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Reception of competing views of seafloor evolution, 1961–1962

1.1 Introduction

Marine geologists had the choice of four competing explanations of the origin and evolution of ocean basins: there was the fixism as espoused by the Ewing brothers (1959), the mobilistic models of seafloor spreading (Hess, 1960d, 1962; Dietz, 1961a), seafloor thinning (Menard, 1960), and rapid Earth expansion (Heezen, 1959a, 1959b; Carey, 1958). By the early 1960s, and except for expansionists, all the above invoked mantle convection.

I want now to trace the debate over ocean basin evolution through 1962. I must, however, first introduce J. Tuzo Wilson, who would about this time replace Hess and Dietz as the most voluble supporter of seafloor spreading. During the 1950s, Wilson was an ardent fixist. He and the theoretical geophysicist Adrian Scheidegger revitalized Jeffreys' contractionism and offered a sophisticated account of orogenesis. Still defending fixism through 1959, Wilson became a mobilist in 1961. Although he was not convinced that mobilism was correct because of its paleomagnetic support, it forced him to wonder if there might be something to mobilism. With this shift in attitude, he soon found ways to accommodate significant elements of Scheidegger's work within his account of orogenesis. Once converted, he never wavered; he championed mobilism with all the ardor with which he had so recently denied it.

After tracing Wilson's changing ideas through the eve of his conversion, I shall discuss the exchange about seafloor spreading between Dietz and J. D. Bernal, a crystallographer by training and a polymath by avocation, who welcomed Dietz's ideas. Returning to Wilson, I shall show that he, aware of Bernal's forthcoming welcome, joined the party and expressed his support of seafloor spreading. I shall then turn to Hess, Menard, Heezen, and Ewing. In a 1961 letter, Menard raised difficulties with Hess's seafloor spreading. Hess responded, and in 1962, Menard raised additional difficulties. Menard also continued to develop his idea of seafloor thinning. Meanwhile, in his 1962 defense of rapid Earth expansion, Heezen attacked seafloor spreading and seafloor thinning, raising difficulties about the geometry and interaction of convection currents. Ewing defended his fixist account of seafloor evolution. He argued that the paucity of terrigenous seafloor sediments, so readily explained by seafloor spreading and Earth expansion, could also be explained by fixism.

I shall conclude by examining a letter that Irving sent to Hess in 1961 after reading the famous 1960 preprint of his paper on seafloor evolution. Irving was happy to see mantle convection as mobilism's cause. However, he was concerned that not enough was yet known about Earth's interior to speculate about mobilism's mechanism, and feared that Earth scientists would again get bogged down in fruitless speculation about mechanism. He wanted efforts to be further directed at proving the reality of continental drift. As it turned out, Hess's seafloor spreading spawned Wilson's idea of transform faults and the Vine–Matthews hypothesis. As we shall see below, once both were confirmed, they provided the concrete evidence that Irving wanted. But Irving at the time was right about the dangers of a further extension of the long drawn-out quest for a mechanism. Even though many accepted seafloor spreading with the confirmation of its two key corollaries, they mistakenly thought that it provided a mechanism. With the transformation of seafloor spreading into plate tectonics, seafloor spreading's dynamics was jettisoned. The tight tie between rising convection currents and the formation of ridges was severed. Plate tectonics was a kinematic theory, it said nothing about mechanism. The reality of continental drift was established and plate tectonics was accepted before its mechanism was revealed.

1.2 Wilson, the man

John Tuzo Wilson (1908–93), known professionally as Tuzo, was born in Ottawa, Canada.[1] His father, J. A. Wilson, was apprenticed as an engineer, and worked in India and western Canada before taking a job with the Canadian government in Ottawa in 1910. By 1918, he was in charge of developing civil aviation in Canada. Wilson's mother, Henrietta Tuzo, in an expedition in 1906 with the Alpine Club of Canada to the Valley of the Ten Peaks in the Rocky Mountains, made the first ascent of the seventh peak, later named Mount Tuzo in her honor. At the camp she met her future husband. They married three years later. Wilson's early life prepared him for hard work and the outdoors. He and his younger sister were taught the primary school curriculum at home by a governess. Well taught, he was ahead of his class when he went to school in 1915. Forced to play with older and bigger boys, he (1990: 267) developed "an independent cast of mind," and "a poor opinion of team sports." Beginning in 1924 at age fifteen, he spent fourteen summers working for the Geological Survey of Canada (GSC). In summer 1925, he had "the good fortune to become a field assistant to Noel Odell," "a fine geologist who had been the hero of the 1924 Mount Everest expedition" (Wilson, 1982: 4; 1990: 268).

In 1926, Wilson enrolled in an honors program in mathematics and physics at the University of Toronto. Compared to fieldwork in geology and inspired by Odell, he found the laboratory work boring (Wilson, 1982: 4). He told his professors that he wanted to study geology. Except for Lachlan Gilchrist, they were surprised and disappointed. Gilchrist designed a program for him to combine physics and geology. He was struck by the contrast between the global approach of physicists and the regional approach of geologists. He wanted geologists to develop a more global approach and underpin their theories with physics. Gilchrist also found work for Wilson as a geophysical assistant during summers.

Graduating in 1930 as the first Canadian student in physics and geology, Wilson, supported by a Massey Fellowship (1930–2), enrolled at the University of Cambridge for a second B.A. degree, where he (1990: 269) had "the good fortune to take lectures from Sir Harold Jeffreys . . . my grasp of mathematics was limited; I understood only a fraction of what he said." Wilson was scheduled to learn exploratory geophysics from Bullard, but worked with James Wordie, because Bullard was delayed in Africa doing a gravity survey of the Great Rift Valley (III, §4.11). They met when Bullard returned, becoming lifelong friends. His supervisor was John Cockcroft, later Sir John and Nobel Laureate.

He obtained his degree, and returned to Ottawa. After a year working with W. H. Collins, Director of the GSC, he was ready to do a Ph.D. in geophysics. Wilson chose Princeton University because he learned that Field, who had encouraged Hess (III, §5.2), Bullard (III, §4.11), and Ewing (§2.2) to work in marine geology, hoped to start offering geophysics at Princeton. But it did not happen. Field at least arranged for Wilson and Woollard, a fellow graduate student, to work with Ewing on his seismic study of New Jersey's coastal plain. He spent a few weekends with Ewing. He also got to know Hess. Wilson was assigned to Professor T. Thom, a structural geologist, and expert on the Beartooth Mountains. Thom gave Wilson $200 to buy a used car, drive to Montana, and survey a section of the Beartooth Mountains. Wilson spent the summers of 1934 and 1935 on the project. He was the first to ascend Mount Hague (12 300 feet). What he found "strengthened" his "belief that geology was rife for change" (Wilson, 1990: 270).

> When I reached the top, I was astonished to find the summit flat, about the size of a football field, and only gently tilted . . . Pondering on the climb later, I realized that, to preserve its flat top, the mountain must have been recently uplifted vertically and not squeezed up like toothpaste some sixty million years ago, which was then the conventional view. This strengthened my belief that geology was rife for change.
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> *(Wilson, 1990: 270)*

Wilson did not think that "rife for change" included continental drift.

With his Ph.D. in hand, he rejoined the GSC in 1936. He worked in Nova Scotia, Quebec, and the Northwest Territories, and developed a longstanding interest in the GSC. Under Collins, the survey had begun using aerial photographs and Wilson used them to trace large structures, bedding of stratified rocks, and glacial deposits, but their use was resisted by older geologists who regarded it "as a form of cheating" (Wilson, 1982: 8). He argued that the Canadian Shield was not a monolithic structure but a mosaic of increasingly younger provinces surrounding very old nuclei. He came to appreciate that aerial photographs allowed one to see large-scale structural features from afar and helped geologists see regional and not just local patterns.

In 1939 he joined the Canadian Army as a member of the Royal Canadian Engineers. Commissioned a lieutenant, he spent four years overseas in Britain. He continued working for the Royal Canadian Engineers until 1946 when he became professor of geophysics in the Department of Physics at the University of Toronto. He did not become a university professor until age 38. When invited to accept the position, Wilson sought the advice of C. J. Mackenzie, President of the National Research Council (NRC) of Canada.

> In 1946 I had to choose whether to remain in the army engineers, where I had reached the rank of colonel, return to the Survey where I was promised that I could soon be Director, enter industry, or succeed Gilchrist as Professor of Geophysics at Toronto. I sought the advice of C. J. Mackenzie, then the wise president of the National Research Council of Canada ... He advised me to go back to the university and to take no administrative job for twenty years for he predicted that I would be successful in research. I accepted his advice and he rewarded me with ample opportunities to travel and organize projects.
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> (Wilson, 1982: 8–9)

Wilson wisely accepted Mackenzie's prophetic advice.

Mackenize's patronage helped Wilson become an influential science advisor in "high" places, especially the NRC. In 1945, Wilson was appointed chair of an Associate Committee of NRC to advise it on geophysical matters. In 1946, this committee joined with Canada's International Union of Geodesy and Geophysics (IUGG) committee to form the Associate Committee of Geodesy and Geophysics of the NRC. He also became a prominent member of IUGG, serving as president (1957–60). The 1957 IUGG meeting was held in Toronto mainly because of his efforts. Wilson was appointed a member of the NRC 1958–64. He used his membership of IUGG and NRC committees well, attending many meetings, giving many lectures, seeing many rocks, and speaking with many geologists worldwide. He eventually took nine trips around the world, continually educating himself about world geology.

In 1950, Wilson embarked on his first world-tour, with extensive stop-offs in Australia and Africa. He was "guided through every state in Australia by local geologists, who explained the regional geology" (Wilson, 1990: 276). They were then, like Wilson, staunchly fixist. King and Plumstead, two avid mobilists, showed him much of South Africa's geology; they failed to convince him that mobilism was correct. Despite his close-mindedness about mobilism, Wilson (1990: 278) later claimed that the trip reinforced his conviction that geologists should take a global approach, studying Earth "as a whole." So he was becoming a globalist in 1950 even though he did not become a mobilist until the 1960s.

Wilson continued his high-paced research efforts until about 1967, when he (1982: 12) thought it "an appropriate time to move on . . . the twenty years of scientific research which C. J. Mackenzie had suggested and which I had enjoyed was up." He accepted an offer to become Principal of Erindale College, a new suburban college of the University of Toronto. Both Tuzo and his wife, Isabel, found the experience rewarding, and Erindale College had become a thriving institution in 1974 when Wilson reached the mandatory retirement age of sixty-five for holding leadership roles in administration. Before he had a chance to retire, however, the Premier of Ontario asked him to be the Director General of the new Ontario Science Centre. Wilson remained an enthusiastic and successful Director General until he retired in 1985.

Wilson was greatly honored for his research and service to his country. In 1946 he became Officer of the Order of the British Empire and Officer of the Legion of Merit, United States. He was elected a fellow of the Royal Society of Canada in 1948, and served as its President in 1972–3. He was elected to the Royal Society of London in 1968. In 1970 he was named Officer of the Order of Canada, and four years later promoted to Companion, Canada's highest civilian honor. He was given a score of medals and awards including: Willet G. Miller Medal, Royal Society of Canada (1958); Civic Award of Merit and Gold Medal, City of Toronto (1960); Logan Medal, Geological Association of Canada (1968); Bucher Medal, American Geophysical Union (AGU) (1968); Penrose Medal, Geological Society of America (GSA) (1968); J. J. Carty Medal, US National Academy of Sciences (1974); Gold Medal, Royal Canadian Geographical Society (1978), Wollaston Medal, Geological Society of London (1978); Vetlesen Prize, Columbia University (1978); Ewing Medal, AGU (1980); Maurice Ewing Medal, Society of Exploration Geophysics (1980); and A. Wegener Medal, European Union of Geosciences (1989). In 1978 the Canadian Geophysical Union established the J. Tuzo Wilson Medal, and he was the first recipient.

1.3 Wilson champions contractionism and continental accretion, 1949–1954

Wilson loved to speculate. He wanted to find general solutions, and was willing to try, even if many, geologists especially, thought his efforts were misguided. Consider, for example, remarks about Wilson by Philip B. King, a prominent, highly respected field geologist, who spent most of his career with the United States Geological Survey (USGS). King constructed a marvelous map of North America (1944) based partly on his own fieldwork. Like Kay, he championed the geosynclinal theory with the evolution of island arcs into mountain belts, and growth of continents around an ancient central core (1959). Wilson made good use of both Kay's and King's maps. In King's 1959 *The Evolution of North America*, he recommended several fixist publications, among them Kay's (1951) *North American Geosynclines* (I, §7.3), Umbgrove's *The Pulse of the Earth* (1947; I, §8.14), and Wilson's (1954) "Development and structure of the crust," his most extensive account of contractionism and continental accretion. King (1959: ix) said of Wilson's work, "It sets forth some bold syntheses of classification and interpretation. Interesting reading, even in those parts which do not altogether inspire belief."

In his defense of contractionism and continental accretion from the late 1940s and first half of the 1950s Wilson makes plain his desire to satisfy physics and geology.

> A comparison is made between the different approaches to the study of the Earth by the field geologist and by the physicist interested in broad terrestrial problems. On one hand, the rapid increase in geological knowledge is giving an increasingly clear picture of the progress of geological history and the nature of the processes which have been involved. On the other hand, the application of new and rapid methods of obtaining measurements of physical properties of the Earth are serving to limit and direct physical speculation about the nature of the Earth's mechanisms. These different approaches must lead to the same conclusion. When reached, it will be a history of the Earth and an explanation of its processes satisfying both to the geologist and to the physicist.
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> *(Wilson, 1952b: 444)*

He was preoccupied with the Canadian Shield and thus with Precambrian geology. Emphasizing uniformitarianism, he argued that mountain belts had formed throughout the Precambrian and in much the same way as they had during the Phanerozoic. Unlike Dana, for example, he rejected the idea that the Canadian Shield formed as a single unit. This led him, as it did King, to argue that the Canadian Shield had itself formed around original old nuclei as ever younger, newly formed, marginal mountain belts were added.

Wilson was enough of a field geologist to want to apply Jeffreys' idealized theory to presently active mountain belts and island arcs, and to adjacent continents. He also wanted to utilize developments in the physics of continuous matter to help explain how Earth's outer layers fail as they contract. Realizing that he needed someone with a stronger theoretical background, he approached Adrian Scheidegger, an applied mathematician at the University of Toronto, who spent 1950 and 1951 on the task. Together, and separately, they argued that contractionism offered the best available solution to the origin of island arcs and mountain belts, and the origin and evolution of continents (Scheidegger and Wilson, 1950; Wilson, 1949a, 1949b, 1949c, 1950, 1951a, 1951b, 1952a, 1952b, 1953, and 1954; Scheidegger, 1953a, 1953b).

Jeffreys maintained that below a depth of 700 km Earth has not appreciably contracted, that it is "contracting, and becoming thinner from a depth of 700 km to about 100 km," and that its outermost layer is no longer contracting, and is separated from the contracting layer by a level of no strain. Scheidegger determined that the outermost layer is under compression, and "fails by thrust faulting in conical zones" along dip angles of less than 45°, while the layer underlying the level of no strain is under tension, and fails by normal faulting at dip angles of more than 45°. Wilson summarized Scheidegger's findings.

> Jeffreys (1929, pp. 278–279) suggested that cooling has not affected the interior of the earth and that, as a consequence, from the center of the earth to within about 700 km of the surface no appreciable change in volume has yet taken place. He proposed that the layers were cooling, contracting, and becoming thinner from a depth of 700 km to about 100 km and that, because the interior was not altering, these layers were stretched out horizontally. He suggested that there was a level of no strain at about 100 km depth, above which the layers had already largely cooled and were therefore under a horizontal crushing stress . . . The shell between 70 and 700 km is considered to be contracting because of cooling, as Jeffreys visualized; and the earthquakes in it are thought to be due to normal faulting, that is, sliding fracture along conical fault zones, as shown in Figure 13. Since these are due to relief of horizontal pressure, these deep cones dip at angles of rather more than 45° . . . On the other hand, the shell above 70 km is in compression due to the contraction below it and fails by thrust-faulting in conical zones, which usually lie immediately above those just mentioned. Since the upper faults are due to compression, the cones dip at less than 45°. The direction of motion in shallow and deep earthquakes is opposed, one set being due to normal faulting, the other to thrust faulting.
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> *(Wilson, 1954: 170–172; Figure 13 is reproduced below as Figure 1.1)*

Scheidegger applied Mohr's (1928) classical theory of fracture to spherical shells, and obtained an excellent match with the geometrical features of island arcs, mountain belts, the trend of earthquakes, and with types of faults. He determined that the outermost shell fails conically around a point of weakness. Assuming that weak regions are located along continental margins, Scheidegger and Wilson argued that contraction explained how island arcs and mountain belts formed (RS1); the fracture's conical shape determined the arcuate shape of island arcs and young mountain belts; the fracture's incline corresponds to the Wadati–Benioff zone, the zone of earthquakes that descends beneath island arcs and active mountain belts. Wilson claimed:

> No system of forces acting upon a uniform spherical shell has been discovered which can explain a system of arcuate failures such as occur on the earth. On the other hand, a non-uniform spherical shell with points of weakness or zones of weakness along continental margins may be capable of failing so that there might be produced a series of arcuate failures near those margins. It seemed to Scheidegger and Wilson most likely that such a system of arcuate failures would rise as a result of sliding fractures due to cooling and tension occurring below the crust in the upper part of the mantle.
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> *(Wilson, 1950: 141)*

They argued that Jeffrey's theory explained the inclined descent of the Wadati–Benioff zone with thrust faults near the surface caused by compression, normal faults below the level of no strain caused by tension, and the absence of earthquakes at the level of no strain (RS1) (Figure 1.2).

Wilson applied this explanation of the origin of present day island arcs and mountain belts globally, grouping them into common types, and explaining their type-differences mainly in terms of their distance from continental margins (RS1). As expected, he emphasized geometry. He emphasized, as others had before, that

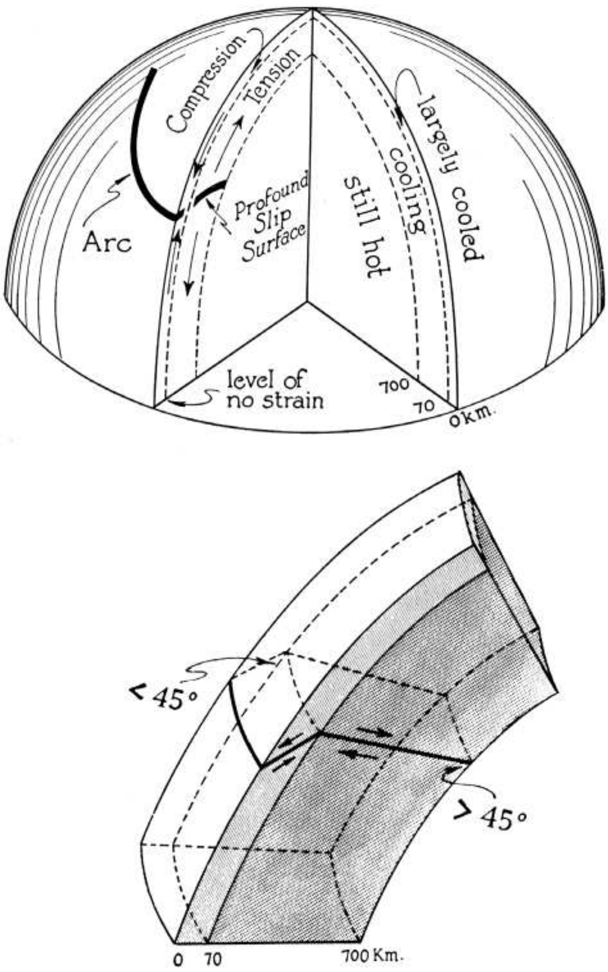

Figure 1.1 Wilson's Figure 13 (1954: 172). His caption reads: "Scheidegger's development of the contraction theory, with detailed sketch of part of one arc." The outermost shell is under compression, earthquakes are due to thrust faulting with shallow cone angles being < 45°, the next shell is contracting because of cooling. It is under tension, earthquakes are due to normal faulting with deep cone angles being > 45°. The two shells are separated by a zone of no strain.

both mega-belts of Mesozoic–Cenozoic mountain and island arcs approximate great circles. One borders (Figure 1.3) the Pacific (East Asian–Cordilleran belt); the other extends from the Alps through the Himalayas to Oceania (South Eurasian–Melanesian belt). Together they form a T, meeting orthogonally at the Banda Sea. They consist of primary and secondary mobile belts. Primary belts have deep-seated connections; secondary ones are more superficial. Both are arcuate.

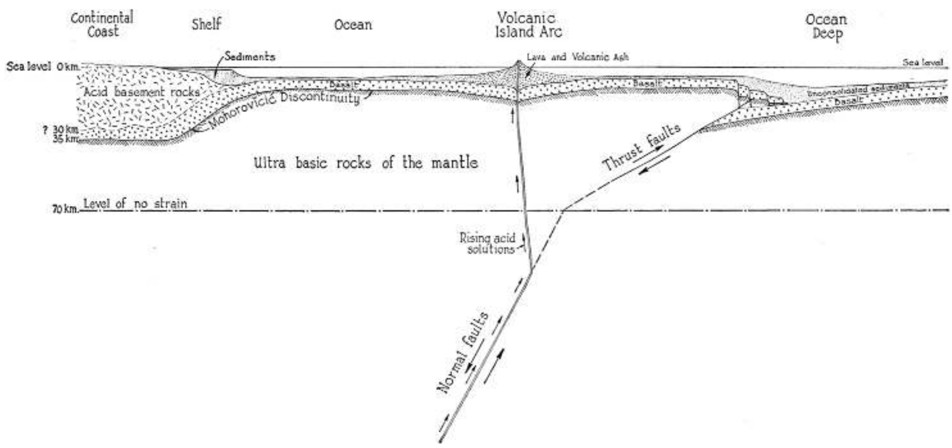

Figure 1.2 Wilson's Figure 4 (1954: 156) illustrates the descending zone of earthquakes beneath single island arcs. Shallow and deep earthquakes are respectively due to thrust and normal faults. The reported scarcity of earthquake foci between 70 and 90 km deep coincided with Jeffreys' zone of no strain.

Wilson identified six diagnostic characteristics of primary arcs:

> (1) they are underlain by all the world's deep earthquakes and most of its major shallow ones, (2) they have associated with them most of the world's active volcanoes which give acid [continental-like] lavas and . . . young intrusive rocks or batholiths of similar composition; (3) they are followed by strips of large negative gravity anomalies; (4) they are accompanied by the world's greatest oceanic trenches; (5) they rest upon . . . visible basement of older gneissic [continental] rocks; (6) they contain peculiar sediments, called *ophiolites*.
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> *(Wilson, 1954: 153–154; my bracketed additions)*

He (1954: 155) defined ophiolites, again following Kay and King, as consisting "of lava, greywacke, and other sediments derived from lava and cherts, containing oceanic rather than coastal fossils and cut by intrusives of ultrabasic composition."

He divided primary mobile belts into five types: single and double island arcs, single and double mountain arcs, and fractured arcs. All but fractured arcs are circular with their convex side facing the ocean. Single island arcs are volcanic (Aleutian, East Asian, South Sandwich Islands); they are associated with ocean trenches, large negative gravity anomalies, and Wadati–Benioff zones. Double arcs (Kodiak, Timor, and West Indian arcs) have an inner volcanic arc and an outer sedimentary (ophiolitic) arc instead of an ocean trench. Single arcs that are located near continents become double island arcs as their trenches fill with sediments, which are squeezed and elevated, transforming them into outer ophiolitic arcs, which are associated with negative gravity anomalies. Single mountain arcs "are similar to single island arcs except that they form part of the continent;" they are volcanic, have deep offshore trenches, and are associated with Wadati–Benioff earthquake zones; the western ranges of the Central Andes served as the defining example

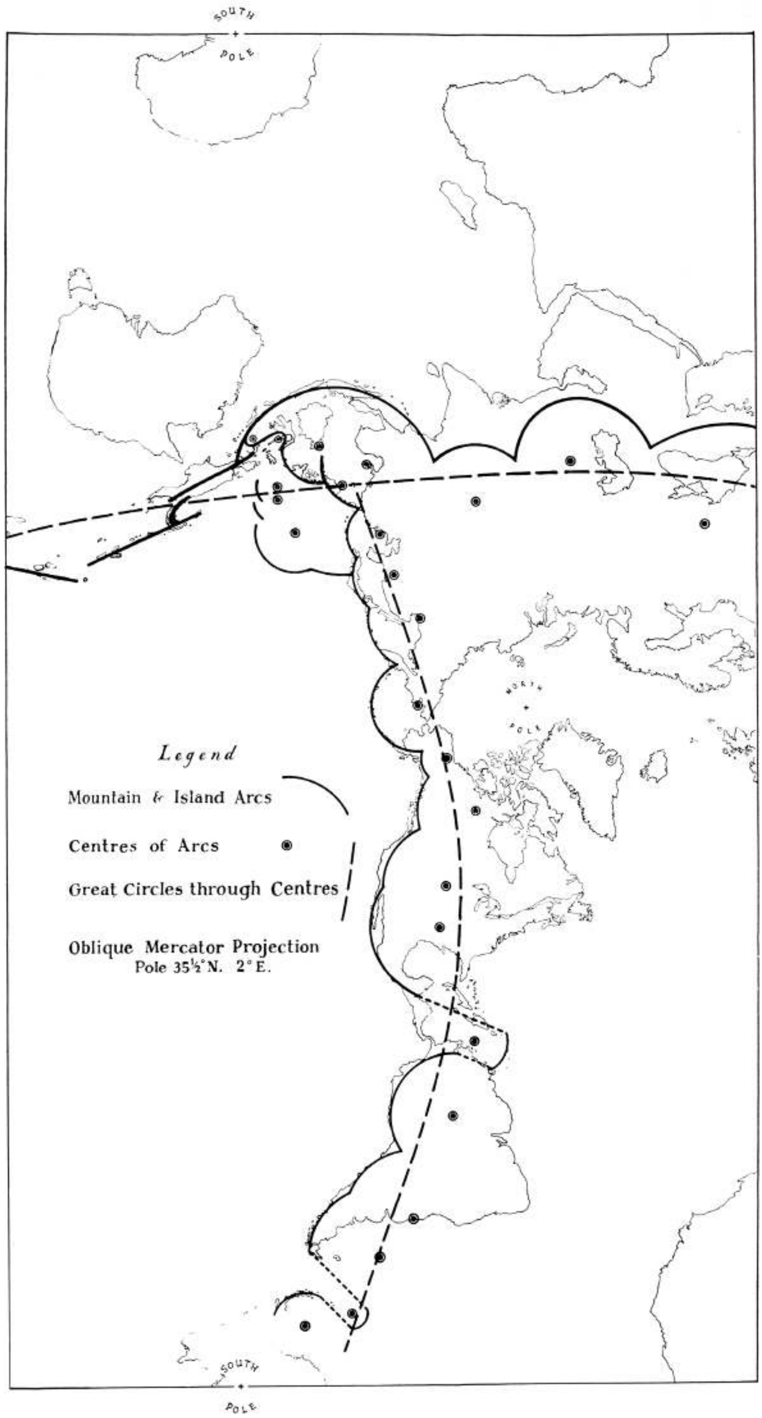

Figure 1.3 Wilson's Figure 3 (1954: 153) illustrates the two worldwide active belts of island arcs and mountains. The circum-Pacific mega-belt is shown in its entirety. Only part of the South Eurasian–Melanesian mega-belt is shown; the South Eurasian arm extends toward Spain; the Melanesian arm extends to New Zealand. The belts meet orthogonally at the Banda Sea, where they form a T. All island arcs and mountain ranges are arcuate except for the straight arcs along the Melanesian arm.