Decade of North American Geology
Geologic Map of North America—Perspectives and explanation

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Cover: Index map showing the area covered by the Geologic Map of North America. Long-dashed line is the central meridian (100°W); short-dashed lines are small circles where the projection cylinder intersects the sphere and the scale is exactly 1:5,000,000.

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INTRODUCTION

John C. Reed Jr., John O. Wheeler, and Brian E. Tucholke

The idea that the Decade of North American Geology (DNAG) project should include preparation of a new geologic map of the continent was conceived early in the DNAG planning process. The minutes of a meeting of the Steering Committee chaired by L.T. Silver on January 29–30, 1980, record that:

> It was generally agreed that the geographic scope [of the DNAG project] would extend from the Arctic Ocean on the north to the southern limits of the Caribbean plate; from the Mid-Atlantic ridge on the east to the Pacific plate in the approximate vicinity of Hawaii. The emphasis would be placed on the geology of the continent; the adjacent sea floor would be carried as it is related to the continental story....

At the same meeting "the need for a new geologic map was discussed extensively with some disagreement." However, at a meeting in May of the same year, a subcommittee appointed to examine the need for a new geologic map unanimously supported the proposal. It estimated that publication costs might be as much as $200,000, compilation costs might be $500,000, and the time required for compilation would be about 5 years. The Steering Committee agreed that a new geologic map covering the area of the DNAG project was needed, and placed compilation of the map on the list of official DNAG efforts.

By May 1981, the compilers and principal cartographers had been selected, the base map chosen, the essential features of the explanation agreed upon, and compilation was under way. However, in spite of this auspicious start, progress of the compilation was much slower than had been optimistically projected. This was partly the result of the size and complexity of the compilation, partly due to evolution of cartography from traditional pen-and-ink compilations and scribing to modern digital methods, but mostly due to the diversion of each of the compilers to other activities and responsibilities within their respective supporting institutions. Hence the delay of more than a decade and a half from the originally planned completion date of 1989!

Preparation of the map was a joint effort of the Geological Society of America (GSA), the U.S. Geological Survey (USGS), the Geological Survey of Canada (GSC), and the Woods Hole Oceanographic Institution (WHOI). John C. Reed Jr. of the USGS served as general coordinator of the project and was responsible for compilation of the on-land geology of the

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conterminous United States, Alaska, Mexico, Central America, the Antilles, and the parts of Siberia, Colombia, and Venezuela; John O. Wheeler of the GSC was responsible for compilation of the on-land geology of Canada, Greenland, Iceland, and the small part of Ireland that lies within the map area; and Brian E. Tucholke of WHOI undertook the Herculean task of mapping the seafloor geology in all sections of the map. Allison R. Palmer, formerly Centennial Science Coordinator for GSA, acted as general advisor and principal liaison with the Society and also contributed to compilation of the geology of parts of the central interior region and Atlantic and Gulf coastal plains of the United States.

James E. Queen did the cartographic design for the map and was responsible for coordination of the geologic cartography. He also scribed all of the geology for three of the map sheets. Jan Dennis, formerly of the USGS, did the color design. Digital cartography was done by Will R. Stettner and Linda Masonic of the Eastern Publications Group (USGS). Alex J. Donatich of the Central Publications Group (USGS) prepared the map explanation, and Nancy A. Shock, also of the Central Publications Group, prepared and edited ArcInfo files for the southwest quarter of the map. Scanning and tagging of geologic polygons was accomplished by Geologic Data Systems of Denver, Colorado, and type placement was by James E. Queen and Linda Masonic using digital methods.

A digital version of the map and accompanying digital database will be prepared under the National Geologic Database project of the USGS under the supervision of David R. Soller.

PREVIOUS GEOLOGIC MAPS OF NORTH AMERICA

John C. Reed Jr.

The compiler of any geologic map stands on the shoulders of countless predecessors and colleagues and depends on the knowledge and insights that they have accumulated. Nowhere is this more important than in the compilation of a map of a region as vast and complex as a continent. It therefore seems appropriate to briefly review some of the early compilations that underpin the new geologic map of North America.

Eighteenth and Nineteenth Century Maps

The first geologic map showing significant parts of the continent appeared in the mid-eighteenth century, when Guettard (1752) published his *Carte Minéralogique où l'on voit la Nature des Terrains du Canada et de la Louisianne* (Cailleux, 1979). This page-sized map at a scale of ~1:20,000,000, drawn by Phillippe Bruache, covers the region from the north coast of the Gulf of Mexico to Baffin Bay and from the Atlantic coast to ~108° west longitude. It includes parts of Iceland and southern Greenland. A line labeled Fl. de l'Ouest may indicate the Columbia River, and the Pacific is labeled Mere de l'Ouest, although no coastline is suggested. The projection is apparently equidistant conic (Snyder and Voxland, 1989) with standard parallels probably 60° and 30° (Cailleux, 1979).

Guettard's map shows 36 types of geological features, including occurrences of metals (silver, copper, iron, gold, lead), nonmetallic resources (coal, clay, gypsum, marble, saltpeter, petroleum, rock salt), rock types (slate, marble, limestone, "talcose stone," schist/shale) and mineral springs (cold mineral spring, warm mineral spring, salt spring, sulfurous spring) and several other types of features ("rolled pebbles," marcasite or pyrite, ochre, "quaking earth," spar, and ferruginous sand). These symbols are scattered over the region from the Gulf Coast to Greenland and westward to beyond the Mississippi. In addition to these symbols, Guettard distinguishes three general belts of rocks, a "schistose metalliferous zone" that includes the continental interior and the Appalachians and extends through parts of Greenland and Iceland, a marly zone that includes most of the Atlantic Coastal Plain, and a sandy zone that includes the outer Coastal Plain and the Atlantic Continental Shelf. It is the delineation of these belts, crude as it may be, that justifies calling his map a geologic map (Cailleux, 1979).

In the century following publication of Guettard's map, knowledge of the geology of North America progressed gradually as information accumulated first in the eastern United States and Canada, and later in the central interior and western parts of the continent, the Canadian Arctic, Mexico, and Central America. Some of the more significant regional maps include those of Volney (1803), Maclure (1809), Hinton, (1832), Lyell (1845), Hitchcock (1853) and Marcou (1853). Discussions of these maps are based chiefly on descriptions in Ireland (1943), Wells (1959), King and Beikman (1974a), Ehrenberg (1989), and Nelson (1999).

Volney's (1803) map covered only the United States (as it then existed) and showed only five general map units, but it was the first colored regional map of part of North America. Wells (1959) suggests that this map is little known because it was published in a volume on climate and soils. Volney had visited Thomas Jefferson several times and sent him a copy of the volume. Jefferson responded with a long letter in which he comments on the geological parts of the volume:

> Of the first [geological] part I am less a judge than most people...[not] having indulged myself in geological inquiries, from a belief that the skin-deep scratches which we can make on the surface of the earth, do not repay our time with as certain and useful deductions as our pursuits in other branches.

The quotation is from Wells (1959), who remarks, "So much for geology from the first of democrats!"

Maclure's (1809) map (revised in 1817) covered the United States from the eastern seaboard to the lower Mississippi and distinguished five geologic units based on Werner's Neptunian classification that was widely used in Europe: Primitive (metamorphic and igneous rocks formed at the time of Earth's creation), Transition (tilted sedimentary rocks with some fossils), Floetz or secondary (fossiliferous flat-lying sedimentary rocks), "Rock Salt," and Alluvial. In the 1817 revision, the "Old Red Sandstone" was added. This latter edition was reprinted and widely distributed and has been described as "a symbolic point of departure for the geological exploration of the American continent" (Ehrenberg, 1989).

Hinton (1832), assisted by "several literary gentlemen in England and America," compiled a geologic map at a scale of 1:16,000,000 that covered all of the United States (as it then existed) and extended north into Canada as far as the 55th parallel. The eastern part of the map was essentially copied from Maclure's maps, and the part west of the Mississippi was apparently derived from the work of Edwin James, who had accompanied Long's expedition to the Rocky Mountains in 1819–1820, but who never published a geologic map. Wells (1959) remarks that the map and the book in which it appears are both "skillfully done, evidently by someone who had some acquaintance with geology, but who added little or nothing beyond information already published."

The eminent Scottish geologist Charles Lyell examined the geology of the eastern United States, parts of Canada, and Nova Scotia in 1841–1842, guided in the field by prominent Canadian and American geologists, including James Hall. On his return, he published a two-volume description of his travels (Lyell, 1845) that included a "Geological Map of the United States, Canada, etc., compiled from the State Surveys of the U.S. and other sources." In the text, he meticulously acknowledges the contributions of some 26 North American geologists, including Hall, and carefully distinguishes between areas he visited and those he had not seen. His map, at a scale of 1:7,620,000 drew heavily on maps by James Hall and David Dale Owen. It was one of the first in North America to abandon the outmoded Wernerian system and to identify the rocks by stratigraphic age as determined by fossils. It also was one of the earliest to delineate the southern margin of the Canadian Shield, the Adirondack Uplift, and the core of the Ozarks, all of which are mapped as "Hypogene (Granite and Gneiss, etc.)."

Jules Marcou produced several geologic maps of "The United States and the British Provinces east of the Rocky Mountains," the earliest of which appeared as Marcou (1853). Ireland (1943) comments that this map was "poor, with smeared blotchy [hand-done] colors" and describes it as covering essentially the same ground as Lyell's map of 1845, but with more geology in the western parts of the United States. Ireland goes on to remark that in a review of the map, J.D. Dana (1854) criticized Marcou's 1853 map as "having many inaccuracies based on questionable and inadequate information" and its author of "conceit, audacity, and ignorance." Shortly after the appearance of his 1853 map, Marcou, still in his twenties, was appointed geologist to accompany the expedition led by Lt. A.W. Whipple to survey a railroad route from the Midwest to southern California. Marcou himself never completed the map that accompanied the report of the expedition (Whipple, 1856), but the map was compiled by W.P. Blake from his field notes. However, Marcou published a revision of his map in Paris (Marcou, 1855) that incorporated some of his observations during the expedition and included a cross section from Fort Smith, Arkansas, to Los Angeles. This map was among the earliest in which the colors were produced by the new process of chromolithography rather than applied by hand. The map is at a scale of ~1:11,000,000 and measures 26 × 16 inches. In spite of the high quality of the printing, it too received harsh reviews, one of which remarked, "...there is here a disregard of published results and an audacious attempt at generalization that has seldom been equaled." However, King and Beikman (1974a) point out that:

> Viewed from the distance of more than a century, one can deplore Marcou's failure to use available data yet commend his bold attempt to present the general geologic aspect of the western country, which his contemporaries had been reluctant to do."

Logan (1866) published a beautifully executed map entitled "*Geological Map of Canada, including parts of other British Provinces and of the United States*." Although the map bears the date 1866, it was actually not published until 1869 (Anonymous, 1870). This precisely engraved and painstakingly hand-colored map is generally referred to as the "Logan Map," but the title block reads:

> Geology of Canada being derived from the results of the Canadian Geological Survey; that of other British Provinces from the labors of Dr. J.W. Dawson, Professors James Robb, J.B. Jukes, and others; that of the United States under the authority of Professor James Hall. Compiled and drawn by Robert Barlow, Surveyor and Draughtsman (Montreal); engraved in steel by Jacobs and Ramboz (Paris).

The map is printed in eight sheets at a scale of 1:1,584,000 (25 mi to the inch). The projection is not stated, but it is probably a conic projection, possible the Bonne projection (Snyder and Voxland, 1989). The central meridian is 76°W. The base map is bounded by small circles; the southern boundary passes approximately through Dover, Delaware; Bloomington, Indiana; and Ponca City, Oklahoma. The western boundary extends from Ponca City, through Grand Island, Nebraska, to near Regina, Saskatchewan; the northern boundary extends from the vicinity of Regina through Akimiski Island (in James Bay) and Battle Harbour, Newfoundland. The eastern boundary is in the Atlantic Ocean and extends from 50°51′N and 48°10′W to 36°40′N and 54°20′W.

The map distinguishes 33 geologic units, which are identified by numbers on the map and explanation. No faults or other structural features are depicted. The Canadian Shield is left blank, except for an irregular belt 200 mi or less wide along its southern and western edges. Newfoundland is largely blank except for parts of its west coast. Geology is also omitted in the crystalline belt of New England, and in the newly established state of West Virginia (still shown as part of Virginia).

Where mapped, rocks of the Canadian Shield are largely lumped as “Lower Laurentian,” but two areas of “Upper Laurentian” (and one Paleozoic inlier) are distinguished in southeastern Quebec. Most rocks of the Keweenawan Supergroup (including the volcanic rocks) are mapped as “Lauzian” and assigned to the lower Silurian; other Keweenawan rocks are shown as “Chazy,” also lower Silurian.

This map was described as “the finest of all our American [geologic] maps” (von Bitter, 1998). A reduced version at a scale of 125 miles to the inch was published as GSC Map 53, which appeared in an atlas that accompanied the Report of Progress of the Geological Survey of Canada from its commencement to 1863 (Logan, 1863). This version of the map is also commonly referred to as “the Logan map.”

A review of geologic mapping efforts in Canada after publication of Logan’s maps is included as Appendix 1. In it, John Wheeler discusses in detail some of the physical, political, and scientific problems in organizing and conducting a national geologic mapping program, and his insightful comments apply equally to similar programs in other countries in North America.

A number of geologic maps of the United States were published in the later half of the 19th century, including those of Hitchcock and Blake (1874), Hitchcock (1881) and McGee (1884). Van Hise (1896) published a map titled “Geological map of the United States and Canada” at a scale of ~1:11,000,000, but the map was intended to illustrate his discussion of the Precambrian rocks of North America. All Phanerozoic rocks (except “eruptive” rocks) were classed as post-Algonkian, and the Precambrian rocks were classed as Archean, Algonkian (including Huronian and Keweenawan). Crystalline rocks of the Appalachians were mapped as “unclassified Paleozoic, Algonkian, and Archean.” The “eruptive” (plutonic) rocks, regardless of age, were classified only as acid or basic. The Van Hise map does not include Mexico, and large areas in the Cordillera of the western conterminous United States and Canada, and all of Alaska are left blank. Nevertheless, the map shows the outlines of the Canadian Shield in some detail. The shield is mapped largely as “Archean, including unseparated areas of Algonkian,” as are the Precambrian rocks along the west coast of Greenland.

Twentieth Century Maps

Willis Map of 1906

The first more or less complete geologic map of all of North America was prepared for distribution at the 10th International Geological Congress held in Mexico City in 1906 (Willis, 1906, 1907). The map was compiled at the suggestion of I.C. Russell of the University of Michigan at the Geological Society of America meeting in Toronto. A committee chaired by Russell guided preparation of the map. Bailey Willis of the U.S. Geological Survey served as the chief compiler, but the geology of Canada was compiled by James White and that of Mexico by José G. Aguilera. Henry Gannett compiled the base map. The projection is not specified, but it is similar to the bipolar oblique conic conformal projection (Snyder and Voxland, 1989) used on the 1965 Goddard map described below. The 1:5,000,000 scale map, issued in four sheets, covers the entire continent, as well as Greenland and Iceland. The Aleutian Islands, Windward Islands, and northern South America are shown in insets. According to Willis (1907), fewer than three months were available for assembling and adjusting the data! The text is in French and Spanish, with place names in the United States and Canada in English.

Geologic units were depicted in 24 solid colors, plus patterns for Paleozoic metamorphic rocks and for “generally pre-Huronian” Precambrian metamorphic rocks. Plutonic rocks of all ages and compositions were shown with a single color; volcanic rocks were lumped similarly. The geologic units were not identified with letter symbols, and because some of the colors are similar, it is difficult to identify units in many places. No faults were shown, and, of course, no offshore geology. Sizeable areas in Alaska, northwest Canada, and the western conterminous United States were left blank.

In spite of these limitations, the 1906 map was an admirable effort. Most of the Canadian Shield was shown as undivided Precambrian, but some intrusive rocks were broken out, as well as some neo- and eo-Algonkian. Some of the eo-Algonkian belts closely approximate currently recognized Archean greenstone belts. The neo-Algonkian includes the Keweenawan rocks around Lake Superior and areas of Proterozoic rocks in northeastern Canada. In the Cordillera, general trends were well shown. Widespread belts of Paleozoic metamorphic rocks were delineated in Alaska and Canada, and the Coast Range batholith was clearly depicted. Details in the Rocky Mountain fold and thrust belt were shown west of Calgary and in Wyoming and Utah, but otherwise the belt is not recognizable. The Basin and Range province and the Laramide uplifts and basins were shown in considerable detail. There was no hint of the San Andreas fault system, but the Franciscan Formation in the California Coast Ranges was shown and was designated as Triassic and Jurassic.

The crystalline belt of the Appalachians was mapped as chiefly Precambrian crystalline rocks in the northwest and Paleozoic metamorphic rocks in the eastern Piedmont and New England. The Valley and Ridge belt was shown in considerable detail. Widespread Paleozoic and Mesozoic rocks were distinguished in the Canadian Arctic Islands and northwest Greenland, but many age assignments were incorrect and there was little suggestion of the Innuitian orogen.

Willis-Stose Map of 1911

An updated version of the 1906 map appeared five years later (Willis and Stose, 1911). The title block states that the map was “compiled by the U.S. Geological Survey in cooperation with the Geological Survey of Canada and Instituto Geologico de Mexico, under the supervision of Bailey Willis and George W. Stose.” The scale was also 1:5,000,000 and the base was essentially the same as the 1906 map, although meridians and parallels are shown at 1° intervals in land areas, the inset maps were rearranged, and many geographic names had been added. No faults or offshore data were shown. Blank areas in northwest Canada were filled; those in Alaska remained and some of them had been enlarged. Blanks in northern Canada remained. Geology along the southeast coast of Greenland was revised using new data.

Forty-two map units were distinguished and were identified by numbers on the map. Precambrian rocks were divided into Archean (5 units) and Algonkian (5 units) plus undivided Precambrian rocks and a unit of "gneisses, schists, and metamorphosed sediments (supposed pre-Cambrian; possibly in part Paleozoic and Mesozoic)." Paleozoic strata were divided into 8 map units, plus a unit of undivided Paleozoic sedimentary rocks and a unit of undivided Paleozoic metamorphic rocks. Other subdivisions included Mesozoic rocks (5 units), and Tertiary rocks (6 units). Igneous rocks comprised only 3 units: "pre-Cambrian intrusive rocks," post-Cambrian intrusive rocks, and "Tertiary and later effusive rocks."

The Canadian Shield was largely lumped as Laurentian, but "Late? pre-Cambrian" and "Earlier? pre-Cambrian" were broken out in a few places, and Precambrian granites were distinguished locally. More detailed subdivision of the Precambrian rocks in the Lake Superior region were shown in a separate column in the explanation. In the Cordillera, the map is much the same as in the 1906 version, but details were added, especially in central and western Alaska, although there was no hint of the Brooks Range. The Snake River Plain was well shown, and blanks in the Basin and Range province were filled.

In the southern Appalachians, the Blue Ridge was largely shown as Precambrian intrusive rocks, but some Paleozoic rocks were distinguished in the Grandfather Mountain window. The Piedmont was mapped as undivided Precambrian with extensive Paleozoic plutonic rocks and Precambrian intrusive rocks in eastern Virginia. Cambrian and Ordovician rocks in western Massachusetts pass northeast at a state line fault into metamorphosed Paleozoic rocks with widespread Paleozoic plutons in northeastern New England. Pennsylvanian sedimentary rocks were shown in the Boston Basin.

Stose Map of 1946

Thirty-five years (and two World Wars) intervened before publication of the next geologic map of North America. George W. Stose compiled the 1946 map "under grants from the Geological Society of America, the American Philosophical Society, and the American Association of Petroleum Geologists, Bailey Willis, grantee," according to the title block. Compilation was carried out "with the cooperation of the U.S. Geological Survey, the Geological Surveys of Canada and Mexico, State and Provincial Surveys of United States and Canada, and individual geologists." The Geological Society of America published the map (Stose, 1946).

The map was at a scale of 1:5,000,000 and was printed in two sheets; the area covered was essentially the same as the 1906 and 1911 maps. The projection is not stated, but seems to be the same bipolar oblique conic projection as was used in the previous maps. Ninety-one map units were distinguished. Of these, 13 were Precambrian, 29 were Paleozoic, 22 were Mesozoic, 23 were Tertiary, and 4 were Quaternary. Volcanic and plutonic rocks were divided by age, and compositions of many were described. Metamorphic rocks were not distinguished, and descriptions of map units contained little information on type and grade of metamorphism. Many subdivisions seem to reflect Stose's background and broad experience in the Appalachians. Faults were not shown, and no offshore information was included. Several small areas were left blank in Alaska, the Canadian Arctic Islands, and northern Greenland, but otherwise the geology of all land areas except western Siberia was shown.

Most of the Canadian Shield was shown as early Precambrian granite and granite gneiss, but many areas of early Precambrian rocks corresponding to greenstone belts were distinguished. Small areas of early Precambrian sedimentary rocks identified as Grenville-Hastings were shown in southern Quebec and eastern Canada. Several areas of anorthosite were identified in Quebec, eastern Canada, and the Adirondacks. Keweenawan sedimentary and volcanic rocks were mapped separately in the Lake Superior region and identified as late Precambrian.

Geology of the Cordillera was shown in much more detail in both age assignments and distribution of units. Details of the thrust belt in western Canada were depicted, and in the Brooks Range there were some indications of the general structural trends. Volcanic rocks of the Columbia River Plateau and Snake River Plain were distinguished, but age assignments were incorrect. The Basin and Range Province showed considerably improved detail. Laramide uplifts and the Colorado Plateau were well shown, but all basement rocks were assigned to the early Precambrian. Detail in the Franciscan belt, the Great Valley, and the Sierran foothills is much improved. Much detail is added in western Mexico and in Baja California.

In the southern Appalachian orogen, the depiction of the geology of the Valley and Ridge belt was improved by a more detailed age breakdown of units. Most of the Blue Ridge was shown as late Precambrian; the Ocoee and Talladega Groups were shown separately. The Carolina Slate belt was shown. Intrusive rocks in the Piedmont were classified as late Precambrian (post-Glenarm), now known to be largely Taconic; and Carboniferous and Devonian, now known to be largely Acadian. In New England, sedimentary and metamorphic rocks were mapped as Devonian, Silurian, and Ordovician, but with no indication of the grade of metamorphism. The plutonic rocks were all shown as Carboniferous and Devonian.

The Innuitian orogen was shown as generalized broad belts of Ordovician, Devonian, and Carboniferous sedimentary rocks. Some Cambrian was identified in northern Greenland, and extensive areas of Triassic rocks were shown in the Sverdrup Islands.

The Windward Islands were all shown as Cretaceous intrusive rocks, obviously a mistake.

Goddard Map of 1965

The direct predecessor of the present map (North American Geologic Map Committee, 1965), herein referred to as the

Goddard map, was published by the U.S. Geological Survey (1965). T.S. Lovering, then president of the Geological Society of America, and the council of the society made plans for preparation and printing of the map (Goddard, 1967). President Lovering appointed a committee chaired by E.N. Goddard of the University of Michigan to direct preparation of the map. In addition to the chairman and the vice-chairman, Marland P. Billings, the committee included nine members representing the United States (except Alaska), Alaska, Canada, Mexico, and Latin America, plus P.B. King. The father of one of the compilers of the present map (Reed) served as the committee member for Alaska. Goddard (1967) notes that the map took 15 years in compilation, preparation, and publication.

The base map chosen was the North American part of the Map of the Americas that had just been published by the American Geographical Society. The Geologic Map of South America had been printed on the same base, so the two maps would fit together. This geologic map of North America was published in two sheets at a nominal scale of 1:5,000,000. The projection is bipolar oblique conic conformal, but with appreciable differences from the earlier twentieth century maps. The areas covered are essentially the same as those on the previous maps.

The map showed faults more than 40 mi in length, but fault types were not distinguished. One hundred seven units were shown. Of these, 76 were sedimentary rocks, 13 were volcanic rocks, 10 were plutonic rocks, and 8 were metamorphic rocks, including one for undivided crystalline rocks. The map also showed bathymetric contours in the ocean basins, the first map of North America to do so, although it did not depict seafloor geology.

The Canadian Shield was shown mostly as Precambrian granite and granite gneiss. Many greenstone belts were shown as Lower Precambrian, which includes the Keewatin, Knife Lake, Yellowknife, and similar rocks. Middle Precambrian rocks include the Penokean rocks of the Southern Province and were also identified in parts of the Slave and Rae Provinces. Precambrian basic intrusive rocks (listed as gabbro, anorthosite, and diabase) were widely mapped in the Grenville Province and in the area of the Duluth Gabbro northwest of Lake Superior. Upper Precambrian rocks included the Keweenawan rocks of the Lake Superior region, and the strata in the Athabasca, Thelon, and other intracratonic basins. Strangely, the breccia and impact melts in the ca. 210 Ma Late Triassic Manicouagan impact structure were shown as Upper Precambrian.

In the Cordillera, much detail was added, especially in Alaska. Folds and faults in the Brooks Range were well shown. The Denali and Nixon Fork faults were shown, but the Kaltag and Tintina faults were missing. The thrust belt was well shown in southern Canada and the northern United States. Several segments of the Rocky Mountain Trench fault system were also delineated but the continuity of the system is not apparent. Faults in the Basin and Range Province were shown in considerable detail, as were the San Andreas, Garlock, and related faults. The Franciscan was shown as Cretaceous and Jurassic, and was distinguished from the Great Valley sequence, which was mapped as Cretaceous. Laramide uplifts were accurately shown, but all of the Precambrian metamorphic rocks in their cores were classed as Lower Precambrian, presumably Archean. The Mexican volcanic plateau and the fold and thrust belts in Mexico were shown in some detail.

In the southern Appalachian orogen, depiction of the Valley and Ridge Province was greatly improved with the addition of faults and much finer stratigraphic division. Basement rocks in the Blue Ridge were shown as lower Precambrian, the Ocoee Supergroup was mapped as Upper Precambrian, and the rocks of the Murphy syncline are identified as Paleozoic. Volcanic rocks of the Slate Belt were identified as Paleozoic and the Glenarm Series and most of the Inner Piedmont were shown as Paleozoic and Precambrian schist and gneiss. In New England, the Taconic klippe was clearly shown, and the general distribution of Paleozoic rocks in the crystalline terrane was depicted, but no effort was made to distinguish metamorphosed from unmetamorphosed rocks. All plutons both in New England and the southern Appalachians were classed simply as Paleozoic.

Many details were added in the Innuitian orogen; fold patterns were apparent because finer stratigraphic subdivisions were shown. No faults were shown.

THE DECADE OF NORTH AMERICAN GEOLOGY GEOLOGIC MAP OF NORTH AMERICA

John C. Reed Jr., John O. Wheeler, and Brian E. Tucholke

Philosophy and Design

Like all of its twentieth century predecessors, the new Geologic Map of North America is designed to depict bedrock and less indurated sedimentary units at or near the surface throughout all parts of the North American continent, as well as selected parts of adjacent continents and islands. In addition, the present map shows similar units across the seafloor. The emphasis is on pre-Quaternary geology, so Quaternary surficial deposits are shown only where they completely conceal the underlying units in significant areas. The extensive glacial deposits of the continental interior and Canadian shield are not shown, but Quaternary surficial deposits are shown in the intermontane basins in the Cordillera, in parts of the Atlantic and Gulf coastal plains, and in the Orinoco basin. By far, the most extensive areas of Quaternary deposits depicted on the map are on the seafloor.

Varnes (1974) points out that all maps, including geologic maps, lie somewhere in a spectrum between those whose purpose is to provide a precise knowledge of a wide variety of the attributes of a specified area (detailed maps), and those whose purpose is to provide general knowledge of broad areas that have specified attributes (generalized maps). A geologic map of a region as large and complex as North America must lie near the extreme of generalization in Varnes' spectrum. Such a map is designed to convey a general knowledge of the geologic units over large regions, but it therefore can indicate only a small number of attributes of the units. Varnes recognizes two types of generalizations that are required in compilation of small-scale maps: (1) spatial or cartographic generalization, in which the boundaries between units are made smoother, tortuosities are simplified, and small inliers of one unit in another are removed, and (2) categorical or typologic generalization, in which units with similar attributes are "lumped."

King and Beikman (1974a) describe the generalization process involved in compilation of their Geologic Map of the United States as follows:

> …Some items on the original maps can easily be sacrificed, such as subdivisions within gross stratigraphic units, convolutions of contacts produced by erosion or topography, little faults unrelated to gross tectonic pattern, patches of some ubiquitous lava or gravel scattered over bedrock, and strips of river alluvium. Other items should be emphasized or even exaggerated, such as inliers of Precambrian rocks amidst younger rocks, and the lay of formations and contacts produced by folding and faulting.

> …The final generalization is always painful to the compiler, because he is thoroughly aware of the significant geologic features he wishes to portray, yet has very little space in which to do so. He is constrained by the limits of legible printing of lines and colors and by the eventual user's limits of comprehension."

King emphasizes that the decisions required in these generalizations depend on the skill, experience, and interests of the individual compiler. One of the present compilers recalls King's reply when asked by a colleague how he went about compiling the Geologic Map of the United States (King and Beikman, 1974b). He described reviews of the literature, study of available source maps, consultations with regional experts, and evaluations of various interpretations and hypotheses, and then remarked "but in the end, the compiler is KING."

Each of the present compilers has been faced with myriad difficult decisions during the generalization process, and each has become painfully aware of the difficulties that King and Beikman describe. While we have tried to be as consistent as possible, each of our compilations was an individual effort. The methods used and the final, integrated map product reflect the state of knowledge of the geology in different parts of the map area, the facilities and equipment available to the compilers, and the individual background, experience, and interests of each compiler, as will be evident to the discriminating map user.

The new geologic map of North America differs from previous maps of the continent in several important respects: It is the first such map to depict the geology of the seafloor, and it is the first compiled since the general acceptance of the concept of plate tectonics. Furthermore, it is the first since radiometric dates for plutonic and volcanic rocks became widely available. It also reflects enormous advances in conventional geologic mapping, especially in the Canadian Shield, the Cordillera, Alaska and the Canadian Arctic, and Newfoundland, as well as in Mexico and northern South America. These scientific advances have led to a very significant increase in the complexity of the map. The new map distinguishes more than 900 rock units, of which 110 are offshore. Thus it depicts more than 7 times the number of on-land units as are shown on its immediate predecessor, as well as many more faults and additional features such as volcanoes, calderas, impact structures, small bodies of unusual igneous rocks, diapirs, and the like.

Contents of the Map

Rock Units

The rock units shown on the Geologic Map of North America are defined on the basis of age, origin, and where possible, composition. Phanerozoic rocks regionally metamorphosed to amphibolite facies or higher (or blueschist facies or higher in active orogenic belts) are distinguished by a diagonal line overprint, as are rocks metamorphosed to granulite facies in the Canadian shield. Other special lithologies and depositional environments such as mélange, predominately continental deposits, and off-shelf (not offshore) marine deposits exposed on land are also indicated by overprints.

The unit labels used on the map are intended to provide the maximum amount of information for each map unit. This greatly simplifies the map explanation and minimizes the need to repeatedly refer to it. However, the system requires long and complex letter symbols. In order to interpret the symbols, it is necessary to be aware of a few simple rules:

1. Ages of rock units are indicated by uppercase letters and by lowercase letters and/or numbers preceding them. The lowercase letters and numbers indicate subdivisions of time-stratigraphic units. Most of these follow standard conventions, but some are not obvious. Major subdivisions of time-stratigraphic units are generally indicated by l—lower, m—middle, and u—upper. In plutonic rocks small uppercase letters E, M, and L indicate Early, Middle, and Late. Further subdivisions are indicated by numbers, starting with the oldest = 1. In the Precambrian, superscripts are used for subdivisions, for example Y^1, Y^2, Y^3. Combined units or units of uncertain age are indicated by double age designations, with the oldest age first. Where only an age designation appears in the unit label, the unit is sedimentary. In a few areas in the Canadian Shield and in the upper Midwest, the symbols Xcs and Xqz are used to identify units of Early Proterozoic sandstone and conglomerate, and quartzite, respectively. In parts of the Northwest Territories in Canada, the suffixes "cb" and "e" were used to distinguish carbonate rock and evaporates in units uDcb, mDcb, and mDe.

2. For volcanic rocks, the age designation is followed by a lowercase "v" (e.g., plTv—Pliocene volcanic rocks). Lowercase letters following the "v" indicate lithology: f—felsic; i—intermediate; m—mafic; sv—mixed sedimentary and volcanic; b—bimodal; k—alkalic (e.g., plTvmk—Pliocene alkaline mafic volcanics).

3. For plutonic rocks, lowercase letters following the age designation indicate lithology: q—quartz monzonite and granite; g—

undivided granitoid; f—felsite; i—granodiorite and quartz diorite; m—diorite and gabbro; y—syenite and monzodiorite; my—alkaline gabbro and syenite; a—anorthosite; and u—ultramafic.

4. For high-grade metamorphic rocks, age of the protolith is given. Lowercase letters following the age designation indicate lithology of the protolith: n—gneiss; sn—sedimentary gneiss; gn—granitic gneiss; and sgn—paragneiss and orthogneiss. Undivided crystalline rocks are indicated by x.

5. Lower-case letters without age designations indicate lithology of units of unknown or unspecified age: u—ultramafic rocks; x—crystalline rocks; g—granitoid rocks.

Age designations for map units are as follows:

Q—Quaternary
pQ—Pleistocene
T—Tertiary
plT—Pliocene
mT—Miocene
pgT—Paleogene
oT—Oligocene
eT—Eocene
paT—Paleocene
Mz—Mesozoic
K—Cretaceous
J—Jurassic
TR—Triassic
Pz—Paleozoic
P—Permian
IP—Pennsylvanian
M—Mississippian
D—Devonian
S—Silurian
O—Ordovician
Є—Cambrian
pЄ—Precambrian
Ꝑ—Proterozoic
Z—Late Proterozoic
Y—Middle Proterozoic
X—Early Proterozoic
A—Archean
W—Late Archean
V—Middle Archean
U—Early Archean

Symbolization

Symbols used on the map are largely conventional. However, because of the wide variety of features depicted, a number of additional symbols were contrived and six different colors were employed to distinguish various line and point symbols. These usages of color line and point symbols are summarized in Table 1.

Color Design

In his discussion of the 1911 geologic map of North America, Willis (1912) describes the problem of designing the color scheme for a large and complex map:

> Color is used on geologic maps to delineate the distribution of various rocks. Legibility is the first requirement, economy in printing the second, and good taste the third. Custom may prescribe certain associations of color with particular implications, which, being long established, control other associations.... The accompanying geologic map of North America represents an application of the proposed principles to a general case of great complexity....

The compilers and designers of the present map can only respond, “Amen, Bailey, wherever you are!” We have tried to adhere to Willis’ principals insofar as possible, but we have had to diverge from them with respect to his third principal, because of the much larger number of rock units and the far greater complexity of the present map. Neither the Geologic Map of the United States (King and Beikman, 1974b) nor the Geological Map of Canada (Wheeler et al., 1996) is an appropriate model, although both have well-conceived and beautifully executed color designs. However, the colors on the U.S. map are selected to emphasize the geology of the extensive areas of Paleozoic, Mesozoic, and Tertiary rocks, while those on the Canadian map are chosen to depict the complex geology of the Precambrian rocks in the Canadian shield. We were also faced with the problem of representing the geology of the seafloor and visually distinguishing onshore from offshore geologic units. In order to adequately represent the geology of these disparate regions, as well as that in other parts of the continent, we were forced to choose colors that do not correspond to many of those on these widely recognized maps or to the international color scheme used by many European maps.

We have followed the custom of using colors to indicate the ages of rocks and patterns to indicate lithology or tectonic setting. Lithologies of most sedimentary units are not distinguished and therefore most are not patterned. Lithologies of volcanic, plutonic, and many Precambrian metamorphic rocks are indicated wherever possible. We used three different series of colors: one for sedimentary and volcanic rocks, one for plutonic rocks, and one for special seafloor units. As mentioned previously, regionally metamorphosed sedimentary and volcanic rocks are indicated by a diagonal line overprint on the normal sedimentary or volcanic colors. Gneissic rocks are indicated by a pattern of irregular, slightly elongate blotches superimposed on the appropriate color. Rocks of uncertain age or units that combine rocks of a wide range of ages are generally shown in tones of gray. Offshore units are generally indicated by paler shades of the colors used on land in order to differentiate the outlines of the landmasses when the map is viewed from a distance. Exceptions to this are the use of light gray for Quaternary deposits offshore, and shades of purple used for submarine basalts adjacent to young spreading centers. A narrow uncolored strip between the shoreline and the offshore units further emphasizes coastlines. Geology beneath some large lakes is shown, but small lakes are left uncolored.

Layout of the Explanation

Because of the large number of map units we have not attempted to identify named stratigraphic units that are included

TABLE 1. COLORS USED FOR LINE AND POINT SYMBOLS

COLOR	ONSHORE	OFFSHORE
Black	*Line symbols*: contacts faults shear zones *Point symbols*: volcanic features diatremes kimberlite bodies	*Line symbols*: contacts faults pseudofaults shear zones *Point symbols:* seeps hydrothermal vents
Brown	*Line symbols:* growth faults Late Proterozoic dikes	*Line symbols*: frontal faults of accretionary wedges slump scars submarine escarpments axes of sediment drift
Blue	*Line symbols*: limits of glaciation Mesozoic dikes selected Early Proterozoic mafic dikes *Point symbols*: diapirs	*Line symbols*: bathymetric and sub-ice contours axes of submarine canyons, seafloor valleys, or channels areas of abundant diapirs
Dark blue	*Line symbols*: limits of continental glaciation selected Early Proterozoic mafic dikes	*Point symbols*: diapirs selected manganiferous deposits
Purple	*Line symbols*: Middle Proterozoic mafic dikes Tertiary dikes *Point symbols*: impact structures carbonatite bodies	*Line symbols*: magnetic isochrons *Point symbols*: impact structures
Red	*Line symbols*: selected Early Proterozoic mafic dikes	*Line symbols:* spreading centers *Point symbols*: significant offshore outcrops dredge haul lithologies phosphate nodules or pavements
Green	*Line symbols*: selected Middle Proterozoic mafic dikes Archean and Archean/Proterozoic mafic dikes	*Point symbols*: diapirs selected manganiferous deposits

within the map units. For this information, users will need to refer to more detailed maps, or ultimately to the digital database that is to be produced in conjunction with this map.

In the explanation, the units are grouped in columns for sedimentary, volcanic, plutonic, and metamorphic rocks, with a separate box for special seafloor units, including basalts adjacent to young spreading centers, and poorly known parts of the seafloor underlain by strongly condensed sedimentary sections, with numerous outcrops of volcanic oceanic crust and pre-Quaternary sedimentary rocks. Within each column, the units are arranged vertically by geologic age, with the oldest at the bottom and youngest at the top. The units are arranged horizontally within the columns, with finer stratigraphic subdivisions to the left and broader subdivisions to the right. The horizontal arrangement is generally as follows:

- Series and groups (shown only in a few places; example: 2uP, upper Permian Ochoan Series)
- Subdivisions of periods (example: lD, Lower Devonian)
- Combinations of subdivisions of periods (example: lmD, Lower and Middle Devonian)
- Periods (example: D, Devonian)
- Combinations of sequential periods in the same era (example: DM, Devonian and Mississippian; in this case *and* is implicit between the names of the periods).

- Ranges of non-sequential periods in the same era (example: DP, Devonian-Permian; here a hyphen is implied)
- Ranges of periods in different eras (example: DTR, Devonian-Triassic)
- Eras (example: Pz, Paleozoic)
- Combinations of eras (example: PzMz, Paleozoic-Mesozoic)
- Units shown only as pre- some era or period (example: pꞒ, Precambrian)
- Units of unknown or unspecified age (example: n, gneiss of unknown age)

Base Map and Projection

The base map was compiled by the U.S. Geological Survey (USGS) for use in all of the continental scale maps published as part of the Decade of North American Geology project, including the gravity anomaly map (Committee for the Gravity Anomaly Map of North America, 1987), the magnetic map (Committee for the Magnetic Anomaly Map of North America, 1987), the geothermal map (Blackwell and Steele, 1992), the seismicity map (Engdahl, 1988) and the stress map (Zoback et al., 1987). It has also been used as the base for the tectonic map of North America (Muehlberger, 1992). The map was prepared with data from World Data Bank II and other sources, including the Department of Energy Mines and Resources (EMR) of Canada and the Dirección General de Geografía del Territorio Nacional (DGGTN) of Mexico. During compilation of the geologic map, some corrections were made to the base, chiefly in northeastern Greenland and in the overlap area between the northern and southern sheets. A 1:10,000,000 version of the base map was published by the USGS in 1982.

The projection is a spherical form of the Transverse Mercator described by Snyder (1987, p. 51):

> In 1979 this projection was chosen for a base map of North America at a scale of 1:5,000,000 to replace the Bipolar Oblique Conic Conformal projection previously used for tectonic and other geologic maps. The scale factor along the central meridian, long. 100° W, is 0.926. The radius of the Earth is taken to be 6,371,204 m, with approximately the same surface area as the International ellipsoid, placing two straight lines of true design scale 2,343 km on each side of the central meridian.

Conceptually, the projection may be pictured as formed by passing a cylinder through a spherical Earth with its axis perpendicular to the plane of the 100th meridian. The radius of the cylinder is taken so that it intersects the sphere in two small circles, each 2343 km away from the central meridian. Points on the surface of the sphere are then projected onto the cylinder from the center of the sphere, as in a conventional Mercator projection. On the map, the small circles formed by the intersection of the cylinder with the sphere are represented by two straight lines parallel to the central meridian and halfway between the central meridian and the sides of the map. Along these lines, the map scale is exactly 1:5,000,000; along the central meridian, the scale is ~1: 5,400,000 (5,000,000/0.926) and near the sides of the map, the scale is ~1:4,240,000. The scale remains constant along any line on the map parallel to the 100th meridian. Thus the distortion is minimal within North America because the central meridian is chosen to bisect the continent as nearly as possible (Fig. 1).

HOW THE MAP WAS MADE

The methods used in compilation of the geology differed among the compilers depending on the state of knowledge of the geology in different parts of the map area, on the facilities and equipment available, and on the background, experience, and interests of the individual compiler.

Siberia, Alaska, Conterminous United States, Mexico, Central America, Colombia, Venezuela, and the Antilles

John C. Reed Jr.

Most of the geologic information was derived from geologic maps at scales of 1:500,000 or smaller, but in some areas, maps at scales of 1:250,000 were used, and in a few cases, more detailed geologic maps were consulted. Extensive use was made of maps included in various volumes of the DNAG Geology of North America series, especially in Alaska, the U.S. Cordillera, northern South America, and the Antilles.

Compilation began in the southeast quarter of the map and the methods of compilation evolved with the development of new techniques of digital cartography. In the early stages of compilation, the initial step was to trace the most significant geologic features on a scale-stable overlay, keeping in mind the limitations on the amount of detail that could be shown on the final map on which 1 mm represents 5 km on the ground. These preliminary tracings were then hand-digitized using the GSMCAD program originally developed as the GSMAP program by R.B. Taylor and Gary I. Selner of the U.S. Geological Survey and refined, improved and renamed by V.S. Williams, also of the USGS. These programs were especially valuable because they made it possible to plot data digitized on any map projection to the Transverse Mercator projection used on the final map.

After the initial digitizing from a particular source map was complete, the file was plotted on the DNAG projection at a scale of 1:2,500,000 (twice publication scale). These plots were then assembled into blocks covering areas of ~10° of latitude by 15° of longitude. The geology was retraced, further simplified, adjusted to remove miss-joins and discrepancies, and re-digitized. The map of each compilation block was plotted out on stable base material. During early stages of compilation, the GSMAP program did not include effective ways of editing and joining lines or tagging and labeling polygons, so the stable base plots were corrected, labeled by hand, and checked by coloring out paper copies. The corrected plots were then photographed and reduced to publication scale. Film positives of the individual blocks then were assembled into a mosaic and adjusted to fit the base map.

Figure 1. Index map showing the area covered by the Geologic Map of North America. Long-dashed line is the central meridian (100°W); short-dashed lines are small circles where the projection cylinder intersects the sphere and the scale is exactly 1:5,000,000.

The mosaics were then scribed, on the assumption that the map would be printed by traditional color separation methods.

As the GSMAP computer program evolved and the GSMCAD program developed, digital editing became much more efficient. During the compilation of the geology of Alaska and Siberia on the northwest quarter the general process of tracing, digitizing, re-projecting, editing, and re-digitizing remained much the same, but editing of linework was done digitally. Finally, during compilation of the parts of the southwest quarter for which Reed was responsible, it was possible to correct linework, tag and label polygons, and produce color plots digitally. By this stage, it was also possible to bring the edited GSMCAD plots of the individual compilation blocks directly into ArcInfo and mosaic them to fit the base map.

Canada, Greenland, Iceland, and Westernmost Ireland

John O. Wheeler

Compilation of these areas was done at the 1:5,000,000 scale, following cartographic practices of the Geological Survey of Canada. This involved compiling at publication scale, which allows the compiler to better judge how to simplify and generalize the geology of congested areas. Preparation of the geologic maps of these four areas was done in different ways. For Canada, compilation was a multistage process undertaken by experts from the Geological Survey of Canada who were highly knowledgeable about the major geological regions of Canada. Many of these same experts also produced 1:2,000,000 scale regional maps to illustrate the Canadian DNAG volumes, as well as acting as authors and editors of the volumes. Wheeler himself compiled the geology of Greenland, Iceland, and westernmost Ireland.

Regional maps of the Precambrian Shield were compiled at 1:5,000,000 scale for the Superior and Southern Provinces by Ken D. Card and for the Grenville Province by A. (Tony) Davidson. These were plotted directly from reductions of geologic maps at larger scales onto 1:5,000,000 scale mylar base maps on the DNAG Transverse Mercator projection. Paul Hoffman, however, compiled the remaining Bear, Slave, Churchill, and Nain provinces of the shield by plotting directly from reductions of larger scale maps onto a 1:5,000,000 scale mylar base map on a Lambert Conformal Conic projection. This map was then transformed by the GSC to the DNAG Transverse Mercator projection.

At the time the map compilation began, it was decided that compilers would use the 1983 Geologic Time Scale (Palmer, 1983) in which the boundary between the Middle and Late Archean eras was at 3000 Ma. In addition, the alphabetical (U, V, W, X, Y, Z) divisions of the Precambrian Eon used by the U.S. Geological Survey (James, 1972) were adopted to provide simple and unambiguous labeling. Thus, on the new Geologic Map of North America, the Middle Archean is labeled as V and the Late Archean as W. Card's first compilation of the Superior Province in 1984 used the 1983 time scale, and this resulted in the absence of any Middle Archean map-unit in the Superior Province on our map.

Subsequent to Card's work, the Middle Archean–Late Archean boundary was placed at 2800 Ma by Lumbers and Card (1991) and at 2900 Ma by the Ontario Geological Survey (Thurston et al., 1991). This led to the delineation of extensive areas of the Middle Archean rocks in the Superior Province, as displayed on the Ontario Geological Survey's 1:1,000,000 scale maps (Ontario Geological Survey, 1991) that accompanied the two monumental volumes describing the geology of Ontario (Thurston et al., 1991, Thurston et al., 1992). Areas of the Middle Archean rocks were included by Card in his revised compilation of 1992 and were published as part of the 8th edition of the Geological Map of Canada (Wheeler et al., 1996). However, by this time Jack Reed had digitized almost the entire western Superior Province as compiled in Card's 1984 map. It was decided that it was too large a task to recompile and re-digitize the Superior Province. Moreover, Card's 1984 geology of the Superior Province had already been incorporated into the Tectonic Map of North America (Muehlberger, 1992). Interested readers are referred to the 1:2,000,000 scale GSC Map 1948A (Card et al., 1998) for the latest distribution of Middle and Late Archean units in the Superior Province.

In the Grenville Province, rapid advances in mapping over the past 25 years was brought about by a vast increase in radiometric dates, especially those by U-Pb methods, and by the application of modern structural studies which identified several extensive, large-scale ductile shear zones. These factors led to changes in the ages and configuration of some map units and of the position and outline of major thrust faults. Davidson, therefore, was required to make several revised versions of his original compilation. The last of these was incorporated at a late stage in the drafting of the northeast quarter of Geologic Map of North America to create a map pattern of the Grenville Province that is reasonably similar to that of the Geological Map of Canada. Davidson's final and more detailed compilation of the Grenville Province was published at 1: 2,000,000 scale as GSC Map 1947A (Davidson, 1998).

Andrew V. Okulitch prepared a 1:5,000,000 scale map of the Innuitian Orogen and Arctic Platform embracing the Middle Proterozoic and younger geology of the Canadian Arctic Islands and the of the intervening seafloor geology. The Early Proterozoic and older geology of the region was compiled by Paul Hoffman. Okulitch's map was plotted directly on the 1:5,000,000 scale DNAG mylar base sheets and used for the Geologic Map of North America. In the western Canadian Arctic Islands, his map was supplemented by seafloor geology compiled by Ashton F. Embry. Okulitch produced a later 1:2,000,000 scale GSC Map 1715A (Okulitch, 1991) on the Lambert Conformal Conic projection with standard parallels at 49° and 77°N. This was used for compiling the Geological Map of Canada, also at the same projection. Okulitch notes that the configuration of submarine and subglacial units are somewhat tenuous, having been extrapolated from adjacent exposed geology approximately constrained by preliminary interpretations of geophysical and well data in northern and western Baffin Bay and in various inter-island channels in and around Sverdrup Basin.

Farther south, the adjacent Hudson Platform of flat-lying Paleozoic and Cretaceous sediments is largely submerged beneath Hudson and Foxe basins and beneath Hudson Strait. This area was compiled by Bruce V. Sanford from his previous studies both on land and from interpretations of industry and GSC marine seismic data calibrated by boreholes (Sanford and Grant, 1990b).

Harold (Hank) Williams compiled a preliminary map of the Appalachian Orogen in Canada at a scale of 1:5,000,000 during the early stages of his work on the Canadian Appalachian DNAG volume F-1. Subsequently, new geologic maps of New Brunswick (Ferguson and Fyffe, 1985), Nova Scotia (Donohoe and Grantham, 1989), and the island of Newfoundland (Colman-Sadd et al., 1990) were published. Williams, however, was unable to revise and update his map because of his demanding responsibilities as editor and chief author of DNAG Canadian Appalachian volume. Therefore, John Wheeler recompiled and updated the Appalachian map from the above maps. Wheeler also revised parts of the Quebec Appalachians in the Eastern Townships of Quebec from Tremblay and Pinet (1994) and in Gaspé from Malo et al. (1992). Wheeler also plotted the seafloor geology of the Gulf of St. Lawrence from the seafloor surveys and map by Sanford and Grant (1990a) and prepared the 1:5,000,000 scale map of the St. Lawrence Platform from the 1:1,000,000 scale maps of Southern Ontario by Sanford and Baer (1971) and the Gatineau River sheet by Baer et al. (1971).

John Wheeler compiled the geology of western Canada west of the Precambrian Shield with the assistance of G. Keith Williams, who provided an initial plot of the geology of the western Interior Plains and eastern Cordillera at 1:5,000,000 scale on the Transverse Mercator DNAG mylar base. His map was derived largely from the Geological Map of Alberta (Green, 1970).

Wheeler first prepared a plot of the geology of the Canadian Cordillera at a scale of 1:2,000,000 on a Lambert Conformal Conic projection from reductions mainly from 1:250,000 scale geologic maps and locally of maps at other scales. A reduction of this map provided the basis for the Cordilleran part of the 1:5,000,000 scale Geological Map of Canada on the same Lambert projection. It also provided the template for the Cordilleran part of the North American map after the projection was transformed to the Transverse Mercator DNAG projection. Finally, a derivative map from the Cordilleran Lambert projection plot at a scale of 1:2,000,000 grouped geologic units into tectonic assemblages extending as far east as 108th meridian (Wheeler and McFeely, 1991).

The geology of the Interior Plains in Saskatchewan and Manitoba was taken from the 1:1,000,000 scale plot of the Phanerozoic geology of Saskatchewan by Paul Broughton (Macdonald and Broughton, 1980) and from the 1:1,000,000 scale plot of the Phanerozoic geology of the Plains in Manitoba by B.B. Bannatyne and H.R. McCabe (Bannatyne and McCabe, 1979). Reductions from these maps were plotted directly on the 1:5,000,000 scale Transverse Mercator mylar base.

John Wheeler compiled his initial map of the geology of Greenland largely from the ten 1:500,000 scale geologic maps available by 1991. The remaining areas were plotted from new data published in preliminary reports of current mapping programs, especially in northeast Greenland. Where no new mapping had taken place, information was used from the 1970 edition of the Geological Map of Greenland at 1:2,500,000 scale. The resulting map of Greenland at 1:5,000,000 scale, as well as of Canada, Iceland, and westernmost Ireland, was submitted to Jack Reed and Jim Queen in December 1992 for further cartographic processing.

The compilation of Greenland geology brought to light difficulties in fitting the new geology from the Peary Land and Nyeboe Land 1:500,000 scale sheets onto the 1:5,000,000 scale DNAG base of northern and northeastern Greenland. It was then pointed out to Wheeler that the coastline on the DNAG base map had been misplaced as a result of insufficient ground control from earlier surveys (Henriksen et al., 2000). Jack Reed, however, came to the rescue and provided the correct coastline derived from more recent surveys.

Wheeler later submitted a revised copy of his Greenland plot to the Geological Survey of Greenland for review. It turned out that the Greenland Survey had just completed a new geological map at a scale of 1:2,500,000. The Survey kindly sent Wheeler an advance copy, which he used to produce a revised map of Greenland for the Geologic Map of North America.

In this regard, the Geological Map of Greenland (Escher and Pulvertaft, 1995) shows a sedimentary assemblage, unit 45, of unknown age, that underlies Caledonian thrusts in the nunataks along the eastern margin of the ice sheet between latitudes 70° and 74°N. Wheeler labeled unit 45 as Y^3 in accordance with its position in the Greenland map legend at around 1100 Ma (Late Middle Proterozoic). Henriksen et al. (2000) point out, however, that in the southern area of unit 45, between latitudes 70° and 71°30′, the unit overlies tillite. If this tillite can be correlated with the Late Proterozoic Varangian (Z) tillites in the fjord zone to the east, then the sediments of unit 45 are probably of early Paleozoic age. However, Henriksen et al. note that in the northern area of unit 45, around latitude 74°N, the unit comprises low-grade metasediments associated with volcanics, unconformably overlain by thick quartzite containing abundant *Skolithos* of latest Proterozoic to earliest Cambrian age. Furthermore, unit 45 is intruded by quartz porphyry, which has yielded zircons dated by SHRIMP studies at ca. 1900 Ma. These data suggest that unit 45 is Early Proterozoic or older. Given these disparities the age of unit 45, shown as Y^3 on the Geologic Map of North America, remains uncertain.

The geology of Iceland was plotted directly onto the DNAG mylar base from the structural outline map of Iceland by Saemundsson (1986; his Fig. 2). At the suggestion of reviewer Peter Vogt, Jack Reed added faults and calderas from Johannesson and Saemundsson (1998).

The geology of westernmost Ireland was plotted, in part, from Figure 11 of Phillips (1981) with modifications whereby the Annagh gneiss complex is labeled as Y^3gn, indicating Grenvillian basement with a range of U-Pb ages from 1.3 to 1.0 Ga (Aftalion and Max, 1987); the Connemara metagabbro-gneiss complex, labeled Om, on the basis of ^{207}Pb/^{206}Pb ages of 490 ± 1 Ma and hence Early Ordovician on the 1983 Time Scale (Palmer, 1983); and the Dalradian Supergroup between these localities, designated as Z, probably entirely Late Proterozoic and perhaps slightly older (Rogers et al., 1989).

Farther south around Dingle Peninsula, which protrudes farthest westward in the upper right-hand corner of the map, the geology was originally taken from Holland (1981; his Fig. 48). It subsequently was revised from an excellent colored map by Richmond and Williams (2000).

Most of the dike swarms shown on the North American map were initially taken from GSC Map 1627A (Fahrig and West, 1986) showing diabase dike swarms of the Canadian Shield. Ken Card compiled the dikes in Superior Province and the adjacent parts of the Grenville and Churchill provinces. Dike swarms concealed beneath Phanerozoic strata south of Hudson Bay were identified by their signature on aeromagnetic maps. John Wheeler plotted the dike swarms in the remainder of the shield. Some simplification was required where dike swarms such as the Matachewan, north of the Great Lakes, and the Mackenzie, in the Slave Province, are particularly congested. On Baffin Island the Borden dikes of GSC Map 1627A, which were considered to be ca. 900 Ma, are now included by Buchan and Ernst (2004) in the widespread Late Proterozoic Franklin swarm dated at 723 Ma.

Elsewhere in Canada, Wheeler plotted representative dike swarms. These included Late Proterozoic dikes in the northern part of the Eastern Cordillera, Tertiary dikes from the Pacific coastal region, a few Triassic-Jurassic dikes in the Canadian Appalachians, and Cretaceous dikes in Sverdrup Basin in the Arctic Islands. Comprehensive coverage of diabase dike swarms in Canada and adjacent United States can be found in Buchan and Ernst (2004) and its accompanying catalogue and reference list.

Greenland dike swarms and sills were compiled by Wheeler from Nielsen (1987) and later updated from a 1997 compilation by Escher and Kalsbeek published in Henriksen and others (2000).

Virtually all the special features in the Canadian part of the Geologic Map of North America and in Greenland were taken from the Geological Maps of Canada and Greenland, respectively. These features include impact structures, point data denoting volcanic centers, diatremes, Alaskan-type ultramafics, evaporite diapirs, kimberlites, and carbonatites. They also embrace overprints identifying areas of Phanerozoic metamorphism, Precambrian granulite facies, offshelf sedimentary assemblages, continental clastics and zones of mélange and tillite.

Finally, it should be noted that the teeth on several thrust faults were shown pointing the wrong way on the Geological Map of Canada (Wheeler et al., 1996). These faults are: (1) the thrust fault surrounding the 4.0 Ga Ugn Acasta Gneiss in the Slave Province just northwest of 65°N and 115°W; (2) the Chantrey Fault Zone, in northern Churchill Province, which extends northeast from near 65°N and 100°W; and (3) the Nachvak Fjord Thrust, in northern Labrador that bounds the X^2 Ramah Group on the west near 64°N. These faults have been corrected on the Geologic Map of North America

Geology of the Seafloor around North America

Brian E. Tucholke

Introduction

Geologists who map and interpret subaerial geological outcrops have tremendous advantages over those who study subaqueous (hereafter "seafloor") geology. Not only do they have access to areally extensive image and topographic data, they also are able freely to walk the outcrops to obtain ground-truth information at virtually any desired scale. Those working on submarine geology, in contrast, must rely almost entirely on acquiring geological data from remote sensing or sampling tools. Financial and logistical constraints (e.g., ship time, instrumentation) further limit the quantity and quality of data obtained. In the very limited instances where marine geologists can "walk the outcrop" in a submersible or via telepresence using a remotely operated vehicle, they have no significant lateral visual perspective on the outcrops being viewed, and sampling capability is limited. This mapping has often been compared to doing subaerial geologic mapping in the dark with a flashlight and a compass.

Another problem in mapping submarine geology is that, compared to subaerial regions, erosion is reduced. Thus it is difficult to access, analyze, and date older rocks and sediments. In addition, outcrops commonly are covered by a veneer of recent sediment that, even if thin, prohibits visual observation of the character and composition of underlying rocks.

One advantage possessed by geologists working from ships is that they can obtain seismic reflection profiles much more easily and efficiently than land geologists. This provides important subbottom information and it shows where older formations crop out or nearly crop out, even if the formations are veneered by recent sediments. However, this data is acquired along relatively few ship tracks, so overall seismic coverage is sparse compared to the vast water-covered regions that need to be mapped.

The above factors, coupled with the fact that significant ongoing efforts in submarine mapping and sampling have been instituted only in the past few decades, mean that the state of geological mapping of the seafloor is very immature compared to that of mapping on the continents. On the previous Geologic Map of North America (North American Geologic Map Committee, 1965), the only information depicted in submarine areas was bathymetric contours. Over subsequent years, seafloor geological maps have been constructed in some detail in a few limited, heavily sampled areas, or where constraints are imposed by extrapolation from nearby or surrounding land areas. In some cases, larger-scale maps that necessarily are quite generalized have been compiled (e.g., Okulitch et al., 1989). The kinds of geological characteristics that these maps document are highly variable, and few attempt to map geology in the "classic" fashion of normal subaerial maps.

With the inception of the Decade of North American Geology in the early 1980s, it was decided that the time was ripe to map the seafloor geology around North America as part of the new Geologic Map of North America. Not only was there a well-defined conceptual geological framework then established from plate-tectonic theory, but enough geological information also had been or was being acquired to justify efforts to map the seafloor geology in a manner consistent with classical mapping of continental geology. This project proceeded over the next two-plus decades. The seafloor geology was mapped largely from primary data rather than being compiled from preexisting maps such as those available for most of the continental geology. For this reason, the text below discusses the rationale, methods, and limitations of this "first-generation" mapping. Integrated with this discussion are brief reviews of salient features of the seafloor geology and the processes responsible for their occurrence.

Nature of Data

Mapping of seafloor geology for the Geologic Map of North America was based on a wide spectrum of materials, ranging from information available in the published literature to unpublished, original data contained in archives of various institutions and agencies.

Original data that were used in the submarine mapping included seismic reflection profiles (both high-frequency echo sounding and low frequency), multibeam bathymetry, sidescan sonar, ages of sedimentary cores, and ages and compositions of rocks obtained with dredges or other sampling devices. These data were integrated with pertinent information extracted from published papers, such maps as were available, and unpublished compilations.

Methods

Pertinent geological information was extracted from available data and compiled on stable-base compilation sheets. The seafloor geology was then interpreted and mapped out on stable-base overlays. For the southeast quadrant and the northeast quadrant south of 60°N, this process was carried out on standard Mercator projection at a scale of 1:4,383,000. The product was then hand-digitized by Jack Reed using the GSMCAD program for transformation to the Transverse Mercator projection of the geologic map. For the remaining area of the quadrants, compilation and mapping was done on stable-base sheets using the projection and scale (1:5,000,000) of the final geologic map.

Over the 20-plus years that it took to complete the seafloor mapping, work on the four quadrants was done in counterclockwise order, beginning with the southeast quadrant. Once a quadrant was completed, available time and resources permitted only limited updating to be done. Thus, in general, data incorporated into the southeast quadrant are the least current, and data for the southwest quadrant are the most up to date.

Contributors

A number of individuals graciously responded to requests to contribute to the new Geologic Map of North America. A.F. Embry, J. Dixon, E.P. Laine, G.S. Mountain, T.L. Holcombe, P. Popenoe, and T. Wiley provided seafloor geologic maps that they created for this purpose. R. Buffler, W. Dillon, L.J. Doyle, C.W. Holmes, K.D. Klitgord, A. Lowrie, R.G. Martin, M. Rawson, D.G. Roberts, and S.P. Srivastava contributed unpublished maps. Others also provided unpublished data as acknowledged in the Bibliography of Sources for Seafloor Geology.[1] These contributions were integrated into the compilation sheets and were updated (or in some cases superceded) as newer or more complete information became available during the long course of the mapping project.

Mapped Seafloor Geologic Features

The seafloor geology in most respects is depicted in the same manner as the land geology. As a practical matter, however, the lesser control by hard data required certain compromises. In addition, the map shows some features that either are peculiar to the seafloor (e.g., hydrothermal vents, iron-manganese nodules) or are uncommon enough there that they merit documentation (e.g., ultramafic rocks). The following sections summarize the seafloor geological features that are included on the map, and they outline procedures adopted to characterize and depict these features.

Bathymetry. Seafloor morphology provides a fundamental source of information for mapping submarine geology. Shapes

[1]GSA Data Repository Item 2005019, list of source materials (doi: 10.1130/DRP2005174.1), is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2005.htm.

of depth contours help to identify features with known geological characteristics (e.g., seamounts, fracture zones), and contour spacing delineates steeper slopes where outcrops are more likely to occur. Bathymetric data used in geologic mapping of the Atlantic Ocean are taken mostly from GEBCO charts, from Ocean Margin Drilling atlases (Shor and Flood, 1984; Shor and Johnson, 1984a, 1984b), and from unpublished charts of the U.S. Naval Oceanographic Office. Bathymetry derived primarily from the gridded digital database (Jakobsson et al., 2000) was used for the Arctic Ocean, and bathymetric maps of Mammerickx (1989) and GEBCO were used in the Pacific Ocean. Contours from smaller, higher-resolution charts were employed where they were available.

Bathymetric contours on the geologic map are given only at 1000 m intervals so as to show the main topographic features of the ocean basins, although more detailed charts were used for mapping. Along continental margins, additional contours are included at 200 m and/or 500 m depths to emphasize shelf morphological features such as glacially scoured valleys and to help indicate the approximate position of the continental shelf edge that normally falls within this depth range. Central Greenland is loaded by thick ice (>3300 m), and parts of the continent consequently are below sea level (Bamber et al., 2001); the zero (sea-level) and –200 m contours on the bedrock surface are shown to illustrate this attribute.

Submarine canyons, sea valleys, and mid-ocean channels. Submarine canyons, sea valleys, and channels were mapped largely from the bathymetric maps, supplemented by data from specific study areas and from features identified in seismic reflection profiles. Line symbols depicted for the channels on the map indicates the level of confidence in position, continuity, and connectivity of the features, as indicated in the explanation.

Most submarine canyons occur along continental margins, and they represent locations where significant volumes of sediment eroded from the continents have been delivered to the deeper basins, particularly during sea-level low stands. A number of these canyons are continuous with sea valleys in shallow water, most of which represent subaerial stream channels that crossed the continental shelf during sea-level low stands. On the steeper continental slopes of margins, the canyons commonly are erosional, although they become depositional on the lower-gradient slopes of the deeper margins and abyssal plains.

Mid-ocean channels constitute exceptional deep-basin features along which turbidity currents have transported sediments for thousands of kilometers. At their heads, they are fed by numerous submarine canyons, and along their lengths they exhibit meandering thalwegs and point bars within their channels, as well as levees and spillover flood-plain-like features on their flanks (e.g., Chough, 1978). They are locally erosional but represent long-term aggradation, with overall sediment grain size generally decreasing down-channel. In the North Atlantic, the Northwest Atlantic Mid-Ocean Channel has transported sediments southward for more than 4000 km from the northwest margin of the Labrador Sea to the Sohm Abyssal Plain south of Newfoundland, and the Immarsuak and Maury mid-ocean channels extend southward from near Iceland for more than 2000 km on the west and east sides, respectively, of the Mid-Atlantic Ridge.

In the North Pacific, available bathymetric coverage is not complete enough to document the exact course of many mid-ocean channels, although data do show that channels extend more than 1200 km from the western Canadian margin across the Alaskan and Tufts Abyssal Plains. Northward motion of the Pacific plate has displaced these channels ~200 km relative to their original sources along the western margin of North America since the middle Pliocene (Ness and Kulm, 1973). Long channels that cross the Aleutian Abyssal Plain to the west are fossil remnants of even longer channels that once had sources along the North American margin, but their eastern reaches have now been subducted in the Aleutian Trench (e.g., Grim and Naugler, 1969).

Outcrop patterns—Age, extent, and composition. Three kinds of data were used to constrain age and extent of seafloor outcrops. The first is direct control provided by biostratigraphic or radiometric dating of materials sampled by cores, dredges, and other devices. The second is age interpreted from the configuration and character of reflections in seismic reflection profiles. In a few places, the ages are constrained by ties to wells or other seafloor samples; otherwise, ages are inferred from relative stratigraphic position and other characteristics of the basin geology (e.g., sedimentation rate). The third kind of data used is seafloor morphology, notably features such as seafloor slope, roughness, and indications of erosional incision. Ages may be constrained by samples in some areas, with the extent of outcrop then extrapolated according to the seafloor morphology. In other instances, only relative ages can be inferred. In general, the quality of control on age and extent of outcrops decrease in the order outlined above.

Decreasing confidence in the limits of outcrops is represented on the map by the use of solid, dashed, and dotted lines, respectively, with the limits marked by dotted lines being largely inferred. Decreasing confidence in the age or age range of the outcrops is broadly indicated by progressively more generalized age assignments, e.g., plT (Pliocene) versus T (Tertiary). Where a question mark precedes an outcrop label, it indicates that the age of the outcrop is uncertain. Question marks after labels indicate uncertainty about either composition or whether the sample(s) defining the outcrop were in situ (e.g., glacial erratics commonly recovered in dredge hauls at higher latitudes can be misleading).

Except for sedimentary outcrops, composition (volcanic, plutonic, metamorphic) is indicated by a subscript following the age designation. In the deep ocean basins, ultramafic and granitic rocks are relatively rare; occurrences of these rocks are indicated by special symbols where they have been sampled, as shown in the explanation.

Indication of an outcrop at a given location does not guarantee that the formation occurs directly at the seafloor. Practically speaking, some seismic reflection data do not resolve outcropping reflections to better than a few tens of meters. In addition, deep-sea cores commonly penetrate 10–20 m below the seafloor, and the ages depicted on the map are for samples from the deepest dated levels in the cores. Thus, where sedimentation rates are low or where the core penetrated an unconformity, the age may be significantly older than that of the surficial sediments. Finally, it is common that a thin carapace (tens of meters or more) of Quaternary sediment lies unconformably on older strata, particularly in shallow-water areas such as continental shelves; generally, these young strata are ignored where they are known to cap older beds unconformably. For all these reasons, mapped "outcrops" may actually be buried by younger sediments up to ~50–100 m thick on continental shelves and up to ~20 m thick in the deeper ocean basins. If Quaternary sediments are thicker than this, even above a significant unconformity, the seafloor normally has been mapped as Quaternary.

Sedimentary outcrop patterns are controlled primarily by seafloor depth, seafloor slope, gravitational mass movements, turbidity currents, thermohaline currents, and tectonics. Consequently, continental margins and platforms, where these factors are most important, exhibit the most frequent outcrops. Shallow continental shelf areas have been subjected to erosion during sea-level lowstands and, at high latitudes, to glacial erosion. The deepest basins are below the calcite compensation depth (CCD), so they may accumulate only a very thin, stratigraphically condensed sedimentary record if detritus is not transported in from the sides of the basin. Older strata in these thin sequences can be exposed easily by mass wasting or erosion by abyssal currents.

Steeper continental slopes are subject to erosion by turbidity currents, primarily in submarine canyons, and to mass wasting, and sediments eroded from the continents commonly bypass these high-gradient slopes during their transit to the deep basins. Conversely, the lower-gradient continental rises and abyssal plains are primarily depocenters, and most of these areas on the map are covered by Quaternary sediment.

Both shallow and deep-ocean currents erode, transport, and deposit sediments. The most notable effects of shallow, westward-intensified currents (the Florida Current and Gulf Stream) are manifested in the Straits of Florida and to the north across the Blake Plateau, where erosion/non-deposition has caused extensive exposure of Paleogene and Neogene sediments and current-controlled deposition has created a sediment drift capped by Quaternary sediment along the western margin of the flow. Erosion and non-deposition by deep currents is most commonly manifested along continental margins, but such effects are common in any location, either regional or local, where currents are intensified along steep slopes (see "Sediment drifts and abyssal-current erosion").

Tectonism, whether attributable to plate motion, diapirism, or other stresses, either exposes pre-Quaternary strata directly, or creates unstable slopes that fail and thus uncover older beds. Most such exposures occur along the subduction and strike-slip margins of the Pacific basin and the Caribbean. The only active extensional margin within the area of the Geologic Map of North America (the Gulf of California) has been rapidly filled with sediment and exhibits relatively few exposures of pre-Quaternary strata.

Occurrence of basement outcrops is affected by the same factors as outlined above. In addition, younger volcanic rocks are emplaced by seafloor spreading at mid-ocean ridges and, to a lesser extent, by volcanism that forms seamounts. These features are discussed more completely below.

In many areas of the deep ocean basins, particularly in areas of rougher topography and/or low sedimentation rate, there are likely to be many more outcrops than are shown on the geologic map. This is especially true in the deep North Pacific basin, where Cretaceous-Paleogene oceanic crust more than ~1000–1500 km from the margin has very thin sedimentary cover (<100 m) that has accumulated below the CCD at very slow rates (millimeters per thousand years). In these areas, labeled as KQsv and TQsv, there are numerous outcrops of pre-Quaternary sediments where gravity movements have removed sediments from steeper slopes and where abyssal currents locally have eroded the seafloor or prevented deposition. Because of the thin sedimentary cover and commonly steep slopes of the underlying basement, there also are numerous exposures of basaltic ocean crust. Seamounts in the region tend to have very thin or no sediment cover on their slopes, and they are generally mapped as basement exposures. Basement ridges and scarps are so numerous and seismic reflection data over them are so sparse that few of these features can be mapped in detail. The limits of most such basement outcrops are highly interpretive and are inferred by using bathymetric data to extrapolate from control points provided by seismic reflection or sample data; thus the outcrops should be considered only generally representative of expected basement outcrop patterns in the Pacific basin.

Oceanic crust and crustal isochrons. Oceanic crust is formed at seafloor-spreading centers and increases in age with distance from the spreading axis. The color coding on the map was designed to emphasize oceanic crust formed at recent spreading centers. The axes of active spreading ridges are shown in red, and where spreading centers have been abandoned, the fossil rift axes are indicated by red dashed lines.

Upper oceanic crust formed by seafloor spreading characteristically is mafic basalt. Thus, in the absence of specific information to the contrary, all outcrops of oceanic crust (e.g., as mapped from seismic-reflection data) are mapped as mafic volcanics. Intrusive, lower-crustal mafic rocks (e.g., gabbros) are included within this category. Gabbro outcrops are rare in the eastern Pacific, although they have been sampled in the failed rift of the Mathematician Ridge (Vanko and Batiza, 1982). They are more commonly sampled in the slow-spreading crust of the Caribbean, Atlantic, and Arctic oceans, notably along fracture zones and on large-offset normal faults that parallel the spreading centers. Outcrops of ultramafic rocks (e.g., peridotites and serpentinites) are relatively uncommon, and they are noted by a symbol where they have been recovered. As is true for the gabbroic rocks, virtually all of these outcrops are within fracture zones or on fault scarps of slow-spreading ridges in the Caribbean, Atlantic and Arctic ocean basins.

Isochrons in oceanic crust are defined from identified magnetic anomalies that are correlated to the geomagnetic polarity time scale. Isochrons of all the major stage boundaries are shown on the map, based on the time scale of Kent and Gradstein (1986). Where isochrons are indicated across exposed ocean crust they are marked by solid lines, and they define the idealized age of the igneous outcrop at the seafloor. If the ocean crust is buried beneath sediments, the isochrons are indicated by dotted lines. Where the isochrons are offset by transform faults or pseudofaults, these features are indicated. Most other isochron offsets are small and are interpreted from breaks in the linearity of magnetic anomalies rather than from actual crustal structure; these small breaks are typically associated with non-transform offsets (see "Faults").

Seamounts. Seamounts depicted on the Geologic Map of North America occur as scattered edifices, in groups or clusters, and in relatively linear chains. Seamount ages shown on the map generally are assumed to be the same as those of the underlying ocean crust unless ages are otherwise established by radiometric dating. In reality, many seamounts, particularly the larger ones, do not originate at the axes of spreading centers. Instead, they form off-axis, so their actual ages are younger than the underlying crust. Ages can be substantially younger than the surrounding crust if seamounts form above melting anomalies in old lithosphere. The most coherent expression of this phenomenon is in the formation of seamount chains that show general, though not necessarily uniform, age progressions. These chains commonly are interpreted to result from the motion of the lithospheric plate across relatively fixed mantle plumes or hotspots. Where there has been sufficient age dating of individual seamounts to indicate an age progression in a seamount chain, seamount ages on the map are assigned to fit the age trend.

Notable seamount chains that are interpreted to have formed above hotspots in the Atlantic are the New England–Corner seamounts off the northeastern United States (Duncan, 1984), and the Newfoundland-Milne seamounts east of the Grand Banks (Sullivan and Keen, 1977). In the northeastern Pacific, the Pratt-Welker seamount chain appears to show an age progression, although it is complicated by more than one episode of volcanism at its younger end (Turner et al., 1980), and the Patton-Miller chain shows an age progression that may continue up to Cobb Seamount and to Axial Seamount at the present spreading axis of Endeavor Ridge (Duncan and Clague, 1985; Desonie and Duncan, 1990). Only the southeast end of the Parker-Pathfinder chain is dated, so any age progression along the chain is uncertain (Dalrymple et al., 1987). Fieberling Seamount Chain in the eastern central Pacific shows a southeasterly trend toward younger ages and may terminate at an abandoned spreading center offshore northern Baja California (Lonsdale, 1991). Numerous other seamounts in the mapped area of the Pacific Ocean are also loosely organized in chains, and some of these may eventually prove to have age progressions when they are sampled and dated. However, it is clear that many seamounts, irrespective of how they are grouped, form by mechanisms unrelated to hotspots (Batiza, 1989), and these mechanisms will be clarified only by much more extensive sampling and dating.

In terms of composition, seamounts contain tholeiites as well as transitional to alkalic basalts and in some cases felsic rocks (e.g., trachytes). The more alkaline compositions are common in large seamounts and in seamounts formed in chains well away from a spreading center (e.g., Batiza, 1989). Growth of large seamounts above hotspots includes an initial alkalic stage that is transitional to a tholeiitic shield-building stage, with late-stage eruption of alkalic basalts and their differentiation products (Clague and Dalrymple, 1987). Sampling of most seamounts within the region of the Geologic Map of North America is very limited, and rocks recovered from the surfaces of seamounts are likely to be biased toward products of late-stage volcanism. Thus the true distribution and relative abundance of mafic versus more alkaline rocks is not well known. On the geologic map, the indicated compositions of sampled seamounts in well-developed chains are based on available data; the indicated compositions of unsampled seamounts in these chains are inferred from the other data along the chains and are followed by question marks. The composition of seamounts outside these chains is assumed to be mafic in the absence of sample data to the contrary.

Lavas from numerous small seamounts between ~5° and 15°N on the East Pacific Rise vary from extremely depleted tholeiites to highly enriched alkali basalts (Niu and Batiza, 1997). Similar compositional variation is also observed in some basalts sampled from the Siqueiros Fracture Zone in the same region (e.g., Fornari et al., 1989). These small-scale compositional variations are not shown on the geologic map, and the outcropping ocean crust in this region is generalized as mafic volcanics.

Faults. The quality of information available on seafloor faults is highly variable. Most of the information is derived from seismic reflection profiles in areas of specific interest, so areas that have been surveyed for petroleum resources or for study of earthquake hazards, for example, are likely to show more data on faults. Faults on the map are indicated as solid lines where they are known and where they also intersect or can be traced to within ~100 m of the seafloor. Faults are dashed where they are approximately located. Dotted lines indicate that the faults are buried (concealed), inferred, or derived from a generalized source where their character is not specified. Only a representative sampling of concealed faults is given, in order to illustrate significant structural trends in underlying strata and basement.

Gravitational mass movements are common on sloping, sediment-covered seafloor. Major slump and slide scars associated with these mass movements are indicated on the map by brown normal-fault symbols.

In oceanic crust, normal faults that have formed at spreading centers are pervasive, but only a few of these are depicted on the geologic map. The vast majority of these faults dip toward the associated spreading axis and are parallel to the seafloor isochrons. The fault throw in fast-spreading crust of the Pacific basin is generally small (tens of meters), but it is commonly hundreds of meters or more in the slow-spreading crust of the Caribbean, Atlantic, and Arctic oceans.

Two classes of faults are peculiar to seafloor spreading centers. One class consists of transform faults and "non-transform offsets" that offset the spreading-ridge axis but have strike-slip motion in a sense opposite to that expected from the direction of ridge-axis offset (Wilson, 1965). Transform faults usually offset the spreading-ridge axis by 30 km or more. Active transform faults that offset spreading-ridge axes are shown on the geologic map as solid lines with strike-slip arrows; outside this zone of active slip, their fossil traces (i.e., fracture-zone valleys) tend to record the directional history of relative plate motion, and they are shown by dashed lines. Where the ridge-axis offsets are less than ~30 km, transform faults devolve into non-transform offsets. These offsets have diffuse and complex sets of faults that exhibit both strike-slip and dip-slip components; they also commonly migrate along the plate boundary, thus creating fracture valleys that have irregular traces in the flanks of a spreading ridge. On the geologic map, non-transform offsets are depicted at the spreading-ridge axes in the same way as transform faults, but the traces of their often complex, off-axis fracture valleys are not shown.

Pseudofaults form a second class of faults peculiar to spreading centers (Hey, 1977). These features are associated with propagation of the tip of a spreading-ridge axis through a ridge-axis offset. The propagation progressively transfers slivers of crust from one plate to the other, and "outer" and "inner" pseudofault traces mark the positions from which, and to which, crust is transferred, respectively. Away from spreading-ridge axes, pseudofaults are shown only where they offset key seafloor isochrons. In the region covered by the Geologic Map of North America, pseudofaults are common in Pacific Ocean crust but, if present, they generally are cryptic in the other ocean basins. The complex geometry of pseudofaults in Pacific Ocean crust is depicted fully in the maps of Atwater and Severinghaus (1989).

With one exception noted below, fault symbols do not portray whether depicted faults are currently slipping or are inactive. As a rule of thumb, however, it can be assumed that faults at plate boundaries have been active in recent times, while those away from plate boundaries are likely to be dormant. Thus, normal faults along spreading centers, thrust faults along subduction zones, and associated transform or non-transform faults within or connecting these plate boundaries accommodate the vast majority of lithospheric strain in the submarine realm. On the geologic map, the bold colors of ocean crust at recent spreading centers readily draw the eye to extensional plate boundaries where active normal faulting is prominent. In order similarly to emphasize compressional plate boundaries, the frontal thrust faults of major active subduction zones are colored brown on the geologic map.

Hydrothermal vents and sulfide deposits. Known hydrothermal vents or vent fields are indicated on or near the axes of spreading centers. Vents in the eastern Pacific Ocean discharge hydrothermal fluids at temperatures of ~200–360 °C along the East Pacific Rise, Gorda Ridge, and Juan de Fuca Ridge. Most of these are associated with polymetallic sulfide deposits. Along these ridges, other identified polymetallic sulfide deposits not known to be associated with currently active venting are identified by separate symbols.

On the Atlantic portion of the geologic map, the only known hydrothermal vents are near Iceland, although abundant venting occurs along the Mid-Atlantic Ridge axis outside the map area to the south. One Icelandic vent is on the southern Iceland continental shelf near the north end of Reykjanes Ridge (German et al., 1994), one is on the northern continental shelf in the Tjornes Fracture Zone (Hannington et al., 2001), and one is on the southernmost Kolbeinsey Ridge (Botz et al., 1999). Reported temperatures of these vents are up to ~250 °C, and they are not known to be associated with significant deposits of polymetallic sulfides.

Seeps. Locations of known seeps that emit fluids at low temperatures (a few to a few tens of degrees C above zero) are included on the geologic map. The seeps appear in a number of different environments, and they often are associated with chemosynthetic biologic communities. Saline seeps occur at the base of the West Florida Escarpment. Seeps of water plus hydrocarbon gasses (typically methane) are associated with hydrate deposits in the sediments of the Gulf of Mexico, the Blake Outer Ridge, and the Cascadia accretionary prism. Gas/oil seeps occur mostly along continental margins; these and other types of seeps are likely to be much more abundant than the limited number of examples currently documented and shown on the map.

Sediment drifts and abyssal-current erosion. Abyssal thermohaline currents transport, erode, and deposit sediments in the ocean basins. These currents are intensified at the western boundaries of basins, they are strongest along steeper seafloor slopes, and they tend to follow bathymetric contours. The most coherent current effects are observed in the North Atlantic Ocean, where currents follow the general bathymetric contours from the Norwegian-Greenland Sea through the Labrador Sea and southward along the eastern margin of North America (McCave and Tucholke, 1986). The currents have deposited major sediment drifts that are hundreds of meters to kilometers thick, and the axes of these drifts are indicated on the geologic map. Prominent examples include Feni Drift southeast of Rockall Bank, Gardar Drift on the east flank of the Reykjanes Ridge, Eirik Drift at the southern end of Greenland, and the Blake, Bahama, and Greater Antilles Outer Ridges in the southwestern North Atlantic basin. Deposition of all these drifts probably began in the Oligocene (Miller and Tucholke, 1983).

Where currents have been intensified along steeper seafloor slopes, non-deposition or erosion has produced outcrops of pre-Quaternary strata. These outcrops are concentrated along continental margins and the steeper parts of sediment drifts, but they also appear in the deep ocean basin, for example, on the northern Bermuda Rise. The most pronounced and longest-lived effects of abyssal current erosion–non-deposition appear in the Cat Gap area near the northwest end of the Bahama Banks, where Lower Cretaceous sediments are exposed at the seafloor (Ewing et al., 1966).

No sediment drifts comparable to those in the Atlantic Ocean appear in the Pacific part of the geologic map. Westward-intensified abyssal currents are not present in this eastern ocean basin, and current effects are limited to local erosion and non-deposition in places where the currents are topographically intensified (e.g, around seamounts and along fault scarps).

Iron-manganese deposits. Authigenic iron-manganese deposits are precipitated from seawater, and they typically occur in the form of nodules, slabs, and pavements. These deposits are shown on the geologic map where they have been sampled, photographed, or observed visually from submersibles. Iron-manganese coatings are common on all rocks that are exposed for a significant length of time on the seafloor, and the thickness of the coating increases with age (typically 2–4 mm/m.y.). Only deposits of significant thickness (at least several cm), or nodules of comparable size, are noted on the map.

Phosphorite deposits. Phosphorite deposits are indicated on the map, based on published occurrences determined by seafloor sampling. These deposits are almost exclusively associated with outcrops of Miocene carbonates on the California Borderland off the U.S. west coast, and with similar outcrops on the Blake Plateau on the U.S. east coast.

Digital Cartography

Will R. Stettner

In August 1997, a publications plan was prepared by the USGS for the digital production of the Geologic Map of North America. Prior to this, cartographic production had begun with the use of traditional scribing of geologic and base information. It should be noted that during the late 1990s, traditional cartography was being phased out in favor of digital techniques. Production of the map was identified as a cooperative venture between the survey's National Geologic Map Database Project and the Geological Society of America. The map was to be printed in four sheets at scale of 1:5,000,000 with an explanation sheet to be published by GSA as part of its DNAG series, and a map database to be coordinated by the USGS National Geologic Map Database. For the printed product, the maps for the northern and southern halves were to have an 11-in overlap in order to display all of Canada when joining the northern two sheets, and all of the United Sates when joining the southern two sheets.

For the eastern two map sheets, the base information (grids, political boundaries, drainage, shoreline) and geologic compilation (geologic contacts, faults and dikes) had been scribed. Positives were prepared from these scribecoats with a common set of registration ticks for the purpose of scanning and digitizing. In August 1998, a contract was established with Geologic Data Systems Inc. in Denver, Colorado, to vectorize, clean, and edit the data using AutoCAD software. This process required multiple reviews between contractor and principal compiler before the data was passed on as DXF files for graphic production using Adobe Illustrator. Graphic production of this map product consistently challenged available software and hardware, requiring numerous upgrades to the present Illustrator 10 and Apple G5.

A similar production flow occurred for the northwest map except that the offshore data was never scribed and was digitized directly from the author's compilation mylars using Adobe Illustrator. The southwest map is the only map for which the feature separates were not scribed. For this map, the onshore geologic compilation was captured by the USGS-written GSMCAD program as 5° × 10° panels. The software ArcInfo was used to mosaic the panels together creating a data set that was then passed on to the contractor for further editing, creation of the north-south overlap, and edge joining to the other map sheets. For graphic production, these data were then imported into Adobe Illustrator, which was also used to digitize the offshore data and base information. For the map sheets and the explanation sheet, Adobe Illustrator was used for the placement of type and text and for the creation of all other graphic elements.

A major challenge throughout the project was the creation and maintenance of data within the 11-in north-south overlap. Clipping, joining, matching, and modifying data for the overlap required great care and effort in order to produce an acceptable graphic product. To serve as review copy Hewlett Packard (HP) large format plots were made from the Adobe Illustrator files. It should be noted that author review, editing, and even compilation of the maps continued throughout the production process. With the use of HP check plots, the maps could be reviewed for content and various graphic elements. Not until all four maps were available as graphic files was it possible to have peer review or final review by authors, an activity which resulted in volumes of modifications and corrections. With the acquisition of an Apple G5, the increased RAM and processing speed made possible the consideration of joining the northern and southern quarters of the map to produce a northern and a southern map sheet. For the northern map sheet, the merger resulted in an unprecedented Adobe Illustrator 10 file of 1470 layers and a file size of 5 MB.

Printing of the maps required 11 ink colors and with the joining of the map sheets now had an image size of 74 × 39 inches. Printing was accomplished at the Pikes Peak Lithographing Co. with a 7-color 77 × 54 Harris press. Since HP plots cannot simulate offset printing of 11 overprinting inks, a proofing process needed to be identified. Changing technology within the printing industry made an actual press run the only viable option. For its complexity, the northern map sheet was selected for this proofing method. As for the actual printing of maps and explanation sheet, printing negatives were not required. Instead, printing plates were exposed directly from digital files. For database preparation, the final Adobe Illustrator files were simplified and exported as DXF files.

DATA SOURCES

Because of the large number of published references and other sources, particularly for the seafloor geology, it is not practical to include a list of source materials with this pamphlet. However, a list of sources is available in the Geological Society of America Data Repository (see footnote 1 on page 14).

Sources for the on-land geology are listed by country, generally arranged from north to south. In Canada they are arranged by regions and by provinces and special subjects (dike swarms, time scales); in the conterminous United States they arranged by states and groups of states.

The list of sources for the seafloor geology contains ~1300 references and is divided into four parts, each corresponding to a quadrant of the map. The 100° meridian defines the boundary between the eastern and western quadrants, and the northern and southern quadrants are defined by the limits of the north and south sheets of the geologic map, with an area of overlap between them. Bibliographic references for the overlap areas generally are cited in a counterclockwise direction for the quadrants (e.g., references for the overlap area in the southeast quadrant may not be repeated for the overlap area in the northeast quadrant), although some are cited for both quadrants where they apply.

In addition, certain materials used in the seafloor mapping and compilation have been archived in the Data Library and Archive at Woods Hole Oceanographic Institution. These include various notes, compilation sheets, and draft proofs of the maps that were marked with final revisions, together with listings of the revisions. These materials, together with the cited sources document the foundation of the submarine mapping for the Geologic Map of North America and thus they constitute a starting point for revisions of the map.

DIGITAL DATABASE

David R. Soller

When plans for the Geologic Map of North America were being made, the notion of geologic map databases was in its infancy. At that time, and for many years thereafter, few geologists were familiar with the design and use of databases to manage geologic map information. In 1998, the GSA and the USGS National Geologic Map Database project agreed to cost-share the digital preparation of this map. The plan was to digitize the hand-drawn, author-prepared geologic compilations for the four map quadrants, in order to provide digital data for two purposes: (1) to allow GSA to print the map, and (2) to permit the National Geologic Map Database project to develop a prototype database for this map. The prototype is intended to serve as the basis for discussion and decisions on how the database for this map will be designed and managed, and served to the public and cooperators.

With the map now printed, the National Geologic Map Database project has begun to design and create the prototype, based on certain assumptions regarding the anticipated content of, and uses for, the map database. At a minimum, the database will contain the descriptive information for geologic units shown on the map. It will serve as the fundamental entity from which products of the map then can be derived; these products may be interpretive, or they may be future editions of the map. To produce any future editions of the map, the database will incorporate all map revisions that are necessitated by detection of compilation errors and by new regional mapping and interpretations. Further, the geologic unit descriptions shown on the printed map can be supplemented in the database by more detailed, richly attributed information derived from the many sources that were used to compile the map. This capability to revise the printed map and to include additional descriptive information for map units is one of the primary reasons for building the database; the other reason is, of course, the analytical capabilities made possible by providing the map in a digital, Geographic Information System (GIS) compatible format.

The creation of this database and its enhancement to include new mapping and more richly attributed information is a daunting task that will take a significant amount of time and effort. Recognizing that a group of dedicated and knowledgeable scientists is essential to make this database useful and to keep its content up to date, GSA will develop a consortium of geological agencies to manage the database. With prototype development of the database, the National Geologic Map Database project provides a basis for this consortium to proceed.

USES OF THE GEOLOGIC MAP OF NORTH AMERICA

John O. Wheeler, Brian Tucholke, and John C. Reed Jr.

The Geologic Map of North America is an essential educational tool for teaching the geology of North America to university students and for the continuing education of professional geologists in North America and elsewhere. In addition, simplified maps derived from the Geologic Map of North America are useful for enlightening younger students and the general public about the geology of the continent.

As a wall map, the major features stand out, portraying the overall architecture of the continent and the ocean basins that surround it. When displayed at earth science institutions and university libraries, it will attract the attention of viewers, who will surely be impressed with the grand design of the continent and may well pause to wonder how it evolved. Some, perhaps, may be inspired to pursue the science of geology.

For the first time, the Geologic Map of North America portrays the geology of the seafloor as well as that of the continents. This essential component adds the large-scale perspective of major plate-tectonic components (e.g., mid-ocean ridges, transform faults, and subduction zones) that is not expressed in the continental geology alone, and it therefore provides a more global context within which to interpret geological patterns. Because this component also emphasizes patterns (and thereby, processes) of sedimentation, erosion, volcanism, tectonism, and crustal production and consumption in the submarine realm, it also affords critical perspectives for interpreting that part of the modern subaerial geologic record that originally developed beneath the ocean surface. The region portrayed on the Geologic Map of North America covers ~15% of the surfaces of the Earth and captures examples of nearly all the essential elements of global geology. Thus the map in and of itself provides a unique tool for teaching, analysis, and research.

Closer inspection of the map reveals labels and patterns indicating ages and compositions of map units. Other cartographic patterns depict, for example, areas of particular metamorphic rocks and disposition of continental sedimentary rocks. Special symbols highlight features such as impact structures, volcanoes, diatremes, and hydrothermal vents. Care has been taken to replicate map patterns accurately from larger-scale regional maps so that these details enhance the credibility of the map.

The new Geologic Map of North America is the template from which thematic maps may be derived. One example is a *tectonic map* (Muehlberger, 1992) depicting the geologic building blocks and related structures, such as faults and folds, that contribute to the assembly of the continent. Another is a *metallogenic map* showing the distribution and nature of important mineral deposits as well as genetic relationships to host geologic formations. Such information identifies formations that are favorable for the discovery of particular types of mineral deposits. This is a key factor in developing exploration strategies in the search for energy and mineral resources and is essential for estimating the mineral and energy endowment of the continent and ocean basins.

The new Geologic Map of North America is the template against which other DNAG continental-scale maps and their databases may be compared and interpreted. These include the Gravity Anomaly (Committee for the Gravity Anomaly Map of North America, 1987), Magnetic Anomaly (Committee for the Magnetic Anomaly Map of North America, 1987), Geothermal (Blackwell and Steele, 1992), Stress (Zoback et al., 1987), and Seismicity (Engdahl, 1988) maps of North America. Other maps depicting, for example, earthquake risk or geochemical parameters can also be compared against this template.

The new Geologic Map of North America can also be the source for more simplified maps that represent features in unique ways. Indeed, a preliminary database from the new map has already been used to produce the North American Tapestry of Time and Terrain (Barton et al., 2002). This map is a simplified presentation of the geology of North America on a shaded-relief base map that is suitable for engaging and educating high school students and the general public. Another simplified map, called Geoscape Canada, portrays the geological landscapes of Canada and has been published recently by the Geological Survey of Canada (Turner et al., 2003). The Geoscape map is aimed at the same audience as the Tapestry map and was derived from two national maps: the bedrock Geological Map of Canada (Wheeler et al., 1996) and the Surficial Materials Map of Canada (Fulton, 1995). In such ways, the new Geologic Map of North America could be modified to reach an audience beyond just professional geologists and aspiring students.

All these considerations demonstrate that the new Geologic Map of North America is essentially a “thinking map” whereby the public, students, and earth science professionals can view, evaluate, and even manipulate geologic patterns and related geologic relationships on a plate-tectonic scale. Use of the map, either by itself or in conjunction with other continental thematic maps and data plots, undoubtedly will lead to new interpretations of the geology of North America. These, in turn, will make possible new insights into the evolution of the continent. Finally, in practical terms, study of the map will enable earth scientists to generate new exploration strategies for the discovery of mineral and energy resources and will facilitate development of better ways to assess and mitigate environmental risks and geologic hazards.

FUTURE REVISIONS AND ADDITIONS

Brian E. Tucholke, John O. Wheeler, and John C. Reed Jr.

Any geologic map must be considered as a work in progress, subject to correction, revision, and addition of new data. This is clearly the case in regard to the Geologic Map of North America. We hope that the map will not be treated as a static document, but that it will be continuously updated and improved in the light of new data and evolving interpretations.

In the better mapped parts of Canada and the conterminous United States, it is doubtful that there will be major changes in the gross configuration of map units. However, even where the geology is relatively simple, concepts and interpretations may suggest ways of subdividing or lumping stratigraphic units so as to better depict the details of the geologic history. An important addition to the map would be a more complete depiction of lithologies of the sedimentary rocks in the continental interior and the coastal plains. This could more clearly portray facies changes in the clastic wedges and cratonic cover between the Cordillera on the west and the Appalachians and Canadian Shield on the east

In areas of more complex geology such as the Canadian Shield and the Cordilleran, Appalachian, and Innuitian orogenic belts, more detailed mapping, more numerous and more precise radiometric dates, and paleontologic age assignments may materially alter the depiction of the geology and the interpretation of the geologic history. Continued refinement of our understanding of allochthonous terranes and increasing availability of geophysical data, particular seismic profiling, may also lead to significant changes in the geologic map and in our understanding of these orogenic belts. Additional geologic mapping in Alaska and the more remote parts of Canada will almost certainly require significant changes in the Geologic Map of North America.

In Latin America and the Antilles, the map could be greatly improved by the efforts of a compiler more familiar with the geology of these regions, and especially by one more familiar with and better equipped to utilize the Spanish-language literature.

Many faults remain unclassified. Future studies of these should lead to better understanding of their senses of movement, their movement histories, and their tectonic significance. New discoveries of special features such as impact structures, diatremes, volcanic features, and small but important intrusions of kimberlite, carbonatite, and other unusual rocks will certainly be added to future revisions of the map.

Because the new Geologic Map of North America is a first attempt to map seafloor geology on such a large scale, and because the work was done over a period of more than 20 years, the compilation was a continual learning process. Insights gained over time dictated revisions of earlier material, particularly in how to "lump and split" information in geologically meaningful ways. The final product reflects a compromise between generalizing locally detailed information and attempting to interpret useful relationships from very limited data in other areas. In areas of where detailed data were available, the level of generalization was dictated largely by the map scale, and future revisions likely will not greatly alter the basic geological relations depicted. However, most of the seafloor geology is so poorly controlled by data that significant future revisions will be possible. These revisions will better constrain outcrops and features that are currently known to exist but are poorly mapped, and they will also add a substantial amount of new information where no data currently exist.

Aside from improved resolution provided by new data, several items come to mind when considering how the seafloor geologic map might be improved. First, under the category of faults, many more faults can be mapped, even with currently existing data and particularly in ocean crust. Depicting these more completely would enhance insight into local and regional stress distribution. Second, the categorization of faults can be improved. For example, faults could be identified as active or inactive, and the current group of concealed, inferred, and generalized faults that are lumped together and depicted by dotted lines could be split to differentiate them from one another. This will require significant effort and interpretation, but cumulative revisions will provide a much clearer picture of spatial and temporal geologic relations. Finally, complete traces of propagating rifts and the fracture valleys that were formed at non-transform offsets of mid-ocean ridge axes could be shown to improve regional perspective on how spreading ridges evolve. Much of this is already possible if seafloor structure interpreted from satellite altimetry (Smith and Sandwell, 1997) were to be fully combined with ship-track magnetic and seismic reflection data.

Whether large seamounts and seamount chains are formed above mantle plumes or by another mechanism is currently a hot topic in marine geology and geophysics. Indicating radiometric ages for these features on the geologic map could be useful not only for identifying where such constraints exist, but also for interpreting patterns of seamount formation. However, because many seamounts are formed by multiple stages of volcanism that span several million years or more, and that also can change in chemical composition, care would have to be taken to relate ages to composition and stage of formation.

Depicting some special features such as iron-manganese nodules may not be particularly helpful to most users of the new Geologic Map of North America. If these features are retained on future maps, it may be useful to indicate where sampling indicates that nodules are *not* found, in addition to where they do occur. Iron-manganese encrustations are almost ubiquitous on old (greater than a few million years) basement rocks, so their separate identification on the map may not be justified in future versions.

Ultimately, users of the map will voice their opinions on the values and shortcomings of the new Geologic Map of North America, and their perspectives will help to direct the future incarnations of this grand view of the geology of North America and its surrounding ocean basins.

APPENDIX 1. REVIEW OF NATIONAL GEOLOGICAL MAPS OF CANADA 1865–1996

John O. Wheeler

Following the publication in 1869 of GSC Map 65 (Logan, 1866) of eastern Canada and adjacent USA, referred to earlier, the Geological Survey of Canada (GSC) produced seven national multicolored geologic maps prior to the Decade of North American Geology Geological Map of North America. The next two maps, GSC Map 411 (Geological Survey of Canada, 1884) at 1 in to 45 mi, and Map 1084A (Geological Survey of Canada, 1909) at 1 in to 100 mi, reflect the eras of geological exploration in western and northern Canada following Confederation in 1867. During this period, most of the major waterways were traversed and much of the eastern coastline explored. In addition, systematic quadrangle mapping at various scales was undertaken around the southern margin of the Canadian Shield, in the southern Cordillera, and in detail in the coal fields of Nova Scotia and New Brunswick.

By 1909, when Map 1084 was published, the geological architecture of Canada was becoming more evident. The extent of the Canadian Shield was moderately well established although the nature and age of the Laurentian (Archean) gneisses and their contained supracrustal formations belonging to the Keewatin and Huronian series were just beginning to be understood. The intrusive sills around Lake Nipigon, originally thought to be Cambrian, were now considered to be equivalent to the Proterozoic Animikie Series. The Athabasca successor basin, considered to be Cambrian, and elements of the related Thelon basin had been identified but the extent of the latter was unknown. Lower Paleozoic platform sedimentary rocks were shown to unconformably overlie the shield along its western margin and also around Hudson Bay. The Interior Plains of western Canada were recognized to be developed on Cretaceous and locally, on Tertiary strata. The main elements of the Canadian Cordillera were recognized: these were dominated by two mountainous belts, one along the Pacific Coast, featured by granitic rocks stretching from southern British Columbia to the Yukon, and, in the east, a second belt of granitic and metamorphic rock extending northwestward, west of the Canadian Rockies, into the Yukon. The Rockies, by contrast, revealed Carboniferous and Devonian carbonate formations overlying Cambrian limestone and quartzite. The Interior Cordillera between the mountainous belts was shown to contain Mesozoic volcanics and sediments overlain by mainly flat-lying volcanics thought to be of Miocene age. Two large islands off the west coast apparently consisted largely of Triassic basalt overlain on Vancouver Island by coal-bearing Cretaceous strata and on Queen Charlotte Islands by Tertiary volcanic and sedimentary formations. Systematic mapping in the Canadian Appalachians led to new discoveries, notably, of a Late Precambrian core within the intricately deformed lower Paleozoic formations of southern Quebec, extension of the Silurian and Devonian beds southwestward from Gaspé, and the assignment of gneisses in the Long Range of Newfoundland to the Archean.

GSC Map 1084 was revised and republished as GSC Map 91A in 1913 (Young, 1913), at a scale of 1 in to 100 mi for use with guidebooks for the 12th International Geological Congress held in Canada that year. Map 91A was the first national map to be published as part of the new "A" series multicolored geologic maps initiated in 1910 and continuing to this day. Notable changes were: the intricate geology of the Rocky Mountain Foothills was more accurately portrayed; the Keewatin rocks of the Abitibi region of the Canadian Shield were clearly differentiated from the Huronian, whose outline in the Penokean Belt is very much like the present; the general outline of the iron-bearing Labrador Trough emerged in northeastern Quebec; in the Appalachians, Late Precambrian volcanics and sediments were found to be widespread in eastern Newfoundland and Triassic strata were discovered in Nova Scotia.

In the 34 years between GSC Map 91A and the next national map 820A, published in 1947 (Geological Survey of Canada, 1947), the GSC made slow progress in filling out the Geological Map of Canada. This was caused partly by loss of staff to World War I, their diversion to strategic mineral studies and exploration in World War II, and to retrenchment during the Depression, and partly to the priority of doing systematic quadrangle mapping in productive or promising mineral districts. This resulted in increased knowledge of geologic details in southern Canada, southwest Yukon, and the northwesternmost Canadian Shield, whereas the central Shield and Arctic remained poorly understood.

GSC Map 820A, at 1 in to 60 mi, reflects these factors. Although the limits of the Canadian Shield were well established, the nature and distribution of its supracrustal formations were well known only in the Abitibi Belt, south of James Bay, where Archean volcanic and sedimentary rocks were distinguished, north of Lake Huron where the Proterozoic Huronian distribution and stratigraphy had been worked out, and in the northwestern Shield around Yellowknife where Archean supracrustal formations are mainly clastic sediments. Hints of Archean supracrustal belts occur north of Lake Superior and west of Hudson Bay. Coal-bearing Cretaceous strata are shown southwest of James Bay. Finally, in the Cordillera, northwest-trending units of upper Paleozoic limestone are associated with Triassic and volcanic and sedimentary strata throughout the length of an intermontane belt in the Cordillera interior. The geology of the remainder of the Canadian Shield and Arctic Islands was poorly understood and shown only in a sketchy fashion. The geology of Newfoundland and Labrador was not shown as these regions were not yet part of Canada.

Map 820A, however, is a prototype for the colors used in all succeeding editions of the Geological Map of Canada. The color scheme used for this map is as follows.

Archean gneiss—pink
Archean supracrustal—purple
Proterozoic—yellowish orange
lower Paleozoic—blues
upper Paleozoic—grays
Triassic, Jurassic, and Cretaceous—greens
Tertiary—yellows
Quaternary—pale yellow
granitic rocks—reds
ultramafic—dark purple

Each geologic system is assigned an appropriately colored box accompanied by the conventional letter symbol. Each system box has an accompanying note of characteristic lithologies as well as a list of the geologic formations that define the appropriate system map unit.

The succeeding national Map 1045A, compiled by H.M.A. Rice (1955), at 1 in to 120 mi, was compiled to accompany the 4th edition of the Geology and Economic Minerals of Canada that was published in 1957. The map now included the geology of Newfoundland and Labrador, this province having joined Canada in 1949. The map displayed the anorthosite intrusions and Proterozoic volcanic and sedimentary units in Labrador and the widespread Late Proterozoic clastics and volcanics of eastern Newfoundland.

The Canadian Shield was not greatly changed except that Archean supracrustal and later Proterozoic sediments were mapped in the Keewatin district west of Hudson Bay, the result of the first helicopter-assisted surveys begun by the GSC in 1952. Elsewhere, in the Precambrian of Manitoba and Saskatchewan, all supracrustals were considered Archean. The volcanic and granitic rocks of the northwesternmost part of the shield were separated out from the Archean supracrustals farther east.

Minor changes in the age and disposition of Mesozoic units were shown in the Cordillera. The configuration of Tertiary sediments east of the Canadian Rockies is approximately that of today.

Map 1045A and its legend adopted the same color scheme as Map 820A but the legend units, labeled by letter, did not list the component stratigraphic units of Map 820A but instead listed and described the lithologies and noted the contained resources of oil, gas, coal, and tar sands.

The next edition of the Geological Map of Canada, Map 1250A, compiled by R.J.W. Douglas (1969), was a landmark map at 1:5,000,000 scale, published in 1969 to accompany the 5th edition of the Geology and Economic Minerals of Canada published in 1970. The map outlines, for the first time, the major features of the geology of Canada, not too different from those of the latest, 8th edition, resulting from the near completion of the reconnaissance geological mapping of Canada. Beginning in 1952, when about a quarter of Canada had been mapped geologically, geologic mapping by the GSC was greatly accelerated by geologic surveys using helicopters and light fixed-wing aircraft. Thus large areas of the Canadian Shield, Arctic Islands, northern Plains, and in the Paleozoic south of Hudson Bay were mapped at 1:500,000 scale, whereas smaller, but still extensive, areas in the Canadian Shield, Arctic Islands, and Cordillera were mapped at 1:250,000 scale. In addition, Provincial geological surveys carried out more detailed mapping at 1:50,000 scale. However, geologic mapping of much of the Grenville Province, the greater part of Baffin Island, and the St. Elias Mountains in southwest Yukon and adjacent British Columbia, remained to be mapped.

Phanerozoic sedimentary and volcanic rocks were dated more precisely than previously because of the increased and more varied expertise available from GSC paleontologists. Age designations for igneous and plutonic rocks were derived from extensive K-Ar radiometric dating, some Rb-Sr whole rock isochrons, and rare U-Pb age determinations. In the Cordillera, this permitted a clearer identification of several Jurassic, Cretaceous, and Tertiary plutons. In the Appalachians, however, most plutons were designated as Devonian except for two each in New Brunswick and Nova Scotia on Cape Breton Island. In Newfoundland, the distribution and shape of granitic plutons was fairly accurate, but all were assigned Devonian ages. In the Canadian Shield, the radiometric dates, designed to identify periods of orogeny (Stockwell et al., 1970), allowed Archean supracrustal successions to be distinguished from those of Early Proterozoic age, except in a broad region straddling the Manitoba-Saskatchewan boundary. Parts of the Canadian Shield considered to be older than that indicated by the K-Ar radiometric method were thought to represent reworked basement and thus were identified by a superscript 1. For the first time, enough information was available to establish the outline of the structural provinces of the Canadian Shield, shown on the inset map at the bottom right hand corner of the explanation for the Geologic Map of North America.

For the Precambrian, the map legend used a time-stratigraphic classification introduced by C.H. Stockwell et al. (1970) in which the Proterozoic Eon is subdivided into the Aphebian, Helikian, and Hadrynian eras roughly corresponding to Early, Middle, and Late Proterozoic eras, respectively. The Archean-Aphebian, Aphebian-Helikian, and Helikian-Hadrynian boundaries are represented by the close of the Kenoran (2480 Ma), Hudsonian (1735 Ma), and Grenvillian (955 Ma) orogenies, respectively. The Helikian era is divided into the older Paleohelikian and younger Neohelikian sub-eras separated by the Elsonian Orogeny which ended at 1370 Ma.

Additional features shown for the first time were: simplified representation of Precambrian diabase dike swarms on the Canadian Shield and of a Triassic-Jurassic diabase dike along the southeast coast of Nova Scotia; application of a stipple pattern to display continental deposits in clastic wedges on the craton and in successor basins within orogenic belts; and numerous faults which help to show the intricate fold and thrust belts. Finally, various symbols are used to distinguish the composition of areas of volcanic rocks, volcanic centers, and the location of small intrusions such as ultramafics, carbonatites, gypsum diapirs. With the exception of miogeosynclinal, foredeep, and cratonic sediments the remaining categories of sedimentary, metamorphic and granitic rocks are labeled with an appropriate letter label.

Map 1250A was the last geologic map of Canada to be produced using manual cartography, scribing, and application of colored scribe coats, and also the last to use geosynclinal basin nomenclature.

The latest or 8th edition of the Geological Map of Canada, GSC Map 1860A, at 1:5,000,000 scale, was published in 1996 to accompany the eight DNAG volumes describing the geology of Canada. Like its predecessor, Map 1860A is another landmark map for Canada. It not only records the grand geological architecture of Canada upon completion of the GSC reconnaissance geologic mapping program but, for the first time, displays the seafloor geology. The latter presented special problems. It was paramount that the coastline be visible. This was done by enhancing the coastline with a white buffer zone and by coloring the seafloor sediments deposited on continental crust using a pale generalized color scheme that could be clearly differentiated from the geology on land.

Beyond the limit of continental crust the submarine geology is represented by the age of the oceanic crust. The intention was to highlight the plate tectonic framework within the oceans surrounding Canada, thereby displaying the contrasting relationships between the Pacific margin, where North America is currently overriding and sliding past Pacific Ocean crust, and the Atlantic margin, which formed while the Atlantic Ocean and Labrador Sea underwent crustal spreading and ocean opening at various times since the Triassic.

The map was compiled by several regional experts (Wheeler et al., 1996) whose names and areas of responsibility appear on the title block of the Canadian map. The map was derived from published and unpublished maps and reports of the GSC, Provincial Geological Surveys, Yukon and Northwest Territories Geology Divisions of Indian and Northern Affairs Canada. Parts of the United States came from maps of the U.S. Geological Survey.

GSC Map 1860A differs from its predecessor in that the Precambrian stratigraphic nomenclature does not follow that introduced by C.H. Stockwell et al. (1970) for Map 1250A and, with the advent of plate tectonics, geosynclinal terminology for various types of sedimentary basins is no longer used as explained in the explanatory notes of the legend for Map 1860A. The more precise dating by U-Pb isotopic methods in the intervening 25 years led to the use of the Geological Time Scale 1989 (Harland et al., 1990) for Phanerozoic rocks with the modification that new U-Pb zircon geochronology (Bowring et al., 1993) has established the Precambrian-Phanerozoic boundary at 544 Ma. In the Precambrian Eon, however, the time scale used favored the subdivision of the Proterozoic according to Plumb (1991) and of that the Archean by Lumbers and Card (1991). Finally, the alphabetical (U, V, W, X. Y, Z) divisions of the Precambrian adopted by the U.S. Geological Survey (James, 1972) were retained for simple and unambiguous labeling. Currently the GSC's 1:1,000,000 scale Geological Atlas of Canada maps are using the Geological Time Scale 1999 by A.V. Okulitch (1999).

Special features such as impact structures, leading edge of terranes accreted in the Phanerozoic, and point data denoting volcanic centers, diatremes, Alaskan-type ultramafics, evaporite diapirs, kimberlites, and carbonatites were compiled by John Wheeler. He collaborated with Michel Sigouin for color design. Sigouin, assisted by John Narraway, produced the map using digital cartographic techniques under the general direction of Vern Foster.

Finally, diabase dike swarms were not included on Map 1860A because of anticipated congestion in the Slave and southern Superior provinces of the Canadian Shield. They are displayed separately on GSC Map 2022A compiled by Kenneth E. Buchan and Richard E. Ernst (2004).

The resulting map is more intricate and complex than Map 1250A published in 1969. This reflects the completion of the geological reconnaissance mapping of Canada in 1978 and recent more detailed surveys by the GSC and Provincial Surveys. The compilation also used data from widespread gravity surveys by the former Earth Physics Branch, now part of GSC, and from Federal-Provincial Aeromagnetic Surveys. The quality and accuracy of the map has been increased as a result of improved methods of dating geological units, notably from advances in micropaleontology (conodonts and radiolaria) and from U-Pb isotopic dating. Altogether, Map 1860A has benefited from a more accurate depiction and correlation of geological formations and a better understanding of their mutual relations. Similarly, extensive submarine geoscience surveys since 1969 by GSC now allow the geology on land to be extended across the Great Lakes and offshore, and to display the age, structure, and patterns of oceanic crust surrounding Canada.

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