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John Tuzo Wilson, 24 October 1908 - 15 April 1993

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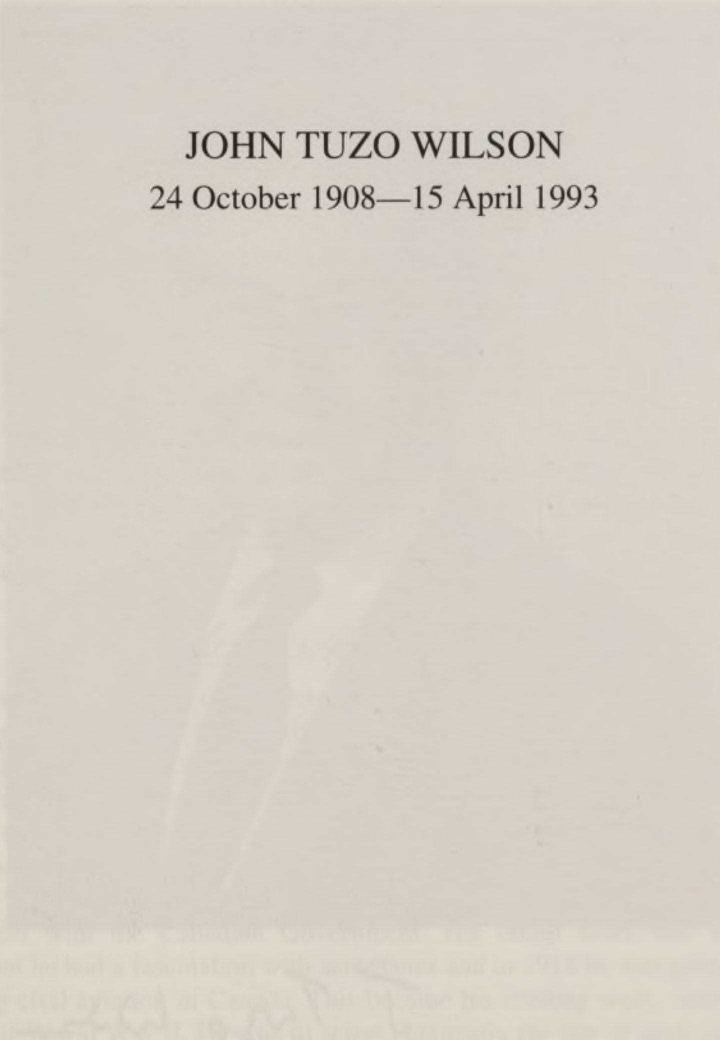

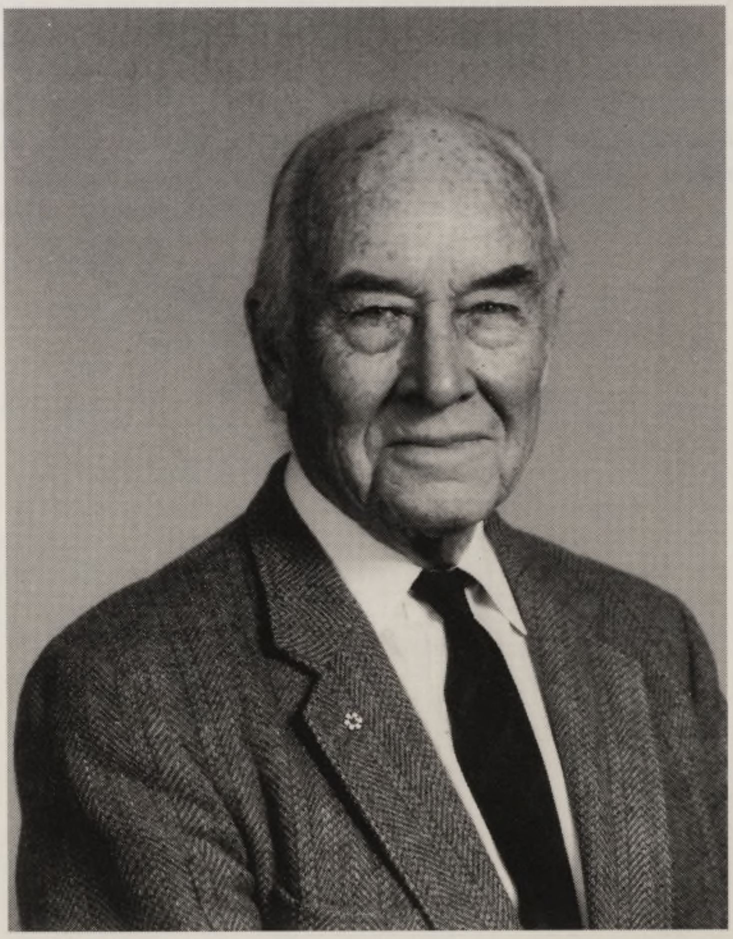

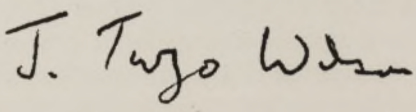

JOHN TUZO WILSON

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JOHN TUZO WILSON died in Toronto on 15 April 1993 in his 85th year. Until a few days before his death he manifested the scientific curiosity about our Earth that he had shown for over 60 years, and his energy appeared to be only slightly diminished from his prime. He was one of the most imaginative earth scientists of his time, and the father of academic geophysics in Canada.

FAMILY BACKGROUND AND EARLY EDUCATION

Wilson was born in Ottawa on 24 October 1908, the eldest child of John Armistead and Henrietta (Tuzo) Wilson. To his family he was known as Jack, or Jock, but during his professional career he began to use his middle name to avoid confusion with another J.T. Wilson. As 'Tuzo' he became known internationally and as such he will be referred to here.

His father was a Scottish engineer, born in 1879, with experience in India and western Canada. He met his future bride, Henrietta Tuzo, while on a holiday in Banff, Alberta. They were married in 1907 and shortly afterward moved to Ottawa, where John A. Wilson had accepted a post with the Canadian Government. His initial work was with the Naval Department, but he had a fascination with aeroplanes and in 1918 he was given responsibility for developing civil aviation in Canada. This became his lifelong work, until his retirement after the end of World War II. He was to select personally the site of such major airports as those at Montreal (Dorval) and Toronto (Pearson).

The Wilson family hosted visitors with interests in aviation from around the world. Tuzo was later to attribute his insatiable love of travel to the excitement aroused by these early visitors.

Tuzo's mother Henrietta was a remarkable woman, from whom her son inherited a love of the earth and an appreciation of Canadian history. Her father had been a doctor with the Hudson's Bay Company, sent west by canoe with the fur brigades to establish a practice in

Victoria, British Columbia. There Henrietta was born in 1873. Much of her early life was spent in England, but in 1898 she returned to western Canada and to the mountains she loved. Gradually she became known as a skilled climber, most of whose ascents were made accompanied only by the Swiss guide Christian Bohren. Her greatest accomplishment came in July 1906, when she and Christian ascended the previously unclimbed 'Peak Seven' in the Valley of the Ten Peaks, west of Banff. Subsequently, when their cairn was located by others and the first ascent confirmed by the Alpine Club of Canada, this peak was named Mount Tuzo.

Following her marriage and move to Ottawa, Henrietta's opportunities for climbing were greatly reduced, but she developed a leadership in civic and national affairs, including the League of Nations, the Red Cross, and the enhancement of national parks in Canada. Both John and Henrietta Wilson survived to the mid-1950s, and thus had the satisfaction of knowing the recognition given to their son early in his professional career.

Tuzo's earliest recollections of Ottawa are those of the small, semi-rural capital that it was before the Great War. The Wilson home stood on two acres of ground overlooking the Ottawa River, in an area that was to become the suburb of Rockcliffe and the home of many diplomats. While still in high school in Ottawa Tuzo obtained summer employment with the Geological Survey of Canada, which regularly employed students as junior assistants on survey parties. The work provided not only an introduction to geology, but also valuable experience in woodcraft and travel in the wilderness. One of Tuzo's mentors had the custom, while the boy was cooking supper over the campfire, of tossing him the samples collected that day, with the question: 'What rock is that, young fellow?' Tuzo was already blessed with an excellent physique; his early years of vigorous field work developed this into a physical stature which seemed charged with energy and which was to remain with him throughout his life.

On his completion of high school, Tuzo had an interest in science and the terrestrial environment, and he resolved to pursue the study of these at the University of Toronto.

University education

There was in 1926 no programme in geophysics, and not even a convenient way of studying both geology and physics. Tuzo enrolled in the Honours Programme in Mathematics and Physics, but continued to work on geological field parties in the summers. He found the instruction and experimentation in physics to be tedious and behind the times, which is somewhat surprising since Professor John McLennan had just reproduced in the Toronto laboratory the spectrum of the green line in the aurora borealis. In any case, he found the summers more inspiring. One of his leaders, to whom he gave special recognition, was the geologist Noel Odell, who had played a prominent role in the 1924 Mount Everest expedition. The situation in the Department of Physics changed greatly when one of the senior faculty, Professor Lachlan Gilchrist, was asked by the Canadian Government to join an investigation of methods of geophysical prospecting for minerals. Gilchrist was to influence Tuzo in two ways: first, by employing him in the summer on geophysical, as opposed to purely geological, investigations, and second by convincing the University to institute a programme in physics and geology. Tuzo thus gained experience in operating magnetometers and electrical field instruments, and he was allowed to study, as he later described it, 'an ill-assorted mixture of geology and classical physics.' But throughout his

life he gave credit to Lachlan Gilchrist for steering him in the direction of geophysics.

Following his graduation in 1930 as the first student in physics and geology, Tuzo enrolled at Cambridge for a second B. A. degree, financed by a Massey Fellowship. He was extremely fortunate in the professors and tutors he was to have. Sir Harold Jeffreys lectured on geophysics, and his presentation made Tuzo realize that his own grasp of mathematics was limited. Teddy (later Sir Edward) Bullard was to have been a tutor, but he was absent on his gravity survey of East Africa for much of Tuzo's stay in Cambridge. Nevertheless, the young men became fast friends, and their careers were to come together as colleagues years later. James Wordie, who had been to the Antarctic with Shackleton, and John Cockcroft were also supervisors of Tuzo's studies. He recalled meeting Joseph Needham whose work was later to be an inspiration as Tuzo's interest in China developed.

For his Ph.D. studies, Tuzo went to Princeton, attracted by the charisma of Professor Richard M. Field, one of the outstanding American earth scientists of the time. Field had the ability to launch major research projects with extremely limited financial resources, and to convince able young scientists to be part of them. Three of Tuzo's close friends at this time were Maurice Ewing, a young instructor at Lehigh University, for whom Field had obtained a grant of $2,000 to study the world's oceans, Harry Hess, of Princeton, who was beginning his study of ultrabasic rocks and ocean deeps, and fellow student D. C. Skeels, who would become a senior scientist at Standard Oil of New Jersey, and, later, director of exploration research at Imperial Oil. Tuzo himself was assigned to Professor Taylor Thom who was an authority on the Beartooth Mountains of Montana. While Thom was an excellent teacher of structural geology, his method of supervision of research students left them very much on their own. Tuzo, having been assigned an area in the Beartooth Mountains for his thesis research, was given an advance of $,200, told to buy a second-hand car, drive to Montana, and live for the summer on what was left over. He did his field work in the mountains entirely on his own, making at least one first ascent during the course of it (Mount Hague, 12,300 ft). While observing the flat top of this recently uplifted mountain, he realized that many of the ideas on mountain building which were then current were very inadequate.

The Geological Survey of Canada and the war years

The recent Ph.D. from Princeton joined the Geological Survey of Canada as an Assistant Geologist in 1936. At that time most of the effort of the Survey was in the conventional mapping of the country at scales of one inch to one mile, or one inch to four miles in remote areas. All members of the staff were expected to lead field parties in the summer, accompanied by students as assistants.

Tuzo's first assignment was to an area in southern Nova Scotia, where some map-areas begun years before during a period of gold exploration remained unfinished. In comparison to the thrust-faulted regime of the Beartooth Mountains, the area probably seemed rather devoid of interest. It is suggestive that Tuzo's only publications resulting directly from the work were the maps (3–10)*, whereas he published, through the Royal Society of Canada, a paper on the glacial geology of part of Nova Scotia (1). Indeed, he developed an interest in the overall geology of the Maritime Provinces which was to be vital to him years later when he studied the oceans. His association with the Society was to be a lifelong one.

*Numbers in this form refer to entries in the bibliography on the accompanying microfiche.

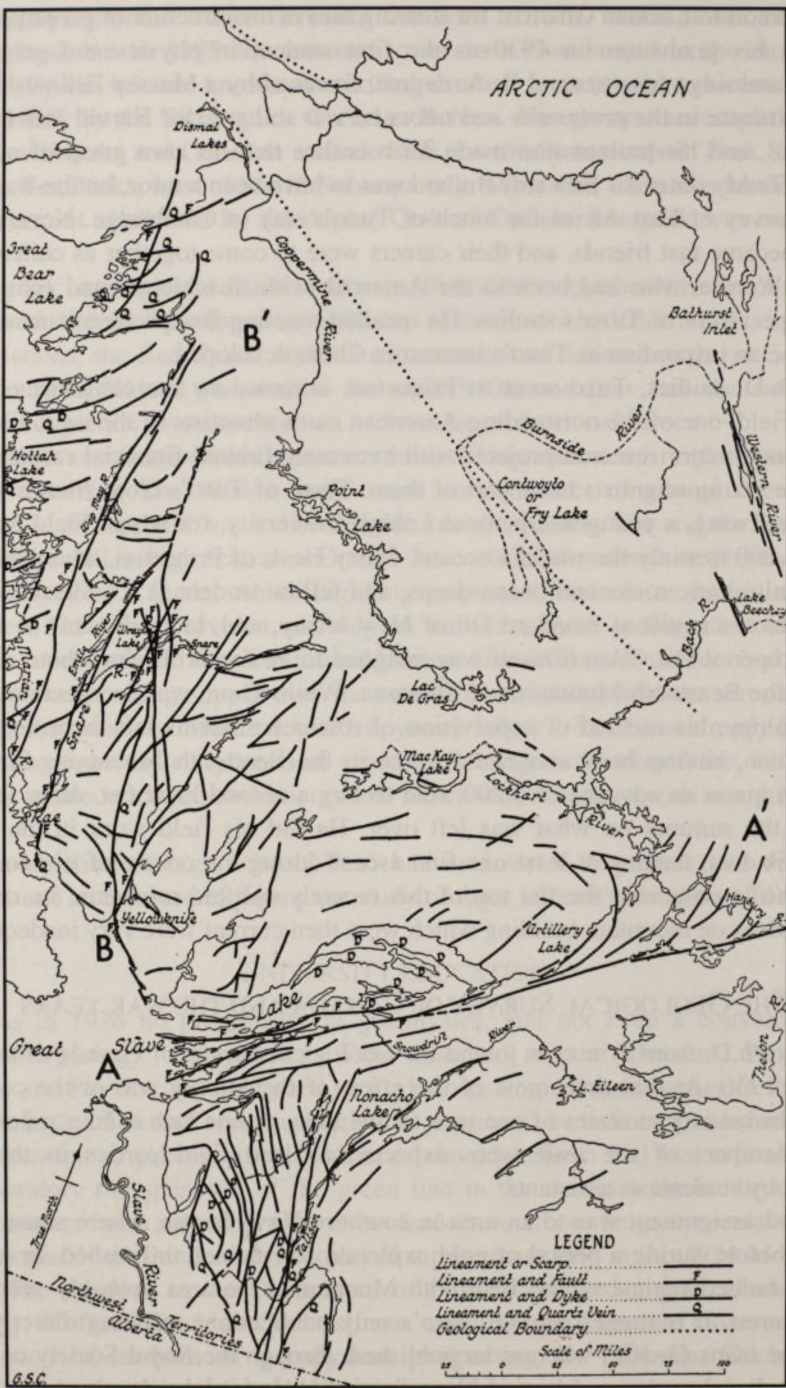

FIG. 1. Lineaments in a portion of the Northwest Territories, as determined from air photos and published in 1941 (15). Letters AA' and BB' have been added to indicate the southerly and westerly boundaries of the Slave craton. (Reprinted with permission from *American Journal of Science*).

In the following years Tuzo was assigned to areas in Quebec and, more significantly, the Northwest Territories. The areas in the Territories were then very remote, and it was a considerable responsibility for a party leader to take a group of students into them. Part of the region, in fact, had probably not been visited on the ground by non-native explorers since the time of Samuel Hearne (1771–2); in tracing Hearne's route Tuzo developed an interest in this explorer. On one occasion when his party was short of food, Tuzo killed a swimming moose by leaning out of his canoe and hitting it with an axe; he had previously read of Hearne doing precisely the same. Geological mapping was of a reconnaissance nature, at a scale of one inch to four miles, and the party made extensive use of air photos to locate themselves on the ground. This in itself was an innovation at the time, but Tuzo attempted to go further. He realized that features such as faults and dikes could be traced on the photographs, between the points where they were visited on the ground. This extrapolation of the 'ground truth' was firmly rejected by the Survey officers, and the published maps (14, 16) show only the slightest indication of faulting, in areas of the shield now known to be rich in structure, both straddling the Archean–Proterozoic boundary. To vindicate his belief in the usefulness of air photos, during the following winter in Ottawa Tuzo compiled the lineaments traceable over a large area of the Territories and published, on his own (15), the structural features deduced from them. This paper helped greatly to establish air photos as a geological tool, and it was important in leading the way toward the recognition of structural provinces within the Canadian Precambrian shield. On one of Tuzo's maps (figure 1) the pattern of lineaments defining the south and west boundaries of the Archean (i.e. older than 2500 million years) craton, now known as the Slave province, are clearly discernible, extending east from Great Slave Lake and north from Yellowknife respectively. It is interesting that his map shows structure along the Wop May River west of the western boundary of the Slave province, for this intensely deformed belt was to become known as the Wopmay orogen (Hoffman 1980) within the Bear province. Not all of the lineaments are faults (a fact Tuzo had recognized); some of the most pronounced ones are now known to be the traces of steeply dipping unconformities.

There is no doubt that Tuzo's experiences with the difficulty of publishing novel ideas through the Geological Survey of the 1930s made him realize that his true place was with a more research-oriented organization. But that is not to say that his years with the Survey were unhappy ones. In 1938 Tuzo married Isabel Dickson of Ottawa; together they had many friends in the city. Isabel was to become an indispensable support to Tuzo in all of his future activities. In any case, war was to intervene before he could make a move; it broke out while he was in the Territories in 1939. On his return from the field he joined the Royal Canadian Engineers, was commissioned a lieutenant, and eventually sent overseas with a tunneling company. He was always very modest about his wartime activities, stating that he would have been of little use in giving advice if it had not been for the assistance of members of the British Geological Survey. Some of the tunneling, and rather more drilling, were actually carried out in Britain, to place explosives that would slow an enemy advance from the coast. But his scientific imagination came to the attention of senior officers, for he returned to Canada at the end of the war as Colonel, Director of Army Operational Research.

In the meantime, Isabel, who had accepted the fact that Survey geologists would be away throughout the summers, was not prepared to be separated for the duration of the war. She travelled to England, where she remained until she and Tuzo returned to Canada by sea in 1944.

The major activity of Tuzo's directorate during 1945–46 was the testing of army vehicles

under severe Arctic and sub-Arctic conditions. A convoy consisting of ten specially designed vehicles for travel over snow was sent north from Churchill to the Arctic islands, west to Great Bear Lake and south to Edmonton. The civilian consultant on the design of the vehicles was Armand Bombardier, a Quebec mechanic, who was to go on to form the company that pioneered the snowmobile, and later, rapid transit equipment. The project itself was designated Exercise Musk Ox. Tuzo himself did not travel with the convoy, but he visited it by air at several locations along the route. The Exercise was a considerable success, all of the vehicles arriving intact in Edmonton, just one day behind schedule. Because the project was not classified, Tuzo was frequently called upon to speak about it; on occasion his topic was misinterpreted as 'Exercising the Musk Ox.'

The University of Toronto – I

Exercise Musk Ox was barely over when Tuzo received a call from Professor E. F. Burton, Head of Physics at Toronto, asking if he would accept the position of Professor of Geophysics in the Department of Physics. He accepted and moved to Toronto in June 1946. The University was to be his base of activity for virtually the rest of his scientific career. For the University, it was certainly the most significant appointment Burton made during his many years as Head of Physics: to bring in as full professor a person with no university experience beyond his Ph.D. in geology! Burton knew Tuzo from the latter's undergraduate days at Toronto but would hardly have followed his subsequent work in geology. It is probable that attention was drawn to Tuzo as a candidate by senior scientists in Ottawa, who had shared in wartime research.

Initially, Tuzo found a group in some disarray. His old Professor, Lachlan Gilchrist, had retired; other members of the group had recently left, and the interests of those remaining were chiefly in geophysical prospecting. In fact, the group was looked upon with suspicion by the 'pure' physicists of the Department.

Tuzo determined to build a research centre that would apply physics to broad problems of the earth. Provided that he had freedom to seek research funds and to attract faculty and research students he was content to remain in Physics. Indeed, he would often state that it was an advantage to be a geologist in a physics department, because he could rarely be asked to do undergraduate teaching! He did label the group the 'Geophysics Laboratory' to give it an identity.

His own early research continued the study of the Canadian Shield through the identification of lineaments on air photos. He recognized that there were provinces of very different structural trend, and probably of different age (23, 25, 26, 31). It is true that others were coming to realize that the Precambrian shields of the earth were not monolithic features, but could be divided into what appeared to be ancient cratons, joined by later Precambrian rocks (e.g. Gill 1949). But Tuzo's studies gave the most detailed trend analysis available for any shield. Furthermore, he realized the absolute necessity of obtaining radiometric ages for Precambrian rocks, and he went to great lengths to establish an age dating facility in the Geophysics Laboratory. There was in the Department an ancient mass spectrometer, which had lain unused for several years. Tuzo succeeded in convincing a group of determined research students to attempt lead-isotope measurements with this instrument. The first to obtain results was C. B. Collins, followed by others including (now) Professors R. D. Russell and R. M. Farquhar. These students were personally supervised by Tuzo,

though he was by no means a nuclear physicist. The facility was gradually improved during the early 1950s, consistent ages were obtained, and the broad outline of the age structure of shields was demonstrated (36, 41, 42, 44, 46, 47, 50). It was the beginning of scientific geochronology in Canada. The view that shields are built around smaller Archean cratons (in the case of the Canadian shield, the Superior and Slave provinces) was confirmed. The age zoning of continents could be extended into Phanerozoic time, and Tuzo wrote several papers (35, 56) on the growth of continents, still considered by him to be fixed on earth.

Following the pioneer work on geochronology, Tuzo determined that, with his interest in broad problems of the earth from a geological perspective, it was not entirely appropriate for him to supervise research students in a Physics Department. Although Tuzo was cross-appointed as a Professor of Geology, he rarely supervised any students after 1955, preferring to publish with research associates or colleagues. This is not to say he was not interested in research students. In fact, he liked nothing better than to expound his ideas over morning and afternoon tea, and to inquire of students' progress, ensuring that the Geophysics Laboratory was always a very exciting place in which to work. But he felt that students should begin their research careers on more specific problems, and that there were by that time others in the group to supervise them. His relationship with the Department of Geology through this period was, in general, a rather distant one. He felt that the Department was devoting too much effort to laboratory petrology, at the expense of broad structural studies.

One of Tuzo's early collaborators as a research associate was the applied mathematician, A. E. Scheidegger, whom Tuzo interested in studying the methods of failure of a cooling, contracting earth. It was recognized that many island groups, and many portions of mountain chains on the continents, form well-defined arcs. Scheidegger showed that, under certain conditions, an earth consisting of a hot core, a rapidly cooling upper mantle, and an already cool crust, could fail in arcuate forms. Scheidegger and Wilson's paper of 1950 (33) was extremely well received by many earth scientists, who were eager for a generalized theory of mountain building. Even in those days before plate tectonics it was realized that there were weaknesses in the hypothesis (the assumption that the cooling was sufficient, and the failure to explain repeated episodes of mountain building), but there is no doubt that the publication first made the name of Tuzo Wilson known to earth scientists internationally. Also, the fact that a theory of mountain building based on contraction could apparently explain many features of the earth undoubtedly contributed to Tuzo's early reluctance to accept continental drift. In 1950 he was invited by Sir Mark Oliphant to visit the Australian National University, and he made the visit into a round-the-world tour. Afterward Tuzo recalled: 'In South Africa all the geologists were disciples of Alfred Wegener and A. L. du Toit, and were anxious to correct my failure to accept continental drift, but I remained inflexible for another nine years.'

This tour was Tuzo's first extensive speaking engagement, bringing wide attention to the vigorous, stimulating style in which he expressed his ideas. I recall a minor incident which took place shortly after his return and which illustrates his great ability to handle skepticism among his listeners. To a group of industrial scientists, including Cecil Green (later to become a major shareholder of Texas Instruments and one of Tuzo's lifelong friends) Tuzo recounted how he had visited the Sphinx and pyramids by walking from Cairo to Giza to avoid the cost of a guided tour, arriving after dark. Cecil immediately asked how he could possibly have seen the monuments, to which Tuzo, after barely a second's hesitation, replied, 'I had matches!'

Throughout these years Tuzo maintained an uneasy truce with the senior members of the Physics Department at Toronto, who never really accepted his work as proper for a physicist.

The one respite came in 1948–49 when his old friend Teddy Bullard was Head of Physics, but for personal reasons Teddy did not remain long (McKenzie 1987). During his brief tenure Teddy was extremely supportive of the work in geophysics, supervising research students of his own in geomagnetism and the heat productivity of rocks. But one of his major interests at the time was the construction of an oceanic heat flow probe at Scripps Institute of Oceanography in California. If Tuzo's later interest in the world's oceans had been developed at the time, he and Teddy might well have collaborated in research.

National and international activities

Tuzo's enthusiasm for his science, and his position in 1946 as the only Professor of Geophysics in Canada, led to his being called upon frequently to serve on national policy-making bodies. The President of the National Research Council, Dr. C. J. Mackenzie, asked him to chair and to re-vitalize the National Committee for the International Union of Geodesy and Geophysics (IUGG). The appointment was a very significant one. At that time the National Research Council played a leading role in the post-war building of science in Canada, and its President was *de facto* scientific advisor to the government. National committees, corresponding to the international scientific unions, were encouraged to take an active view of their science within the country, in addition to fulfilling their liaison role. Their advice was heeded by the university grants arm of the Council, and they even had modest budgets to carry on projects of their own. Tuzo's committee was extremely active in coordinating geophysics in Canada, and in drawing attention to deficiencies. As an example, in the years leading up to the International Geophysical Year (IGY) of 1957–8, it was realized that, although the study of glaciers as indicators of climate change was to be an IGY discipline, there was virtually no university research in glaciology in Canada. Tuzo arranged for the establishment of programmes in glaciological research at several Canadian universities. At the same time, the publication of the first glacial map of Canada (56) was successfully encouraged. Tuzo contributed a great deal of information to the map, resulting from his analysis of air photos of the Canadian Shield.

The 1950s were years of major expansion of geophysical activity at Canadian universities. Almost invariably, universities considering faculty appointments in the sciences turned to Tuzo for advice. He assisted in bringing candidates to the attention of Dalhousie and Queen's Universities and the University of Western Ontario, Alberta and British Columbia; most of those appointed had had some connection with the Geophysics Laboratory at Toronto.

Difficult to document because of confidentiality, but known through comments made by Tuzo to his associates, was the fact that his advice was frequently sought in the appointment of scientists to senior government positions. There is no question that his advice was taken seriously in very senior appointments to the Defence Research Board, the Dominion Observatory, and some of the national museums.

It was not long before the activity of the national committee came to the notice of the international union. Tuzo attended the General Assemblies of 1948 (Oslo), 1951 (Brussels), and 1954 (Rome), becoming a Vice President of the IUGG at the last. The 1957 General Assembly, which would mark the beginning of the International Geophysical Year (IGY), was to have been held in South America. When it turned out to be impossible to carry out arrangements there, Tuzo arranged an invitation from Canada, and hosted the Assembly at the University of Toronto. The General Assembly was a great success, marked by the

excitement generated by the IGY, the largest attendance in the Union's history, the presence of the first sizable delegation of scientists from the U.S.S.R. to attend an international meeting, and by an *éclat* which characterized all events. It was almost a foregone conclusion that Tuzo would be elected President.

Very soon, he became involved in a problem that was to occupy international bodies for years: should the Academia Sinica (Beijing) or the Academia Sinica (Taipei) represent science in China? The matter was of some urgency, since the Academia (Beijing) had initially indicated its intention to participate in IGY, but had withdrawn when the Academia (Taipei) applied for admission to IUGG. Tuzo was asked by the IUGG executive to visit both academies, to assess their activities in geophysics, and to attempt to achieve global participation in IGY. He already had an invitation to visit and lecture in the U.S.S.R., and he resolved to travel from Moscow to Beijing by the Trans Siberian Railway, and to return home by way of Taipei. He thus became the first western scientist in very many years to observe geophysical work in the U.S.S.R. and China, and to travel on the Railway. His sincere interest in science and absolute freedom from political bias opened doors for him in all countries. His visit to the Academia in Beijing led to friendships with Chinese scientists which lasted throughout his life, and which would be invaluable years later when the Ontario Science Centre arranged exhibits of Chinese science.

Two popular books: *I. G. Y. The Year of the New Moons* and *One Chinese Moon* resulted from these international activities. Tuzo was always careful to point out that he was not one of the instigators of IGY, and that it had been planned by an international bureau chaired by Sydney Chapman. But during his term as President of the IUGG he most effectively encouraged global participation in it. Unfortunately, the problems of accommodating both the Academia Sinica (Beijing) and the Academia Sinica (Taipei) in international bodies was not to be resolved for many years.

University of Toronto – II

Tuzo remained continuously on the faculty of the University of Toronto during his international activities, but when these became less demanding, after 1960, he was able to devote all of his efforts to research. The next seven years were to be the most creative of his career, marked by a series of his most innovative publications. At some point in the late 1950s he abandoned his former belief that the continents were fixed on earth and began to examine the consequences of large-scale displacements of continents and oceans. It is fascinating in retrospect to trace this conversion. According to his own statement, quoted above, it would be nine years after his first visit, in 1950, to South Africa before he could accept continental drift. It is known that he remained unconvinced at the time of the 1957 General Assembly of the IUGG in Toronto, where there was an important discussion of the paleomagnetic evidence for drift.

Tuzo's acceptance of ocean-floor spreading and continental displacement first became apparent in his contribution to discussion (63) of a paper by R. S. Dietz (1961). It was a very perceptive discussion, involving also J. D. Bernal, of Dietz's comprehensive model of upper-mantle convection, spreading of the ocean floor from ridges with its subsequent pushing under continents by 'transcurrent faults.' Reading it in hindsight, one is impressed by how close Dietz, Bernal and Tuzo were to the complete model of plate tectonics that would develop in another four years. Indeed, Bernal wrote: 'One gets the impression that with it (i.e. Dietz's model) a stage has been reached like the last but one in fitting together a jigsaw

puzzle...' Bernal's objection dealt principally with mantle properties, especially the fact that Dietz's upper-mantle faults did not explain deep-focus earthquakes. Tuzo appeared ready to accept most of the evidence, including that provided by paleomagnetism, but he particularly welcomed the fact that two models of earth behaviour which he had helped to develop need not be discarded: 'Besides admitting of some features of compression in mountains, the new theory admits of continental growth...' Tuzo's principal objection was that Dietz had not fully provided a mechanism for continental crust to thicken under continental shields. He pointed out that if, over time, material from the interior is added to continents, their sialic crust must thicken everywhere for isostasy to maintain continental freeboard. Dietz had visualized 'underplating' of sialic material, but only around continental margins. The objections of both Bernal and Tuzo would eventually be largely answered with the recognition of the full significance of deep subduction zones, and of the presence of relict subduction zones under continental interiors.

By the time of a subsequent discussion on the tectonics of the Canadian Shield (65), Tuzo was obviously prepared to accept large-scale continental displacement:

> ...continental blocks can join and rift at random....The fact that two provinces of the Canadian Shield have been together during post-Cambrian time does not necessarily mean that they were formed close together or that the sediments lying on one province were derived from the province now beside it.

The transformation was complete.

Tuzo then turned his attention to the study of the Atlantic Ocean, beginning with the study of a major fault system in the Maritime provinces of Canada, the region in which he had carried out field work 25 years before. He proposed (67,68,70) that a system of left-lateral transcurrent faults of eastern North America, designated by him the Cabot fault, could be considered the extension of the Great Glen fault of Scotland, which was known to have a similar sense of displacement. The connection between the two systems was most convincing when the Atlantic Ocean was closed as it would have been in pre-Jurassic time. Thus, Tuzo was forced to acknowledge the possibility of major continental displacement, although his emphasis at this time was clearly on the fault structure itself. In the second paper of the series he wrote: 'If continental drift has taken place, and if this reconstruction is correct, it shows that the Cabot fault and the Great Glen fault in Scotland might have been joined...' Clearly Tuzo's ideas on the fixation of continents and oceans had changed. Furthermore, his detailed examination of the geology along the Cabot and Great Glen fault systems was to be of crucial importance in his later study of the history of the Atlantic Ocean. But first, he was to turn his attention to oceanic islands.

By early in 1963 Tuzo had not only accepted the ideas of ocean-floor spreading and continental drift, he was actively contributing to them. His analysis of the ages of oceanic islands (68) revealed not only their great youth as compared to the continents, but also a trend toward older ages with increasing distance from a mid-ocean ridge, tending to confirm ocean-floor spreading from these ridges. As a driving mechanism he accepted (73) a system of mantle convection currents, rising under and spreading from, the ridges. However, he recognized that some oceanic islands do not fit the pattern. The Hawaiian islands, for example, lie far from a ridge, yet exhibit present-day volcanic activity. According to his own recollections, Tuzo attributed his interest in Hawaii to an ascent of Mauna Loa. In any case, it led to one of his most imaginative and influential papers (72). He proposed (fig. 2) that the source of volcanic rock for the Hawaiian islands is a plume rising from a 'hot spot' within the stable core of a

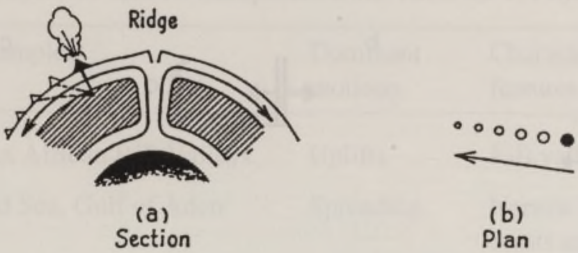

FIG. 2. Model for the origin of the Hawaiian Islands (72). (Reprinted with permission from *Canadian Journal of Physics*).

mantle convection cell. As the Pacific lithospheric plate moves across this fixed source, older islands of the chain are carried 'downstream', while the present-day volcanic activity lies over the source. The existence of a chain of older islands north and west from Hawaii lent strong support to the hypothesis. This concept, so elegantly simple when reduced to Tuzo's cartoon (fig. 2), has a consequence which goes far beyond the origin of the Hawaiian islands themselves. Dating of the older islands in the train permits the determination of the velocity of plate motion, relative to the hot spot which is supposedly fixed in the mantle. At about the same time, Vine and Matthews (1963) published their explanation of the magnetic character of the ocean floor, in terms of magnetization of new ocean floor in the earth's reversing magnetic field and its subsequent spreading from a ridge. The papers are complementary: the magnetic stripes providing a relative velocity of plate motion across spreading lines, the island trains an 'absolute' velocity relative to the mantle. The concept of a global framework of reference points provided by plumes or hot spots was to be greatly extended by others. Incidentally, Tuzo's paper on the Hawaiian islands was rejected by a leading earth-science journal before it was published in the *Canadian Journal of Physics.*

By the end of 1963 the main concepts of ocean-floor dynamics were recognized and accepted by most earth scientists. These included two types of plate boundaries: accreting boundaries, marked by mid-ocean ridges; and consuming boundaries marked by Benioff zones of deep-focus earthquakes, to become more generally known as subduction zones. But the formulation of a global pattern of lithospheric plates remained unsatisfactory, because not all plate boundaries fitted these types. Tuzo decided to concentrate on the study of the ocean floor when he accepted the invitation of Teddy Bullard to spend a term at the Department of Geodesy and Geophysics, University of Cambridge, in the winter of 1964–1965. It was an ideal environment, enhanced by discussions with Fred Vine and Drummond Matthews and with Harry Hess, visiting from Princeton. The latter's most active period of research was past, but Tuzo often attributed his own acceptance of ocean-floor spreading to Hess's early models.

It was well known that the major ocean ridges show frequent perpendicular offsets, by fractures which can be mapped bathymetrically and which, in part, are seismically active. Tuzo recognized that the conventional theory of faulting, as applied to a medium that is conserved, must be modified if the ocean floor is characterized by non-conservation. Thus, the shear motion across a fault joining two ridge segments ends abruptly at these segments. For this reason he referred to these faults initially as half-shears, but because they can also transform an

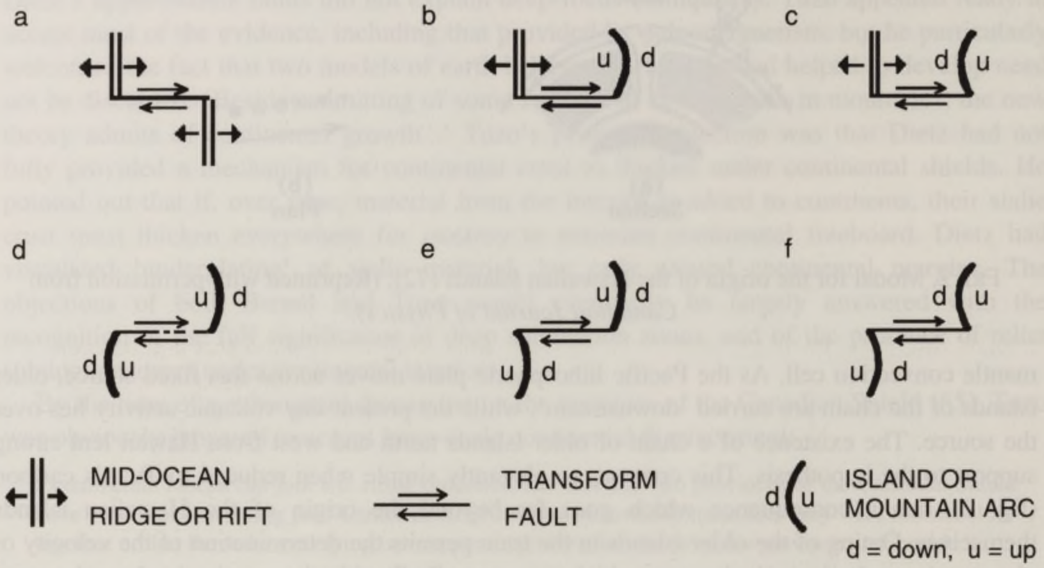

Fig. 3. Transform faults (dextral): a) ridge to ridge; b) ridge to concave arc; c) ridge to convex arc; d) concave arc to concave arc; e) concave arc to convex arc; f) convex arc to convex arc

accreting boundary into a consuming one, or vice versa, he modified this to 'transform faults' (74). In this way was born the most striking example of a new concept in structural geology in many years. Once again the elegance of the concept is best shown by one of Tuzo's own diagrams (fig. 3). As the diagram illustrates, the distinguishing feature of the transform fault as a plate boundary is the fact that the vector velocity difference between the adjacent plates is parallel to the boundary, in direct contrast to accreting or consuming boundaries. A remarkable feature is shown in fig. 3a, where a transform fault appears to offset a ridge. Because of the plate motions, the sense of shear across the transform is the reverse of what would exist if the fault were a conventional transcurrent fault. Furthermore, as Tuzo pointed out, while traces of the transform may be seen in the bathymetry beyond the ridge segment, they will be seismically inactive because there is no relative motion across them. These properties were confirmed through earthquake mechanism studies by Sykes (1967).

The recognition of the transform fault as a type of plate boundary revolutionized the analysis of the kinetics of global plate motions. Tuzo left to others the assembling of global models of finite numbers of plates and the detailed analysis of the permitted types of intersection of three boundaries at triple junctions. But he was a past master at explaining to a general audience the concepts of the transform fault and the trace of a hot spot. He would demonstrate how a folded-paper model could be made to represent the spreading ocean floor, and then pass a piece of paper across a candle flame, at charring height, to produce a representation of the Hawaiian Islands.

The third major area of Tuzo's research during this fruitful decade concerned the life history of oceans. He returned to the study of the north Atlantic Ocean, in fact to the area of

TABLE 1: The Wilson cycle of oceans. (Simplified from Table 15-1, *Physics and Geology*).

Stage	Examples	Dominant motions	Characteristic features
1. Embryonic	East African Rift Valleys	Uplifts	Rift valleys
2. Young	Red Sea, Gulf of Aden	Spreading	Narrow seas with parallel coasts and central depression
3. Mature	Atlantic Ocean	Spreading	Ocean basin with active mid-ocean ridges
4. Declining	Pacific Ocean	Shrinking	Island arcs and adjacent trenches around margins
5. Terminal	Mediterranean Sea	Shrinking	Young mountains and uplifts
6. Relic scar (geosuture)	Indus Line in the Himalayas	Shrinking and uplifts	Young mountains

the Cabot–Great Glen fault system, and showed (81) that there was strong evidence for the closing of an earlier Atlantic and reopening along a similar, but not identical, line. Small areas of rock, including fossil assemblages, were left on the 'wrong' side of the ocean. It is true that for as long as continental drift had been considered, the opening and closing of oceans must have been implied, and even the term 'proto-Atlantic' long predated the era of plate tectonics. But Tuzo's documentation of closing and re-opening of the Atlantic was beautifully detailed. It led (83) to his categorization of the world's oceans in terms of their stage of maturity in a life cycle (Table 1). This cycle became known as the Wilson cycle of oceans.

Tuzo had been cross-appointed as Professor of Geology, and could therefore supervise research students in that Department. One occasion on which he took advantage of this arrangement was to propose to student Barry Clark that a careful mapping of the coast of Baffin island, for comparison with the coastal geology of Greenland, could provide evidence as to whether they had ever been joined. In 1964, years after he had supervised a student in geophysics, Tuzo travelled with Clark by small fishing boat along the precipitous Baffin coast and ascended cliffs several hundreds of feet high in order to start the student on his mapping (79).

By 1967 plate tectonics was accepted by the great majority of earth scientists, and Tuzo was an acknowledged leader in the study of the earth. At this very time he was asked by the President of the University of Toronto, Claude Bissell, to be the Principal of a new suburban college of the university, Erindale College. At first glance the request was an unusual one, because Tuzo had never shown great interest in university administration; he had never, for example, been head of a department. Later, he credited Isabel with convincing him to accept the post. The challenges facing the principal were daunting: it was a time of student unrest in many countries, the 'college' had 300 acres of land but only one inadequate building, and the relationships of both students and faculty to departments

on the main campus were unclear. Assisted by a very able Dean (Professor E. A. Robinson) Tuzo set out to confront these. He and Isabel moved into the principal's residence, which had been the country house of the original estate acquired by the University. Their hospitality to students, faculty, and visitors to the College became famous: in a period of seven years, 10,000 guests were entertained in their home. The permanent buildings, both academic and residential, were designed with a sense of openness, attractive to students. Fields of study and research were chosen to be slightly different in emphasis from those on the main campus. In his own field, Tuzo prevailed in having a single department of Earth and Planetary Science, combining both geology and geophysics, and he stimulated the development of lines of experimental research, such as rock magnetism, which would benefit from the undisturbed suburban environment. Altogether, Erindale College was in a very flourishing state when he left it in 1974.

Tuzo continued to publish during his term as Principal. While he produced some papers on tectonics with Erindale colleagues Kevin Burke and William Kidd (101, 103), he also moved into a more philosophical field, the structure of scientific revolutions (88, 99). He compared the change in the study of the earth which had taken place in the 1960s to the effect of quantum mechanics on chemistry and physics, or to genetics on biology. Not specifically trained in the philosophy of science himself, he acknowledged the influence on his thinking of writers such as Kuhn (1967). He urged the acceptance of plate tectonics as the new paradigm, which according to Kuhn was at the heart of every scientific revolution, and which could unify, even simplify, the study of the earth. By the late 1960s there were two outstanding opponents to plate tectonics and continental drift: Sir Harold Jeffreys on physical grounds, and V.V. Beloussov for geological reasons. Beloussov and Tuzo engaged in a debate by exchange of open letters in 1968 (*Geotimes, 13).* Beloussov raised several points of objection, citing problems of geology to which, he claimed, plate tectonics provided no solution; he made no reference to its obvious successes. Tuzo's reply was eloquent: 'The chief difference between us is not about what you say, but arises from what you have omitted to say.' And further: 'If indeed the Earth is, in its own slow way, a very dynamic body and we have regarded it as essentially static, we need to discard most of our old theories and books and start again with a new viewpoint and a new science.'

While still Principal of Erindale College, in 1972–3, Tuzo served as President of the Royal Society of Canada (R.S.C.). He had always been a strong supporter of the Society, publishing through its journals since 1938, and being elected to fellowship in 1948. Tuzo was an effective leader of, and eloquent spokesman for, the R.S.C., but he was limited in what he could accomplish by the one-year term of office which was then the rule.

During those busy years the Wilson family escaped, in the summers, to a venerable cottage which they had acquired on the Precambrian shore of Go Home Bay, Lake Huron. But it was not all relaxation. Tuzo and Isabel, with the help of friends, enlarged the original building to provide space for a study, where he continued to write. The renovated building was christened 'Awry on the Rocks'. Tuzo's interest in Chinese culture led him to the conclusion that the junk is a very practical water craft. He commissioned one to be built in Hong Kong, had it imported to Toronto, and with the help of his brother and friends sailed it to Go Home Bay. Fortunate were the cottage guests of Tuzo and Isabel, of whom there were many, who were taken on an evening sail on Lake Huron in the lantern-festooned junk. Others could see Tuzo at the helm during the television series 'Planet Earth', which he assisted to produce and introduced.

The Ontario Science Centre

In 1974, when Tuzo was 65 years old and preparing to retire from Erindale College, he was asked by the Premier of Ontario to be the Director General of the Ontario Science Centre. The Centre, built by the Province as a contribution to the celebration of Canada's centennial of 1967, consisted of a group of imaginatively planned buildings, designed by the Canadian architect Raymond Moriyama, spanning a beautiful wooded hillside. It was already a considerable success by 1974, attracting 1,500,000 visitors annually, of which 300,000 were children. From the first it had featured a hands-on approach to exhibits, stressing the fun of science. But some voices were raised, suggesting that the Centre was moving too far in that direction, away from the concept of a museum of science. The government of the day decided that a scientist of international stature, with a record of expressing his ideas in a clear and stimulating manner, was needed to direct its course. Tuzo was the obvious choice, and he accepted.

His philosophy soon became clear: there was room for elements of both types of institution at the Ontario Science Centre, but he wished to stress the hands-on approach, including as necessary replicas of scientific instruments. He wrote:

> Thus, besides science museums, which hold stocks of artifacts, there are science centres which show manufactured models. Everyone knows that the best way to teach science is by doing experiments. Science centres are in effect public science laboratories and they are exceedingly popular. To point out this difference upsets many curators, but the solution lies in their own hands. Many, if not most, institutions are a mixture. It is perfectly reasonable to display what artifacts one can alongside participatory exhibits that enable the public to try scientific experiments with their own hands. (105)

Tuzo entered into the role of Director General with great enthusiasm, making himself completely accessible to visitors, sometimes to the dismay of his senior administrators who had difficulty locating him. He delighted in joining a visiting class of school children, and personally explaining some experiment.

He did find that being considered the spokesman for science in Ontario led to his being asked to serve on a number of investigative commissions quite outside of his own field. Tuzo had often given generously of his time to bodies such as the National Research Council and the Science Council of Canada, but as a spokesman for earth science. Now he was called upon to chair a commission on aluminum wiring in homes, and to serve on one investigating the consequences of branchline railway abandonment. But he reserved time to give great support to two new programmes at the Centre: the providing of travelling exhibits to take science to remote areas of Ontario, and the arranging of temporary exchanges with other countries. For the first, experimental apparatus and displays were sent by van or even aircraft in the case of some inaccessible settlements. The interest expressed from northern Ontario led to the suggestions of a northern equivalent to the Science Centre. With the active support of Tuzo and his staff, Science North was built in Sudbury. Tuzo's influence, as well as that of the very supportive local mining community, resulted in a very strong earth science component in this extremely successful new centre.

Public response at the Ontario Science Centre led to the conclusion that temporary exhibits which featured the relevance of relatively simple science to human progress were much more successful than those which were too esoteric. For example, an exhibition on the technologies of the Indians and Inuit, with native persons performing the work and emphasizing the necessity to their survival, received wide acclaim. The outstanding example of a visiting exhibition held at the Centre was that on the origin and development of science in China. Here, Tuzo drew upon his acquaintance with Joseph Needham and upon his relations with the Academia Sinica.

Following his visit in 1958, he and Isabel had travelled extensively in China in 1971, while he lectured on plate tectonics. With the contacts he had, official sanction was obtained, to be followed by three exchange visits of designers and consultants between Canada and China, before the exhibition was opened in the summer of 1982. Seventeen Chinese artisans lived in Toronto for the period of the exhibition, working each day in a replica of a market place. The emphasis was clearly on ancient science as applied to everyday life, and included demonstrations on making paper, printing, moulding and glazing porcelain, growing silkworms and designing earthquake-resistant buildings. It was an enormous success.

Tuzo was to remain Director General until his retirement in 1985. Under his leadership, travelling exhibits were sent to China, England, Japan, Malaysia, the United States, and delegations of designers were received at the Centre from many countries who were planning science centres of their own. He retired from the Ontario Science Centre in characteristically unconventional style: entering the farewell banquet held in his honour in a rickshaw pulled by a science student.

University of Toronto – III

In 1985 Tuzo settled happily into a modest office at the University of Toronto, prepared to turn his attention again to global tectonics, to writing his autobiography, and to investigating aspects of the history of exploration in Arctic Canada. He still held one academic position, largely ceremonial: from 1983 to 1986 he was Chancellor of York University.

More than 20 years had passed since the early days of plate tectonics. Tuzo acknowledged the progress that had been made, but his writing from this period gives the impression that he felt that important aspects were being overlooked. He returned to the study of hot spots, which in the interim had been actively pursued by others. Following Crough (1983), he accepted the view that rifts themselves may result from the coalescing of lithospheric fractures radiating from uplifts over hot spots and extended this (109) to investigate the consequences of continents over-riding rifts. A quotation from this paper will illustrate his view on the progress of global tectonics:

> Collisions between ridges and coastlines may occur at a variety of angles, including cases where ridges are parallel to coastlines, oblique to them, or at right angles. The consequences of different angles vary so much that failure to consider these differences seems to have been a major cause of deficiencies in tectonic theories.

He proceeded to give the consequences, with examples current and past, of these collision types. They include (respectively parallel, oblique and perpendicular): thrust mountains (the Cordillera of western Canada); coastal shearing leading to transported terranes (Gulf of California); and continental uplift and rifting (Gulf of Aden). Tuzo's fascination with the entry of the East Pacific Rise into the Gulf of California led to an ongoing difference of opinion with some American earth scientists. The conventional view was that the Rise was terminated by the San Andreas transform fault, and thus by Wilson's own rules could proceed no farther into the continent. But Tuzo countered that the rules applied only within the lithosphere and that deeper upwelling of hot mantle material, equivalent to an extension of the East Pacific Rise, could persist under the continent as far as the thermal region of Yellowstone. It was a disagreement largely unresolved at his death, but Tuzo remained convinced of his model. One of his last papers (115) proposed that rich gold deposits in Nevada (known to be fourteen million years old) formed at the very time that portion of the continent passed over the Yellowstone plume.

Conclusions

Tuzo Wilson's approaches to science and to life were straightforward. He was fascinated by the study of the earth, convinced always that 'beneath all the chaotic wealth of detail in a geological map lies an elegant, orderly simplicity.' He himself had the wonderful capacity to assimilate and retain the detail, while arriving intuitively at simple yet elegant models. He liked people; it is difficult to think of any other scientist of any country or any time who had more friends throughout the world. He would engage eagerly in honest scientific debate with those who held conflicting views, and the only persons for whom he had little time were administrators who placed bureaucratic obstacles in his way. To students he was a great inspiration, to the public a superb expositor of science, to his family a loyal husband, father and grandfather. When the end came, his supporter of 55 years, Isabel, his children Patricia and Susan and his three grandchildren were close by.

> [F]ew people have been so fortunate in having enjoyed so happy and rewarding a life as I, and I am grateful to an immense number and variety of people who have speeded me on my headlong way.

Acknowledgments

For Tuzo's early career, and for a number of quotations, I have drawn upon two autobiographical articles (105 and 113). I am extremely grateful for the support and assistance kindly given by Isabel Wilson, for the suggestions of Professor Richard Gregory of Bristol on the section dealing with the Ontario Science Centre, for discussions with Tuzo's former colleagues at the University of Toronto on his contributions, and for a friendship with Tuzo which began the week he arrived at that University in 1946.

The frontispiece photograph was taken by Mr Delroy Curling, Department of Physics, University of Toronto in 1992. It is reproduced with his permission.

Honours

1946	Officer, Order of the British Empire
	Officer Legion of Merit, U.S.A.
1970	Order of Canada, Officer
1974	Order of Canada, Companion

Medals and Awards (Post-Graduation)

1930–1932	Massey Fellowship to University of Cambridge
1950	R. M. Johnston Medal, Royal Society of Tasmania
1958	Willet G. Miller Medal, Royal Society of Canada
1959	S. G. Blaylock Medal, Canadian Institute of Mining and Metalllurgy
1960	Civic Award of Merit and Gold Medal, City of Toronto
1968	Logan Medal, Geological Association of Canada
	Bancroft Award, Royal Society of Canada
	Bucher Medal, American Geophysical Union
	Penrose Medal, Geological Society of America
1974	J. J. Carty Medal, U.S. National Academy of Sciences
1978	Gold Medal, Royal Canadian Geographical Society
	Wollaston Medal, Geological Society of London
	Vetlesen Prize, Columbia University

	J. Tuzo Wilson Medal, Canadian Geophysical Union
	Priestly Award, Dickenson College, U.S.A.
	Rennie Taylor Award, American Tentative Society (Science Writers of U.S.A.)
1980	Ewing Medal, American Geophysical Union
	M. Ewing Medal, Society of Exploration Geophysics
	*Albatross Award, American Miscellaneous Society
1981	Huntsman Award, Bedford Institute of Oceanography
1983	Citizenship Award, Ontario Association of Professional Engineers
1986	Encyclopedia Britannia Medal and Award
1989	A. Wegener Medal, European Union of Geosciences
	Killam Award, Canada Council

In addition, Tuzo was the holder of fifteen honorary degrees and was a foreign member or associate of seven academies.

Two seamounts rising from the floor of the Pacific Ocean, near the junction of three plates some 200 kilometres west of Vancouver Island, were named the Tuzo Wilson Seamounts in his honour.

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The complete bibliography appears on the accompanying microfiche. A photocopy is available from the Royal Society Library at cost.

*The Albatross carries the citation on its base: 'For making the faults go the wrong way'.