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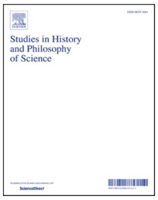

Aesthetic Considerations in the Development of Plate Tectonics

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ABSTRACT

Aesthetic considerations played a substantial and positive role in the development and acceptance of plate tectonics, the modern theory of the earth's major geological features and the unifying framework of the earth sciences. Here I give an overview of how aesthetics influenced plate tectonics and take a detailed look at a handful of examples from this history where elegance and simplicity tipped the balance in favour of a given hypothesis. I discuss some implications of this case study for extant accounts of aesthetics in science and argue that the positive role aesthetics played can be explained by recent accounts that posit an indirect and contingent link between knowledge and psychological mechanisms underlying aesthetic appreciation.

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1. Introduction

In this paper, I show how aesthetic factors influenced the development of plate tectonics, the unifying theory of the earth sciences. The history of plate tectonics has been written about by philosophers and historians before, so why do we need to revisit that history? For three reasons. First, the way that aesthetic factors influenced the development of this theory is underexplored – when explored at all – in previous work (Frankel, 2012; Giere, 1988; Glen, 1982; Hallam, 1989; Le Grand, 1988; Oreskes, 1999; Pellegrini, 2019; Schindler, 2018; Weber and Šešelja 2020; Šešelja and Weber, 2012).[1] Second, to see how and when aesthetic factors influence science we need to consider historical cases in detail. Although much of the literature on aesthetics in science contains case studies the cases are typically briefly described, giving more a taste of how aesthetic judgements influence scientific reasoning rather than an in-depth picture of how that happened (e.g., Engler, 1990; Kivy, 1991; Breitenbach, 2013; Todd, 2017; Ivanova, 2021, the papers in Bueno et al., 2018 and in Ivanova and French, 2020) though there are some notable exceptions and the trend is towards more case studies (Chandrasekhar, 1987; Glynn, 2010; Ivanova, 2017; Kragh, 2011; McAllister, 1996; Ritson, 2023; Stuart, 2023; Turner, 2019; Wragge-Morley, 2020, 2023; Wylie, 2021). The history of plate tectonics provides many examples of how aesthetic factors influence scientific reasoning, making it an excellent case to study to understand this puzzling phenomenon. Third, there's long been a widespread impression that aesthetic factors only play a role in highly abstract fields like physics and mathematics. Although this is changing (Currie, 2023; Ivanova, 2021; Kozlov, 2023; Turner, 2019; Wylie, 2021) more work is needed on aesthetics in 'messier' sciences like biology, psychology, and geology. This paper is, to the best of my knowledge, the first in-depth discussion of how aesthetic factors influenced the development and acceptance of plate tectonics.

I begin with a brief overview of plate tectonics and aesthetic properties (section 2) before discussing how the theory was guided by aesthetic considerations from its beginning as continental drift in the 1910s (section 3.1) to the theory as we know it today (section 3.2). In section 4, I discuss three cases where elegance and simplicity tipped the balance in favour of a given hypothesis, showing that aesthetic judgements played a substantial and helpful role. In section 5, I look at ways of explaining this intriguing fact in a way compatible with the historical evidence that aesthetic considerations are sometimes misleading (Hossenfelder, 2018; Ivanova, 2020) and discuss recent accounts which posits an indirect link between beauty and knowledge.

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[1] Anderson, 2002 is the only paper-length discussion of aesthetics and plate tectonics I've come across; it criticises the 'standard model' of plate tectonics for not being simple and elegant enough (2002:56, 63).

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2. Overview of plate tectonics and aesthetic properties

2.1. Brief overview of plate tectonics

The theory of plate tectonics is one of science's big success stories, and aesthetic considerations played a significant role in its development and acceptance. Plate tectonics is *the* grand unified theory of the earth sciences, developed over the past century in two 'growth spurts', or periods of rapid development. The first, in the 1910 and '20s, gave rise to the theory of continental drift – the immediate precursor to plate tectonics – and the second, in the 1960s, gave rise to the modern theory. As a contemporary textbook has it,

> Plate tectonics remains the first and only global geodynamics theory which orchestrates all known tectonic phenomena including earthquake zones, mountain building, structural patterns, nature of sedimentary basins, magnetism, and metamorphism – *plate tectonics is an elegant and comprehensive synthesis* of Earth's geodynamics. (Frisch et al. (2011:4), italics inserted)

Briefly put, plate tectonics says that the lithosphere (the uppermost, brittle layer of the earth) is broken up into rigid plates separated by narrow zones where the plates move apart from or under or slide past each other. Underneath the plates, there is a layer of molten rock (the asthenosphere), which rises to the surface in the cracks left by diverging plates, mostly along midocean ridges, and becomes part of the lithosphere as it cools. Plates are moved by gravitational 'slab pull' from subducted plate segments, 'ridge push' as newly minted seafloor is pushed aside to make room for more upwelling magma, and convection currents in the asthenosphere driven by radioactive heat from the earth's core. Based on two simple assumptions – that plates are rigid and that their relative movements can be described as rotation around a pole – the theory predicts plate movements with astonishing accuracy.

2.2. Aesthetic properties

Frisch et al. claim that the theory is elegant, and such praise is common. Two features of the theory are particularly often praised for its aesthetic appeal: its geometrical simplicity and its unification of a wide variety of phenomena. Plate tectonics explains much by making few and uncomplicated claims about the planet: "[m]uch of the beauty of plate tectonics lies in the geometric exactness and simplicity of this geometry of movement" (Cox and Hart (1991:9)), "[t]he beauty of plate tectonics lies, in large part, in the simplicity with which the kinematics can be described – as rigid plates" (Molnar (2003:305)). It also provides a streamlined framework for understanding its large-scale geological features: it's "an elegant and comprehensive synthesis" (Frisch et al. (2011:4)) and the "plate tectonic model explains most of the geologic and geophysical features of trenches and island arcs with elegant simplicity" (Cox and Hart (1991:30)). Hypotheses about mobile continents, seafloor spreading, different kinds of plate boundaries, and more, were joined under the simple geometrical framework of McKenzie and Parker (1967) and Morgan (1968), and this fitting together of wide-ranging ideas in an uncomplicated way evoked great pleasure. Judging by how the scientists expressed themselves, this pleasure was distinctly aesthetic.

Scientists describing what they find beautiful in a theory often talk about the harmony of how parts of it fit together. ('Beauty' is here taken to range from harmony and elegance to neatness and prettiness.) For example, Henri Poincaré talks about the "intimate beauty which comes from the harmonious order of its parts" (in Ivanova 2017:2584), and Subrahmanyan Chandrasekhar, following Heisenberg, takes beauty to be the "proper conformity of the parts to one another and to the whole", which causes "wonderment and surprise" (1987:70).[2]

Philosophers of aesthetics also often note that beauty is partially based on harmony or goodness of fit (Scruton (2009:96), (Todd (2017:228)). As Cochrane says, "we find objects or events beautiful when many parts seem to harmoniously fit together" (2021:42). Furthermore, beauty is often explicated in terms of unity in complexity (or 'simplicity in diversity'): despite differences, the parts are connected at a deeper level (Cochrane (2021:36), McAllister (1996:21, 110), Engler (1990:27)). I take it that a delight in harmony, unity, and simplicity (and their close kins wideness of scope and non-gerrymandering)[3] is a standard aesthetic response to central aesthetic properties. What we find beautiful might be a nonevaluative property onto which we project aesthetic value or an objective, intrinsically beautiful property of the theory (Breitenbach, 2013; Ivanova, 2017; McAllister, 1996). Regardless, it's clear that we attach aesthetic value to certain properties, valuing them as good(or bad)-for-their-own-sake in the way typical of aesthetic engagement[4] (e.g., Cochrane (2021:14); Kant, 2000).

However, simplicity, unity, and fit can also be invoked as purely descriptive properties (Todd (2017:215)). It's notoriously difficult to pinpoint what's aesthetic in a noncircular way and this is even more challenging in scientific contexts where aesthetic judgements tend to be closely connected to epistemic judgements. Cain Todd (2008) argued that without a well-motivated individuation of the aesthetic we should assume that 'aesthetic' judgements in science are masked epistemic assessments. This view, which requires rejecting scientists' explicit statements of their (aesthetic) experiences, is tempting only if we think that aesthetic judgements cannot be epistemically significant. New work on aesthetics in science (including Todd's later work) show that aesthetic and epistemic judgements are closely intertwined: we need not deny either that scientists express genuinely aesthetic experiences or these experiences' close connection to epistemic evaluations (see section 5).

3. Aesthetic considerations in the development and acceptance of plate tectonics

3.1. Continental drift

Continental drift provided a simple framework for explaining the large-scale features of the earth – in particular, mountain building and similarities among continents currently divided by oceans – by stating that the continents move horizontally through the seafloor, which is made of denser material and behaves like a highly viscous liquid, and that the geological structure of the earth is caused by the way that continents

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[2] See also Weinberg: "There is another quality besides simplicity that can make a physical theory beautiful – it is the sense of inevitability that the theory may give us. In listening to a piece of music or hearing a sonnet one sometimes feels an intense aesthetic pleasure at the sense that nothing in the work could be changed, that there is not one note or one word that you would want to have different" (Weinberg (1993:107)). "The beauty that we find in physical theories … is very like the beauty conferred on some works of art by the sense of inevitability that they give us" (1993:118).

[3] An ad hoc or gerrymandered theory has a wide scope without being unified, reducing its goodness of fit ("The reason why the Standard Model is so ugly is that it is obtained by gluing, by brute force, the current theories of the electromagnetic force, the weak force, and the strong force into one theory" (Kaku and Thompson, in Ivanova (2020:94)). Ad hoc theories are problematic also for other reasons, like their lack of independent support (see Schindler, 2018 for an overview).

[4] This is often contrasted with valuing something for its practical utility, but practical and aesthetic value are not necessarily opposed (Saito, 2007).

move around.[5] The developer of drift, Alfred Wegener, argued that his theory could explain more phenomena and explain them better than competing theories could (e.g., (Wegener, 1977:117)). Wegener is credited with developing the theory, and deserves that credit, but many of his ideas were not new (Oreskes (1999:54–5), Le Grand (1988:46)).[6] What was new was the way he put those ideas together into a coherent and detailed theory that could explain both geological and geophysical evidence. The various pieces of evidence had seemed incompatible with each other and led to the development of theories which each could explain only half the evidence and was disconfirmed by the other half (Wegener (1977:25)). The theory that best fitted the geological and palaeontological evidence was contraction theory, which was generally accepted in Europe, and the one that best fitted geophysical evidence was permanence theory, which was generally accepted in North America (Oreskes, 1999). Contraction theory said that the earth is cooling and that as it does so it gradually shrinks, much like an apple becomes wrinkly when it dries (Suess 1904–24, Wegener (1977:29)).[7] The continuous change and strong lateral forces exerted on the earth's surface were used to explain the complex folding of the Alps and the distribution of fossils, including the presence of marine fossils in mountains. Permanence theory said that oceanic and continental crust resulted from different kinds of minerals solidifying at different temperatures as the earth cooled, causing the continents and ocean basins to be different in kind, which fitted the geophysical data (particularly the fact that the crust is in isostatic equilibrium which, given the mass difference between continental mountains and ocean basins, must mean that they differ in density). The oceans and continents deformed over time but were always in the same relative position to each other, hence 'permanence' (Dana 1847, Oreskes (2003:5)).[8] Both permanence and contraction theories struggled to explain the evidence that the other theory was designed to explain, as Wegner was quick to point out (Wegener, 1977:38–40). Drift theory, however, fitted both the geological and geophysical evidence (*ibid.*). It thus unified phenomena explained by both contraction and permanence theories, and it did so through a simple hypothesis: light and thick continents move horizontally through dense seafloor, which acts on a geological timescale like a viscous liquid, and major geological features are caused by the way that continents move apart and collide with each other.[9]

Wegener's theory struggled with both fleshing out the details and finding a plausible mechanism for drift.[10] However, what mattered to Wegener was the plausibility and elegance of the overall idea. Let's first consider his focus on the big picture. Wegener's attitude can be seen in the major revisions he made to *the Origin of Continents and Oceans* and in explicit statements, such as where he discusses geological evidence in favour of drift:

> Even though the theory in certain individual cases may still be uncertain, the totality of these points of correspondence constitutes an almost incontrovertible proof of the correctness of our belief that the Atlantic is to be regarded as an expanded rift. (1977:117)[11]

In other words, Wegener's argument was abductive: he presented evidence which was not necessarily convincing when taken separately but which pointed in one direction, and argued that this was best explained by his account.[12]

During the first weeks of his work on drift, Wegener wrote in a letter to Wladimir Köppen "that his hypothesis of continental displacements was not an imaginative creation or a fantasy but … a radical reorganization of existing observational data into a new picture, *producing simplification and coordination in the place of previous complexity and contradiction*" (Greene (2015:240), italics inserted). Some of these virtues have clear aesthetic overtones. We don't need to invoke aesthetics to explain why he wanted to avoid contradiction, but the distaste for complexity and desire for simplification and coordination are aesthetic attitudes concerning the goodness of the way 'the new picture' fits together (see section 2.1).

That aesthetic properties were important to Wegener is also seen by the praise he accepted. (Incidentally, this praise shows that he wasn't alone in aesthetically appreciating the theory.) When talking about the uneven distribution of mountain chains across the globe, Wegener quotes Émile Argand as saying that

> the *elegance* with which drift theory explains these significant facts, which were not known when the theory was originated, *is certainly a strong point in its favour*. Strictly speaking, none of these facts really proves drift theory … but *they all fit in excellently* … to an extent that makes them highly probable. (1977:131, italics inserted)

So Wegener wasn't alone in taking the aesthetic properties of drift as support for the theory.

You might object that what Argand appreciated was that drift could explain 'significant facts' and that it made novel predictions which turned out to be correct: the appreciation was strictly epistemic, not aesthetic. But Argand explicitly expresses the aesthetic praise as something additional: the explanations and novel predictions are one thing, but the *elegance* with which the theory explains the facts 'is certainly a strong point in its favour'. Similarly, the 'excellent fit' of facts that 'strictly speaking' don't prove drift – I assume he means there are other possible explanations for the data – is taken to raise the probability of the theory. This isn't just about the likely truth of drift. It's about the

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[5] We now know that the continents are passively dragged along with the seafloor they are connected to (Frisch et al., 2011) instead of ploughing *through* the seafloor: this is one of the few significant cases of a hypothesis from drift theory not being incorporated into place tectonics.

[6] Wegener presented the first account of continental drift in two papers in 1912 (Frankel (2012:38)), expanded it into a book in 1915 (*Die Ehtstehung der Kontinente und Ozeane*, transl. *The Origin of Continents and Oceans*), which was published in expanded and revised editions in 1920, 1922, and 1929. The version relied on here (Wegener, 1977) is a reprint of the English translation of the fourth edition. Independently of Wegener, Frank Taylor proposed a version of drift theory in 1910. His account was not widely read, and it is unlikely that Wegener knew of it when developing his theory (Oreskes (1999:82), Frankel (2012:70)).

[7] "The dislocations visible in the rocky crust of the earth are the result of movements which are produced by a decrease in the volume of our planet. The tensions resulting from this process show a tendency to resolve themselves into … horizontal (i.e. thrusting and folding) and vertical (i.e. sinking) movements" (Suess (1904:107)).

[8] Permanence theory was originally a version of contraction theory, but the claim that the earth had contracted was later abandoned (Le Grand (1988:23)).

[9] See Oreskes (1999:54–5) and Frisch et al. (2011:2–3).

[10] It's sometimes claimed that this is why drift was rejected in North America, but as Oreskes' (1999) excellent historical account shows, this was not the case.

[11] See also van der Gracht, who organised a 1926 symposium on continental drift and said that the "manner in which *major* facts fit into this theory is very suggestive of the fundamental truth that such a thing as considerable inter- and intra-continental drift occurs. The details of the picture, and particularly the mechanical and physical explanation, will need considerable further research" (van der Gracht (1928:75)).

[12] Oreskes, 1999 doesn't comment on this, although she has an in-depth discussion of Wegener's argumentative style in relation to how methodological and stylistic differences in American and European earth science contributed to the rejection of continental drift in America (1999:126, 153–5, 157). According to Oreskes, the major methodological divide of the earth sciences was between inductivism and deductivism, where induction does not include abduction (1999:145, 303–4) and deductivism is basically the hypothetico-deductive method (1999:141, 157, 284). She says that "Wegener's treatise was explicitly deductive" (1999:154). But Wegener's arguments were often abductive. The issue might be terminological, for Oreskes says that "[h]is was a causal-theoretical account, in which a basic principle was used to illuminate a wide range of geological evidence, not the other way around" (*ibid.*), and 'illuminate' sounds more like 'explain' than that the evidence deductively follows from a basic principle.

aesthetically satisfying way drift explains orogeny.[13] Why think that? Because, first, Argand uses aesthetic terms and, second, it looks like an entirely standard aesthetic reaction, namely the appreciation experienced when the parts (whether parts of a painting, music, fictional narrative, or scientific theory) fit together in a harmonious way.

Wegener also quotes the famous South African field geologist Alexander du Toit as saying that it's the geological evidence that will decide the fate of the theory

> because arguments based on such matters as the distribution of fauna are not competent here; they can generally be explained equally well, *even if less neatly*, by the orthodox view that assumes the existence of extended land bridges. (1977:14, italics inserted)

It mattered not only that drift theory could explain the distribution of fossils and present-day species – so too could other theories – but that it could do so *neatly*. I take 'neatly' here to mean that it provided a tidy, straightforward explanation without unmotivated elements or loose ends.[14] Furthermore, it could explain *both* the geological and palaeobiological data, thereby unifying different fields. Wegener allowed considerations of elegance, simplicity, and unity to play an epistemically significant role in the case he built for Drift; these theoretical virtues were both aesthetically valued and major selling points for the theory.

3.2. Plate tectonics

Aesthetic considerations played a similar role in the second growth spurt, when plate tectonics as we know it today was developed. Although the research happened at a much larger scale, with well-funded teams of scientists collecting an amount of data that scientists before the 1940s could only have dreamt of,[15] many of the important theoretical developments were made by scientists who didn't have access to conclusive evidence but relied on their aesthetic sensibilities in extrapolating from what they did have access to.

Continental drift never became the consensus view, but in Europe, South Africa, and Australia it became a staple account alongside contraction theory and permanence theories, further developed by luminaries like John Joly, Reginald Daly, Alexander du Toit, and Arthur Holmes (Oreskes, 1999). In North America permanence theory still held sway (Oreskes (1999:124–7), Le Grand (1988:117–8)). North American earth scientists were not taken in by continental drift's aesthetic appeal: "It was too large, *too unifying*, too ambitious. Features that were later viewed as virtues of plate tectonics were attacked as flaws of continental drift" (Oreskes (2003:11, italics inserted)). The enticement of this unifying theory was resisted because it (and Wegener) clashed with the prevailing American methodology of strict empiricism and 'multiple working hypotheses' (Chamberlin, 1970; Oreskes, 1999), resulting in decades spent looking in the wrong direction.

Work on Drift slowed to a trickle, not least due to the disruption of research by World War II. This was a blessing in disguise for plate tectonics, for many earth scientists joined their countries' navies and while at sea collected data on the structure and composition of the seafloor. Some of the most important new evidence for drift/plate tectonics was based on these data.[16] The importance of this research for submarine warfare and detection of nuclear tests opened the eyes of government funding bodies to the usefulness of geophysical research, dramatically increasing resources in the post-war years (Menard (1986:37–42), Oreskes (2003:17)).

Some of the research was a continuation of work done by Felix Vening Meinesz, Harry Hess, and David Griggs in the 1930s, who had extended Holmes' argument for convection currents as the mechanism behind drift and orogeny (Le Grand (1988:116–7), Oreskes (2003:13–6)). Scripps Institution of Oceanography (directed by Roger Revell) and Lamont Geological Observatory (directed by Maurice Ewing) sent scientists on near-continuous expeditions in the two decades immediately following the war. When winter conditions made research in northern seas impossible, they sailed to the southern hemisphere, and vice versa (Menard (1986:41)). Continuously, and aided by recent technological advances, they collected core samples, studied earthquakes, and collected all the data they could gather on bathymetry, heat flow, gravitational variations, and the composition of the seafloor with echograms, magnetometers, and seismic refraction studies (explosives).[17] Gravitational measurements revealed huge structural features of the seafloor, such as the immense mid-ocean ridges, deep-sea trenches, and what was later recognised as transform faults. Seismology showed that the seafloor, far from being the previously imagined smooth surface, mostly consisted of steep hills relatively unburdened by sediments (Menard, 1986:51–2)) – suggesting it was young.

In the early 60s, Hess and Robert Dietz independently proposed what Arthur Holmes had suggested decades earlier (Morley (2003:79), Cox (1973:15–6), Menard (1986:152–61)), namely that new seafloor is created through upwelling magma in cracks left by diverging plates and powered by enormous convection currents in the asthenosphere. The magma becomes part of the 'spreading' seafloor as it cools to solid rock and moves away from the rift to sink beneath continents (where trenches form). When the subducted seafloor sinks into the hot asthenosphere it melts to become part of the mantle material, which in turn becomes part of the lithosphere when it reaches the surface in midocean ridges or in volcanic eruptions. If one accepted mantle convection, "a rather reasonable story could be constructed to describe the evolution of ocean basins … Whole realms of previously unrelated facts fall into a regular pattern, which suggests that close approach to satisfactory theory is being attained" (Hess, 1973:27)).

Dietz (1961) called this process 'seafloor spreading', and the name stuck. Hess and Dietz's picture, supported by the old considerations in favour of drift together with the recent gravitational and magnetic data, gave new support to the hypothesis of mobile continents. Some of the most intriguing of these data were from Ron Mason and Arthur Raff's magnetic survey of the north-eastern Pacific from the late 1950s, published as maps (Mason & Raff, 1961, Morley (2003:78)).[18] These maps astonished the scientific community, for they showed a clear and

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[13] Keep in mind that the evaluation can be *both* aesthetic and epistemic.

[14] Wegener (1977:35) also criticises the land bridge hypothesis for requiring "further hypotheses which are 'ad hoc' improbabilities".

[15] See Menard (1986) for an excellent account of the research teams and their developing ideas leading up to the formulation of plate tectonics.

[16] Unfortunately, much of it was classified. One of the best examples of scientists finding a way to share important but classified data is Bruce Heezen and Marie Tharp's (1977) map of the ocean floor, which was based on – but did not reveal – the data that they were prohibited from sharing, providing the scientific community with an accurate depiction of major structures of the seafloor (Oreskes (2003:23)).

[17] By noting the velocity with which pressure waves travel from an explosion one can discover the thickness and some of the structure of different layers of the seafloor. The seismologists struggled for many years to get the explosives and the hydrophone (the 'receiver' of the seismic waves) down to the seafloor until an "astonishingly simple technical solution" was found: "[i]f the ocean is considered to be just one more layer of the earth, the problem vanishes. The hydrophones and explosions could be at the surface of the sea" (Menard (1986:35)). Thus started the "standard procedure to throw a 0.2 kg explosive charge overboard every 2 min" which accidently killed a researcher in 1961 (Menard (1986:42)).

[18] These maps are regularly described as beautiful. Tanya Atwater recalls "sorting through [Lamont's] voluminous data sets to plot out magnetic anomaly profiles from all the world's spreading centres. … [W]hile I was at it I conducted a magnetic anomaly "beauty contest". After all these decades of ships collecting new data, that old *Eltanin*-19 crossing still won first prize" (2023:386, note 5). It is "wonderfully clear and symmetric and exceptionally easy to read" (*ibid.*), suggesting that its beauty is connected to its quality as data, and thus that epistemic and aesthetic evaluations are connected (see sections 2.2, 5).

remarkably regular pattern of stripes of positive and negative magnetic anomalies parallel to midocean ridges and roughly in line with the coast, and the pattern didn't correspond to other features of the seafloor. This came to be known as the 'zebra pattern' and it puzzled the scientific community for some years until explained by the 'Vine-Matthews-Morley hypothesis' (Vine and Matthews 1963).[19] This hypothesis is the upshot of the seafloor speading hypothesis and the geomagnetic reversals hypothesis (discussed below), stating that the new magma created at spreading centres takes on the polarity of the geomagnetic field at the time of cooling. As this field periodically changes polarity the direction of the magnetic field will be recorded in a pattern of stripes of normally and reversely magnetised rock parallel to the ridge axis and symmetrical on either side of it, showing a linear relationship between the age of the seafloor and its distance from the ridge.

The zebra pattern revealed by the magnetic surveys is exactly what one would expect from constant seafloor spreading and periodic geomagnetic reversals.[20]

Lawrence Morley, who independently from Vine and Matthews proposed the hypothesis, recounts the immediate confidence he felt about it:

> I had [the zebra map] on my mind for nearly two years before I spotted the Dietz paper on ocean floor spreading. Eureka! (2003:80)
>
> I never had any doubts about the concept. It locked three disparate and unproven theories together in a mutually supportive way: the theories of continental drift, sea floor spreading, and the periodic reversing of the geomagnetic field. It was like finding the key piece to an enormous jigsaw puzzle that made everything fit together. (2003:83)

Note how much weight is put on aesthetic and explanatory factors here. The (abductive) support of the three hypotheses was strong when they were taken together, because it resulted in one simple, unified, and well-fitting picture. Morley was certainly not alone in being immediately convinced on seeing this 'key piece of the jigsaw puzzle'. Here is how Mason recalls receiving the hypothesis:

> Vine and Matthews' hypothesis offered an *elegant explanation* of how the magnetic lineations of the northeast Pacific could have come about, although in this case there was no obvious connection with an ocean ridge. … I had absolutely no doubt as to the correctness of their hypothesis. (Mason, 2003:41; italics inserted)

Significant pieces of evidence were missing and so was a central piece of the big picture (the connection with a mid-ocean ridge[21]). And yet Mason was utterly convinced that the hypothesis was true! It elegantly made sense of the available data and *seemed so right* that he was willing to accept that the strong universal generalisation expressed by the Vine-Matthews-Morley hypothesis was true.

The pleasure these scientists felt when engaging with this hypothesis, based on the way it fitted together different ideas in a mutually supportive framework and the elegance of the ensuing explanation of the magnetic lineations, also gave them a great confidence in it. Compare Paul Dirac, who wrote that "one has a great confidence in [a] theory arising from its great beauty, quite independently of its detailed successes" (1980:40, quoted in Ivanova (2020:88)). Luckily, pleasurable feelings don't always cause immediate acceptance of the object of those feelings.[22] But this case shows what can be harder to spot in less extreme cases, namely that the pleasure of seeing how everything fits perfectly together – a typical aesthetic delight – is closely connected to acceptance.

By 1963, after the publication of the seafloor spreading and Vine-Matthews-Morley hypotheses, almost all the pieces of plate tectonics were assembled. But no one had yet given a good mathematical description of the plates' movements, and some features – like the fracture zones that offset midocean ridges – were still puzzling. The pieces came together with two additional simple hypotheses: that plates are rigid bodies and that their movements are described by Euler's theorem of motion on a sphere.

In continental drift it was assumed that the continents behaved more or less like rigid plates, and, from Holmes onward, that the seafloor did the same.[23] What was new was the decision to model the lithosphere as broken up into perfectly rigid plates with all the action happening along their boundaries and in the asthenosphere underneath them. Doing that allowed one to use Euler's theorem of rigid-body rotations (discussed below) to describe how the plates moved, and suddenly everything fell into place. Like so many other important discoveries in the history of plate tectonics, this idea was hit upon independently by two groups: Dan McKenzie and Robert Parker (McKenzie and Parker, 1967) and Jason Morgan (Morgan, 1968).

Euler's theorem says that any movement of a rigid body on the surface of a sphere corresponds to a rotation of that body around some axis that passes through the centre of the sphere. The movement of one such rigid body relative to another traces small circles whose centre is their common rotational axis. 'Teddy' Bullard et al. (1965) used this theorem to fit continents together but failed to see its implications for lithospheric movement in general. For example, it perfectly described the curious fracture zones at each side of the mid-Atlantic ridge that can "almost be fitted with a set of great circles – almost but not quite. Morgan found that the fracture zones could be fitted much more accurately by a set of small circles drawn about a point that he soon realised had the significance of being a pole of relative motion between two plates" (Cox (1973:46)).

McKenzie used a map of earthquake zones to come up with the plate boundaries. In this he was greatly aided by Tuzo Wilson's famous 1965 paper (Wilson, 1965), where Wilson argued that all active plate boundaries are connected as a network spanning the globe and introduced a new, third kind of plate boundary (transform faults). The two previously recognised boundaries are what is now called 'constructive plate boundaries' (like midocean ridges) and 'destructive plate boundaries' (subduction zones). These boundaries are often offset by huge faults (fractures) where the plates slide past each other ('conservative plate boundaries', or 'transform faults'). These faults end abruptly where they intersect constructive or destructive boundaries, 'transforming' into these other kinds. Looking at a map of the epicentres of earthquakes and volcanoes, you see a map of plate boundaries, because most of the seismic activity happens along active boundaries. Such maps were essential for Morgan and McKenzie/Parker when they worked out the geometry of plate movements, as they were the best source of information on the size, shape, and location of tectonic plates. Wilson's "original theory was worked out for flat plates on a plane" (Cox (1973:45)); with the help of Euler's theorem, his global network could

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[19] Morley came up with the idea before Vine and Matthews, but his paper was rejected by two journals and it took some years until the community learnt that he had had the same idea (Vine (2003:57)).

[20] Assuming that the negative anomalies (low intensity magnetism), as measured at surface level, correspond to reversely magnetised rock – which it does – as more direct measurements were unavailable in the 60s.

[21] Vine and Matthews' data was from the Carlsberg Ridge and lacked the symmetry that is so striking in the zebra pattern maps (from the Juan de Fuca Ridge).

[22] But see Dechêne et al. (2010) on the 'illusion of truth' effect: we are more likely to accept what we find aesthetically pleasing.

[23] "For me the central idea [of plate tectonics] is the rigidity of plate interiors. It is this property that allows the surface motions of the earth to be described *by so few parameters*. Other versions of the theory – continental drift, palaeomagnetic reconstructions, and sea floor spreading – implicitly or explicitly used this property, but did not recognise its importance" (McKenzie (2003:183; italics inserted)).

be fitted to the globe. This turned out to describe the plate movements perfectly, even where it looks extremely complex. Tanya Atwater recalls questioning McKenzie and Parker about the adequacy of their account for the complex Mendocino fracture zone, and they replied that it lay on the intersection of three plates. "Three plates! Of course. So elegant, so simple, so powerful" (Atwater, 2003:250). Atwater's exclamation could have been made about plate tectonics in general, and it nicely expresses the general attitude towards the theory: it is so elegant, so simple, and so powerful.

So far, we have seen that aesthetic factors influenced the development of continental drift and its transformation into plate tectonics from a bird's eye perspective. Let's have a closer look at some examples.

4. A 'harmonious major picture', troublesome rocks, and elegant fit

More than once did individual scientists and the scientific community stick with strong, simple, elegant theories in the face of apparently contradictory evidence, and more than once were they reluctant to incorporate data when this would have made their otherwise elegant theory complicated. That is, sometimes aesthetic considerations were weighted heavier even than fit with data. In this section, we'll see three examples of aesthetic considerations shaping research in this way.

The Squantum 'tillite'. As mentioned, for Wegener what mattered was to paint a compelling big picture, not to be right in all the details, and he was happy to let a "harmonious major picture" (1928:98) overrule apparent counterevidence. Central to the case he made for continental drift was palaeoclimatological data showing that there had been extensive glaciation in areas that are now tropical or sub-tropical, which he (rightly) interpreted as evidence that these landmasses had once been located much closer to the poles. However, some pieces of apparent counterevidence threatened to undermine this picture, like the so-called 'Squantum 'tillite''.[24] A tillite is a rock formed of sediment deposited by a glacier and consists of pebble-sized and larger rocks contained in a fine-grained matrix. It's central to the rock's classification that it's formed by a glacier, so it must have formed somewhere cold enough for glaciation. The Squantum 'tillite' is found just outside of Boston and dated to the Permo-Carboniferous, at a time when – according to Wegener (and today's view) – North America had a latitude between 10 and 30°: not a location known for being cool.[25] Wegener (and other drifters; e.g., Holmes (1928:433)) questioned the interpretation of the data, arguing that it did not constitute evidence against drift in general or his historical reconstruction in particular, and he used both empirical evidence and fit with drift theory to argue against the classification of the Squantum rocks as tillites:

> We have a multitude of indications for the past geological climate in the United States, and although we admit that several details are uncertain, they yet match and *give us a harmonious major picture*. *In the main, it is clear and simple* that there is cumulative and concordant evidence that in the upper Carboniferous the United States was within the edge of the pluvial tropical belt, and during the Permian in the hot tropical desert zone. (Wegener, 1928:98–9, italics inserted)

The 'harmonious major picture' he extracted from *much* of the data was enough to overrule the contradicting data (like the Squantum 'tillite'). The evidence for the hot climate of North America during the Permo-Carboniferous was 'clear and simple' but *only after discarding the conflicting data* by arguing that it wasn't correctly interpreted and therefore didn't contradict his reconstruction of continental locations. It's pretty bold to prefer harmony and simplicity to fit with the data, yet they sometimes contain errors – as was indeed the case here: the rocks are not tillites. Wegener's aesthetic preferences worked like a counterbalance to misleading data, pushing him to explain away the data that didn't fit his harmonious major picture instead of (over)fitting his theory to it.

Geomagnetic data. Like Wegener, many of the scientists involved in the development of plate tectonics eschewed a perfect fit with data for an elegant big picture. As mentioned, the discovery of geomagnetic field reversals was essential for understanding the zebra pattern and for developing plate tectonics. But observations were made early on that cast doubt on field reversals. For instance, Nagata Takeshi and Uyeda Seiya discovered that some rocks heated beyond their so-called Curie temperature took on the *reverse* polarity of the magnetic field they were in (Nagata, 1952).[26] If this phenomenon was widespread, then stripes of reversely magnetised seafloor wouldn't support the hypothesis of geomagnetic field reversals. The discovery of these 'self-reversing' rocks, as they became known, "contributed greatly to the ongoing scepticism" of continental drift (Pitman (2003:89)). As Opdyke explains, "[s]ince both this newfound support for continental drift [palaeomagnetic evidence of apparent polar wandering][27] and the argument for field reversals rested on palaeomagnetic observations and were often argued by the same people, they were lumped together as radical and unreliable" (Opdyke, 2003:98). That's unsurprising. What *is* surprising is that the scientists who were positively inclined towards drift didn't take the data on self-reversing rocks as undermining field reversals and thereby withdraw the support it gave drift.

This is arguably because the drifters valued aesthetic properties like simplicity and elegance higher than perfect fit with data. Faced with the choice between a simple, elegant, and unifying explanation and greater empirical adequacy, they chose the elegant explanation. Note that in this case, the interpretation of the data wasn't questioned (Heller & Petersen, 1982). The scientists were genuinely giving up empirical fit in favour of explanatory simplicity: the two cases of magnetic reversals (self-reversing rocks, on the one hand, and magnetic anomalies along spreading ridges and laboratory experiments on the magnetic properties of rocks, on the other) were treated as expressions of the same underlying phenomenon (remanent magnetism), and yet the data on self-reversing rocks were dismissed as 'rare' 'exceptions' (Cox et al. (1964:1539–40)) which didn't threaten the elegant explanation.

The Vine-Matthews-Morley hypothesis. This willingness to dismiss what didn't fit simple and elegant hypotheses and extrapolate from what did fit them is also seen in the development of the Vine-Matthews-Morley hypothesis. As Menard puts it, "Fred Vine and Drummond Matthews had to believe three hypotheses simultaneously at a time when few scientists believed any one of them. They also had to disbelieve the only observation directly related to the hypothesis" (Menard, 1986:212). One of these hypotheses was seafloor spreading, to which there was apparent counterevidence in the form of old rocks found near midocean ridges. But as Harry Hess wrote in a letter to Menard in 1966: "if these are disregarded everything fits just as it should" (in Frankel, 1982 :36).

Not everyone was convinced. Walter Pitman recalls his reaction to the hypothesis:

> in the end [it] proved to be a brilliant insight. But the data they presented, taken from over the Carlsberg Ridge in the northwest Indian Ocean, were not very impressive with regard to

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[24] See Wegener (1928:97–8) for a discussion of other apparent traces of glaciation in North America in the Permo-Carboniferous.

[25] Evidence from other landmasses showed that the whole planet couldn't have been cold enough for glaciation during this period.

[26] See Heller and Petersen (1982:368–9) for more examples.

[27] Magnetic data on 'apparent polar wandering' showed where the poles would have had to be located if the landmasses from which the data was collected had remained stationary: however, if one accepted that continents had drifted one could instead use it to recreate earlier positions of the landmasses relative to a stationary magnetic pole.

> correlatability, linearity, and symmetry. I was sceptical and dismissive, as were most others. (Pitman, 2003:89)

Still, Vine and Matthews (and, independently, Morley) extracted one of the most aesthetically pleasing *and* successful hypotheses in all of earth science from these noisy and underwhelming data. How? A plausible explanation is that their ability to focus on the essentials only and thereby extract the correct big picture from ambiguous data was partially due to – or, an expression of – the central role that aesthetic considerations played in their theorising. Their aesthetic preferences acted as useful restrictions on their interpretations of the data and attempts to explain them (cf. Elgin, 2020).

Vine is unusually open about being guided by aesthetic considerations. He was converted to drift from an early age based on not much more than the perfect fit between the coastlines of Africa and South America, saying that "I decided it had to be true; it was too simple and elegant" (in Frankel, 1982:12)). The data Vine and Matthews relied on lacked the clarity and symmetry that's so striking in Raff and Mason's zebra pattern maps (the *Eltanin*-19 magnetic profile; see section 3.2). Still, the inconclusive data from the Carlsberg Ridge combined with a nose for elegant explanations allowed him to develop and accept this celebrated hypothesis.[28]

It's time to lift our gaze from the details and consider what lessons we should draw from the case study; we turn to that in the next section.

5. The epistemic significance of aesthetic experiences

There's recently been a debate about whether plate tectonics was accepted because of the evidence in favour of it or partially because of sociological factors (Pellegrini, 2019, 2022; Weber and Šešelja 2020; Šešelja and Weber, 2012). It might seem that this paper adds another reason to think that its development and acceptance was not sufficiently responsive to epistemic considerations. But that's not what we should take out of this case study. On the contrary, the historical evidence presented here supports the conclusion that aesthetic sensibilities can be helpful in developing predictively successful, strong theories that don't easily succumb to misleading data.

How can the pleasure we find in elegance and other aesthetic properties play such a positive epistemic role?

Perhaps by signalling understanding, as some accounts of aesthetics in science propose (Ivanova, 2020; Elgin, 2020; Kosso 2002). Understanding-focused accounts tend to deny that understanding is factive, thereby making room for an epistemic role for aesthetic judgements that doesn't link them to the truth of a theory (Elgin (2020:35); Ivanova (2020:86)).[29] This case study suggests that aesthetic pleasure signals something stronger than non-factive understanding: it helped the scientists to *get it right*, providing valuable guidance in their efforts to explain our planet's large-scale geological structures and going beyond grasping or framing information without regard for its truth. However, as Milena Ivanova argues (2020:95), it's hard to reconcile the idea that beauty can lead to truth with the historical track record of both beautiful but unsuccessful theories (like Copernicus', with its beautifully circular planetary orbits) and successful, ugly theories (like the standard model in physics).[30] This doesn't make truth irrelevant: as Adrian Currie notes, one can deny "that truth plays any direct role in constraining aesthetic judgement or appreciation (although no doubt, through epistemic engagement, the two are indirectly linked)" (Currie, 2023:318, fn. 4).

If they are *indirectly* linked we can explain the fact that beauty turned out to be a useful guide in 20th century earth science while allowing that it's a fallible guide that sometimes leads us astray. In Currie's account, the link is the sustained, active, 'knowledge-directed' work ('epistemic engagement') that 'attunes' aesthetic sensibilities for epistemic purposes – work, we might add, which tends to be a good way of actually gaining knowledge. An example of attunement is when budding scientists, by making field sketches, learn to "see like geologists" by drawing on and improving aesthetic skills of observation and representation (Currie, 2023:325; Turner, 2019; Wylie, 2021).[31] While this is an important insight,[32] it's an account of the *refinement* of pre-existing aesthetic, non-epistemic sensibilities for epistemic purposes (2023:328). But pre-tuned aesthetic judgements can also be epistemically significant. For example, features that tend to be aesthetically pleasing – figure-ground contrast, simplicity, symmetry, and prototypicality – serve as cues for 'epistemic feelings' (see below). And recall Vine's claim that he believed that South America had once fit with Africa because "it was too simple and elegant". This happened "when I was about fourteen or younger" based on reading one page of his (drift-agnostic) school textbook (Frankel, 1982:12)). That gave Vine minimal opportunities for attunement, yet his confidence was already connected to aesthetic appreciation. This suggests that something more basic than attunement connects aesthetic and epistemic experiences.

Intriguingly, recently accounts from philosophical aesthetics (Armstrong & Detweiler-Bedell, 2008; Cochrane, 2021), psychological aesthetics (Reber et al., 2004), 'neuroaesthetics' (Ramachandran & Seckel, 2012), and accounts focusing on aesthetics in mathematics (Reber, 2018; Todd, 2017) have converged on the view that there is a deeper – though still psychological and contingent – link between aesthetic and epistemic judgements.[33] Tom Cochrane, for instance, sees aesthetic values like beauty as "exploit[ing] the psychological mechanisms that humans possess for the distal detection of something of potential practical value" (Cochrane, 2021:19), in the way that taste helps us detect nutritional value before digestion. Beautiful objects exploit our mechanisms for detecting knowledge by exemplifying patterns that we recognise "will allow lots of details to be reconciled or predicted" (2021:42), giving us "the pleasure of things fitting together" (2021:43).[34] This doesn't mean that beauty always leads to knowledge; far from it. Thus there's no unequivocal connection between beautiful and true theories. However, since we might be rewarded with (aesthetic) pleasure we seek out those patterns that help us 'reconcile or predict' otherwise puzzling phenomena by embedding them in larger, simpler patterns (2021:51), potentially leading us to knowledge (by detecting those patterns) along the way. Applied to our case, their sense of beauty guided the scientists towards patterns (of continental movements, seafloor spreading, field reversals, etc.) that were central to explain 'lots of details', which is why this guidance was so successful.

This is compatible with Cain Todd's (2017) account, where he argues that aesthetic experiences are closely connected to epistemic feelings, perhaps to the extent that they are "jointly aesthetic-epistemic in nature" (2017:227). Epistemic feelings include the experience that you have something 'on the tip of your tongue', that you made an error, confidence in your reasoning process, or feeling you know the answer to a question. Their connection to aesthetic experiences is (partially) suggested by how both respond to processing fluency (how effortlessly we

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[28] Compare Chandrasekhar on Einstein: "he arrived at his field equations by qualitative arguments of a physical nature combined with an unerring sense for mathematical elegance and simplicity" (1987:71).

[29] But see Kosso, who takes understanding to be "grasping the interconnectedness of facts" (2002:43): the apparent interconnections are presumably real, so grasping them involves grasping truths.

[30] See also Currie, 2023; Hossenfelder, 2018.

[31] Compare Bird 2020, who argues that aesthetic appreciation of theories is based on recognising similarities with exemplars used in science education.

[32] Owing much to Turner, 2019, as Currie acknowledges.

[33] See also Murphy, 2023; Kozlov, 2023 on how the aesthetic and epistemic are connected in scientific experiments.

[34] Compare Ivanova: "[Feynman] argues that for a physicist beauty is felt when one can grasp the 'pattern' of nature" (2017:2587).

process information), including how "symmetry, simplicity, fluency, order, clarity" "occur as the objects and causes of both aesthetic and epistemic experiences" (2017:227),[35] and how the "pleasure of understanding" is often connected to "harmony or fit" (2017:228). If aesthetic experiences are upshots of the same psychological mechanisms as epistemic feelings (i.e., a metacognitive monitoring of the adequacy of one's cognitive processing: see Proust, 2013) it's no wonder that aesthetic claims can look like masked epistemic evaluations (Todd, 2008). It's also not surprising that aesthetic experiences *can* be epistemically valuable as metacognition is moderately accurate, sometimes even making us aware of whether we're on the right track before we have conscious access to reasons for our (lack of) confidence (Reder, 1987; see also Koriat, 2008; Fernandez Cruz et al., 2016; Boldt et al., 2017). This could help explain why accepting a theory and finding it beautiful tends to go hand-in-hand, as in the case of Wegener and Vine,[36] and also the unease with concluding either that apparent aesthetic judgements in science are masked epistemic ones or that they are genuinely aesthetic.

6. Conclusion

As we saw in the last section, there are promising ways of explaining the substantial and positive contribution that aesthetic considerations made to the development of plate tectonics. Clearly, more needs to be said to turn this promise into a detailed explanation, but this isn't the place for it. What I hope to have convinced you of is that plate tectonics provide an interesting example of aesthetic considerations in science, showing that aesthetics influence research well beyond highly abstract areas such as theoretical physics and mathematics. This helps us get a realistic sense of the variety of aesthetic considerations in science and provides an additional case against which to test explanatory accounts. The history of plate tectonics is, to use an earth science metaphor, a fruitful dig for examples of aesthetic considerations guiding research and should be considered when trying to explain this puzzling aspect of scientific reasoning.

CRediT authorship contribution statement

Mariona E. Miyata-Sturm: Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing.

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[35] See Reber et al., 2004; Reber, 2018 for pure processing fluency accounts of aesthetics, and Armstrong & Detweiler-Bedell, 2008; Cochrane, 2021 for convincing criticisms.

[36] "Indeed, where there do seem to be cases of theories that are claimed to be beautiful while acknowledged not to be true, or vice versa, it has been noted … [that they are] in the minority" (Todd, 2008, p. 67).

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