The Bits and Pieces of Plate Tectonics

Parts of North America that always seemed geologically peculiar now appear to have been plastered onto the continent over the past 400 million years

Two hundred million years ago, Vancouver, British Columbia, was probably situated on an idyllic tropical isle. Four hundred million years ago, Lovelock, Nevada, may have been part of a chain of volcanic islands far off the coast of the North American continent. Even Eastport, Maine, seems to have been a latecomer to this continent (which has been around for at least several billion years), having been part of Europe until about 300 million years ago.

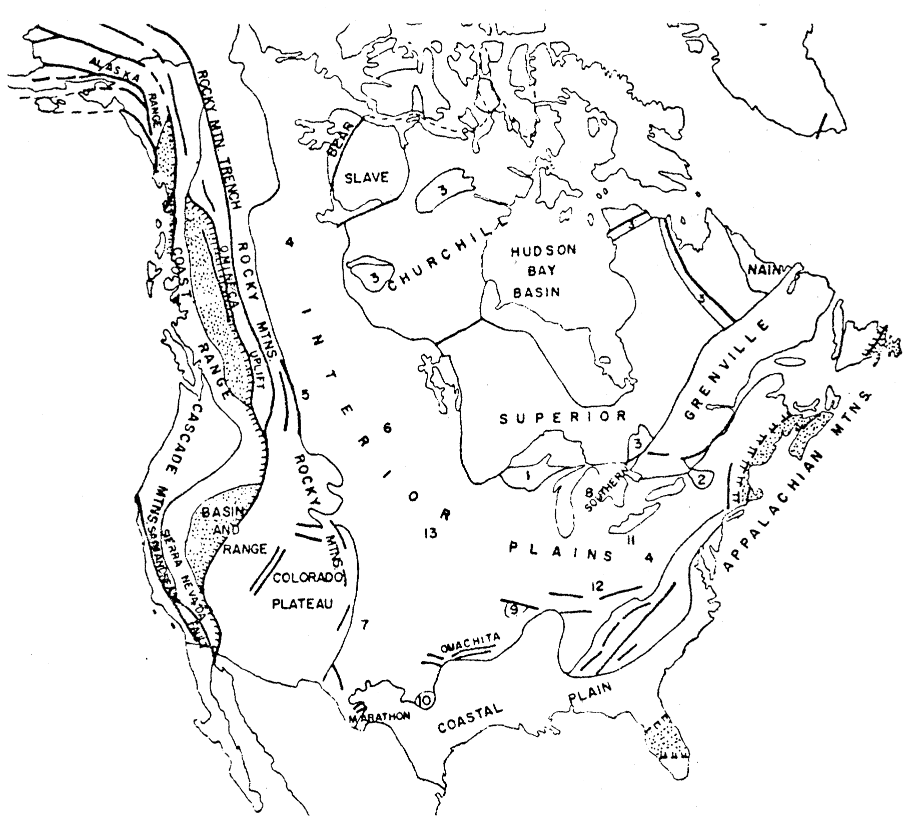
These areas and others have seemed for decades to be geologically peculiar and out of place. Geologists could not easily fit the rocks of coastal Alaska or New England with the rocks that surrounded them. Paleontologists found that the fossils in these rocks resemble those of Asia and Europe, not those of the rest of North America. But these areas remained simply peculiar until the advent of the theory of plate tectonics. Then, geologists could imagine continents plowing across the globe, sweeping up bits and pieces of rock and breaking off hunks of other continents as they jostled each other. Now, researchers in the relatively new field of paleomagnetics, the study of the earth's ancient magnetic field as recorded in rocks, are helping to identify late additions to the continents and for the first time tracing their origins.

The idea that the edges of continents had been extended as a result of plate motions was put forward even as the bare outlines of plate tectonics began to gain wide acceptance. Conventional wisdom had lumped together all the rocks along the east and west coasts of North America as originating in the thick layers of sediment that collect just offshore. In 1968, Tuzo Wilson of the Ontario Science Center, Toronto, boldly concluded that some of those rocks, the geologically peculiar ones, were once parts of other continents. He suggested that part of Florida had come from Africa, coastal New England and Newfoundland from Europe, and parts of Nevada, British Columbia, and Alaska from Asia.

"I have never been very good at details," Wilson recalls, "but it struck me that, once you proposed continental drift, the logical conclusion seemed to be that pieces of North America had come from elsewhere."

"Most of us thought, at the time, that these [Wilson's] were good ideas," says James Monger of the Geological Survey of Canada in Vancouver, "but without much basis. It was a very well-educated guess . . . remarkable insight." The hard geological and paleontological data needed to substantiate Wilson's insight were not long in coming. In fact, much of the basic data had been in hand for many years and some of the ideas had already been proposed, but before the theory of plate tectonics had been put forward they never made enough sense to win many adherents.

The absence of a comprehensive paradigm in the field was at times inhibiting. Warren Hamilton of the U.S. Geological Survey (USGS) in Denver knew he was describing in a 1963 paper on Idaho rocks the same kind of rocks that are found in the Aleutian Islands, a typical chain of oceanic volcanic islands. Hamilton hesitated to spell out in 1963 the obvious conclusion that Idaho contained the remnants of an island chain. Only a few people took plate tectonics seriously then, but by 1969 Hamilton felt free to describe in detail how California must have been put together as the edge of North America swept up pieces of ocean



Tuzo Wilson's 1968 map showing parts of North America (strippled areas) that he thought were once parts of other continents. It is generally accepted now that these areas, with the possible exception of Florida, were indeed added to North America only within the past several hundred million years, but many seem to have arrived as island arc complexes. On the west coast, the exotic terrains are now known (from north to south) as the Alexander, Stikinic, and Sonomic blocks. Coastal New England, Nova Scotia, and most of Newfoundland are known as Avalon. [*Source: The American Philosophical Society*]

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Cross section of a rock containing the honeycombed tests of now-extinct fusulinids used to identify displaced terrains. Scale bar is 5 millimeters long. [Source: James Monger]

crust, ocean sediments, and island arcs (like the Aleutians).

In the past 10 years, the study of such plate-edge tectonics has centered on British Columbia and southern Alaska, where a 500-kilometer-wide swath of the coast seems to be a geological sandwich of Pacific island arcs, ocean floor, and other fragments swept up over the last few hundred million years. One of the first pieces of evidence used to support this theory centered around calcareous fossils of one-celled animals, called fusulinids, that showed up in British Columbia, although before that particular kind of fusulinid had only been associated with China, Japan, and Indonesia. Their presence in North America might have been due to special environmental conditions, but Monger and Charles Ross of Western Washington University in Bellingham suggested in 1971 that the Canadian fusulinids may have been carried by movements of the ocean crust from their natural habitat to the edge of the ancient North American coast. Instead of sinking into the mantle, as most ocean crust does when it runs into a continent, the crust carrying the fusulinid microfossils was pinned against the coast by island arcs that were too light to sink. This addition of island arcs to North America is now known as the Stikine block, after the town of Stikine, British Columbia.

Strong evidence for another alien block, or displaced terrain, did not come until 1977 when David Jones and Norman Siberling at the USGS at Menlo Park, California, proposed that a long, narrow block, which they call Wrangellia, after the Wrangell Mountains, lies between the Strikine block and the Pacific. Rather than being distinguished by exotic fusulinids, Wrangellia is still recognizable because its distinctive sequence of rock layers is unlike any other in North America. It shows up in southwestern British Columbia, on Vancouver Island and the Queen Charlotte Islands, and in a strip near the coast extending into mainland Alaska. A possible isolated block of Wrangellia occurs as far inland as the Hells Canyon region of northeastern Oregon and western Idaho.

Using the same approach of mapping rock types, Jones, Henry Berg, Michael Churkin, and Donald Eberlein of the USGS at Menlo Park identified a distinctly different sequence of rocks in a sliver that includes the Alexander Archipelago, which is squeezed in between Wrangellia and the Stikine block. Robert Speed of Northwestern University has recently proposed that another displaced terrain called Sonomia lies in northwest Nevada in the same general area first pointed out by Wilson. Speed believes that the island arcs forming Sonomia arrived at the ancient coast much earlier (about 250 million years ago) than those arriving to the north. These dates and the total extent of Sonomia remain controversial, but researchers agree that a sizable section of Nevada was not always a part of North America.

Although the geological and paleontological evidence had convinced many workers that much of the coast north of Washington State had rafted in as volcanic islands and ocean crust from the Pacific, it was new geophysical evidence that finally gave the idea complete respectability. By measuring the direction of the earth's magnetic field frozen into the rocks of each block, paleomagneticians have shown that these displaced terrains were as far south as the vicinity of the equator when their rocks solidified from lava.

For example, John Hillhouse of the USGS at Menlo Park found that Wrangellia, which now lies between 50° and 60°N, was within 15° of the equator 200 million years ago and was rotated about 90° from its original position before it reached North America. Rob Van der Voo of the University of Michigan and Sherman Grommé of the USGS at Menlo Park have shown that the Alexander block moved from 40°N to its present position at 55°N. According to David Stone of the University of Alaska, the Alaska Peninsula also followed an independent path until it joined up with Wrangellia about 75 million years ago. Although all the blocks have definitely moved northward while separate from North America, paleomagnetic data cannot be used to find how far west in the Pacific the blocks began their journeys because the data provide information on past latitudes but not longitudes.

Combining the three types of evidence, Edward Irving of Canada's Department of Energy, Mines and Resources (DEMR) in Ottawa, Monger, and Raymond Yole of Carleton University, Ottawa, have proposed that the two principal displaced terrains, the Wrangellian and the Stikine blocks, first joined together and then slid up the coast to their present position. The joining of the two blocks about 135 million years ago as well as their fusion with the coast caught strips of oceanic crust in between that are still evident today. By about 65 million years ago, the generally northward motion of the ocean plate off the coast began to carry the united block toward its present position, according to this scenario. The last part of the trip, which ended about 40 million years ago, may have been along a San Andreas-like fault where the blocks moved northward on the Pacific plate, just as southern and Baja California now moves past the North American plate along the San Andreas fault.

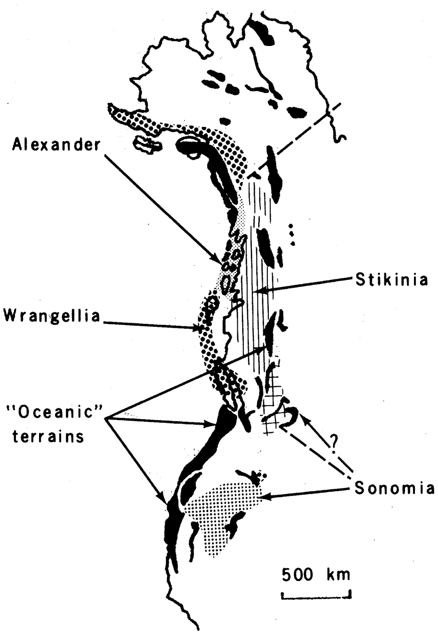
Similar additions to plate edges seem to have been made in Siberia, southeast Asia, the Philippines, Japan, and elsewhere, but their origins are only just beginning to be studied. Amos Nur of Stanford University and Zvi Ben-Avraham of the Weizmann Institute of Science in Rehovot, Israel, have speculated that many of these displaced terrains originated in the breakup of a single continent called Pacifica. Two hundred and twenty million years ago, the hypothetical continent would have been nestled against Australia and Antarctica in the previously proposed supercontinent of Gondwanaland. When Gondwanaland broke up to form the present-day southern continents, the Pacifica portion shattered into five major pieces that were strewn around the Pacific.

The Pacifica theory has received little support from researchers in Alaska and British Columbia, who point out that nearly all of the displaced terrains there had marine origins as volcanic island arcs, ocean crust, or sediments and not as continental crust. In any case, not all of these blocks, they note, are true crustal fragments (commonly called microplates). Rather, some are thinner scraps of crust that have been pushed up onto the continental edge. The possibility remains that true continental fragments may have been swept up by the major continents around the Pacific, where some submerged plateaus are suspected of containing continental rocks.

Paleomagneticians are providing additional support for another of Wilson's "continental fragments" along the northeast coast of North America. Geologists have long recognized that the rocks of coastal New England, Nova Scotia, and eastern Newfoundland had been transformed by high temperatures and pressures 500 million years later than the rocks farther inland. As on the Pacific coast, the fossils found in this coastal strip made a much better match with those across the adjacent ocean than with those nearby. Paleomagnetic confirmation of this block's motion before it joined the rest of the continent came slowly, owing to its long and complex history. It now appears that this block, called the Avalon block, did not become part of North America until about 300 million years ago, according to Dennis Kent and Neil Opdyke of the Lamont-Doherty Geological Observatory. Paleomagnetic data have also expanded the geologically defined boundaries of Avalon into central Newfoundland, on the basis of data collected by Pierre Lapoint of Canada's DEMR, and possibly into northern Maine, according to data from Laurie Brown of the University of Massachusetts.

Exactly how Avalon moved about before fusing to North America remains unclear. Kent and Opdyke suggest that at least part of Avalon, which they call Acadia, slid up from the vicinity of Georgia about 300 million years ago along a major fault, much as the Wrangellia-Stikine block slid northward into position. Once in position, everyone agrees, what was to become the new continental edge became locked in the heart of Pangaea, the supercontinent that encompassed for a time most of the earth's landmasses. When the bulge of west Africa finally pulled away from North America and the new Atlantic Ocean began to open, the new split in the Pangaean landmass left Avalon attached to North America and carried Great Britain, which Kent and Opdyke suggest slid northward with Avalon, to the opposite side of the Atlantic.

Even earlier, wider ranging travels have been proposed for coastal New England and eastern Canada by Van der Voo. In order to resolve problems with the formation of mountain belts around the Atlantic, Van der Voo has proposed a new continental plate called Armorica consisting of southern England, Wales, northern Germany, Poland, France, Spain, and probably eastern New England, Nova Scotia, and Newfoundland. Five hundred million years ago, according to Van der Voo's hypothesis, Armorica broke away from Gondwanaland, where it was attached to present-day North Africa, and eventually crashed into the east coast of North America. This



One conception of the displaced terrains of British Columbia and southern Alaska. [Source: Adapted from a map by James Monger]

raised the Taconic Mountains, the predecessor of the Appalachians. The new plate was then struck by the remainder of present-day Europe, creating the Caledonian Mountains of northern Great Britain about 395 million years ago. Finally, Armorica, along with Avalon, slid out of the way to the north as Gondwanaland plowed into North America to form the Appalachians.

Much of this story of plate-edge tectonics remains tentative. The 1500-kilometer-long fault required for Avalon's slipping along North America has yet to be identified by geologists, who generally prefer matching up the rocks on either side of a suspected fault slippage to shuffling crustal blocks around according to paleomagnetic data. At the same time, the paleomagneticians have their hands full collecting and analyzing enough samples to build a detailed picture whose magnetic record has not been distorted beyond recognition by the repeated mountain building.

The last of Wilson's proposed fragments, the one forming central Florida, remains unconfirmed, but a preliminary study suggests that it too was a recent addition to the continent. Charles Helsley of the University of Hawaii examined the paleomagnetic record in a rock core from a deep borehole in Florida. He found that part of Florida seemed to be at a high latitude 450 million years ago, although the rest of North America is thought to have been near the equator at that time. Because Florida is usually fitted against North Africa (which was also at high latitudes) in reconstructions of Pangaea, Florida may have traveled with Africa until North America picked it up.

Even the southern edge of North America may have been altered by the addition of displaced terrains. According to most reconstructions of Pangaea, North and South America fell so close together that there was no room for anything resembling today's Central America. Wulf Gose and Gary Scott of the University of Texas's Marine Science Institute in Galveston recently suggested that the growing gap between North and South America, which began to open about 180 million years ago as the Atlantic started to form, was filled by blocks of crust spinning into place from the Pacific. According to their data, perhaps four of these blocks fell into place one by one. By determining paleomagnetically when each block stopped spinning on its own and began moving with North America, Gose and Scott found that the regions roughly defined as Mexico, the Yucatàn, Honduras, and Nicaragua-Costa Rica each rotated as much as 170° before attaching themselves. Where they came from is not clear. The paleomagnetic record shows that the blocks did not move much in the north-south direction, and so Gose assumes that they came out of the west, the method's blind spot, from the Pacific.

The geological data supporting a Pacific origin for Central America are not as detailed as in other cases, but Gose believes that their paleomagnetic data are consistent with what is known about the regional geology. That includes a great fault through northern Mexico and the southwestern United States proposed by Lee Silver of the California Institute of Technology. This fault would have allowed the bulk of North America to swing away to the northwest as the Atlantic opened; this movement would mesh with the observed counterclockwise rotation of Mexico.

It has become obvious over the last 10 years that the jostling of the major crustal plates is really quite a messy business—large plates sweep up small bits and pieces of crust and exchange scraps of their own crust through collisions with other large plates. Much of this understanding resulted from the synergism between geology, paleontology, and paleomagnetics. Further progress will depend on continued detailed sampling and even closer cooperation between the geologists and paleontologists "who know the rocks" and the geophysicists who are deciphering the paleomagnetic record.

—Richard A. Kerr