures illustrate that samples from a single outcrop, so very close in space and time, may behave very differently during demagnetization. In B), the recent overprint on the primary NRM is much larger and extends to higher demagnetization levels than in A). This convincingly demonstrates Zijderveld’s argument that ‘blanket demagnetization’, i.e. demagnetization at one specific demagnetization level only (which was determined before in a set of pilot samples), should be avoided.

in an increasing number of studies, and this became a major concern to him. To solve the difficult remagnetization problems, he decided to move away from tectonic paleomagnetism. To properly address NRM in old rocks, first the nature of the NRM had to be understood in sufficient detail. At that time, he probably did not realize the far-reaching consequences of his decision. He embarked on rock-magnetic studies in order to better understand the ins-and-outs of magnetic minerals in natural rocks, as potential carriers of the NRM. In contrast to most scientists, who worked with (supposedly) ideal synthetic material, he studied natural material because that was what really represented nature. Emphasis was placed on the analysis of the grain-size dependence of various rock-magnetic parameters of pure concentrates of magnetic minerals dispersed in a non-magnetic matrix. In the recent compilation of Hunt et al. (1995), the outcome of this research line is given considerable attention.

In the mid to late seventies, soon after he had started working on rock magnetism, Zijderveld also initiated investigations on the magnetostratigraphy of young rocks where the primary nature of the NRM could be tested with the help of the geomagnetic polarity time scale (GPTS). As usual, he was skeptical in the beginning (his attitude was rather critical and cautious in general: ‘first see, then believe’), but after acquiring encouraging results, Hans became convinced that magnetostratigraphy could contribute substantially to earth sciences by providing a dating tool for sedimentary sequences. Thus, the collaboration with stratigraphers from the faculty at Utrecht was initially aimed at the dating and correlation of biozones in marine sediments, but it rapidly progressed far beyond this level, as we'll see further on. His interest in instrumentation remained, and during a lecture tour in the USA funded by the Vening-Meinesz prize (a prestigious Dutch earth sciences award named after the famous geophysicist Vening-Meinesz), he was introduced to a new type of magnetometer, the so-called cryogenic magnetometer, which has sensors based on SQUID technology (superconducting quantum interference device). Hans was impressed by the sensitivity and the ease of sample handling, which were significantly better than those of spinner magnetometers, the work-horses of paleomagnetic laboratories in the early 1970s. Soon afterwards, the Utrecht paleomagnetic laboratory was the first in Europe to acquire a cryogenic magnetometer, and this new instrument made a large throughput of samples possible, so essential for magnetostratigraphic studies.

In 1981, Zijderveld became professor of paleomagnetism, having accepted a chair endowed by the Utrecht University fund ('bijzonder hoogleraar'). His 'oratio' was entitled 'Het magnetisch geheugen in de aardwetenschappen': The magnetic memory in the earth sciences. Magnetostratigraphic results obtained from Late Miocene sections in Crete (Langereis et al. 1984) were becoming controversial (later, in the 1990s, it appeared that this was related to inaccuracies of the GPTS itself) and to prove that the Utrecht interpretation was correct, Zijderveld moved in the mid eighties to even younger rocks of Pliocene age which yielded well accepted results. Meanwhile, the magnetostratigraphic work was extended to studies of geomagnetic variations, with emphasis on high-resolution studies of geomagnetic reversal records. The cooperation with stratigraphers was intensified. Particularly Dr. Frits Hilgen, collaborating closely with Cor Langereis, perfected the concept of cyclostratigraphy by showing that astronomical solutions for the orbit of the Earth around the Sun are reflected in the Pliocene sedimentary rhythms of southern Italy and Sicily.

This was a breakthrough in chronostratigraphy, which enabled the dating of sediments up to an age of 5 Ma with a precision of about 2 kyr, an unprecedented accuracy (we use Myr (or kyr) when a duration is implied, and Ma (or ka) for an age or datum level). In addition to excitement in the paleomagnetic and stratigraphic communities, these results generated much uproar in the radiometric age dating community because of the possibility of independent cross-checks on radiometric ages. Moreover, the GPTS itself could now be refined. Evidently, this research was (and is) given a high priority. The most recent version of the GPTS (Cande & Kent 1995) fully incorporates Hilgen's (1991a, b) work. The GPTS also appeared to be of great value for the study of continental rocks which are difficult to date. By magnetostratigraphic correlation to the GPTS one can assign numerical ages to continental sequences as well.

Nearing the end of his academic career, Zijderveld revived the geodynamic paleomagnetic work on Neogene rocks because those rocks could now be dated with great precision. In addition, the intricacies of the NRM acquisition mechanisms in sediments have been addressed in more detail and for some sediments delayed acquisition was convincingly demonstrated (Van Hoof & Langereis 1991). In 1992, Zijderveld was elected 'Fellow of the American Geophysical Union' as recognition of his contributions to the field of paleomagnetism. Meanwhile the quest for more sensitive magnetometers continued and Zijderveld persuaded '2G Enterprises' to develop a new cryogenic magnetometer. The first copy of the instrument (world-wide), which is equipped with sensors based on a much more sensitive SQUID type, was installed at 'Fort Hoofddijk' in the fall of 1994. Indeed it appears to be an order of magnitude more sensitive.

Extending and building on the programs initiated by Zijderveld, current research of the Utrecht paleomagnetic group includes investigations into magnetostratigraphy, development of the GPTS and geomagnetic variations, remanence acquisition mechanisms of sedimentary rocks, magnetic properties of minerals and rocks, and Neogene geodynamics of the Mediterranean. The paleomagnetism group belongs to the Vening-Meinesz Geodynamics Research School. Tenured faculty include Cor Langereis (head of laboratory) and Mark Dekkers, two former PhD-students of Zijderveld. The group receives support as grants from Utrecht University, the Netherlands Science Organization and the European Union.

This special issue

This commemorative issue starts with two articles related to the Esterel, Zijderveld's thesis area. Rochette et al. compare the scatter of the secular variation of the geomagnetic field at the (paleo)equator during a period of frequent geomagnetic reversals (present) and during the Permo-Carboniferous superchron when no reversals occurred during 70 Myr. The equatorial Holocene site consists of the Galapagos Islands and the equatorial Permian site is the Esterel in southern France. During a superchron the scatter in secular variation is shown to be lower than during periods of a frequently reversing field. Rochette et al. also point out that the remanence acquisition mechanism in the 'old' Permian volcanics is crucial to their interpretation. This suggestion is elaborated on in the next article by Vlag et al. discussing rock-magnetic properties of the Esterel volcanics. The observations of magnetite and hematite co-occurring in samples and occasionally ambiguous conglomerate tests hint at a non-instantaneous character of the NRM acquisition. The third article of this issue by Giddings et al. describes the fully automated alternating-field demagnetization set up, as nicely developed by the paleomagnetic group at the Australian Geological Survey Organization, for the dedicated requirements of single-sample measurements.

Then, the tectonic paleomagnetism articles are grouped together. We ordered them according to the age of the rocks studied, starting with the youngest. Study areas include Greece, Indonesia, Iran, Greenland, Poland, and the Iberian Peninsula. They show that paleomagnetic work in collision zones can help to unravel geological history, but also that knowledge of the NRM-acquisition mechanism is essential to the geodynamic interpretation. Haubold et al. report results on Oligocene intrusive, extrusive and sedimentary rocks in northeastern Greece and propose to subdivide the area into four structural units that underwent different clockwise and counterclockwise rotations. Wensink discusses the paleomagnetic data of Cretaceous rocks from Sumba (Indonesia) in the framework of the complex Australo-Asian convergence history. Sumba has had an equatorial position since the Jurassic. It formed part of the Asian mainland but became detached from it at the end of the Cretaceous. Lemaire et al. discuss the position of the Turan (micro)plate during the convergence of the more southerly located Iranian microplate, which was part of the Cimmerian (mid-Tethyan) continent, and Eurasia in Triassic-Jurassic times. The Turan plate is argued to have been at a lower paleolatitude than predicted from values for Eurasia for post-Permian times. A shortening of at least 7° between the Turan and Eurasian plates is proposed to have occurred during Triassic and Jurassic times. Abrahamsen et al. show in a study of dyke swarms in northern Greenland that, based on their paleomagnetic properties, two groups of ages are likely: a Carboniferous swarm and two Late Cretaceous or Early Tertiary swarms. The latter two post-date the opening of Baffin Bay. Kadzialko-Hofmokl & El-Hemaly report on the remagnetization history of Carboniferous rocks in the Intra-Sudetic Basin (Poland). By comparing measured directions with reference apparent polar wander paths, they document the secondary nature of the NRM. Osete et al. discuss new data for the Late Carboniferous to Late Triassic segment of the apparent polar wander path (APWP) of the Iberian Peninsula. They propose a smooth APWP for this time span without the loop suggested by literature data, some of which Osete et al. argue to be of doubtful quality.

Next, three articles related to magnetostratigraphy follow, again organized from young to old according to the ages of the rocks. The first magnetostratigraphy article by Li et al. documents the correlation to the GPTS of continental sediments in Gansu Province in central China with ages varying between 11 and 0 Ma, in a nice application of the dating of continental rocks through the use of the GPTS. The Tibetan Plateau underwent a continuous uplift from the Late Miocene onward, which accelerated at approximately 3.6 Ma. In addition to establishing ages for mammal findings, this study illustrates the importance of knowing the geological ages to derive geodynamic conclusions about such issues, like in the present case, as uplift rates. The next article by Goguitchaichvili et al. reports on the difficulty of establishing correlations in sequences of lava flows in southern Georgia. Rock-magnetic experiments indicate that the NRM is mostly residing in single-domain grains. The area did not undergo tectonic rotations since the Early Pliocene. The magnetostratigraphic section is concluded with a study by Gialanella et al. on Late Permian magnetostratigraphy of sediments from the eastern Russian Platform. The rocks were difficult to date because of the lack of fossils and ash layers, but they record the end of the Late Carboniferous-Permian superchron, also termed Kiaman Reversed Superchron. Despite the occurrence of several hiatuses (suggested by conglomerates), the Russian sections can be correlated reliably to the Tethyan realm, if the duration of the Tatarian is set at $\sim$ 15 Myr, i.e. longer than accepted to date ($\sim$ 10 Myr). Supporting arguments are discussed.

The issue concludes with two contributions showing rather different applications of paleomagnetic data. The first, by Van Hoof et al., reports on 'archeomagnetic dating' of several historical fireplaces in the Netherlands. An age is derived by comparing the paleomagnetic direction recorded in bricks from the fireplaces with the secular variation curve for the area (British master curve). Turning this method around, paleomagnetic directions of fireplaces with known ages (from historical accounts or ^{14}C dating) can be used to refine the master curve, which constitutes a nice illustration of a combination of geomagnetism and archeology. The final article in this issue by Dekkers reviews 'environmental magnetism', a relatively new branch in paleomagnetism. In environmental magnetism, the magnetic properties of rocks can be used as proxy parameters for the analysis of paleoclimate, provenance of sediments, and anthropogenic pollution.

Acknowledgements

To conclude, the guest editors would like to express their thanks to a number of people and organizations. The European Geophysical Society (EGS) is thanked for their agreement to let us organize the symposium 'Analysis of paleomagnetic data: a tribute to the work of Hans Zijderveld' at the annual EGS conference in 1996 in The Hague, Netherlands. The lustrum fund organization of Utrecht University is gratefully thanked for its support for invited speakers. The invited speakers and other contributors made the symposium a memorable occasion, which was enormously appreciated by Hans Zijderveld himself. The editors of 'Geologie en Mijnbouw' are thanked for making their journal available for this special issue, which contains some of the material presented at the EGS symposium. The editorial assistance of Dick Batjes in producing this issue, is appreciated. Certainly, the authors are thanked for their contributions and the reviewers for their quick and thoughtful reviews. This work was conducted under the programme of the Dutch national research school, the Vening Meinesz Research School of Geodynamics.

Finally, the guest editors, all three former PhD students of Zijderveld, are very grateful for their scientific training. They will always remember the hefty discussions on 'reddened' draft versions of articles, which were commented upon line by line from the beginning to the very end, regardless of the time it would take to complete. It was not uncommon that Hans Zijderveld could be found busy, plotting some relevant data in painstaking (and time-consuming) detail, in order to convince his sometimes stubborn protegé or student to adopt a somewhat more cautious view. Undoubtedly speaking for all who have worked with Hans, we thank him for sharing with us his dedication to good science!

Appendix

List of PhD theses based on paleomagnetic studies at 'Fort Hoofddijk', in chronological order, 1957–1996

Den Boer, J.C. 1957 Étude géologique et paléomagnétique des Montagnes du Coiron. Geologica Ultraiectina 1, 64 pp

Dietzel, G.F.L. 1960 Geology and Permian paleomagnetism of the Merano region, province of Bolzano, Italy. Geologica Ultraiectina 4, 57 pp

Van Everdingen, R.O 1960 Paleomagnetic analysis of Permian extrusives in the Oslo region, Norway – Skrifter Norske Vidensk. Akad. Oslo: Mat. Naturv. Kl. 1: 1–80

Van Hilten, D. 1960 Geology and Permian paleomagnetism of the Val-di-Non area (Western Dolomites, Northern Italy). Geologica Ultraiectina 5, 95 pp

Van der Lingen, G.J. 1960 Geology of the Spanish Pyrenees, north of Canfranc, Huesca Province – Estudios Geologicos XVI: 205–242

Kruseman, G.P. 1962 Étude paléomagnétique et sedimentologique du bassin Permien de Lodève, Herault, France. Geologica Ultraiectina 9, 66 pp

Schwarz, E.J. 1962 Geology and paleomagnetism of the valley of the Río Aragón Subordan north and east of Oza – Estudios Geologicos XVIII: 193–240

De Boer, J. 1963 The geology of the Vicentinian Alps (northeastern Italy), with special reference to their paleomagnetic history. Geologica Ultraiectina 11, 178 pp

Guicherit, R. 1964 Gravity tectonics, gravity field, and paleomagnetism in NE-Italy. Geologica Ultraiectina 14, 125 pp

Van der Voo, R. 1969 Paleomagnetic evidence for the rotation of the Iberian Peninsula – Tectonophysics 7(1): 5–56

Mulder, F.G. 1971 Palaeomagnetic research in some parts of central and southern Sweden. Sver. Geol. Unders., Ser. C 653, 56 pp

Klootwijk, C.T. 1974 Paleomagnetism of Indian rocks and implications for the drift of the Indian part of Gondwanaland. 209 pp

Zijderveld, J.D.A. 1975 Paleomagnetism of the Esterel rocks. 198 pp

Poorter, R.P.E. 1976 Palaeomagnetism of Precambrian rocks from Norway and Sweden. 78 pp

Dijksman, A.A. 1977 Geomagnetic reversals as recorded in the Miocene red beds of the Calatayud-Teruel Basin (Central Spain). 156 pp

Van den Ende, C. 1977 Paleomagnetism of Permian red beds of the Dôme de Barrot (S. France). 170 pp

Dankers, P.H.M. 1978 Magnetic properties of dispersed natural iron-oxides of known grain-size. 142 pp

VandenBerg, J. 1979 Paleomagnetism and the changing configuration of the Western Mediterranean Area in the Mesozoic and Early Cenozoic Eras. Geologica Ultraiectina 20, 178 pp

Lanser, J.P.L. 1980 Paleomagnetism of some Late Quaternary sediments. 142 pp

Hartstra, R.L. 1982 Some rockmagnetic parameters for natural iron-titanium oxides. 145 pp

Langereis, C.G. 1984 Late Miocene magnetostratigraphy in the Mediterranean. Geologica Ultraiectina 34, 180 pp

Dekkers, M.J. 1988 Some rockmagnetic parameters for natural goethite, pyrrhotite and fine-grained hematite. Geologica Ultraiectina 51, 231 pp

Linssen, J.H. 1991 Properties of Pliocene sedimentary geomagnetic reversal records from the Mediterranean. Geologica Ultraiectina 80, 230 pp

Hilgen, F.J. 1991 Astronomical forcing and geochronological application of sedimentary cycles in the Mediterranean Pliocene-Pleistocene. Geologica Ultraiectina 93, 139 pp

Van Hoof, A.A.M. 1993 Geomagnetic polarity transitions of the Gilbert and Gauss Chrons recorded in marine marls from Sicily. Geologica Ultraiectina 100, 123 pp

Scheepers, P.J.J. 1994 Tectonic rotations in the Tyrrhenian arc system during the Quaternary and late Tertiary. Geologica Ultraiectina 112, 352 pp

Van Velzen, A.J. 1994 Magnetic minerals in Pliocene and Pleistocene marine marls from Southern Italy, rock magnetic properties and alteration during thermal demagnetization. Geologica Ultraiectina 122, 153 pp

Krijgsman, W. 1996 Miocene magnetostratigraphy and cyclostratigraphy in the Mediterranean: extension of the astronomical time scale. Geologica Ultraiectina 141, 207 pp

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Frankel, H. 1988 From continental drift to plate tectonics – Nature 335: 127–130

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