The Diving Dutchman : het marien-gravimetrisch onderzoek van F.A. Vening Meinesz (1887-1966)

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Summary

Felix Andries Vening Meinesz (1887 – 1966) was the youngest son of a former mayor of Amsterdam. In 1910 he was employed as a young engineer by the forerunner of the present Dutch Geodetic Committee to measure the acceleration due to gravity in order to assist in astro-geodetic arc measurements. Relative measurement of the period of one swinging pendulum would usually – given a sufficiently long period of observation - suffice for this, because "swinging is a controlled, slowed-down way of falling under gravitational pull". But in the Netherlands it became clear that interference from other sources thwarted the proper execution of this technique. Vening Meinesz developed an alternative method of measurement using pairs of isochronous pendulums swinging in the same plane with equal amplitude but in opposite phase. He later perfected that design to incorporate the use of an optical signal-stacking process so that the difference in the angles of elongation of the swinging pendulums could be photographically recorded; a result that may be considered as the angle of elongation of a fictitious pendulum, not disturbed by horizontal accelerations, and isochronous with the original pendulums.

Earlier attempts to "measure gravity" in this way on board of a steamship had met with no success. But, by serendipity, Vening Meinesz was made aware that a submerged submarine, powered by electromotors, would provide an ideal stabilised platform for such measurements at sea. Vening Meinesz was, at short notice, offered the opportunity to bring that idea successfully into practice thanks to the close connections of his employer with the Dutch Navy.

One of the reasons that the Dutch Navy and her Submarine Service continued to support Vening Meinesz, whose family motto was "Nunquam Deorsum" ("Never Down"), in his "Ever Deeper" scientific diving expeditions was a deeply felt need to improve her dented image, proof of which was the rejection of the proposed "Vlootwet" (Naval Rebuilding Project) by the Dutch Parliament in 1923. Another reason was the concomitance between the training requirements of the new submarine crews on their way to the Dutch overseas colonies and Vening Meinesz's scientific research programme. Expeditions with Submarine K XIII in 1926-27 and in 1929-30 raised considerable interest in scientific circles, whilst the K XVIII 1934-35 expedition provided the Dutch government with welcome publicity to support the acceleration of its fleet-rebuilding programme. The symbiotic relationship between Government, Navy, Science and Industry – Vening Meinesz's marine gravimeter had become industrially produced on a small scale – appears to reflect in a nutshell the postwar "military – industrial" complex developed in the United States, where, in an early stage, Vening Meinesz's research had resulted in the foundation of several marine-geophysical / oceanographic institutions.

In this way, during the interwar period of very restricted government interference with the sciences, Vening Meinesz pioneered the transition from a nineteenth century pattern of large-scale, comprehensive, multidisciplinary, "one-off" oceanographic expeditions to a more regular pattern of specialised marine-geophysical / oceanographic expeditions along a continuously updated line of investigation carried out more or less annually.

Through Vening Meinesz' innovative approach concerning marine-gravimetric instrumentation and procedures, new insight would be obtained in geodetic and

geological problems. Besides, that approach provided – quite unexpectedly - the first opportunity to measure the characteristics of oceanic wave movements.
The global pattern of marine-gravimetric observations, systematically carried out during the interwar period and obtained by him in the course of several expeditions, improved his understanding of the distribution of, and the forces acting upon, the masses in the earth and, as a consequence, his understanding of the shape of the equipotential surface of the earth at mean sea level – the geoid – and its nearest mathematical representation – the oblate ellipsoid of revolution or "spheroid" used for geodetic longitude and latitude measurements.

Using the International Gravity Formula corresponding with that "spheroid", Vening Meinesz derived formulae to determine locally the distance between geoid and "spheroid" and developed a technique to convert one national geodetic grid system into another. His derivation – well before the age of satellites - of a formula to extrapolate the earth's gravity field at mean sea level to a height of several hundreds of kilometres now appears to us farsighted.

Until the beginning of the twentieth century the shape of the earth had been derived by extrapolating continental arc-measurements and depended on where, how, and by whom those measurements had been executed. Consequently, there was little agreement about the actual position of non-natural boundaries between adjacent states with differing opinions about this subject. That problem existed, for example, along the common boundaries between Canada – still part of the British Empire – and the United States, each of which used their own geodetic system. At the end of the nineteenth century – coinciding with the Gold-rush to Klondike, a state-boundary town – the joint and detailed North American Geodetic Survey had been initiated to resolve matters and determine unambiguously the position of shared-state boundaries.
Whilst earlier surveyors in smaller mountainous areas, such as the Andes and Himalayas, were able to take into consideration the influence of such obviously uneven mass distributions, the much larger area of the Great Plains had no such markers. The surveyors there had to assume that, here as elsewhere, "an elastic earth-crust floated on a denser, plastic substrate in a state of hydrostatic equilibrium" except, presumably, where affected by very recent erosion or sedimentation.
However, the only person who had already proved that such a large area could be in isostatic equilibrium was Vening Meinesz; during the K XIII expedition of 1926-27 he had shown that the weighted average of all gravity anomalies was close to zero across the Atlantic and Pacific oceans and therefore that an isostatic equilibrium over large areas did exist.
A repeat expedition with a US submarine, conducted by Vening Meinesz in 1928 at the request of American surveyors, confirmed that a state of isostasy existed in the Gulf of Mexico, even in areas of recent sedimentation such as the Mississippi delta.

Other navies invited Vening Meinesz to install and demonstrate his apparatus and even to conduct marine-gravimetric surveys. A deep knowledge of the theory and practice of marine gravimetry, an innate "savoir-vivre", and a recognised organisational talent were to make Vening Meinesz a leading authority in the international geodetic community, providing him with an extensive research network. He also initiated unique co-operation between geologists and geophysicists. This would raise marine geological research from an intuitive to an empirical scientific discipline.

Whilst expedition results in the Gulf of Mexico had shown that region to be in isostatic equilibrium, elsewhere Vening Meinesz had found areas ("Minus"-zones, a pun on the name of the discoverer), where the existence of large negative gravity anomalies suggested that forces other than gravity alone had to be active in order to maintain such large scale gravitational imbalances. Many of these zones coincided with deep-sea troughs forming part of elongated sediment-filled basin-complexes. Some of these ran outside of, but parallel to, the seismically active volcanic island arcs of the East and West Indies. But both types appeared as relatively narrow, elongated arcs with a large gravity deficit; a "Minus"-zone for geophysicists; a "geosyncline" for geologists. The fact that the "Minus"-zone of the East Indies extended to the relatively seismically quieter foothills of the Himalayas and the Ganges basin strengthened the impression that this zone could be a mountain range "in statu nascendi". American geologists spoke in the same vein about the West Indian island arc, when, in the course of the interwar period, results of further marine gravitational exploits became available.

At about the same time the debate about Wegener's "Continental Drift" hypothesis reached, for the time being, its climax. Wegener had argued, based on terrestrial, mainly qualitative (paleogeographical, paleoclimatological and geological) data, that the continents could have moved as "rigid rafts" through a "viscous oceanic substrate" in the same way as "icebergs ploughing through water". As a consequence, mountain chains, such as the Rocky Mountains or the Andes, might be considered as an expression of a "ship's bow-wave" and deep-sea troughs as corresponding with a "ship's wake". But the exogenous tidal and centrifugal forces invoked by Wegener were proved to be insufficient by far to realise the movements he suggested. For Vening Meinesz, moreover, Wegener's notion of a "viscous oceanic substrate" appeared incompatible with the rugged relief he had interpreted from his echo-soundings. These and other objections kept many convinced that mountain-formation or orogeny occurred worldwide in an episodic but synchronous fashion, proceeding from geosynclines on the boundary between fixed, rigid continents and their sunken counterparts, the oceans; an arrangement created by the shrinking of a rigid lithosphere in reaction to a cooling down and compacting viscous substrate. Most geologists dismissed the few researchers who assumed that one or other endogenous dynamic process – such as convection current systems – could be behind Wegener's "Drifting of Continents". Among these few was Vening Meinesz, who not only became a fierce proponent of such endogenous dynamism, but also an energetic researcher seeking convincing evidence in support of those – for the time being – elusive current systems, which he thought to be crucial in the process of orogeny.

Vening Meinesz interpreted the above-mentioned "Minus"-zone as the gravitational expression of a bulge of lighter crustal material, protruding into the underlying, heavier substrate (mantle) which was created by horizontal compressional forces in the crust and sustained by currents generated in a convection cell in the substrate. The pattern of temperature gradients required for such convection was considered to be created by an enrichment of heat-generating radio-active material in the continental crust relative to that in the oceanic crust or the substrate. Vening Meinesz thought that, depending on the rheological characteristics of the surrounding crust and the orientation of the convection current, the appearance of the protrusion in cross-section might vary between a (faulted) kink to an inclined overthrust. Afterwards he amplified this hypothesis by invoking a subsequent, reverse halfturn rotation of the convection current to restore the imbalance in the temperature / density relationship, resulting from the presence of lighter crustal material deeply protruding in surrounding heavier mantle material. As a consequence, sedimentary infill would bulge upwards to form a mountain-chain.

As a first step in support of this hypothesis, Vening Meinesz successfully determined the viscosity of the mantle-rock – a critical value to be used in future modelling exercises – by analysing the evolution of the isostatic rebound of Scandinavia since the last ice-age. Helped by his thorough grounding in rheological theory of elasto-plastic materials, he carried out further modelling exercises, invoking very much simplified assumptions regarding the processes involved. He was, after all, convinced that the complexity of the geological phenomena at an interface such as the earth's crust belied the simplicity of the actual processes. Dutch and American researchers developed working models of the evolution of a "Minus"-zone in an attempt to simulate the course of events leading to mountain formation as perceived by Vening Meinesz. Although their results tended to confirm Vening Meinesz's theory, hardly any geologist in the prewar period gave them serious consideration.

Vening Meinesz thought that he could deduce evidence for the existence of convection in the earth from a slowly westwards-shifting major anomaly in the earth's magnetic field, which had been measured in 1912 and again in 1942. In addition, he correlated the spatial pattern of earthquake hypocentres in the East Indies with shear-zones thought to occur within a convection current in the mantle. The geologist Umbgrove provided Vening Meinesz with a further supporting argument when he suggested that a rotation of a rigid lithosphere around the plastic substrate / mantle could be driven by a system of convective cells. A slow but considerable meridional rotation would then account for the relocation of Upper Carboniferous, ice-age relicts in India, South Africa and South America from their original position – assumed by Umbgrove to be within a present-day area of glaciation - to their current geographic position. Given the oblateness and the rigidity of the earth's crust such rotation would, according to Vening Meinesz, result in a pattern of shear fractures, which happened to delineate the present outline of continents. Vening Meinesz derived further support for his belief in the existence of convection cells in the earth from the correlation between the present relief of the lithosphere, as resolved in terms of a spherical-harmonic analysis, and the evolution of the earth from an initially homogenous mass to the present tripartite arrangement of crust, mantle and core. This he interpreted as the result of the differentiation caused by the development of an increasing number of convection cells in the mantle.

In combining his own observations, simulations and geological insight, Vening Meinesz became convinced that the present distribution of continents and oceans had not changed for millions of years. Mountain building was a short-lived and rare occurrence as a part of a slowly unfolding geosynclinal cycle; the present was therefore an exceptional period! He considered negative gravity anomalies, deep-sea troughs, earthquakes and volcanoes caused by convection currents active beneath the continents as fundamental to tectonic processes, such as orogeny.
At the end of the interwar period it was clear, that relative shifting of entire continents over large distances had become anathema for Vening Meinesz.

During the war gaps in the detailed knowledge of the oceans had become obvious to the naval, commercial and scientific communities and were to give the impulse to a renewed effort in marine-geophysical research. The United States in particular would increase such research efforts as it deemed necessary to meet its military strategic objectives.

As to oceanographic research, the results of marine-geophysical techniques, such as heat-flow measurements and seismometry, would throw new light on the composition of the ocean floor. The results of marine magnetometry revealed an intriguing pattern of magnetic anomalies in the oceanic substrate. In about 1960, Harry Hess – one-time "student" of Vening Meinesz – came up with the hypothesis of "sea-floor spreading", based on lateral correlations of the typical topography of the Central Rift in the Mid-Atlantic Ridge area. This hypothesis focused less on continents, but rather on Mid-Oceanic Ridges as being zones where hot, relatively less dense (sub)crustal material ascended from the mantle and, by spreading laterally and consolidating, forced the ocean to open, apparently "shifting continents".

The lack of global geodetic control experienced during the war called for further developments in geometrical geodesy. This kind of surveying was concerned with arc-measurements and large-scale triangulation in order to improve knowledge about the shape and size of the reference-ellipsoid, assuming that the earth's geometrical and gravitational centres coincided. But, as Vening Meinesz had expected, the deflection of the vertical and the acceptance of the theory of isostasy and related matters assumed greater importance. This stimulated further acquisition of marine-gravimetric data in order to combine continental / topographical arc-measurements and a worldwide network of gravity data within the framework of physical geodesy. Eventually, data obtained by the first earth satellites proved to be instrumental in forcing through the introduction of a Worldwide Geodetic System (W.G.S.) based on that concept. The availability of such a System in conjunction with the arrangement of the satellites, would allow the positioning of non-natural (imaginary) boundaries – such as "mid-coast lines" - with an, until then, unequalled accuracy.

Immediately after the liberation in 1945 the Dutch government realized that it had to rectify the country's arrears in matters scientific and charged Vening Meinesz with carrying out a "fact finding mission" to the United States. There he was welcomed by his wide circle of friends in high places, who assisted him in his investigations into the organisational, financial and implementational aspects of fundamental research.. After his return he was to act as one of the advisors to the government concerning the foundation of an organisation for the advancement of pure scientific research, which was eventually established in 1950.
At the same time Vening Meinesz was appointed director-in-chief of the Royal Dutch Meteorological Institute (K.N.M.I.), a post he held until 1951. He then became President of its Board until 1966, committing himself to all aspects of research carried out at the Institute. In tthe former capacity he created a separate oceanographic department and oversaw the commissioning of two weather-ships to be stationed at alternating locations in the North Atlantic Ocean. At the same time the Dutch Navy commissioned two oceanographic vessels. However, for operational, financial and personnel reasons, the opportunities to carry out marine-gravity research dwindled.
Paleomagnetism – the study in magnetic properties of rocks in order to determine the relative intensity and direction of the earth's magnetic field at the time the rock

concerned was magnetised – provided, in time, a feasible and interesting substitute field of geophysical and geological research in the Netherlands. Results of research there and elsewhere, based on rocks of different ages and continents, were to show, that the polarity of the earth's magnetic field had changed episodically; and that either the magnetic poles were fixed in place and the continents were moving in time relative to each other, or that the continents were fixed in place in which case the magnetic poles would have moved in time along pathways, which differed from continent to continent. The former solution appeared to many to be the more acceptable and, towards the end of his life, even Vening Meinesz seemed inclined to support it.

Bullard's 1964 reconstruction of the movement of continent-size "plates" – the term may have been coined by Vening Meinesz in 1928 – over a spherical surface had once again convincingly demonstrated the fit of the edges of the continental shelves on both sides of the Atlantic, leading to the conclusion that the Atlantic Ocean had been closed in the past, provided – as Professor Rutten remarked – that Iceland was left out of the equation.[1] The question whether Iceland might indeed be considered a recently created, exposed part of the Mid-Atlantic Ridge System was answered in 1966, when Vine showed the correlation between the pattern of positive and negative magnetic anomalies on both sides of the Central Rift of the nearby, submarine Reykjanes Ridge.[2] Magnetostratigraphic analyses of that pattern suggested the rate of spreading away from the Central Rift of Iceland to be in the order of 1 cm/yr in each direction, resulting in a maximum age of creation of Iceland of about 16 – 18 million years, well after the opening of the Atlantic.

Bullard's reconstructions and Vine's deductions confirmed Hess's "sea-floor spreading" hypothesis. In 1968 this evolved into the theory of "Plate Tectonics", which, in its simplest form, states tthat the earth's crust is made-up of a number of discrete plates. Each plate is composed of continental and oceanic crust material of such rigidity that, when being moved by convection currents in the substrate, deformation is most likely to occur along its edges. Most geologists agreed that the creation of crust in one place must result in destruction of crust elsewhere (ignoring those, who claimed the earth to be an expanding body). Deep-sea troughs appeared to be the loci where one plate could disappear below the other; the physical and chemical reactions created by that process would result in the occurrence of earthquakes, volcanism and orogeny. The theory of Plate Tectonics became the leading model in global tectonics as soon as it appeared that the data from boreholes, drilled under the supervision of the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) Committee, confirmed the prognoses based on marine-geophysical data, interpreted according to that theorie. But, as usually is the case, the theory is a simplification of a much more complex reality and many new questions came up and are awaiting answers.

The well known geologist Van Bemmelen later explained graphically how his views concerning the evolution of the earth from a static ("fixist"), episodically reactive body to a continuously dynamic ("mobilist") entity were influenced by developments in

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[1] M.G.Rutten, "Discussion", in: P.M.S.Blackett et al (red.) *A Symposium on Continental Drift* Vol 258 van de *Phil Trans R.S. London* (1965) 59 – 68; 321

[2] F.J.Vine, "Spreading of the ocean floor: new evidence", in: *Science 154* (1966) 1405 – 15

marine-geophysical research.[3] His doctorate, written in 1927 under the strict supervision of the Delft Professor Molengraaff, a follower of Wegener, reveals a "mobilistic" view. However, by 1930, Wegener's hypothesis had already become discredited and Dr. Van Bemmelen turned "fixist". Only at the end of the 1960s did he convert again to some sort of "mobilism", that interpreted "Continental Drift" quite differently from Wegener.
Whilst Jeffreys continued to be an opponent of "Plate Tectonics", pending conclusive prove by experiment, it appears a quirk of fate that none of the other "founding fathers" of global geophysics – Vening Meinesz, Holmes, Hess and Ewing – would live to experience the full acceptance of that dynamic theory by the geological community.

Vening Meinesz contributed significantly to the rapid advancements in the geosciences which started in the interwar period.

Through his marine-gravimetric surveying techniques he enabled the integration of continental arc-measurements and world-wide gravimetric data in a physical geodetic network to determine the shape and the internal mass-distribution of the earth. (Ref. Chaps. 4e and 9d)

As to other branches of the geosciences, Vening Meinesz kept an eye open for the implications of the results of his dedicated oceanographic research, which contrasted with the multi-disciplinary approach to such research which was usual in the early twentieth century. Consequently his empirical data put him in a position to temper the speculations and intuitive thoughts of other geoscientists. (Ref. Chap. 6d)

By means of a converging way of reasoning he demonstrated the conversion of indirect observations – such as those interpreted from his gravity measurements – to knowledge about the configuration of the ocean floor and its substrate, and opened these domains for (marine)-geological research. (Ref Chap. 6e)

Finally by using imaginative thinking to reconcile geologists' intuition with geophysical observations and theory, Vening Meinesz attempted to resolve the evolution of the intractable structure and behaviour of the earth's crust. He deduced that the deformation and segmentation of a rigid lithosphere was a consequence of its wholesale rotation under the influence of convection currents in a viscous mantle. (Ref. Chap. 8d)

Vening Meinesz's exploits, however, contributed not only to the progress in the geosciences, but also, especially during the Interwar period, to the gradual improvement in public appreciation of the Dutch Navy.

His earlier expeditions with a submarine were – most likely – only made possible due to the close personal relationship between the Secretary of the Navy, Cdr. (ret.) Westerveld, and Capt. Luymes, Chief of the Hydrographic Service of the Navy, who was also a member of the above mentioned Geodetic Committee, the employer of Vening Meinesz. These expeditions went off unnoticed, but their results were internationally well received, prompting both the Navy to greater openness in its affairs and the Government to continue its efforts to overcome public cries for disarmament and parliamentary opposition against the rebuilding of the fleet. (Ref. Chap. 4)

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[3] R.W.van Bemmelen, "The undation theory", in: *Geologie & Mijnbouw* 56 (Den Haag 1977) 263

In the light of developments in Germany the K XVIII expedition of 1934 / 35 proved to be a successful move by the Government (cleverly further exploited by the media) to overcome the bad publicity from an armed raid in the West Indies (1929) and the mutiny of "De Zeven Provinciën" (1933). The resulting "media hype" made Vening Meinesz a well known public figure, and contributed to further public appreciation of the Navy and to gains for the governing parties in the 1937 parliamentary elections in spite of the worldwide political and economic crises. (Ref. Chap. 7h)

Vening Meinesz was by no means a desk-bound scientist and he was actively involved in marine-gravimetric research on board submarines until an advanced age. His intellectual curiosity was combined with an intrinsic and imaginative problem-solving power, which served him well in unveiling the secrets hidden within his findings. He proved to be able to think "out of the box" of geodesy and he stimulated a younger generation to do likewise. He was an "artful dodger", who performed difficult tasks without obvious effort. Disinterested exchanges of ideas, datasets or experiences and true friendships characterised the Christian-humanistic ideals Vening Meinesz embodied. Once, at the end of his life, Vening Meinesz remarked ironically how he had failed as an engineer.[4] After all, engineers ought to be pragmatic and distance themselves from hypothesising. But it was, in actual fact, through combining observation and imagination that he worked out the hypothesis of mountain formation that later on would appear to have been a foundation stone for the hypothesis of "seafloor spreading" and, consequently, of Plate Tectonics.

In spite of the extensive network of internationally renowned researchers and other friends he built up and kept in touch with during his lifetime, Vening Meinesz continued to live as a bachelor, committed to scientific study. He established his emotional "pied-a-terre" at his home in Amersfoort which he shared with his sister Coba and his loyal housekeeper. After Coba passed away in 1965 life became for him more lonely, despite his close family-circle.
Vening Meinesz died on 10th August 1966 as a consequence of medical complications which had arisen during a lengthy stay in hospital after he broke a hip in a fall. His interment in the family-grave at the "Zorgvlied" cemetery in Amsterdam and followed the service of thanksgiving in the "Bergkerk" in Amersfoort on 15th August,.

It has been said that those who wish to have influenced the life of others in a positive way, should have planted a tree, have made a long expedition and have written a book. With his planting of several woods, some fifteen expeditions and ten books Vening Meinesz certainly more than met these criteria!

[4] G.J.Bruins and J.G.J.Scholte. "Felix Andries Vening Meinesz", in: *Biographical Memoirs of Fellows of the Royal Society* Vol 13 (1967) 303.