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To Accompany Map CP-48

Explanatory Notes for the Geologic Map of the Circum-Pacific Region, Arctic Sheet

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Explanatory Notes to Supplement the

GEOLOGIC MAP OF THE CIRCUM-PACIFIC REGION, ARCTIC SHEET

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EXPLANATORY NOTES FOR THE GEOLOGIC MAP OF THE CIRCUM-PACIFIC REGION, ARCTIC SHEET

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ABSTRACT

The Geologic Map of the Circum-Pacific Region, Arctic Sheet, covers the North Pacific Ocean, the Arctic Ocean, part of the North Atlantic Ocean, and the surrounding land. It includes areas between northern China, northern Scandinavia, and northern Mexico. For land areas, strong colors indicate the geologic age of outcrops, patterns designate the lithology, and line symbols mark faults. For water areas, pale colors indicate the type of seafloor sediment. Colored symbols mark recently active volcanoes. These map elements are augmented in oceanic areas by illustrations in this text that show deep-sea columnar sections and offshore rock samples. Water areas on the main map also contain seafloor contours, and land areas contain streams, important cities, and national boundaries. Major submarine and topographic features are named throughout the map.

INTRODUCTION
by
George W. Moore

CIRCUM-PACIFIC MAP PROJECT

The Circum-Pacific Map Project was established in 1973 to produce a comprehensive set of maps to combine the earth-science information of land areas with that only recently available from the deep sea. This international project is an activity of the Circum-Pacific Council for Energy and Mineral Resources. It receives its direction from six regional panels of geologists and geophysicists who represent national earth-science organizations around the Pacific Ocean. The six panels and their chairs during preparation of this map were as follows: Northwest, Eiji Inoue (Japan); Northeast, Kenneth J. Drummond (Canada); Southwest, H. Frederick Doutch (Australia); Southeast, José Corvalán D. (Chile); Arctic, George W. Moore (United States); and Antarctic, Campbell Craddock (United States). George Gryc (United States) is general chair of the project.

Four complete seven-sheet map series have now been issued by the Circum-Pacific Map Project. They are the base, geographic, geodynamic, and plate-tectonic series. Still in the course of preparation and publication are the geologic, tectonic, energy-resources, and mineral-resources map series.

The seven sheets in the base map series (1977-1989) are printed in two colors and show closely spaced latitude and longitude lines to aid in the accurate plotting of data. The sheets in the geographic series (1978-1990) are printed in four colors and show cultural features and newly compiled submarine contours and topography tinted in shades of blue and orange respectively. The sheets in the geodynamic series (1984-1990) include gravity anomalies, lithospheric stress, earthquake mechanisms, historical faulting, volcanoes, and crustal thickness. The sheets in the plate-tectonic series (1983-1992) depict active plate boundaries, major faults within the plates, present-day directions and rates of plate motion, earthquake epicenters, young volcanoes, and seafloor magnetic lineations.

GEOLOGIC MAP OF THE CIRCUM-PACIFIC REGION

The Geologic Map of the Circum-Pacific Region was issued 1983-2000 as a series of six 8-color overlapping equal-area sheets at a scale of 1:10,000,000; a composite sheet at a scale of 1:17,000,000 is in preparation.

The six 1:10,000,000 sheets are designated the Northwest, Northeast, Southwest, and Southeast Quadrants, and the Arctic and Antarctic Sheets. The centers of the azimuthal equal-area projections are at the centers of the sheets, so distortion at the margin of each sheet is only about 5 percent. Therefore, a variety of analyses can be undertaken on the sheets with almost the precision provided by a globe.

The 1:17,000,000 Pacific Basin sheet, also equal-area but with greater marginal distortion, shows the regional relations around the entire Pacific Basin. It covers 220° of longitude, or more than half the Earth.

An explanation printed on the geologic map identifies the symbols used to depict the various map elements. This text explains the map elements further and provides additional information (fig. 1).

GEOLOGIC EVOLUTION OF THE ARCTIC AND NORTH PACIFIC

by
George W. Moore

The first-order features on the Arctic Sheet of the Geologic Map of the Circum-Pacific Region are its continents and ocean basins (fig. 1). Traditionally, geologists considered these features to be primeval components of the surface of the Earth, but Alfred Wegener, beginning in 1912, championed the idea that the continents move about on the surface. After that, the theory of plate tectonics (Wilson, 1965) added that seafloor spreading continuously creates new ocean floor—as at the Juan de Fuca Ridge—and subduction (where one plate descends beneath another) continuously destroys it—as at the Aleutian Trench.

We now know that some rocks on the continents are as old as 4 billion years (Archean), but the world's seafloor is nowhere older than about 180 million years (Jurassic). Details of the age of the seafloor for this map sheet appear on a companion map, the Arctic Sheet of the Plate-Tectonic Map of the Circum-Pacific Region (Moore, 1992). The oldest seafloor on the Arctic Sheet is 153 million years, near Makarov Seamount off Japan, and the youngest is still forming, along the Mid-Arctic (Nansen), Mid-Atlantic (Reykjanes), and Juan de Fuca Ridges.

Interior areas of the continents are marked by cratons—ancient flat stable areas. Archean and Proterozoic rocks (red and brown on the map) crop out on shields at the centers of the cratons, and broad little-folded overlying bands of Paleozoic rocks (purple and blue) lie on platforms around the shields (fig. 2).

The old Archean rocks of the cratons contain complex geologic structures. They once had the rough topography and varied crustal thickness of present-day mountain regions. The mountains had deep, low-density crustal roots that rose up by isostacy—a process similar to floating. Over a period of about 1 billion years, repeated uplift of the deeply rooted areas, followed by erosion of the resulting mountain highlands, gradually led to a uniform crustal thickness for the cra-

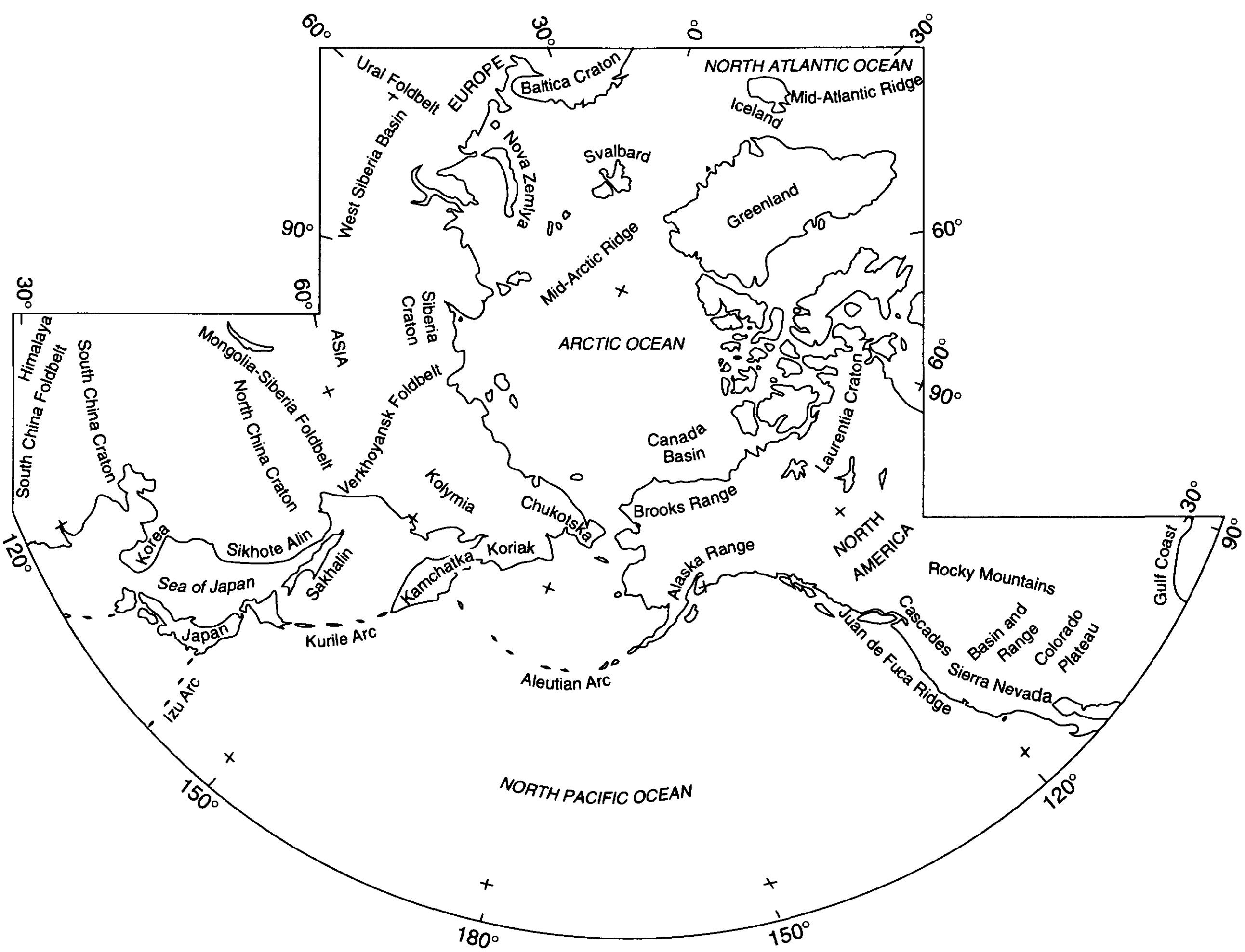

Figure 1. Principal morphostructural features of the Arctic Sheet.

tons. After that, no further impetus for differential uplift existed, and the cratons have remained low and stable.

The continents, even including the cratons, are made up of tectonic terranes—fault-bounded bodies of rock that have geologic histories different from those of adjacent terranes (Howell and others, 1987). The cratons are the oldest tectonic terranes, and on this map they consist of the Laurentia Craton (North America and Greenland), the Baltica Craton (Scandinavia), the Siberia Craton, the North China Craton, and the South China Craton (including Korea).

Some of the oldest rocks on the surface of the Earth crop out within the Arctic Sheet. Volcanic conglomerate at Isua, Greenland, is 3.81 billion years old (Baadsgaard and others, 1984); and gneiss (originally granite) at Granite Falls, Minnesota, is 3.68 billion years old (Goldich and others, 1980).

These localities lie on parts of a stable shield. Until a breakup about 700 million years ago, that shield was continuous with a locality that contains the Earth's presently oldest known materials, reworked zircon crystals of 4.2 billion years ago in metamorphosed sandstone near Mt. Narryer, Australia (Compston and Pidgeon, 1986).

Most geologists believe that the Earth formed about 4.5 billion years ago, based on the radiometric dating of meteorites assumed to be the same age (Patterson, 1956). A more precise age combines the isotopic ratios of old lead in meteorites with those of bedded lead ores on the Earth that range in age from 2.6 to 3.5 billion years (Dalrymple, 1991). The samples contain both initial lead and uranium-derived lead, and their differing known ages of formation permit solving for the age of the Earth and the other bodies in the Solar System, giving a result of 4.54 billion years.

Crustal rocks began forming soon after the origin of the Earth, but the first cratons required about 1 billion years to stabilize. Therefore, the oldest rocks on this map, which formed when the Earth was less than 500 million years old, were not yet stable and were subject to uplift and erosion like those of young mountain belts. They formed at island arcs, and only later did continental collisions at subduction zones gradually assemble them into continents.

True cratons became possible about 3.5 billion years ago. We are not certain where they lay during the Archean and the Early Proterozoic. Rogers (1996) pointed out evidence that about 3 billion years ago Laurentia and Australia may have constituted a combined continent, which he named Ur. The situation is clearer near the end of the Proterozoic, when most of the Earth's cratons had assembled into a supercontinent called Rodinia (Hoffman, 1991).

Continental rifting began to fragment Rodinia about 700 million years ago, truncating the Laurentia Craton against a newly formed Pacific Basin (Stewart, 1970). Australia and Antarctica likely constitute the southern part of the other half of that craton (Karlstrom and others, 1999). On the basis of a similar early Paleozoic fauna, the Siberia Craton probably rested against western Canada (Condie and Rosen, 1994). The Baltica Craton was next to Laurentia at a closed-up North Atlantic (Ross and Scotese, 1997). The position of the two China cratons is less certain, however, and they may have been independent of Rodinia.

Tightly folded rocks, marked on the map by narrow linear bands of the geologic-age colors, generally occur along lines of continental collision. Old lines of continental rifting (passive continental margins) com-

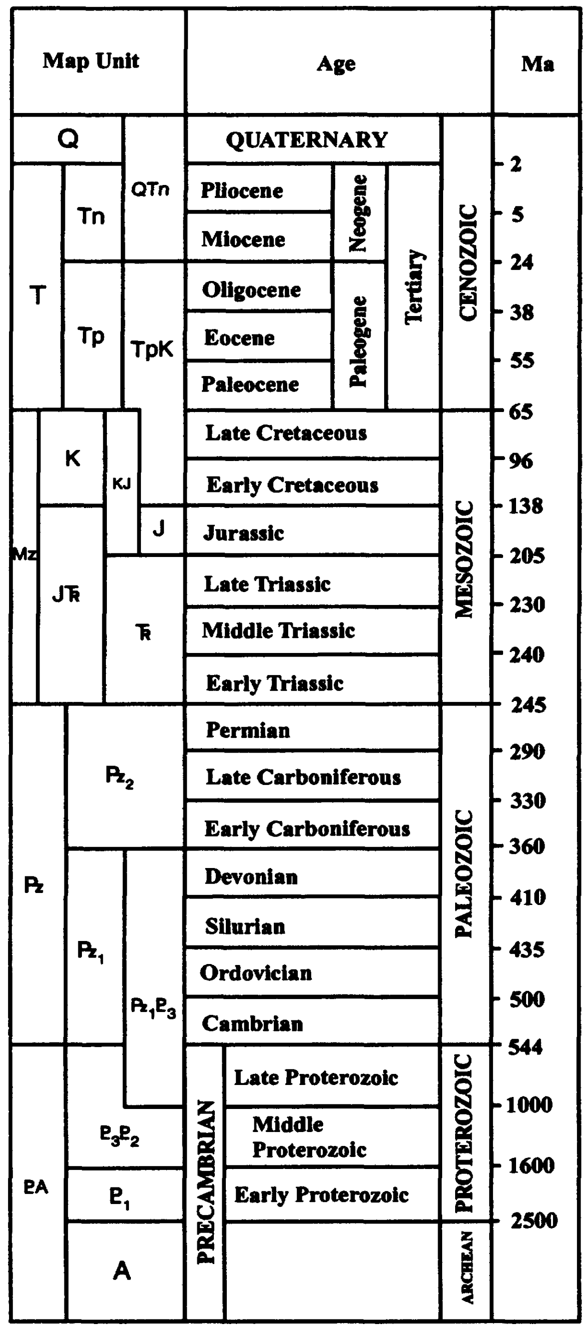

Figure 2. Geologic age of map units on the Arctic Sheet.

monly underlie these foldbelts, either on both sides, or on one side next to an accreted island arc.

Continental rifting and continental collision both take appreciable time to complete. Rifting must work its way slowly down through 40 km of continental crust before basaltic crust begins to form along the axis. During this 20 to 40 million year process, the continental crust thins and slides down toward the rift axis. Early sedimentary basins follow such rifts, then the flanks rise owing to hot mantle material near the surface, followed by renewed subsidence as the system cools (Moore and Eittreim, 1987). After that, sedimentation is continuous along the boundaries between the continents and the new ocean basin.

The consolidation along a line of continental collision also takes 20 to 40 million years. Sedimentary layers that had formerly draped across the margins become part of the foldbelt, along with overlying deposits formed during the collision process.

Abundant granite and granite gneiss in the Archean suggest an early origin for the volcanic-arc process of crystal settling that separates light-colored granitic rocks from dark-colored rocks derived from the Earth's mantle. The granitic bodies lie between greenstone bodies that were originally basaltic lavas erupted at seafloor-spreading axes. The greenstone was squeezed between colliding granite-bearing volcanic arcs at subduction zones.

Igneous rocks of all ages on the Arctic Sheet provide a clue to how one important process in the Earth works. The composition of extrusive (volcanic) rocks along former volcanic arcs is systematically displaced toward darker-colored types than the intrusive (plutonic) rocks formed at depth along such arcs. To both the extrusive and intrusive igneous rocks, we applied a three-fold classification: (1) felsic (light colored), (2) intermediate, and (3) mafic (dark colored). On the map, intermediate extrusive rocks (andesites) are the most abundant type, whereas intermediate intrusive rocks (diorites) do not show up at all.

To some extent, this effect comes from the fact that coarse-grained rocks look lighter colored than fine-grained rocks of the same chemical composition. Diorite does of course crop out in the area of the map sheet, but in bodies so small that at the scale of the map we necessarily grouped it with more extensive nearby felsic (granite) or mafic (gabbro) intrusive rocks.

The crystal-settling process at volcanic arcs seems to allow diorite magma to pass up to volcanoes to produce andesite, but it does not preserve the diorite when the intrusive rock crystallizes at depth. Heavy dark minerals crystallize on the walls of the magma chamber. When they reach large size, they break away and settle through the magma to produce gabbro on the floor of the chamber. All the while, volcanoes erupt intermediate-composition magma to the surface as andesite. When the magma chamber does fully crystallize, light-colored felsic intrusive rocks remain. Therefore, either the underlying gabbro or the granite can appear on the map, but the diorite is missing.

The youngest Archean rocks contain extensive beds of banded iron formation (chiefly 2.7 to 2.6 billion years old). They seem to have formed when oxygen produced by photosynthetic bacteria became sufficiently concentrated to precipitate dissolved iron from the ocean.

Proterozoic rocks (2.5 to 0.5 billion years old) constitute the remainder of the shield areas on the Arctic Sheet, and they underlie extensive little-deformed sediment cover on the continental platforms. During the 2 billion years of the Proterozoic, plate-tectonic processes seem to have operated at rates comparable to those of earlier and later eras.

Late in the Proterozoic, about 800 million years ago, the Rodinia Supercontinent comprised most of the world's cratons. As noted above, Australia and Antarctica (along with India on the far side) pulled away from Rodinia about 700 million years ago to produce the west coast of North America. About 600 million years ago, Australia, Antarctica, and India began to close with Africa and South America to produce the large Southern Hemisphere continent of Gondwana. The South America edge of Gondwana broke away from what remained of Rodinia to produce the east coast of North America.

During the interval from 600 to 500 million years ago, at the dawn of the Paleozoic Era, the remaining parts of Rodinia (North America, Siberia, and Baltica) moved from south polar regions to equatorial regions, and then these three cratons separated widely from each other. Multicellular organisms had originated immediately before this time interval (at about 670 million years ago), and by the end of it, the warm intervening Iapetus Ocean of the Cambrian Period had spawned most of the phyla of organisms that live today.

During the Paleozoic Era, from 544 to 240 million years ago, abundant marine fossils help record a succession of plate-tectonic events on the Arctic Sheet. Individual closures between continent-sized terranes took as much as 100 million years, and the mountain-building times commonly differed along the length of a suture. The first major episode of deformation, from 500 to 400 million years ago, occurred when Baltica and adjoining terranes closed against Greenland and eastern Canada (Caledonian/Taconic Orogeny). This was followed by the closure of Gondwana (Africa, South America) against North America and Baltica roughly 300 million years ago (Hercynian/Variscan/Allegheny Orogeny). At about this time also, Siberia closed against Baltica to create the foldbelt along the Ural Mountains (Zonenshain and others, 1990). By the end of the Paleozoic Era (Permian Period), these collisions had created the new supercontinent of Pangea, which again brought together most of the world's cratons. Pangea shared the globe with the Panthalassa Ocean.

The Pangea Supercontinent extended from pole to pole. Glaciation was widespread, and circulation in the giant Panthalassa Ocean may have been less conducive to the maintenance of life than were the dispersed continents and oceans of former times. In any case, a grave biotic crisis took place at the end of the Permian Period, and three quarters of the Earth's life forms became extinct.

During the Mesozoic Era (blue green and green on the map), from 240 to 65 million years ago, continents of more ordinary size redeployed in the ocean basins, and smaller terranes consolidated with them. Also, the Siberian Traps erupted on the west side of the Siberia Craton. These flood basalts, from a mantle hotspot beneath the Eurasia Plate, cover about 600,000 square kilometers to an average thickness of 2 km. Plate movements did not cause them. Instead they likely came from a mantle plume rising from a reheated pile of sunken subduction slabs above the liquid outer core of the Earth.

Continental thinning across the central Atlantic Ocean and through the Gulf of Mexico and Mediterranean Sea began in the Triassic, as marked by half grabens containing Triassic red beds of the Newark Group in the eastern United States and Canada. During the Jurassic (about 160 million years ago) basaltic oceanic crust emerged along this rift, which split Pangea through the Gulf and Mediterranean from the Pacific to the Tethys (Asian) side of Panthalassa. At the same time, major augmentation took place at the east and south sides of Eurasia. During the Jurassic, Kolymia closed against the east side of the Siberia Craton at the Verkhoyansk Foldbelt, and during the Cretaceous, Chukotskia closed against Kolymia to complete the east tip of Eurasia. Arc-type volcanic and granitic rocks mark the subduction that preceded such collisions, and whichever side of the suture they lie on indicates the direction of dip of the subduction zone.

The North and South China Cratons had amalgamated in an oceanic setting during the Permian. They accreted to the south side of Eurasia during the Cretaceous, and subduction from the Pacific Basin then immediately began along the margin at Japan. North America moved west as rifting of the Atlantic began, and it collided with the Sonomia island-arc terrane (Nevada) during the Triassic. The Stikinia Terrane arrived at the west coast of North America during the Jurassic, and Wrangellia during the Cretaceous. Also during the Cretaceous, continental rifting extended northward and southward from the previously opened central Atlantic to create the margins of the modern Atlantic Ocean.

Oceanic plates on both sides of the Pacific, now well recorded on the seafloor by never-subducted Mesozoic and Cenozoic oceanic crust, moved northward and caused northward dispersion of coastal terranes along major strike-slip faults such as the Tanlu in China and precursors of the San Andreas in the United States. The Northern Alaska Terrane swung quickly from the Arctic Islands of Canada toward the Pacific Basin to open up the Canada Basin of the Arctic Ocean.

During the Cenozoic Era (orange and yellow on the map), from 65 to 0 million years ago, northward terrane dispersion continued along both sides of the Pacific Basin. Conspicuous effects in North America include extension at the Basin and Range and opening of the Gulf of California (Muehlberger, 1996). Seafloor spreading continued at the Mid-Atlantic and Mid-Arctic Ridges, and that continuous spreading axis, which spans half the globe, narrows to a feather edge near the north coast of Siberia. India swept up and amalgamated island arcs off the south coast of Eurasia, and then the combined assembly crashed into the continent to form the Himalaya and the Tibetan Plateau. This collision continues to push China northeastward, where it has opened up Lake Baikal, reversed the displacement on the Tanlu Fault, and opened the Sea of Japan. Because the Africa Plate is virtually motionless, the Mid-Atlantic Ridge has moved sideways toward the west over the Earth's mantle, so that eruptions that mark the trace of the Iceland Hotspot, which is fixed in the mantle, cross Greenland and finally end today on the ridge.

DESCRIPTION OF ONSHORE MAP UNITS

by
George W. Moore, Kenneth J. Drummond,
and Yoji Teraoka

Quaternary (Q)

Alluvial, deltaic, lacustrine, glacial, and eolian deposits throughout the map sheet, locally including Pliocene units. Marine carbonate deposits include raised coral reefs on the Ryukyu Islands. Marine clastic deposits in coastal areas of northern Siberia, Sakhalin, Sikhote Alin, Kamchatka, and Japan. Mafic extrusive rocks in Alaska, north China, North Korea, the Kurile Islands, the Kamchatka-Koryak Belt, the Aleutian Islands, the Alaska Peninsula, and Baja California. Intermediate extrusive rocks are characteristic of the continental volcanic arcs of Japan, Kamchatka, and the Cascades, and the island arcs of the Ryukyu, Izu, Kuril, and Aleutian Islands. Flood basalt in Iceland.

Quaternary and Neogene (QTn)

Marine, glacial, and terrestrial deposits in the West Siberia Basin. Marine and paralic deposits in China and Japan. Loess in north China, and alluvial deposits in China. Basalt flows in China and mafic to felsic rocks at many volcanic arcs such as Japan and the Izu and Kuril Islands.

Neogene (Tn)

Marine clastic deposits intercolated with pyroclastic deposits in Siberia, China, Sikhote Alin, Sakhalin, and Kamchatka. Nonmarine deposits widespread in Siberia, China, and Sakhalin. Marine and locally lacustrine deposits at volcanic arcs such as Japan and the Kuril Islands, accompanied by a large amount of felsic and mafic extrusive rock. Felsic intrusive rocks in Japan. Plateau basalt of the northwest United States (Columbia and Modoc Plateaus and Snake River Plain). Mafic volcanic rocks of central British Columbia. Continental sediment in the interior plains of the United States. Marine deposits of the U.S. Pacific continental margin and Gulf Coastal Plain. Flood basalt in Iceland.

Tertiary (T)

Terrestrial deposits in China. Marine and continental sediment and felsic volcanic rocks in Alaska.

Paleogene (Tp)

Marine deposits in European Russia and the West Siberia Basin. Marine and continental deposits intercalated with felsic, intermediate, and mafic extrusive rocks in the Sikhote Alin, Kamchatka-Koryak, and Verkhoyansk-Chukotsk Foldbelts. Marine and paralic deposits including reef limestone and pyroclastic rocks accompanied by felsic to marine extrusive rocks in Japan. Flood basalt in Franz Joseph Land. Continental and lacustrine deposits in the interior plain and plateau areas of North America. Marine sediment of the U.S. Pacific continental margin and the Gulf of Mexico coastal plain. Andesite and rhyolite of the southern plateau of British Columbia and the Cascade Range of Washington and Oregon. Marine basalt of the U.S. Pacific margin and the Oregon and Washington Coast Range. Felsic volcanic rocks of the interior plateaus of Canada and the western United States. Flood basalt on the east coast of Greenland.

Paleogene and Cretaceous (TpK)

Predominantly felsic to intermediate extrusive rocks and felsic intrusive rocks in Japan and the Sikhote Alin and Verkhoyansk-Chukotsk Foldbelts. Continental sediment and felsic volcanic rocks of Alaska and the British Columbia interior plateau. Felsic intrusive rocks of the British Columbia Coast Plutonic Complex, including Paleozoic and Mesozoic metasediments.

Cretaceous (K)

Marine sedimentary rocks in the Ural Foldbelt, the West Siberia Basin, and Svalbard. Continental and marine sedimentary rocks accompanied by a large amount of felsic, intermediate, and mafic extrusive rocks on the Siberian Platform and the Sikhote Alin, Verkhoyansk-Chukotsk, and Kamchatka-Koryak Foldbelts. Marine and continental sedimentary rocks interbedded with felsic, intermediate, and mafic extrusive rocks, and mafic and felsic intrusive rocks in Japan, the Kolyma Massif, and the Verkhoyansk-Chukotsk Foldbelt. Predominantly marine and volcanic-marine facies throughout the extended Rocky Mountains from the Alaska Peninsula to Mexico. Northern Alaska and the interior plains are predominantly marine clastic rocks in the Lower Cretaceous becoming nonmarine in the Upper Cretaceous. Intrusions predominantly felsic and intermediate. Felsic intrusive rocks constituting part of the Sierra Nevada Batholith of California and the Peninsular Batholith of Baja California. Marine sedimentary rocks in the Arctic Islands of Canada.

Cretaceous and Jurassic (KJ)

Marine and continental sedimentary rocks in the Ural Foldbelt. Marine and continental sedimentary rocks accompanied by felsic, intermediate, and mafic extrusive rocks, and felsic and alkalic intrusive rocks in northern China and the Siberian Platform and in the Mongolia-Siberia, Kamchatka-Koryak, and Verkhoyansk-Chukotsk Foldbelts. Marine sedimentary and mafic extrusive rocks, locally metamorphosed, on Sakhalin and Hokkaido. Mostly continental sedimentary rocks, locally of Paleogene age, in China and Korea. Felsic and intermediate intrusive rocks, locally accompanied by felsic to mafic extrusive rocks, in China and Korea. Extrusive rocks accompanied by felsic intrusive rocks especially abundant on the eastern margin of the Asian continent, such as in north and southeast China. Primarily synorogenic sediment within the Rocky Mountains of North America. Severely deformed marine sedimentary rocks with associated volcanic rocks in the Chugach Terrane of south coastal Alaska and the Franciscan Assemblage of California. Intermediate volcanic rocks of central Alaska.

Mesozoic (Mz)

Marine sedimentary rocks in the Sikhote Alin of Russia. Continental sedimentary rocks; felsic, intermediate, and mafic volcanic rocks; and felsic intrusive rocks in China. Marine sedimentary and intermediate volcanic rocks in Baja California. Marine sedimentary rocks in Sonora, Mexico.

Jurassic (J)

Marine sedimentary rocks in the Mongolia-Siberia and Verkhoyansk-Chukotsk Foldbelts and near Tibet. Marine and continental sedimentary rocks and felsic intrusive rocks in Japan and Korea. Felsic intrusive rocks on the flanks of the Sierra Nevada Batholith, and in Mexico in the Peninsular Ranges Batholith and on the Vizcaino Peninsula. Marine sedimentary rocks on the Arctic Islands of Canada.

Jurassic and Triassic (JTR)

Continental and marine sedimentary rocks, felsic to mafic extrusive rocks, and felsic intrusive rocks in the Verkhoyansk-Chukotsk Foldbelt. Marine sedimentary rocks (associated with mafic and locally felsic to intermediate extrusive rocks) intruded by felsic to mafic intrusive rocks in the Mongolia-Siberia Foldbelt and in Japan. Locally metamorphosed in Japan. Predominantly marine and volcanic-marine facies throughout the extended Rocky Mountains from the Alaska Peninsula to Mexico. The interior of North America is composed of both marine and nonmarine sedimentary rocks. Felsic intrusive rocks of the Alaska Peninsula, Yukon, central British Columbia, and the eastern Sierra Nevada. Mafic volcanic rocks (in part Permian) of Alaska, including pillow basalt, diabase, and associated peridotite, dunite, radiolarian chert, and slate. Mafic volcanic-arc rocks at the Interior Plateau of British Columbia, Vancouver Island, and the Queen Charlotte Islands of the Insular Belt.

Triassic (TR)

Continental sedimentary rocks in the Ural Foldbelt, and marine sedimentary rocks in Svalbard. Marine sedimentary rocks, locally paralic in the upper parts, and felsic intrusive rocks in the Mongolia-Siberia and Verkhoyansk-Chukotsk Foldbelts and in China and Japan. Mafic intrusive and extrusive rocks in north China. Felsic to intermediate extrusive rocks intercalated in places within sedimentary rocks throughout Asia, except on the North and South China Cratons. Mafic flood basalt and felsic, intermediate, and mafic intrusive rocks on the Siberia Craton and in the Mongolia-Siberia and Verkhoyansk-Chukotsk Foldbelts, in part late Paleozoic.

Late Paleozoic (Pz_2)

Predominantly marine clastic and carbonate rocks, locally metamorphosed, at Nova Zemlya, the Siberia Craton, China, Korea, and Japan, and the Ural, Sikhote Alin, Mongolia-Siberia, and Verkhoyansk-Chukotsk Foldbelts. Felsic intrusive rocks in central China and along the Mongolia-Siberia and Verkhoyansk-Chukotsk Foldbelts. Local Permian continental sedimentary rocks in the Mongolia-Siberia and South China Foldbelts and on the Siberia and North China Cratons. Felsic to mafic extrusive rocks are commonly intercalated with the upper Paleozoic strata in the Mongolia-Siberia Foldbelt and in central China. The North China Craton lacks strata of Late Ordovician to Early Carboniferous age. Oceanic volcanic rocks and blueschist with associated sedimentary rocks of southwestern Alaska and north-central British Columbia. Former continental-margin sedimentary rocks of northern Alaska and the Yukon. Platform and former continental margin rocks of the western and southern United States. Marine sedimentary rocks in the Arctic Islands of Canada and in Greenland.

Paleozoic (Pz)

Marine sedimentary and mafic intrusive rocks in the Mongolia-Siberia, Kamchatka-Koryak, and Verhoyansk-Chukotsk Foldbelts. Marine and continental sedimentary rocks in the Basin and Range and Rocky Mountains of the United States and Canada. Felsic intrusive rocks of northern Alaska and the Yukon. Volcanic rocks of the western Coast Mountains of British Columbia.

Early Paleozoic (Pz_1)

Marine sedimentary rocks in Scandinavia and Svalbard. Marine, continental, and ultramafic rocks in the Ural Foldbelt. Marine sedimentary rocks, locally metamorphosed, in China, Korea, Japan, the Siberia Craton, and the Mongolia-Siberia Foldbelt. Felsic intrusive rocks in the South China and Mongolia-Siberia Foldbelts, in central China, and on the Siberia Craton. Continental-margin marine rocks bordering the Laurentia Craton and Rocky Mountains of Alaska, Canada, and the conterminous United States. Deep-water marine sedimentary and associated volcanic rocks in the central and western Rocky Mountains. Marine sedimentary rocks in the Arctic Islands of Canada.

Early Paleozoic and Late Proterozoic (Pz_1P_3)

Shallow-water marine clastic rocks and metamorphic rocks accompanied by extrusive and felsic intrusive rocks on the Siberia Craton, at the Kolyma Massif, and at the east end of the Mongolia-Siberia Foldbelt. Marine sedimentary rocks in Nova Zemlya. Late Proterozoic and nonfossiliferous or poorly fossiliferous early Paleozoic sedimentary rocks on the South China Craton. Extrusive rocks, felsic intrusive rocks, and metamorphic rocks in South China. Metamorphic complexes (Yukon-Tanana and Neroukpuk) of the Yukon Basin and northeast Alaska. Undifferentiated metasedimentary and metavolcanic units of the Rocky Mountains, from greenschist to upper amphibolite facies.

Late and Middle Proterozoic (P_3P_2)

Marine sedimentary rocks of the Ural Foldbelt and Nova Zemlya. Felsic intrusive rocks in Scandinavia and flood basalt at the flank of the Baltica Craton. Continental and marine sedimentary rocks of the Riphean System, accompanied by felsic to intermediate volcano-plutonic complexes on the Siberia Craton and at the east end of the Mongolia-Siberia Foldbelt. Marine sedimentary rocks and metamorphic rocks of the Baikalian Stage and local felsic extrusive rocks accompanied by shallow-water sedimentary and felsic intrusive rocks on the Siberia Craton. Marine sedimentary and metamorphic rocks of the Sinian System on the North China Craton and in other parts of China.

Proterozoic and Archean (PA)

Marine sedimentary and metamorphic rocks in South Korea, on the North China Craton, and in the Himalaya, accompanied by felsic intrusive rocks. Metamorphic complexes of east-central British Columbia.

Early Proterozoic (P_1)

Marine sedimentary and felsic and mafic intrusive rocks on the Siberia Craton. Marine sedimentary and felsic intrusive rocks on the North and South China Cratons. Metamorphic rocks at Chukotska and on Alaska's Seward Peninsula. Marine sedimentary, mafic extrusive, and felsic intrusive rocks on the Laurentia Craton, including Greenland. Marine sedimentary rocks at the Balck Hills, South Dakota. Marine sedimentary and felsic intrusive rocks in the U.S. Rocky Mountains, the southwestern United States, and northern Mexico.

Archean (A)

Metamorphic and granitic rocks on the Baltica Craton and Nova Zemlya. Marine sedimentary and metamorphic rocks on the North China Craton, accompanied by extrusive rocks and felsic intrusive rocks. Metamorphosed mafic volcanic rocks and associated sedimentary rocks with intrusive igneous rocks, Slave and Superior Provinces of the Laurentia Craton and the Wyoming Province of the Rocky Mountain Front Ranges of the United States.

SEAFLOOR SEDIMENT, ARCTIC REGION

by
Floyd W. McCoy

Information from two databases was used to produce the seafloor-sediment map of the Arctic Region. The primary database was derived using samples from the Lamont-Doherty Earth Observatory (Columbia University, United States) archive of deep-sea cores and additional samples from cores in repositories of other marine institutions. A secondary database was developed from published and unpublished sources.

The primary database uses quantitative criteria on sediment composition to determine sediment types. Data were developed using sediment descriptions derived from smear-slide analyses supplemented by measurements of the total calcium carbonate ($CaCO_3$) content in the entire sample. A smear slide is a thin film of sediment held under a cover slip on a glass slide with mounting compound, such as Canada balsam, and is an excellent method for describing fine-grained sediment such as silt and clay. Calcium carbonate content was determined using several techniques, most commonly the acid-weight-loss method. These techniques provide a systematic and uniform framework for defining mappable sediment units, used with success on all the other geologic map sheets of the Circum-Pacific Map Series. Unfortunately, few cores from the Arctic Ocean are in the collections at marine institutions in the United States, greatly limiting information to form the primary database.

Accordingly, additional information was gathered from published and unpublished sources of sediment criteria, based on smear-slide analyses with calcium carbonate measurements to add to the primary database. Sources new to this sheet are listed in the accompanying References and Additional Sources of Data. If either smear-slide descriptions or carbonate data were not complete, information was not used in the primary database, but placed in the secondary database.

The secondary database was composed of incomplete quantitative information on sediment components, qualitative sediment descriptions, and previous maps depicting sediment distribution. Information was from the published and unpublished scientific literature, with all sources listed under the references. Most significant here were previous map compilations of regional surface-sediment distribution such as those of Rawson and Ryan (1978), Gramberg and others (1989), the USSR-Canadian Arctic circumpolar geologic map (Okulitch and others, 1989), the USSR geologic map (Mazarovich and Krasilnikova, 1990), and Tucholke and McCoy (1986). These maps commonly do not show data points; data points used here are from sources cited in the references.

Many of these data in the secondary database are contradictory and incomplete, thus difficult to combine into one consistent and interpretable database and then to map according to the sediment classification scheme used for this map. Sediment descriptions may be misleading, for example, if based on quick field observation, on insufficient laboratory data such as coarse-fraction analyses, or on poorly defined or differing terminology and classification schemes. Equipment capabilities for sediment sampling also must be considered, such as the effectiveness of tallow at the end of a sounding line (commonly used in the last century), or the efficiency of modern corers, grab samplers, underway samplers, dredges, and so forth. For these reasons, descriptions based on smear-slide information from cores are the preferred basis for describing seafloor sediments and form the primary data assemblage for this map.

The classification scheme for marine sediment published in 1891 by Murray and Renard was retained in modified form. This classic scheme employs a nomenclature defined by a one-third/two-third division for nonbiogenic/biogenic components respectively. It is a descriptive scheme that identifies components forming the sediment, and avoids terms that identify sediments according to sedimentary processes such as "turbidites", "tillites", and so forth.

Nonbiogenic components, predominantly allochthonous from land (terrigenous), are classified by median diameter of the dominant particles using the Wentworth grade scale subdivisions of gravel, sand, silt, and clay. For simplification, adjectival modifiers of multiple-noun designations are not used with these terms, thus eliminating terrigenous-sediment categories such as "silty clay", "sand-silt-clay", "mud", "diamictite", or "mixtites". Pelagic clays are classified with "clay", because these pelagic deposits are predominantly allochthonous clay residues remaining after dissolution of calcareous biogenic debris, which have subordinate amounts of authigenic components, and because differentiation between allogenic and authigenic clay is impossible in smear slides.

Biogenic components are calcareous and siliceous skeletal debris that are predominantly formed locally (autochthonous), at least on a regional basis. Biosiliceous is used to distinguish biogenic from nonbiogenic siliceous detritus. The calcareous clay and biosiliceous clay categories define seafloor areas of mixing between biogenic and nonbiogenic material; both are probably underestimated, because they require smear-slide or $CaCO_3$ data not always available. Marl is an abridgment of the Murray and Renard term "marl ooze", which consists of calcareous clay and silt.

Biosiliceous mud is equivalent to marl, but it contains siliceous rather than calcareous skeletal material. It is designated "mud" to discriminate it from biosiliceous clay and to identify it as a mixture of clay- and silt-sized biosiliceous debris. Oozes contain at least 60 percent biogenic constituents and 30 percent or more clay-sized material, which may be either biogenic or nonbiogenic.

Calcareous gravel/sand/silt, diatomaceous silt, and volcanic gravel/sand/silt define sediment that contains less than 30 percent clay-sized material. These sediment types have been mapped only where adequate sedimentologic data are available. Volcanic or calcareous gravel/sand/silt occur on seafloor areas around volcanic islands and carbonate banks, for instance, but are not shown unless sufficient information exists for both a textural and compositional definition. Diatom frustules occur predominantly as silt-sized particles; other biosiliceous debris does not form a dominant silt component in Arctic Ocean sediment.

Primary control in establishing trends of, and boundaries between, sediment types were documented oceanographic and biologic water-column phenomena, in addition to geologic phenomena influencing seafloor sedimentation such as proximity to glaciers, large rivers, and so forth. Details of sediment distribution, such as on continental shelves, on insular slopes, on banks, and within fiords, cannot be distinguished at this scale. Little to no data exist on sediments within many of the inlets, passages, and fiords; sediments here are presumed, or are extrapolated from the few data available, commonly over considerable distance. Locally, coarser clastic debris deposited from icebergs and ice floes (dropstones) may be significant, but at this scale, local patches are not mappable; a single cobble-sized dropstone in a core-top sediment sample does not define that sediment as a "gravel", for example. Floating ice may not be a significant transporting mechanism of coarse clastic debris into the hemipelagic and pelagic environment (McCormick and others, 1993), but could be significant in transporting fine detritus (Mullen and others, 1972; Clark and Hanson, 1983). Sediment types and distributions in the Arctic Ocean are complex and poorly understood.

In the overlap areas between the Arctic Sheet and the Northeast and Northwest Quadrants, sediment depictions have been transferred to the Arctic region unchanged, even though more up-to-date information might suggest some changes in those depictions. This was done to maintain compatibility between the sheets. However, this required the use of two significantly different sources of information for mapping sediment distribution off Siberia east and west of longitude 114° E.

Merging disparate data sets that used differing mapping conventions, sampling gear, laboratory procedures, sediment classification schemes, and definitions of sediment terms, has been especially difficult. The consequent map thus is an attempt to bring the differing information together and can be no more than a suggestion of what sediments lie on the Arctic Ocean seafloor. This map attempts to depict unconsolidated sediment recovered primarily by coring and presumably exposed on the ocean floor at the sediment-water interface. The sediment is not necessarily of Holocene age, nor are the deposits necessarily the result of Holocene sedimentary processes.

Cited references were used in defining sediment types and distributions. Additional sources consulted are not listed if already noted by other maps or compilations used for this synthesis. For the overlap areas of the Northwest and Northeast Quadrants, references for sediment mapping are listed with those maps. Published accounts of biostratigraphy and magnetostratigraphy provided an indication of the stratigraphic completeness of core-top material as representative of modern seafloor sediment.

Interpretation of Russian data into this sediment classification format by I.S. Gramberg, E.E. Musatov, and Y.E. Pograbitsky, Russia Ministry of Geology, is especially appreciated. Additional assistance in data compilation and map preparation was provided by Rusty Lotti of Lamont-Doherty Earth Observatory, John K. Hall of the Geological Survey of Israel, and Frances R. Mills of the U.S. Geological Survey. Mapping was supported by the U.S. Geological Survey under contract to the Associated Scientists at Woods Hole (Massachusetts, USA) and by the Circum-Pacific Council for Energy and Mineral Resources. This sediment map, in addition to others of the Circum-Pacific Map Series, reflects decades of support to curatorial facilities at major United States oceanographic institutions by the U.S. National Science Foundation and the U.S. Office of Naval Research.

OFFSHORE GEOLOGY, CIRCUM-PACIFIC REGION

by
George W. Moore

For the Geologic Map of the Circum-Pacific Region, triangles labeled by geologic age and lithology designate selected seafloor outcrops, including pre-Quaternary sediment samples within 1 m of the seafloor (figure 3). These serve as adjuncts to the Quaternary seafloor sediment shown by colored patterns and to the Deep Sea Drilling Project and Ocean Drilling Program columnar sections shown in the explanatory notes. The samples consist of dredge hauls, sedimentary rocks taken with heavily weighted dart corers, and Cretaceous and Tertiary strata penetrated by gravity and piston cores in areas of very slow deposition and seafloor erosion. Samples on the continental shelves have been selected to extend the outcrop geology of land areas as far seaward as possible. Where samples on the continental shelves are too numerous all to be included, older samples have been selected preferentially, along with those that alter patterns which might be inferred simply from offshore extrapolation of the continental geology.

Deep-sea drilling has shown that the Earth's crust under the ocean basins is much younger than that under the continents. Whereas the oldest continental rocks span a large fraction of the 4.54 billion year age of the Earth, those of the oceans do not exceed 180 million years, or less than 4 percent of the Earth's age. Newly formed oceanic crust, such as that along the Mid-Arctic and Juan de Fuca Spreading Axes, is flanked by progressively older oceanic crust. The world's oldest ocean crust, Middle Jurassic in age, occurs in the western Pacific.

Many volcanic seamounts and oceanic plateaus have a geologic age that matches that of the oceanic crust which underlies them. These prominences formed where eruption rates were anomalously great along spreading axes. Adjacent magnetic lineations indicate that many of these thick volcanic bodies formed where a spreading axis was offset by a long and presumably leaky transform fault.

Other seamounts, such as those of the midplate-hotspot type, are believed to have formed above essentially fixed magma sources that were overridden by a lithospheric plate so as to produce a line of islands and seamounts that is progressively older along the line. Most prominences of this type, such as the well-known Hawaiian Ridge, are younger than the underlying oceanic crust.

Water-chilled basalt, fine-grained and glassy, crops out near spreading axes where insufficient time has elapsed since the young oceanic crust was formed to accumulate a cover of sediment. Along fault scarps, dredges commonly recover coarse-grained basalt and gabbro, more slowly cooled at depth below the seafloor. Along major transform faults, the crust is disrupted to sufficient depth to expose such metamorphic rocks as greenschist and, in some places, serpentinite from the Earth's mantle.

Serpentinite, gabbro, and basalt also crop out along some trench slopes. Uplift and disruption of crustal material in the upper plate of a subduction zone is believed to cause these exposures. From other trench slopes, dredges recover Tertiary and older sedimentary rocks, also disrupted by the subduction process.

Accumulation is sufficiently slow in the central Pacific Basin to cause lower Tertiary strata to crop out or to lie within 1 m of the seafloor over broad areas (figure 4). The Pacific Basin has a typical depth of between 5,000 and 6,000 m, well below the ordinary level at which the rate of calcium carbonate deposition is exceeded by that of its dissolution. Thus, carbonate skeletons of foraminifers and nannofossils, the principal sediment materials in areas that are shallow or are highly productive biologically, are eliminated from the sediment of much of the deeper basin.

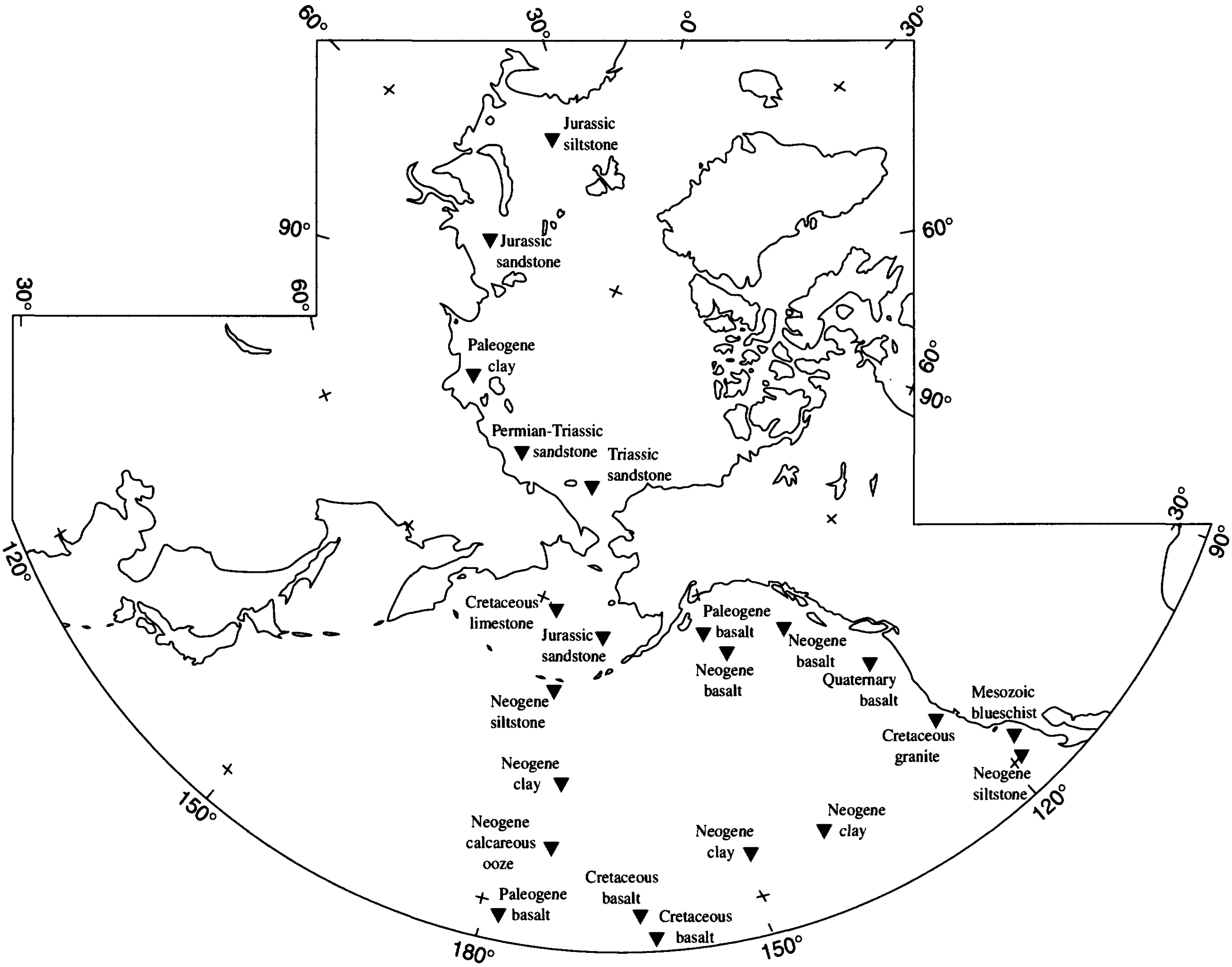

Figure 3. Offshore bedrock samples from the Arctic Sheet.

Opaline skeletons of diatoms and radiolarians are also subject to dissolution. Although some of the more robust fossil radiolarians survive near areas of high surface productivity, over much of the basin windborne dust from the continents and clay and zeolitic reaction products from volcanic material are the main components of a thin and discontinuous late Cenozoic sedimentary section.

Thick Quaternary deposits ring the Pacific Basin and cover the adjacent abyssal plains as a result of sediment plumes from streams, deep-sea fans, and slide-generated turbidity currents. Along the Equator, a belt of Quaternary carbonate ooze, 1,000 km wide and as much as 20 m thick, occurs where nutrient-rich water wells up along the Equatorial Divergence and enhances biologic productivity. In other parts of the deep basin, however, productivity is insufficient to balance seafloor dissolution. Many such places are at a steady state of no net accumulation, and in others, erosion of underlying older deposits occurs by means of both dissolution and bottom currents such as those generated by the sinking and lateral flow of cold dense water from near Antarctica.

Principal sources for the offshore geology of the Arctic Sheet are Gramberg and others (1992), Hanna (1952), Jarrard and Clague (1977), Marlow and Cooper (1980), Riedel and Funnell (1964), and Vedder and others (1974). Additional data were obtained from the marine data file of the National Geophysical Data Center of the U.S. National Oceanic and Atmospheric Administration, through the courtesy of Carla Potter. Several samples of abyssal clay from within 1 m of the seafloor were dated especially for this map series on the basis of their fossil ichthyoliths by Patrica S. Doyle, Scripps Institution of Oceanography. Samples used on the Arctic Sheet were collected by ships from the Hawaii Institute of Geophysics, Lamont-Doherty Earth Observatory, Oregon State University, Russia Academy of Sciences, Russia Ministry of Geology, Scripps Institution of Oceanography, University of Washington, U.S. Coast Guard, U.S. Geological Survey, and U.S. Navy.

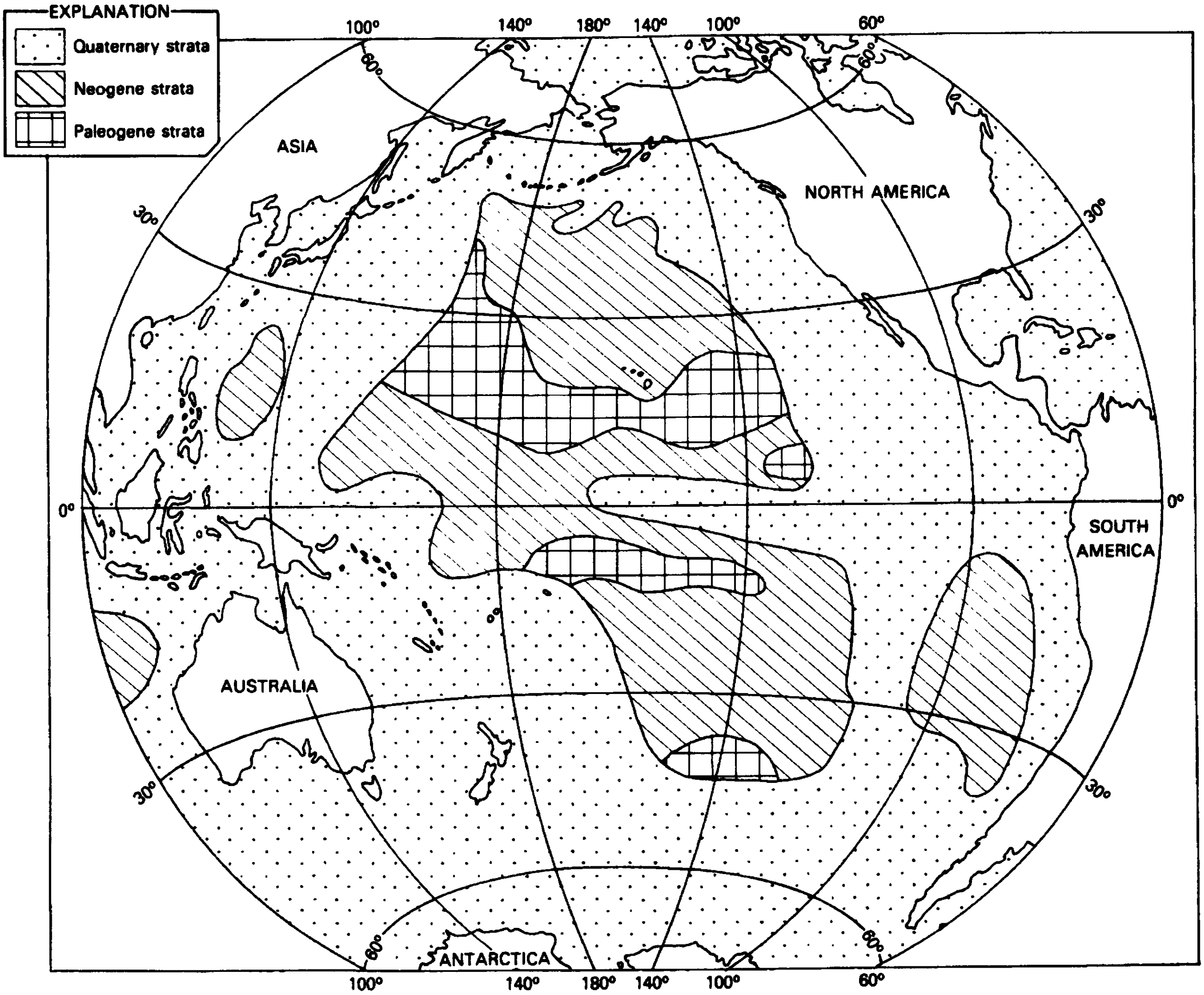

Figure 4. Areas of the Circum-Pacific region where Paleogene and Neogene strata lie within 1 m of the floor of the deep ocean. Cold bottom currents, principally from the region around Antarctica, are believed to erode overlying Quaternary deposits, mainly by dissolving silica and carbonate minerals but also by bottom-transport processes.

DEEP-SEA COLUMNAR SECTIONS, ARCTIC REGION

by

Theresa R. Swint-Iki and Anne L. Gartner

The columnar sections of Deep Sea Drilling Project (DSDP) Sites 1 through 330 within the Circum-Pacific region were compiled by Paul W. Richards from a computerized data set provided by Peter B. Woodbury, through the cooperation of the Scripps Institution of Oceanography; these sections were later revised to add more detail, using data from the Initial Reports of the DSDP, 1969-1974. Columnar sections for subsequent sites of the DSDP and the Ocean Drilling Program (ODP), through ODP Site 913, were compiled by us from data in the Initial Reports of the DSDP and the ODP. Borehole sites for the Geologic Map of the Circum-Pacific Region, Arctic Sheet, are shown on fig. 5. Columnar sections from the DSDP and ODP sites are inclusive of ODP's Leg 151. The information in these columns is intended to convey general age and lithologic information.

To display the most representative columns, the cores shown here for the Geologic Map of the Circum-Pacific Region, Arctic Sheet, were selected on the basis of total depth of penetration, age of the oldest sediment, and whether or not basement was reached (fig. 6 and 7).

The sediment-classification scheme employed is that used by the DSDP and ODP. Letter symbols on the figure are used to denote geologic age. The amount of detail shown on the columns is controlled by a relatively small scale of 1 cm to 100 m that limits representation of lithologic units to those thicker than 10 m. The geologic age units were selected and labeled to permit direct comparison with geologic units on land on the map sheet. Intervals in the columns without an age symbol represent uncored intervals of unknown age between cored intervals or layers of cored sediment of undetermined age.

Information from the cores has firmly linked the geology of the ocean basins with the geology of the continents, and it has contributed fundamentally to our understanding of the history of the Earth. The first few cruise legs in the North Atlantic and North Pacific laid to rest the idea that sediment in the ocean basins might record all of the Earth's history. We now know that the crust under the oceans is at most only 1/25th of the age of the Earth. Data from the cores also virtually proved the theory of plate tectonics by showing that the basal sediment on each side of a spreading oceanic ridge gradually becomes thicker and older with distance from the ridge. Evidence in the cores records the rearrangement of continents, the evolution of life in the sea, changes over time of global climate, reorientation of ocean currents, worldwide changes of sea level, and changes in the Earth's magnetic field. The drilling has recently moved north of the Arctic Circle, which has added to our understanding of the evolution of this polar region and its profound effect elsewhere on oceanic currents, climate, and life.

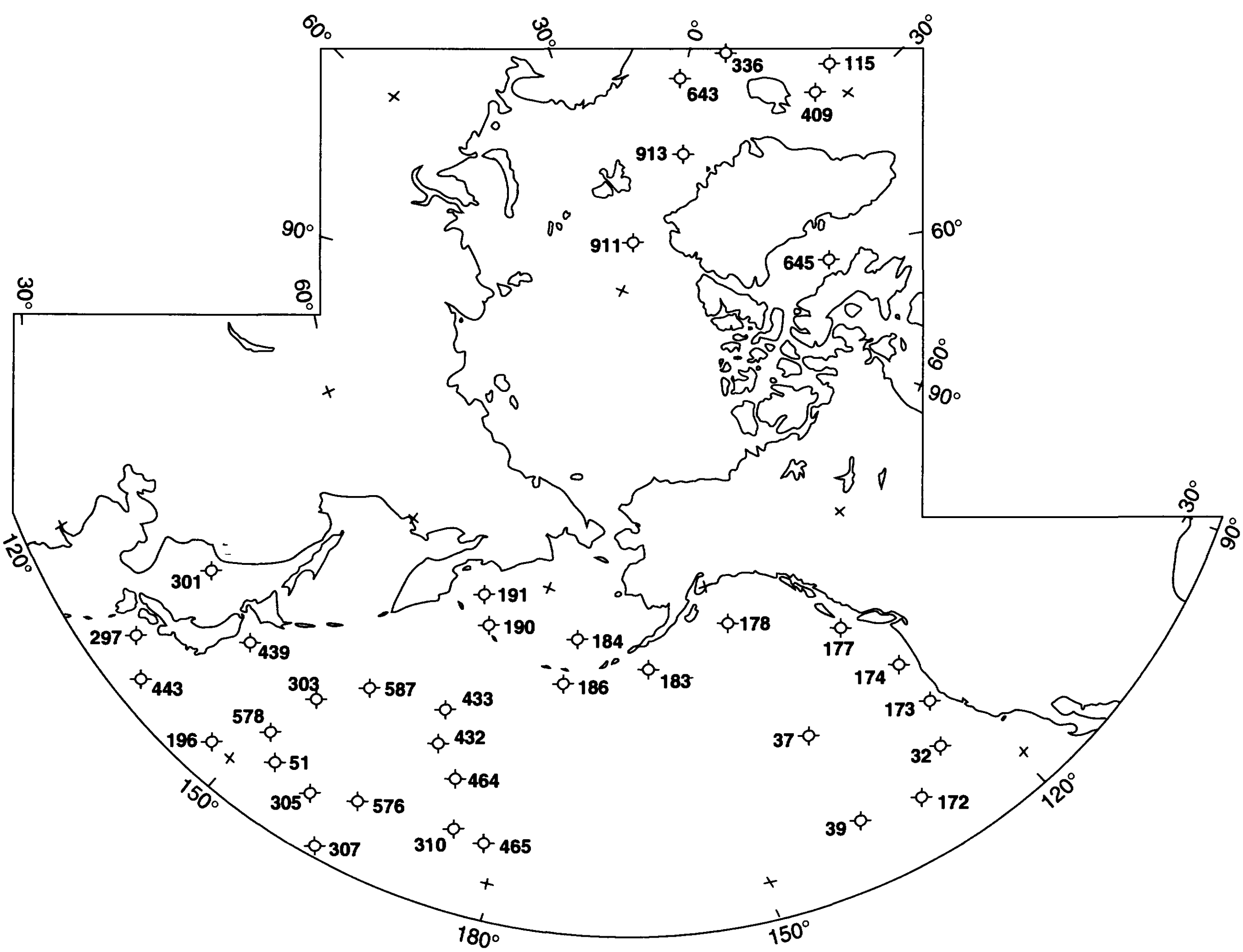

Figure 5. Index map of the Arctic Sheet showing the location of Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) boreholes illustrated in figures 6 and 7.

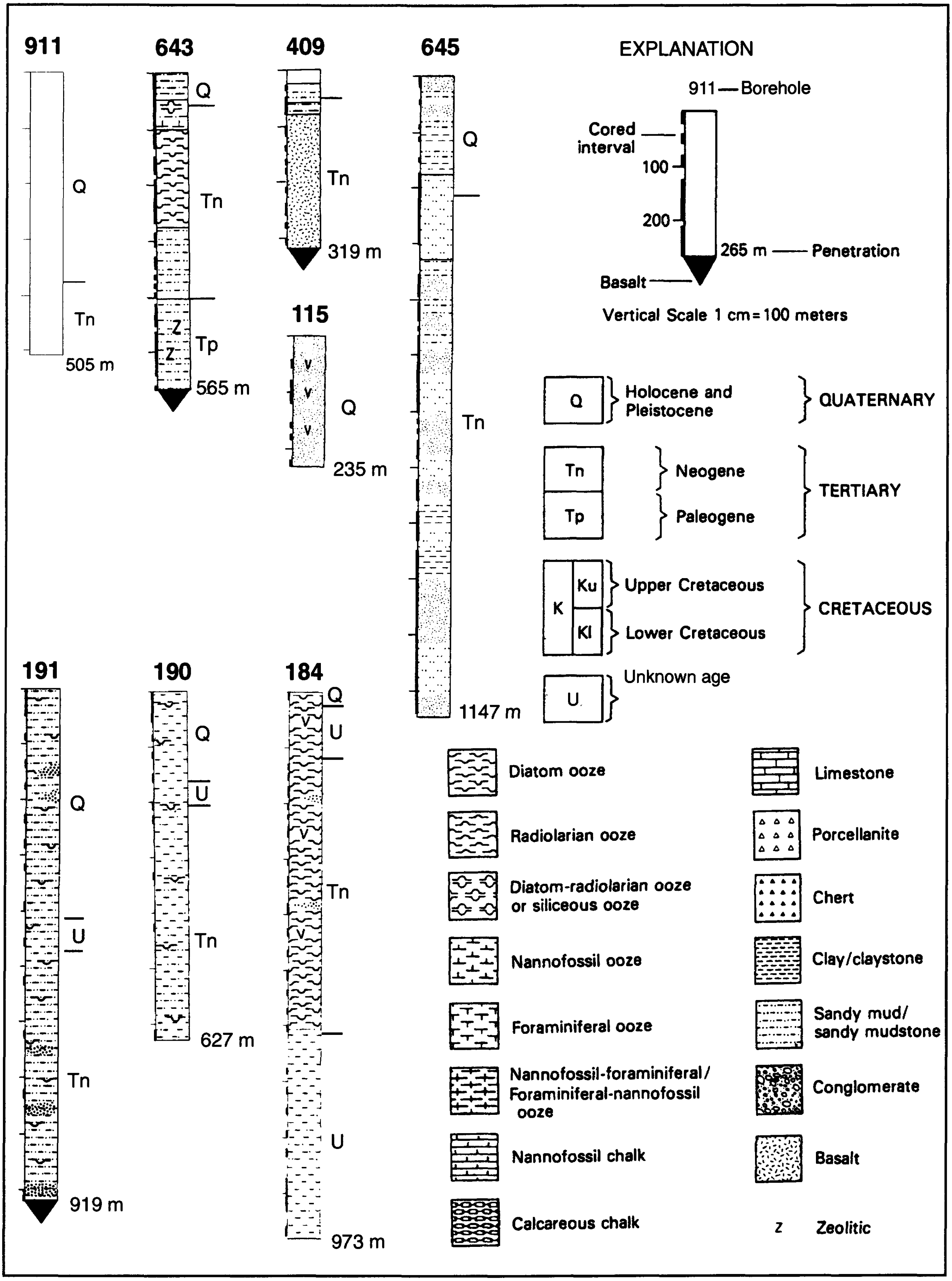

Figure 6. Columnar sections of selected Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) boreholes within the Arctic Ocean and the Bering Sea. Locations shown on figure 5.

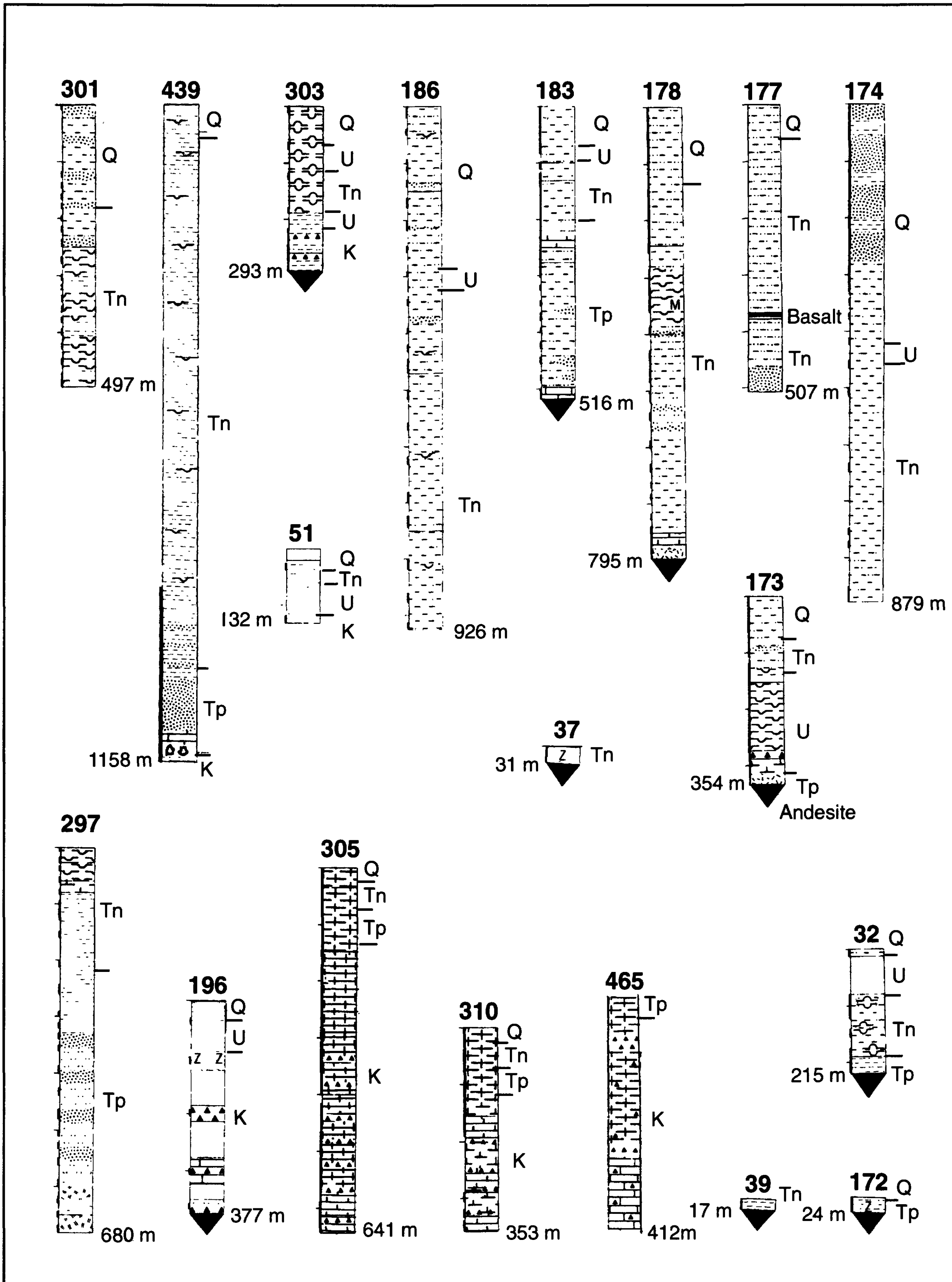

Figure 7. Columnar sections of selected Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) boreholes within the North Pacific Ocean. Locations shown on figure 5, explanation on figure 6.

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