The Tectonics of North America—A Discussion to Accompany the Tectonic Map of North America Scale 1 : 5,000,000

GEOLOGICAL SURVEY PROFESSIONAL PAPER 628

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By PHILIP B. KING

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THE TECTONICS OF NORTH AMERICA—A DISCUSSION TO ACCOMPANY THE TECTONIC MAP OF NORTH AMERICA, SCALE 1:5,000,000

By PHILIP B. KING

ABSTRACT

The "Tectonic Map of North America," on a scale of 1:5,000,000, has been compiled by the United States Geological Survey in collaboration with other national geological surveys, and with the assistance of various individuals. The compilers made use of tectonic maps of some of the countries—maps that have been published or are in process of publication. In addition, many other basic maps and reports were consulted.

North America is divided tectonically into foldbelts of different ages and platform areas where flat-lying or gently tilted rocks lie upon basements of earlier foldbelts. The two most extensive platform areas are those with Precambrian basement in the central craton, and those with Paleozoic basement in the Atlantic and Gulf Coastal Plains. Configuration of the upper surface of the basement beneath the platforms is shown by contours on a 500-meter interval.

The foldbelts include three of Precambrian age whose principal exposures are in the Canadian Shield, but which also emerge in various outlying areas. The foldbelts of younger ages lie nearer the edges of the continent, and include four that are mainly of Paleozoic age, two that are mainly of Mesozoic age, and two that are mainly of Cenozoic age. Each foldbelt was formed during a geotectonic cycle many geologic periods in length, beginning with a geosynclinal phase, passing through a time of orogeny, and ending with a postorogenic phase.

On the "Tectonic Map of North America" the foldbelts are distinguished by different colors according to age; where several significant times of deformation occurred within them, these are represented by tints of the prevailing colors. The different kinds of rocks which make up the foldbelts are shown by patterns of these colors.

In the foldbelts, the principal sedimentary rock units on the map are those which formed in the eugeosynclinal and miogeosynclinal areas. In some foldbelts, deposits are preserved which were laid down in successor basins during or shortly after the main orogenies. In the foldbelts of western North America various subdivisions are also shown in the Cenozoic sedimentary rocks and terrestrial volcanic rocks.

Among the plutonic rocks of the foldbelts, granitic rocks are most extensive; they form large to small masses mainly in the eugeosynclinal areas. More mafic and more alkalic varieties are separately indicated. Ultramafic rocks are important in places, especially near the Pacific Coast and in the Caribbean region; most of these were emplaced in their present positions by tectonic rather than by magmatic processes.

INTRODUCTION

This discussion is a companion to the "Tectonic Map of North America," which is being published separately by the U.S. Geological Survey. It is intended to aid the use and understanding of the map, by providing explanations more lengthy than could be included in the legend of the map itself. Such a discussion is the more desirable because the map embodies innovations derived partly from techniques of tectonic mapping that have been developed during the last few decades by geologists in other countries, and that may not as yet be well known, or be well understood in North America.

TECTONIC MAPS DEFINED

A tectonic map portrays the architecture of the upper part of the earth's crust—that is, the features produced by deformation and other earth forces—and represents this architecture by means of symbols, patterns, and colors. Such a map differs from the more familiar areal geologic map, whose primary aim is to represent the surface distribution of rocks of various kinds and ages. Nevertheless, most tectonic maps contain some indication of the ages and kinds of rocks from which the structures were made, and areal geologic maps contain some indication of the structures of the rocks represented, so that distinctions between the two kinds of maps are not absolute. Tectonic maps are nearly synonymous with structural maps, just as the subject of tectonics is nearly synonymous with that of structural geology. Nevertheless, geologists commonly make a vague distinction between structural geology and structural maps, which deal primarily with the description, representation, and analysis of structures, mostly on a restricted scale, and tectonics and tectonic maps, which synthesize these data over greater areas, inevitably with a larger amount of interpretation.

Many other kinds of maps are being made which show earth features, some of which resemble and some of which differ from tectonic maps as here defined:

1. Paleotectonic maps show geologic and tectonic features as they existed at various times during the geologic past, rather than the sum of the tectonics as it exists today. Most of the paleotectonic maps that have been made portray in much detail the sedimentary facies and the thickness of strata in the cratonic areas, but show few of these details in the more intensely deformed areas.

2. Neotectonic maps are a kind of paleotectonic map in that they represent the tectonic features produced during one part of geologic time, in this case the Quaternary or at most the Quaternary and latest Tertiary. Because of the epeirogenic nature of much of this latest deformation, neotectonic maps emphasize the broad upwarps and downwarps of the crust.
3. Paleogeographic maps show the probable extent of lands and seas as they existed at various times during the geologic past. They thus resemble paleotectonic maps, but involve a much greater element of interpretation.
4. Paleogeologic maps show the areal geology of a surface of unconformity that has been covered by a younger body of strata. This buried areal geology has tectonic significance, but it is generally not feasible to represent it on a tectonic map; tectonic maps and paleogeologic maps should supplement rather than duplicate each other.
5. Geophysical maps show the instrumentally determined values of gravity, magnetic intensity, or other physical properties of the earth, generally by means of contours. The contours express numerical values produced by the summation of many earth processes, not all of which are known. The data are not themselves tectonic, although many of them have ultimate tectonic causes. Interpretations of these geophysical data are frequently helpful in making tectonic maps.

HISTORICAL SKETCH

Geologists have been making structural and tectonic maps since the early days of the science. Even some of the early structural maps showed folds, faults, and structure contours in much detail, but most of them dealt with rather small areas on large scales. On the other hand, the earlier tectonic maps, covering larger areas such as whole countries, continents, or the world, were on small scales and were primarily intended to portray the tectonic or the historical-geological predilections of their authors. Only in recent decades have tectonic maps approached the scope and refinement of areal geologic maps.

In the United States, many excellent structural maps appeared during the first part of the century in the folios and professional papers of the U.S. Geological Survey; among these, the structural maps by N. H. Darton of various areas in the Western States are classic (fig. 1). Since 1916, many excellent structural maps of small to large areas have also been published in the "Bulletin of the American Association of Petroleum Geologists." A parallel evolution of structural and tectonic maps occurred in Europe, where notable maps have portrayed, for example, the folds and faults of the Jura Mountains (fig. 2), and the superposed nappes and structural layers in the Alps (fig. 3).

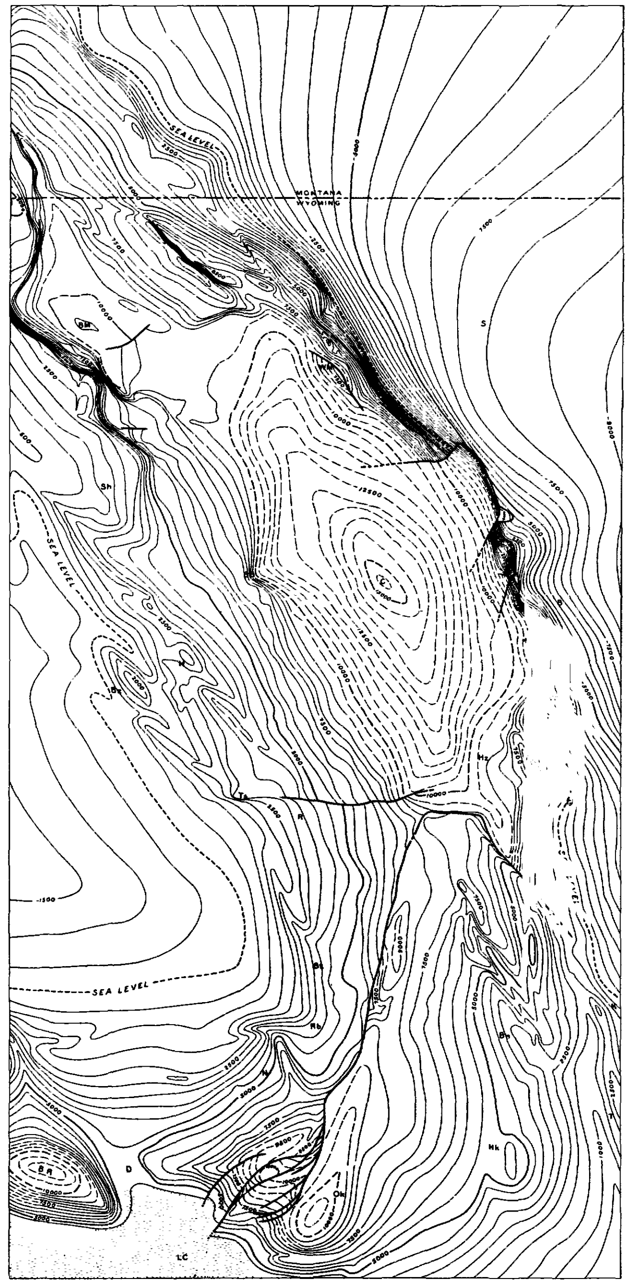


FIGURE 1.—Structural map of Bighorn Mountains uplift, Wyoming and Montana, by N. H. Darton (Darton and Salisbury, 1906, p. 13). Configuration of uplift shown by contours on base of Madison Limestone. Dashed lines show approximate configuration where all sedimentary rocks have been removed by erosion. Heavy lines are faults. Stippled areas are covered by Tertiary deposits.

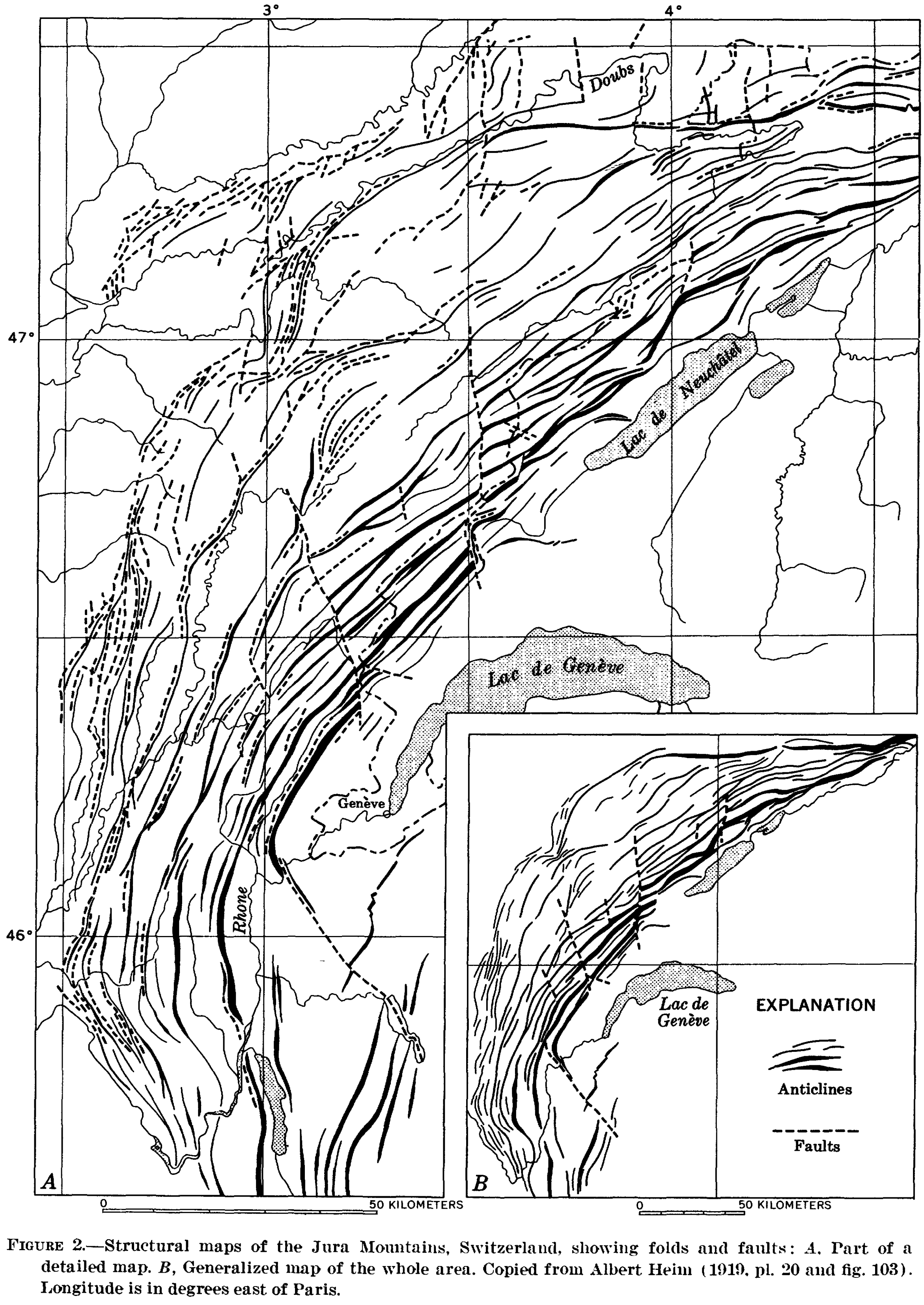


FIGURE 2.—Structural maps of the Jura Mountains, Switzerland, showing folds and faults: *A*, Part of a detailed map. *B*, Generalized map of the whole area. Copied from Albert Heim (1919, pl. 20 and fig. 103). Longitude is in degrees east of Paris.

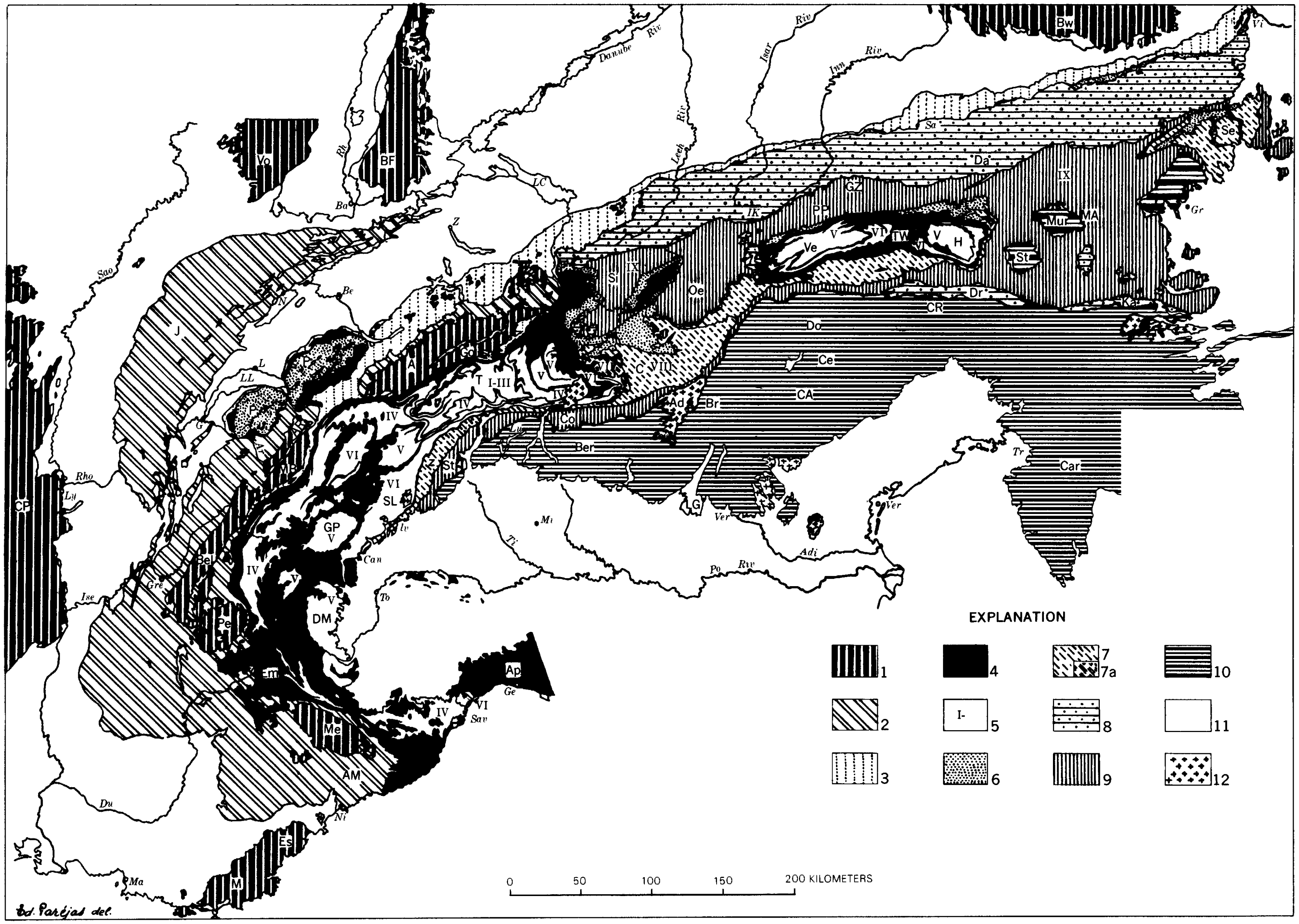


FIGURE 3.—Tectonic map of the Alps, by Rudolf Staub, simplified by Collet (1927, pl. 12). Explanation of symbols: 1, Crystalline massifs of the foreland. 2, Jura Mountains and sedimentary cover of foreland. 3, Nappes of High Calcareous Alps. 4, Schistes lustrés of Pennine nappes. 5, Crystalline core of the Pennine nappes. 6, Mesozoic of Grisonides. 7, Crystalline core of Grisonides. 7a, Crystalline core of the Bernina nappe. 8, Mesozoic of Tirolides. 9, Crystalline core of Tirolides. 10, Dinarides. 11, Molasse and Quaternary. 12, Postorogenic eruptive massifs.

One of the most ambitious of the early tectonic maps was the "Carte tectonique de l'Eurasie" on a scale of 1:8,000,000, that was compiled and hand colored by Émile Argand. He presented this at the 13th International Geological Congress in Brussels in 1922 as a companion of his epoch-making treatise on "Le tectonique de l'Asie" (Argand, 1924). A colored reproduction of this map on a scale of 1:25,000,000 was published by the 13th Congress in 1928. The state of tectonic knowledge at the time is suggested, however, by the large blank areas which were left in various parts of the map.

Argand's map had a great seminal influence among geologists, as it created a desire for comparable maps of other areas or continents. Thus, in 1922 the Committee in Tectonics was organized in the Division of Geology and Geography of the U.S. National Research Council, and the first report of its chairman, Rollin T. Chamberlin (1923, p. 3), stated:[1]

One of the great needs in our field is a series of tectonic maps of the different continents. An important advance in this direction has recently been accomplished by Argand, whose magnificent structural map of Eurasia was one of the outstanding exhibits at the International Geological Congress at Brussels last summer. Our Committee voted to commence work on a tectonic map of North America which would bring out the trends of folding, the principal lines of faulting, the axes of doming, and related structural features. Messrs. Willis and Mansfield are to undertake this very important project.

Later, the Committee on Tectonics realized that there were still insufficient tectonic data available to represent all of North America, and decided to restrict its objective to preparation of a tectonic map of the United States. The task of compiling this map began in 1934 when Chester R. Longwell assumed chairmanship of the committee. Early aspirations of the committee in regard to the map are suggested in Longwell's prospectus (Longwell, 1934, p. 3):

It is suggested that the map represent the following features: trend-lines in folded belts, with axes of individual major folds so far as the scale of the map permits; direction and degree of important overturning of folds; cross folds or important changes in pitch of major fold axes; direction and degree of regional dips; all important faults, with appropriate symbols and figures showing, so far as known, direction and degree of dip, amount of throw and nature of displacement—whether normal, reverse or strike-slip; major thrusts (with a special convention or color to designate overthrust masses); belts of *en echelon* faults; important areas of metamorphic rock, with strike and attitude of cleavage so far as it can be shown; areas of Precambrian rocks related to orogenic zones, as discussed recently by Bucher; all major igneous masses; swells and basins in areas of unfolded rocks (possibly by structure contours); salt domes and anticlines; monoclinal folds.

Time relations should be indicated, so far as practicable, by conventional patterns or colors. If conventions are chosen judiciously, they may be superposed in areas that have experienced repeated diastrophism. It may even be feasible to indicate important vertical movements in folded belts, such as the late uplift of the Appalachian region. Considerable ingenuity will be required to represent all the complex disturbances in some western areas, even where adequate information is available. It does not seem practicable to show the geologic ages of individual faults. However, faults that are recognized as 'active' can be distinguished from those supposedly 'dead'; and it may be desirable to indicate that faults in an important group are essentially contemporaneous.

Many of these aspirations were realized on the "Tectonic Map of the United States" as it finally evolved, but some had to be discarded as infeasible. Nevertheless, representation of most of the items listed has been attempted on various tectonic maps made subsequently. Final specifications for the "Tectonic Map of the United States" developed as the work of compilation progressed, and were discussed and adopted by members of the committee during periodic meetings. The work of compiling the map was divided among the committee members, each assuming responsibility for one part of the country; in the end, 14 different parts were thus compiled. Compilation of the map was largely completed by 1939, but there were inevitable discrepancies between the results of the various compilers so that the results required review and editing; this was done by Philip B. King under Longwell's direction. Drafting and printing of the map were delayed by the exigencies of World War II, and it was not published until 1944.

Completion of the "Tectonic Map of the United States" prompted the making of the comparable "Tectonic Map of Canada," which was compiled by a committee of the Geological Association of Canada under the chairmanship of Duncan R. Derry (Derry, 1950). On this map, many of the same specifications as those for the United States map were followed, but they included some innovations required by the differing tectonic features of that country.

In Europe, in the meantime, Hans Stillé had been developing his philosophy of geotectonics and his classification of tectonic features in a lengthy series of publications, which were mostly illustrated by tectonic sketches (fig. 4). A desire was felt among many of Stillé's European colleagues to represent his and other tectonic concepts in the form of more precise and elaborate tectonic maps, and in this effort leadership was assumed by the Soviet geologists. A. D. Arkhangelsky (1941) had developed "an historico-morphological method, which enables the earth's crust to be tectonically zoned according to the degree of completion of the

[1] For the subsequent actions of this committee, see the annual reports of the Division of Geology and Geography of the National Research Council. The history of the committee has also been narrated by Longwell (1944a, p. 1767–1769), from whose account the succeeding paragraphs are largely abstracted.

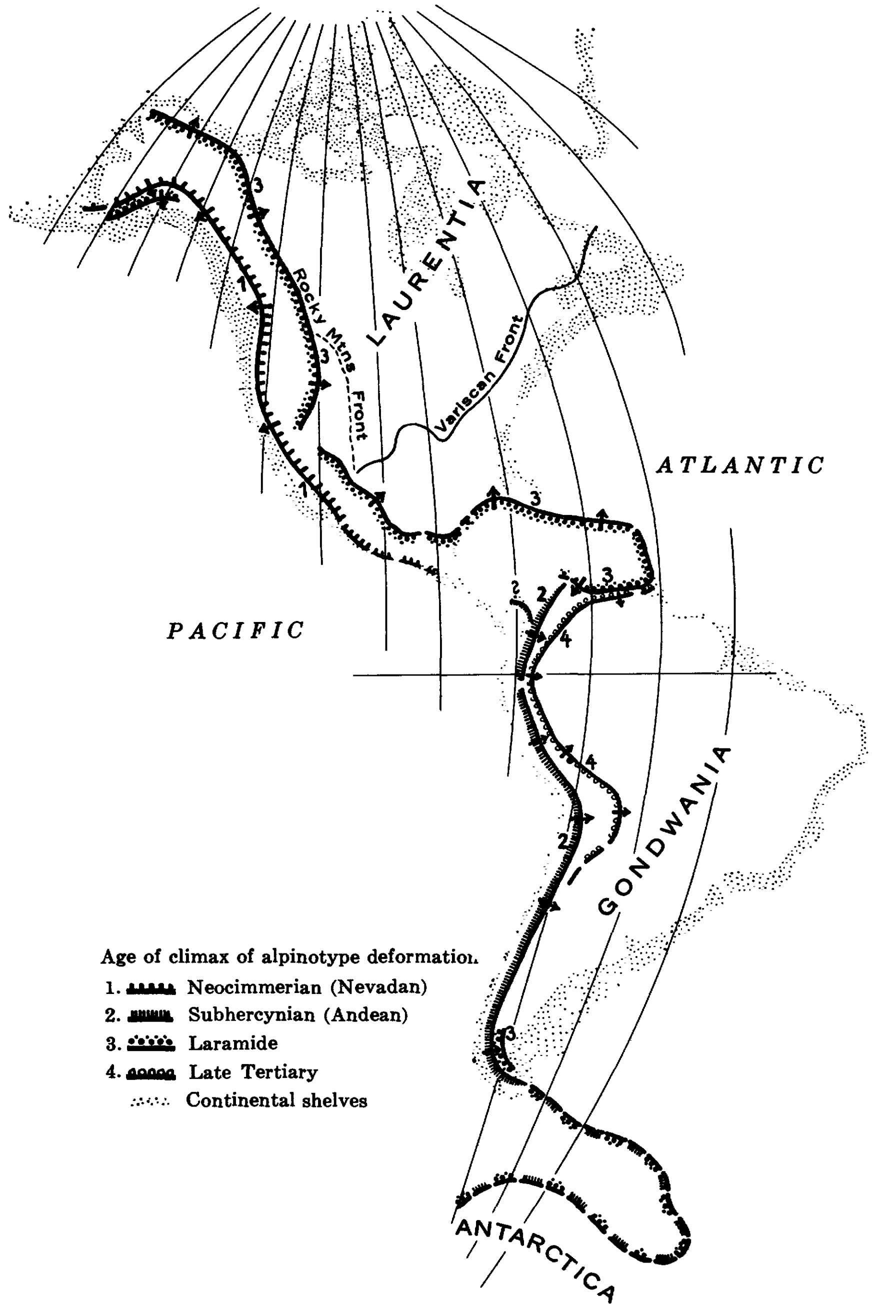


FIGURE 4.—Tectonic sketch map showing the chief belts of folding in the American Cordilleran system, by Hans Stillé (1936, p. 138).

processes of folding of the geosynclinal regions undergoing transformation into a platform."[2] He prepared a "Tectonic scheme of Eurasia" on a scale of about 1:40,000,000 that was published in the "Proceedings of the 17th International Geological Congress" (Arkhangelsky, 1939, pl. 2, p. 304). It remained for N. S. Schatsky to elaborate these methods and make possible the preparation of tectonic maps on larger scales.

The first map by Schatsky, published in 1953, covered the Soviet Union and adjacent areas in color on a scale of 1:4,000,000, but in a very generalized manner. This map was preliminary to a more detailed compilation that was made in collaboration with N. A. Beliaevsky, A. A. Bogdanoff, and M. V. Muratov, with the aid of 41 contributors. The resulting map was published in

[2] Brief summaries of the Soviet work on tectonic maps are given by Spizaharsky and Borovikov (1966) and by Yanshin (1966a), from which most of this and succeeding remarks are taken.

1956, in color on a scale of 1:5,000,000, and represented not only all the Soviet Union, but also those parts of neighboring countries that lay within the area of the map base.

At the 20th International Geological Congress in Mexico in 1956, a Subcommission for the Tectonic Map of the World was organized within the Commission for the Geologic Map of the World. Preliminary to preparation of the world map, the subcommission encouraged the compilation of tectonic maps of the various continents. One of the first products was the "Tectonic Map of Europe" on a scale of 1:2,500,000 prepared by geologists of many European countries, which was issued in 1964 (Schatsky, 1962); its specifications closely followed those of the tectonic map of the Soviet Union and adjacent areas of 1956, but with elaborations.

At the 21st International Geological Congress in Copenhagen in 1960, the U.S. Geological Survey agreed to assume leadership in preparing a tectonic map of North America, in collaboration with other national geological surveys in North America, and with the cooperation of various research institutions and interested individuals. To facilitate this collaboration a committee on the map was established, with George V. Cohee as chairman. Philip B. King was designated as chief compiler. Work on the tectonic map was begun by the compiler in June 1961, and was carried to completion in December 1966. The completed map was exhibited at the 23d International Geological Congress in Prague in 1968, and printed copies were available in 1969.

Tectonic maps of many other countries or continents have now been published or are in preparation, complete listing of which would be tedious here. Also, work by the subcommission is now far advanced on the long-planned "Tectonic Map of the World" (see Bogdanoff and others, 1966).

APPRAISAL OF EXISTING TECTONIC MAPS

The specifications of the tectonic maps previously mentioned, and others not listed, differ from each other in many particulars. These differences reflect evolving and diverse methods of tectonic mapping, as the methods have not been stabilized like those used for conventional areal geologic maps. To some extent these variations are useful; little future progress can be made in tectonics if the subject is to be ruled by a single set of dogmas, nor can progress be made in tectonic mapping if the maps are forced to adhere to a single set of specifications. Some of the variations reflect special conditions in the different regions, not only as to the kinds of tectonic features to be represented, but also as to the amount and quality of the information available. Other variations indicate wide divergences in the objectives of the compilers. To evolve specifications for the "Tectonic Map of North America," all the varieties of existing tectonic maps were reviewed, in an effort to find and emulate the better features of each.

The basic components of all tectonic maps are twofold: Those of the first order indicate the nature of the rocks from which the structures are made by means of patterns and colors. Those of the second order represent the structures themselves (folds, faults, and the like) by means of symbols. On all tectonic maps there is a further subdivision (either stated or implied) of the first-order components between those of the platform or cratonic areas, where the surface strata are gently tilted or warped, and those of the foldbelts where the rocks are much deformed and intruded. This subdivision appears on the early tectonic map by Argand (1928), where Eurasia is subdivided into "pays tabulaires" and "pays plissés" by means of color patterns.

The following examples indicate some of the ways in which first-order components are shown on tectonic maps:

1. Some color patterns are used, mainly in the foldbelts, and the remaining areas, mainly in the platforms, are uncolored. *Example*, "Tectonic Map of United States," 1944, 1962.
2. Color patterns show stratigraphic units that have some rudimentary tectonic significance. *Examples*, "Tectonic Map of Canada," 1950; "Tectonic Map of Australia," 1960; "Geologic-tectonic Map of Northern Venezuela," 1962.
3. The platform areas are colored with layer tints; the foldbelts are colored according to a few widespread epochs of climactic orogeny (for example, Caledonian, Variscan), the rocks of the foldbelts being subdivided in turn into tectonic units ("structural stages") that formed prior, during, and after the orogenies. *Examples*, "Tectonic Map of U.S.S.R. and Adjacent Areas," 1956; "Tectonic Map of Europe," 1962; "Tectonic Map of Eurasia," 1966.
4. Colors in the foldbelts represent primarily the ages of folding of the respective units, these ages being more minutely subdivided than in (3). *Example*, "Tectonic Map of Canada," 1969.
5. Colors in the foldbelts show rock sequences classified according to "geotectonic cycles" the age spans of the "geotectonic cycles" differing from one foldbelt to another. *Examples*, "Tectonic Map of Mexico," 1961; "Tectonic Map of U.S.S.R.," 1967.

Representation of second-order structural features, shown by symbols, offers fewer problems in tectonic mapping than representation of first-order components. Most of the features to be represented and the symbols used for them are reasonably standardized, so that they are much the same from one map to another. New or unusual symbols for special structural features, to suit the desires of the compiler are not objectionable or confusing, because these symbols can be identified in the legend.

REPRESENTATION OF PLATFORM AREAS

The objectives in showing platform areas are similar on all tectonic maps, however much they may differ in appearance—namely, to express the gentle tilting and warping of the covering strata, the different structural layers of which they are composed, and the configuration of their basements.

On the two versions of the "Tectonic Map of the United States (Longwell, 1944b; Cohee, 1962), platform areas are largely left uncolored, except for inliers of Precambrian rocks and for narrow bands of color which indicate the edges of structural layers that are significantly unconformable on the layers beneath (for example, bases of Pennsylvanian, Cretaceous, lower Tertiary, and upper Tertiary). Among other purposes, these colored borders differentiate the platform of the Atlantic and Gulf Coastal Plains from the platform of the central craton. Configuration of the strata is indicated by brown structure contour lines at a uniform interval of 500 feet, an effort being made to select contoured horizons that can be extended as widely as possible; on the 1944 version of the map 19 horizons were used, on the 1962 version 36. In selecting horizons for contouring on the first version of the map, the highest horizon that would give good results over a wide area was chosen; this was due to the state of knowledge at the time, when configuration of the deeper horizons was largely speculative. This consideration was abandoned in the second version, on which some of the areas were contoured on the top of basement rocks rather than on strata in the cover. On the two maps, portrayal of the platform areas is effective for detailed study, but the general absence of colors detracts from their usefulness as wall maps.

A different method of representing platform areas was introduced on the "Tectonic Map of the U.S.S.R. and Adjacent Areas" (Schatsky and others, 1956), and has been closely followed on many subsequent maps. Contours are drawn on the surface of the basement rocks at 500- or 1,000-m intervals, and the whole area filled in with layer tints that indicate the depth to basement. Basements of Precambrian and Paleozoic ages are shown on the map referred to, and are distinguished by layer tints of different colors; basements of other ages, in other colors, are shown on subsequent maps The configuration of strata within the sedimentary cover is shown by colored contour lines that are superposed on the basement contours and layer tints. This method of representation produces a very effective wall map, as the configuration of the base of the sedimentary cover is visible at a glance, leaving the configuration of the strata within the cover to be ascertained by more detailed study.

Besides the features discussed, many recent tectonic maps differentiate "foredeeps" or "marginal homoclines" at the edges of the platforms by means of special color patterns. Many maps show the "foredeeps" by means of stripes of the same color as the adjacent foldbelt, alternating with stripes in the same color as that of the underlying basement; this is intended to indicate the historical significance of the "foredeep." Nevertheless, "foredeeps" and "marginal homoclines" are actually parts of the platform, in which the strata and their basement have been deeply downwarped or steeply tilted against the adjoining foldbelts. The present reviewer questions the need for distinguishing these features by separate color patterns. The method might be helpful in regions of scanty information, but where much information is available their nature is evident from the contouring of the basement and the higher strata.

REPRESENTATION OF FOLDBELTS

"TECTONIC MAP OF UNITED STATES"

On the two versions of the "Tectonic Map of the United States" (Longwell, 1944b; Cohee, 1962) the miogeosynclinal and other areas of folding and faulting are illustrated mainly by structural symbols in black, without colored overprint, the strength of the deformation being suggested by the relative crowding of the symbols. Other tectonic features in the foldbelts are indicated by color patterns: (1) Precambrian rocks; (2) metamorphic rocks, mainly eugeosynclinal (of Paleozoic age in east, of Mesozoic age in west); (3) intrusive rocks, the ages being indicated by different colors; (4) sedimentary rocks in postorogenic depressions (of Triassic age in east, of late Cenozoic age in west); (5) terrestrial volcanic rocks in the western foldbelts, mainly postorogenic and of Cenozoic age.

Ages of deformation in the foldbelts are not indicated on the "Tectonic Map of the United States." The gross ages of the foldbelts in the United States have long been familiar to geologists—the Paleozoic deformation in the Appalachian region on the east, and the Mesozoic and Cenozoic deformation in the Cordilleran region on the west—and to attempt further refinements requires an untangling of many superposed deformations, or of extrapolation beyond available data (see also Longwell, 1944a, p. 1772). The gross ages of deformation are implied by the representation of metamorphic and intrusive rocks of Paleozoic age in the east, and of Mesozoic and Cenozoic ages in the west. This method of representation, although satisfactory for showing the tectonics of a single country, is less well adapted to representation of continents or other large regions, where the ages of deformation in the foldbelts are much more diverse.

"TECTONIC MAP OF AUSTRALIA"

On the "Tectonic Map of Australia" (Geological Society of Australia, 1960) the whole continent is shown in color patterns, which represent stratigraphic units. The classification of the units is as follows:

Stratified rocks. Sedimentary and volcanic rocks, the latter shown by black overprinted patterns, where present.
- Cenozoic: Undifferentiated; Tertiary.
- Mesozoic: Undifferentiated.
- Paleozoic: Upper (Permian to Upper Carboniferous); Middle (Upper Carboniferous to Middle Devonian); Lower (Middle Devonian to Cambrian).
- Proterozoic: Undifferentiated; Upper (subdivided into upper and lower); Lower (subdivided into upper and lower).
- Archean: Undifferentiated; gneiss; sediments and metasediments.

Intrusive igneous rocks. (Each rock type shown in same color throughout, the ages of the different bodies being indicated by letter symbols: acid (granite and porphyry); alkaline (mainly syenite); intermediate to basic (hypabyssal); ultrabasic.

Each stratified unit is shown by the same color pattern over the entire continent; the units are not themselves tectonic, as their tectonic significance varies from one region to another. However, the tectonic significance of each is indicated in an accompanying table, of which the entries for the lower Paleozoic unit are a sample:

Queensland, folded Tasman geosynclinal zone in east, gently folded sediments in west; New South Wales, Tasman geosynclinal zone; Victoria, Tasman geosynclinal zone; Tasmania, geosynclinal deposits, moderately to strongly folded; South Australia, folded Adelaide geosyncline, with gently warped strata to northwest; Western Australia, marine and continental deposits, gently folded; Northern Territory, intracratonic basins, gently folded.

The method of representation of the first-order components used on the "Tectonic Map of Australia," while differing from that on the "Tectonic Map of the United States," is equally objective. It is well adapted to a continent where detailed tectonic information is only partly available; thus, the existence of many basins, uplifts, and other features in the poorly known northwestern part of the continent is suggested mainly by the distribution of the color patterns, rather than by structural symbols.

"TECTONIC MAP OF U.S.S.R. AND ADJACENT AREAS," AND "TECTONIC MAP OF EUROPE"

Representation of first-order components in the foldbelts on the "Tectonic Map of U.S.S.R. and Adjacent Areas" (Schatsky and others, 1956) has served as a prototype for many subsequent tectonic maps, and notably for the "Tectonic Map of Europe" (Schatsky, 1962); the features of these two maps will be considered here.

On both maps, foldbelts are colored according to the age of the assumed climatic orogeny, although the rocks within the foldbelts themselves may be much older or much younger. On the "Tectonic Map of the U.S.S.R. and Adjacent Areas" eight ages (or regions) of folding are distinguished, three in the Precambrian and five in the Phanerozoic: namely, Archean, Proterozoic, Baikalian (Riphean), Caledonian, Hercynian, Mesozoic of Pacific border, Alpine, and Cenozoic of Pacific border. On the map of Europe eight ages (or regions) of folding are distinguished, five in the Precambrian and three in the Phanerozoic: namely, Archean, Svecofennian (Karelian), Gothian (Daslandian), Jotnian, Baikalian (Cadomian, Assyntian), Caledonian, Variscan (Hercynian), and Alpine; there are additional categories for Precambrian folding undivided and Paleozoic folding undivided.

Each foldbelt is subdivided in turn into many map units, of which the units on each map for the Variscan or Hercynian regions are given below as samples:

"TECTONIC MAP OF U.S.S.R. AND ADJACENT AREAS"

Regions of Hercynian folding

19. Precambrian of cores of anticlinoria.
20. Lower structural stage undivided (*China and Taimyr*, Cambrian; *Tien-Shan*, Riphean-Ordovician).
21. Lower structural stage, lower substage (*Kazakhstan*, Riphean-Cambrian; *Altai*, Cambrian-Ordovician; *Ural*, Riphean-Cambrian; *east slope of Ural*, Riphean-Ordovician).
22. Lower structural stage, upper substage (*Altai*, Ordovician; *Kazakhstan*, Cambrian$_3$-Ordovician; *Ural*, Ordovician and locally Cambrian).
23. Middle structural stage, lower substage (*Tien-Shan and Kazakhstan*, Silurian-Devonian$_{1-2}$; *Ural*, Silurian-Devonian and locally Ordovician; *China*, Silurian-Devonian; *Altai and Taimyr*, Ordovician$_2$-Silurian).
24. Middle structural stage, upper substage (*Tien-Shan, Kazakhstan and Altai*, Devonian$_2$-Carboniferous$_1$; *China*, Devonian$_1$-Carboniferous$_1$; *Taimyr*, Devonian-Permian; *Ural* Devonian$_3$; *elsewhere* Devonian$_2$-Carboniferous$_1$).
25. Upper structural stage, interior basins (*China*, Carboniferous$_1$-Permian; *Tien-Shan and Kazakhstan*, Carboniferous-Permian; *Ural*, Carboniferous$_3$-Triassic$_1$).

26. Upper structural stage, regional depressions (*Ural foreland*, Carboniferous$_2$-Triassic$_1$; *Kuznets*, Carboniferous-Triassic *Taimyr foreland*, Permian-Triassic; *Donetz*, Carboniferous-Permian).

Intrusive igneous rocks: Ultramafic intrusives, Caledonian granitoids, granitoids undivided, late Hercynian granitoids, and alkalic intrusives.

"TECTONIC MAP OF EUROPE"

Regions of Variscan or Hercynian folding

KV. Reworked massifs of Karelian and older folding (*Sudetes, Armorica, Bohemia*).

BV. Reworked massifs of Baikalian folding.

CV. Reworked massifs of Caledonian folding.

VB, etc. Ancient cores reworked by Variscan folding (various ages indicated by second index letter).

Migmatized older Paleozoic and Precambrian of *Urals*.

Eugeosynclinal (interior) zones

eV. Undivided.

eV1. Lower structural stage (*western Europe*, Cambrian-Silurian; *Great Caucasus*, Riphean-Paleozoic$_1$; *Ural*, Paleozoic$_1$-Devonian$_2$).

eV2. Middle structural stage (*western Europe and Great Caucasus*, Devonian-Carboniferous$_1$; *Balkans and Anatolia*, Silurian-Carboniferous$_1$; *Ural*, Devonian$_2$-Carboniferous$_1$).

Miogeosynclinal (exterior) zones

mV. Undivided (*south Ireland and Trans-Caspian region*, Devonian-Carboniferous).

mV1. Lower structural stage (*western Europe*, Cambrian-Devonian; *Armorica*, Cambrian-Devonian; *Morocco*, Cambrian-Carboniferous; *Great Britain*, Silurian-Devonian$_1$; *Little Caucasus*, Paleozoic$_1$; *Ural*, Ordovician-Devonian$_3$; *Moravia*, Devonian$_{2-3}$).

mV2. Middle structural stage (*western Europe*, Devonian; *Armorica*, Carboniferous$_1$; *Little Caucasus and Swientokrzysky Mountains*, Devonian-Carboniferous$_1$; *Ural*, Devonian$_2$-Carboniferous$_2$; *southern France and Moravia*, Devonian$_2$-Carboniferous$_1$; *Morocco*, Carboniferous$_1$).

mV2–3. Middle and upper structural stages, undivided (mostly Devonian-Carboniferous$_1$; *Great Britain*, Devonian$_3$-Carboniferous$_3$).

All zones

V3. Upper structural stage (*western Europe*, Carboniferous-Permian$_1$; *Balkans, Anatolia, and Swientokrzysky Mountains*, Carboniferous$_2$-Permian; *Morocco*, Carboniferous$_2$-Permian$_1$; *Caucasus*, Paleozoic$_3$; *Mangyshlak*, Permian$_2$-Triassic).

Va. Foredeeps.

$\frac{\text{KZ}}{\text{Va}}$ Foredeeps covered by Mesozoic and Cenozoic sediments.

Intrusive igneous rocks

Variscan granitoids: (a) Synorogenic, (b) postorogenic.

The type of representation used on these two maps is claimed by its proponents to be "an historical-morphological method," in that it shows not only the morphological (structural) features, but also how these features and the foldbelt as a whole developed through geologic time.[3] The climactic orogeny of the foldbelt is selected as the one during which a previous geosynclinal region was consolidated into a platform—a time when formation of alpinotype structures gave place to formation of germanotype structures. Each orogenic era (Caledonian, Variscan, Alpine, and so forth) is conceived of in broadest terms. Each orogenic era affected extensive areas along linear belts and had a wide time range; thus, the climactic orogeny in the "regions of Variscan folding" might have occurred several periods earlier or later at one place in the foldbelt than in another.

Evolution of a foldbelt is expressed by a sequence of "structural stages" ("étages structuraux"), which succeed each other in an invariable order, which are explained as follows (Schatsky and Bogdanoff, 1957, p. 16 1959, p. 8).

> The long history of geosynclinal regions is generally characterized by inherited development. Their cross-sections therefore lack such sharply distinguished structural stages as the basement and blanket of cratons. However, close analysis of the structure and history of development of geosynclinal regions also uncovers a series of clearly defined structural phases; each of these phases, corresponding to a given stage of development of the geosynclinal region, consists of a group of formations that is often separated from those above and below by regional unconformities. Deep-seated (lower) structural phases are usually dominated by volcanically derived and sedimentary formations (of the spilite-keratophyre type and others), corresponding to early stages of geosynclinal development. The middle structural phases often contain carbonates, shales and graywacke formations, pierced by granitoid intrusions. Upper structural phases contain flysch, molasses, coal-bearing basins and other formations.

Thus, the distinction between successive "structural stages" is two-fold; each "stage" is, first of all, a distinctive body of rocks whose facies is closely related to the tectonic evolution of the foldbelt, and second, each body of rocks is separated from those above and below by regional unconformities.

Use of the term "structural stage" for subdivisions of the sequence in foldbelts creates an unfortunate confusion with the "stratigraphic stage," which is defined as *a time-stratigraphic unit next in rank below a series* (American Committee on Stratigraphic Nomenclature, 1961, article 31, p. 658–659; see also Gignoux, 1955, p. 12–15), hence a unit which is essentially of the same age and scope at all places (for example, Oxfordian, Cenomanian, Maestrichtian). Study of the excerpts from the legends which are quoted above makes it abundantly clear that "structural stages" *are rock-stratigraphic and not time-stratigraphic units;* the range of a single "stage" may be from Upper Carboniferous to Lower

[3] This and the next paragraph are paraphrased from Schatsky and Bogdanoff (1957) and from several pamphlets that have been prepared by them for the Subcommission for the Tectonic Map of the World. See especially Schatsky and Bogdanoff (1960) and Bogdanoff (1962).

Triassic in one place, from Permian to Triassic in another, or from Carboniferous to Permian elsewhere, yet the rocks of the "stage" are presumably of much the same sedimentary facies from one locality to another.

The legend for the "Tectonic Map of the U.S.S.R. and Adjacent Areas" does not seem to provide for longitudinal subdivisions of foldbelts, even though such subdivisions might have had different histories. This is rectified on the "Tectonic Map of Europe," in which the foldbelts are divided into eugeosynclinal (internal) and miogeosynclinal (external) zones, each with its own sequence of "structural stages" (see excerpt from legend quoted above).

The concept of "structural stages" in the sequence of strata of foldbelts is valid, although it is questionable whether unconformities make significant boundaries between them. "Stages" can be recognized in most of the foldbelts of North America, an ideal example being in the Paleozoic rocks of the Ridge and Valley province of the southern Appalachians:

4. Coarse clastic deposits, continental or brackish water, with coal measures; broadly "molasse." (Mainly Pennsylvanian, with Lower Permian locally at top; base varies downward from base of Pennsylvanian to as low as Upper Devonian).
3. Fine-grained marine clastics, including both typical "flysch" and broad sheets of deposit. (Largely middle Paleozoic; base varies from base of Middle Ordovician to base of Upper Ordovician, or even higher.)
2. Carbonate sequence (largely Cambrian and Lower Ordovician, but with top at variable levels, as indicated above).
1. Basal clastic sequence; quartzite, arkose, shale, basal conglomerate on Precambrian rocks. (Earliest fossiliferous Cambrian, but extending downward into unfossiliferous strata classed as Cambrian?).

Sequences of "stages" with very similar lithologic characters but with widely variable time ranges, can be recognized in parts of the other foldbelts of North America. In some foldbelts are incomplete or repeated sequences of "stages," and in still others are sequences of "stages" of very different lithologic character (as in the California Coast Ranges).

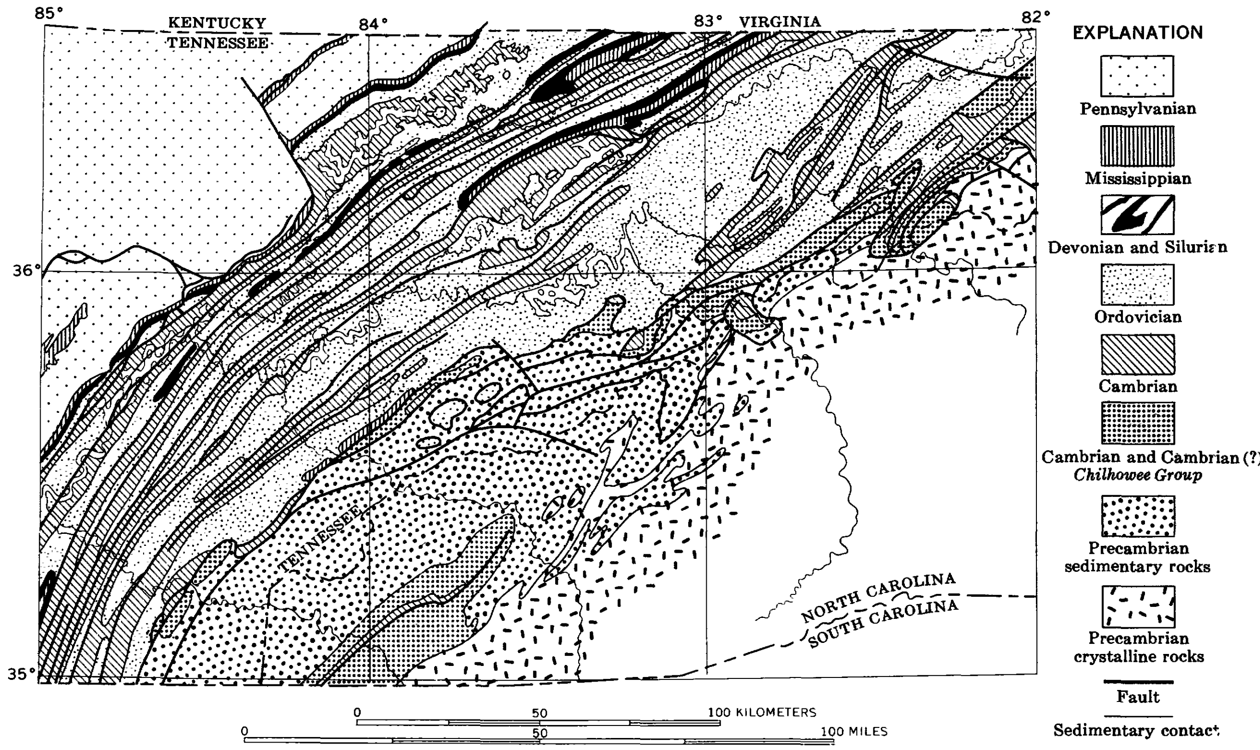
Nevertheless, the present compiler has doubts as to the value of "structural stages" in tectonic mapping. Does representation of the outcrops of the "stages" on a tectonic map give a true picture of the historical development of the foldbelt? Is it possible to represent adequately both the morphology of a foldbelt and its history of development on a single sheet of paper? The "structural stages" in foldbelts characteristically crop out where the rocks are much deformed, hence their outcrops may be very narrow. These deformed areas are, further, the ones where the structural features represented by symbols are most crowded, thus adding to the complexity of the map pattern (fig. 5). The surface area occupied by a "stage" in a deformed region may have little relation to its relative lithologic or historical significance; moreover, outcrops of the "stages" may be interrupted by later superposed structures, or by overlapping postorogenic deposits (fig. 6). The true significance of any "structural stage" can only be represented on a paleotectonic map which will show its original extent beyond its present outcrops, both where the "stage" has been removed by erosion, and where it has been buried beneath younger strata.

A final comment can be made on the method of coloring the foldbelts on the two maps. The colors used express the climactic times of orogeny in the foldbelts, different units of the sequence being shown by tints of the prevailing colors, whatever the actual ages of the units. The maps thus vividly emphasize the foldbelts, producing an eloquent picture on the wall, but the technique makes detailed study of the foldbelts difficult without constant reference to the legend. Precambrian basement rocks are shown in many different colors, from one foldbelt to another, and postorogenic deposits of the internal and external basins are give the same color as the climactic orogeny, although they may be many periods younger. In some foldbelts the outcrops of the actual deformed strata are rather small, as they are nearly buried by extensive postorogenic deposits. Many of these postorogenic deposits are a platform cover, which is coextensive with the platform cover of surrounding regions. Drawing a boundary between foldbelt color and platform color in postorogenic deposits becomes highly subjective, unless there are abundant subsurface data.

"TECTONIC MAP OF CANADA"

The specifications of the two maps just discussed combine several disparate items—the nature of the rocks, the evolution of the rock sequence, and the ages of deformation. Many later tectonic maps use similar specifications, but with significant divergences in the relative emphasis given to the different items.

The "Tectonic Map of Canada" (Stockwell, 1969) thus places primary emphasis on the ages of deformation. On this map, 15 orogenies are differentiated, five in the Precambrian and 10 in the Phanerozoic, namely: Kenoran (late Archean), Hudsonian (late Aphebian or Early Proterozoic), Elsonian (late Paleohelikian or early Middle Proterozoic), Grenvillian (late Neohelikian or late Middle Proterozoic), East Kootenay (middle Hadrynian or Late Proterozoic), Taconic (early Late Ordovician), Acadian (Middle to Late Devonian), Ellesmerian (Early Mississippian), Appalachian (Late Mississippian to Early Pennsylvanian), Melvillean


85°
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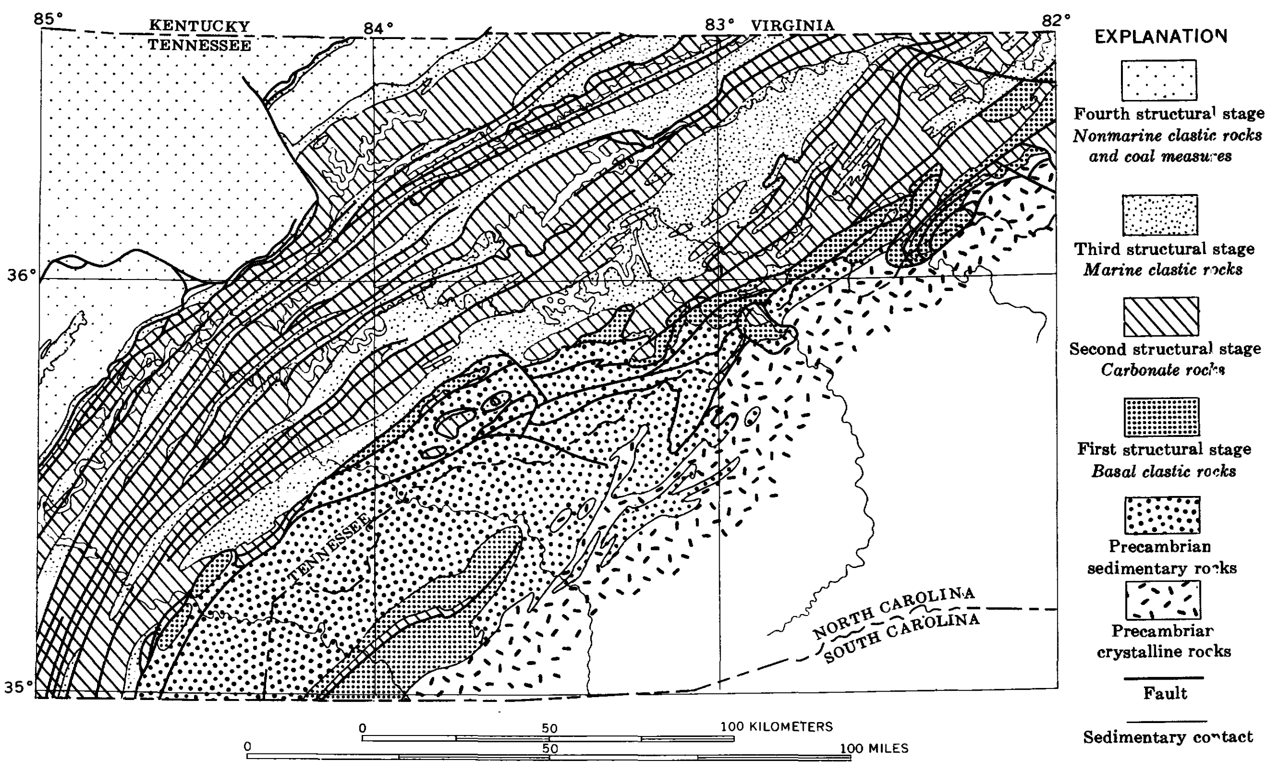
VIRGINIA
82°
36°
35°
TENNESSEE
NORTH CAROLINA
SOUTH CAROLINA
0
50
100 KILOMETERS
0
50
100 MILES
EXPLANATION
Pennsylvanian
Mississippian
Devonian and Silurian
Ordovician
Cambrian
Cambrian and Cambrian (?)
Chilhowee Group
Precambrian
sedimentary rocks
Precambrian
crystalline rocks
Fault
Sedimentary contact

A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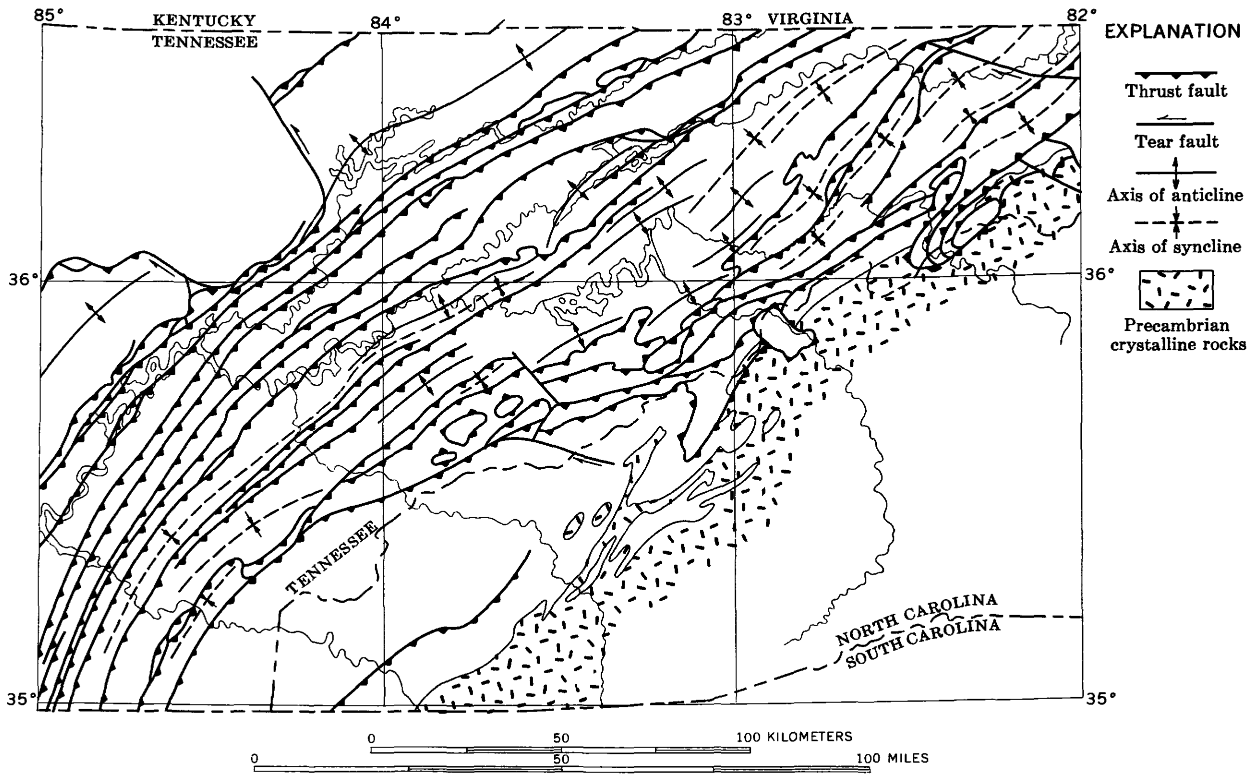
35°
TENNESSEE
NORTH CAROLINA
SOUTH CAROLINA
0
50
100 KILOMETERS
0
50
100 MILES
EXPLANATION
Fourth structural stage
Nonmarine clastic rocks
and coal measures
Third structural stage
Marine clastic rocks
Second structural stage
Carbonate rocks
First structural stage
Basal clastic rocks
Precambrian
sedimentary rocks
Precambrian
crystalline rocks
Fault
Sedimentary contact

B



C

FIGURE 5 (left and above).—Three maps of eastern Tennessee and western North Carolina showing different methods of representing the geology in a region of strongly deformed rocks. In figures *A* and *B* the representation of time-stratigraphic and rock-stratigraphic units much obscures the representation of structural features, even though their scale is about 3 times that of the "Tectonic Map of North America." Compiled from geologic maps of Tennessee and North Carolina. *A*, Map showing time-stratigraphic units (geologic systems). *B*, Map showing rock-stratigraphic units ("structural stages"). *C*, Structural map, showing folds and faults.

(Late Pennsylvanian), Tahltanian (Early to Middle Triassic), Inklinian (Late Triassic to Early Jurassic), Nassian (Middle Jurassic), Columbian (Late Jurassic to Early Cretaceous), and Laramide (Late Cretaceous to Eocene).

Each orogeny is correlated over the whole country; for example, rocks affected by the Appalachian orogeny are mapped not only in the Appalachians but also in the Arctic Islands. The areas affected by the different orogenies are shown by separate colors, the color of the dominant orogeny being used also for areas reworked from earlier orogenies and for unconformably overlying deposits. The rocks affected by each orogeny are subdivided in turn according to their lithology and origin, their degree of metamorphism, and the deformation to which they have been subjected; some have undergone two or more prior orogenies.

Two examples of the subdivisions of the rocks of the foldbelts which are made on the "Tectonic Map of Canada" are quoted below, one for the Precambrian, one for the Phanerozoic:

Hudsonian orogeny (H); folding and granitic intrusions during late Aphebian.

Hg, Granitic intrusions emplaced during the Hudsonian, including highly granitized gneisses. Hgd, discordant intrusions.

Hb, Basic intrusions. Hb′, mainly gabbro. Ha, mainly anorthosite.

Hn, Aphebian sedimentary and volcanic gneiss and schist. Hng, mixed with granitic material. Hr, granulite and charnockite.

Hm, Aphebian miogeosynclinal deposits. He, Aphebian eugeosynclinal deposits.

Heu, Aphebian and(or) Archean slightly metamorphosed eugeosynclinal deposits. Hnu, gneissic equivalents.

Hu, Aphebian and(or) Archean sedimentary and volcanic gneisses, commonly mixed with granitic material. Huu, metamorphic rocks in largely unmapped areas, with undivided granitic intrusions.

HKg, Granitic intrusions, emplaced during the Kenoran and reworked during the Hudsonian. HKg, intrusions emplaced during the pre-Kenoran and reworked during the Kenoran and Hudsonian.

HKe, Slightly metamorphosed Archean eugeosynclinal deposits, folded during the Kenoran and reworked during the Hudsonian.

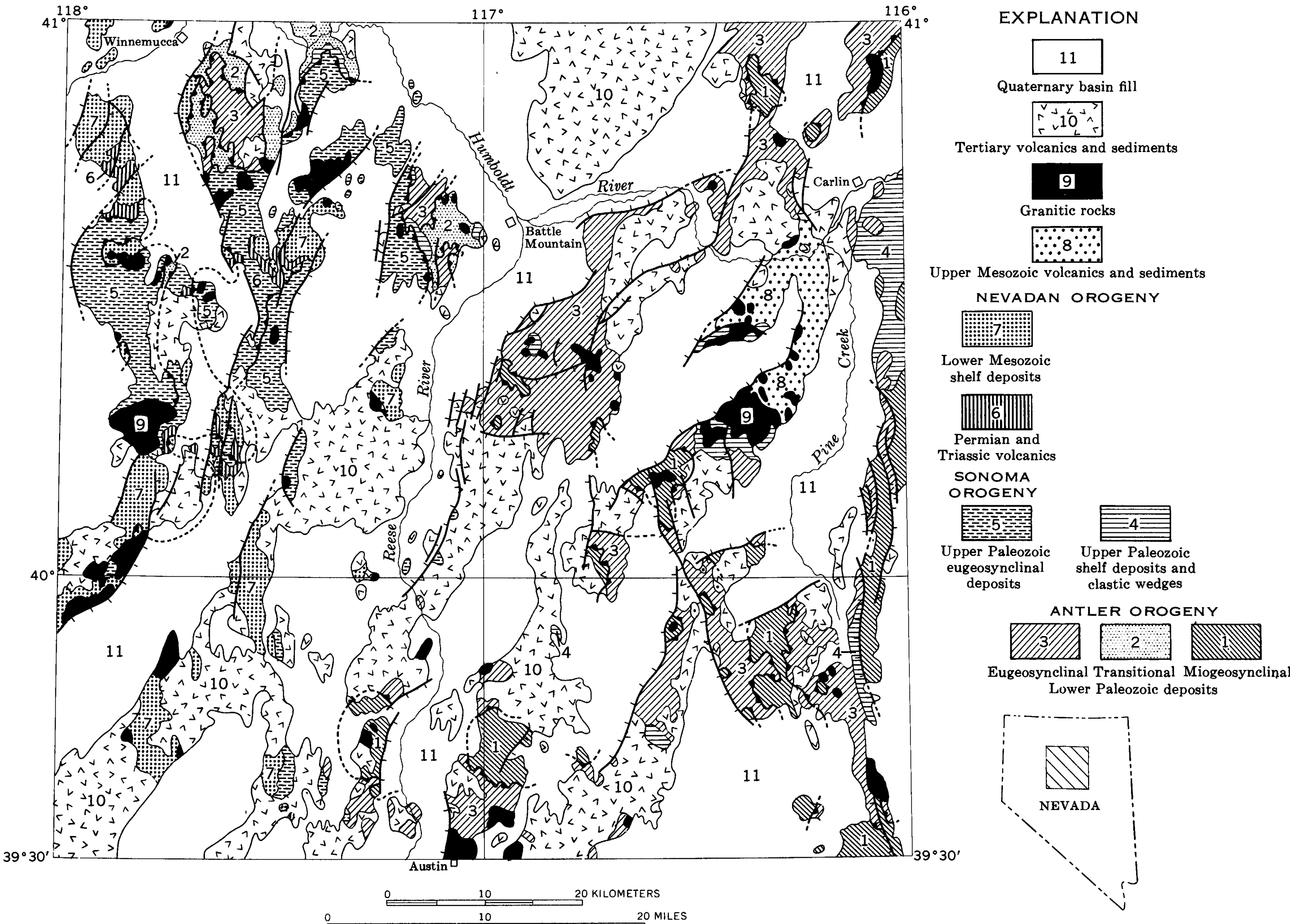


FIGURE 6.—Tectonic map of north-central Nevada illustrating the difficulty of making a meaningful representation of "structural stages" on small-scale tectonic maps in an area of complex superposed rocks and structures. The Paleozoic and Mesozoic rocks consist of three sequences, each divisible into "structural stages." During Paleozoic and Mesozoic time the sequences were telescoped by low-angle thrusting; later, their rocks were invaded by plutons, partly covered by postorogenic deposits, and disrupted by block-faulting, so that they are now exposed in small, disconnected areas. Compiled from county geologic maps of Nevada, and from various U.S. Geological Survey publications.

HKn, Gneissic equivalents, mixed with granitic material.
HKr, Granulite and charnockite.

Acadian orogeny (A); folding and granitic intrusions mainly during the late Middle to early Late Devonian. A′, folding during middle Early Devonian. A″, folding possibly during Late Silurian.

Ag, Granitic intrusions.

An, Upper Ordovician to Middle Devonian miogeosynclinal deposits. Am′, Cambrian to Middle Devonian. Ae, Silurian to Middle Devonian eugeosynclinal deposits. Ae′, Ordovician to Middle Devonian eugeosynclinal deposits. An′, derived gneiss and schist.

A′m, Hadrynian to Early Devonian miogeosynclinal deposits.

A″g, Granitic intrusions. A″b, basic intrusions.

A″e, Lower Ordovician to Middle Silurian eugeosynclinal deposits. A″n, derived gneiss and schist.

ATg, Granitic intrusions emplaced during the Taconic and modified during the Acadian. ATb, basic intrusions emplaced during the Taconic and modified during the Acadian.

ATm, Cambrian to Ordovician miogeosynclinal deposits folded during the Taconic and refolded during the Acadian. ATM, metamorphic equivalents. ATe, Upper Hadrynian to Middle Ordovician eugeosynclinal deposits, folded during the Taconic and refolded during the Acadian. ATE, metamorphic equivalents. ATn, derived gneiss and schist.

AK″M, Hadrynian or older metamorphosed miogeosynclinal deposits, folded during the middle or late Hadrynian and modified during the Acadian. AK″E, similar metamorphosed eugeosynclinal deposits. AK″n, derived gneiss, schist and migmatite.

AK′g, Granitic intrusions emplaced during the early Hadrynian or before and modified during the Acadian.

AK′M, Metamorphosed early Hadrynian or older miogeosynclinal deposits folded during the early Hadrynian or earlier and refolded during the Acadian. AK′ng, derived gneiss and schist, mixed with granitic material.

AK′e, Earlier Hadrynian or older eugeosynclinal deposits folded during the early Hadrynian or earlier and refolded during the Acadian.

The orogenies listed above are differentiated partly by geologic evidence—stratigraphically dated unconformities, intrusive relations, and the like—for which the record is unusually complete in parts of Canada. To a considerable extent, however, they are based on the extensive radiometric dating program of the Geological Survey of Canada, and especially potassium-argon dating. Most of the rocks that have been dated are either intrusive or metamorphic.

The five Precambrian orogenies are widely spaced, their climaxes being at about 2,400, 1,700, 1,300, 900, and 700? m.y. (million years) ago, or 700, 400, 400 and 200? m.y. apart. The five Paleozoic orogenies lie within a span of 200 m.y. (Middle Ordovician to Late Pennsylvanian), and the five Mesozoic orogenies within a span of 155 m.y. (Early Triassic to end of Cretaceous). The figures cited might suggest an acceleration of orogeny through time, but the large number of Phanerozoic orogenies recognized in Canada would be merely phases of the three or four orogenic eras recognized in Europe and the U.S.S.R., whose climaxes occurred at different times in different places. Very likely the widely spaced Precambrian orogenies recognized in Canada are actually groups of orogenies like those in the Phanerozoic, for which the individual records have become blurred.

The classification of the Precambrian rocks and orogenies in the Canadian Shield on the "Tectonic Map of Canada" is useful and expressive. It blocks out large regions or provinces which have been subjected to orogenic events of widely varying ages, showing within each province the intrusive and supracrustal rocks that formed during, or only a little before, the climactic orogeny, as well as the relics of older rocks affected by earlier orogenies that were reworked by the climactic orogeny. Representation of the Precambrian rocks of the Canadian Shield will be discussed at greater length later (p. 33–36).

The classification of the Phanerozoic rocks and orogenies is less appealing to the present compiler. The large number of orogenies differentiated, and the large number of rock units mapped in each category obscure the broader relations. The differentiation gives the impression, perhaps unintended, of many distinct foldbelts built against each other, whereas the orogenic units are actually not sharply defined in either time or place; this compiler considers these units to be subdivisions or phases of gross foldbelts that evolved during lengthy tectonic cycles. Moveover, unless unusually complete age data are available, such a classification involves a large measure of inference and speculation. A comparable classification would be difficult to make elsewhere in North America, where the available age data are less complete.

"TECTONIC MAP OF MEXICO" AND "TECTONIC MAP OF U.S.S.R."

A divergence in another direction from the specifications of the "Tectonic Map of the U.S.S.R. and Adjacent Areas," and the "Tectonic Map of Europe" is illustrated by two maps—the "Tectonic Map of Mexico" (de Cserna, 1961) and the "Tectonic Map of the U.S.S.R." (Spizaharsky, 1966). On these maps, emphasis is not on the climactic orogenies in the foldbelts, nor on details of the orogenic episodes, but on the broad tectonic cycles during which the foldbelts were built.

On the "Tectonic Map of Mexico" the country is interpreted as being composed of "structural belts," each of which became consolidated during a "geotectonic cycle," the cycle being the interval of time during which an orthogeosynclinal belt became a craton.[4] The fol-

[4] The theoretical basis for the map is summarized from de Cserna (1960) and from the brief text printed on the map.

lowing structural units, or belts, are recognized in Mexico: basement complex (Precambrian); Jaliscoan structural belt (early Paleozoic?); Huastecan structural belt (late Paleozoic to early Mesozoic); Sonoran belt, poorly defined (early Mesozoic); Mexican structural belt (Mesozoic and Cenozoic); Gulf Coast geosyncline (largely Cenozoic); Trans-Mexican volcanic belt (Quaternary); and Quaternary clastic deposits. On the map, rocks of the Jaliscoan belt are shown in tints of purple, those of the Huastecan in tints of blue, and those of the Sonoran and Mexican in tints of green, the colors suggesting the relative ages.

Within the "geotectonic cycles" several phases are recognized, namely: (1) an orthogeosynclinal phase, with development of eugeosynclines and miogeosynclines; (2) an anatexitic phase, with emplacement of batholiths and regional metamorphism in the eugeosynclinal area, and deposition of a flysch wedge over the miogeosyncline; (3) an orogenic phase during which the miogeosynclinal rocks and the flysch wedge were folded and thrust toward the foreland; (4) a taphrogenic phase, during which the whole terrane was block-faulted, molasse was deposited, and subsequent magmatic activity produced both intrusions and extrusions.

The Jaliscoan and Huastecan structural belts are exposed only in small areas, and their original extent and subdivisions are hypothetical. The Mexican structural belt forms most of the surface of the country, and the rocks produced during its "geotectonic cycle" are clearly displayed; they are classified as follows on the map:

Mexican geotectonic cycle (or structural belt)

Sedimentary and metamorphic rocks	*Magmatic rocks*
Clastic volcanic debris.	Final volcanic rocks.
Postorogenic debris or molasse, continental and marine.	Subsequent volcanic rocks and subsequent intrusive rocks.
Preorogenic clastic or flysch wedge.	Anatexitic intrusive rocks.
Eugeosynclinal and miogeosynclinal deposits.	

A somewhat similar rendering appears on the "Tectonic Map of the U.S.S.R." (Spizaharsky, 1966), but in more elaborate form, partly because of the more varied tectonic features of the country, partly for theoretical reasons. The foldbelts of Phanerozoic age in the Soviet Union are divided into 13 systems, each colored differently, of these, 2 are called "geosynclinal" and are presumably still in process of deformation, the remainder are called "folded" because the cycle of deformation has been completed. These foldbelts are: *geosynclinal systems*, Pacific and Alpine; and *folded systems*, Uralian, Kazakhstanian, Altay-Sayan, Baikal, Mongolo-Amur, Tien-Shan, Zaysan, Sikhote-Alin, Verkhoyansk, Chukotka, and Taimyr.

The rocks of each system are subdivided in turn into tectonic units, of which the following is a sample:

Uralian system (or foldbelt)

Tectonic regime	Supracrustal rocks	Intrusive rocks	Age
"Orogenic" structures.	Undivided structural stages.		Late Triassic to Early Jurassic
Superposed structures and intrusives.	None present in this system.		
Geosynclinal and parageosynclinal structures (second group).	Fourth structural stage.	Granites.	Permian to Early Triassic.
	Third structural stage.	Alkaline rocks. Granites and granodiorites. Gabbro and diorite. Ultramafics.	Carboniferous
	Second structural stage.	Granites and granodiorites. Gabbros. Ultramafics.	Middle Devonian to lower Carboniferous (Tournaisian)
	First structural stage.	Alkaline rocks. Granites and granodiorites. Plagiogranites. Gabbro. Ultramafics.	Ordovician to Early Devonian
Geosynclinal and parageosynclinal structures (first group).	Third structural stage.	Granites. Gabbros.	Late Proterozoic to Early Cambrian.
	Second structural stage.		Middle Proterozoic.
	First structural stage.	Alkaline rocks.	late Early Proterozoic to early Middle Proterozoic.
Basement structures.	Undivided.	Granites. Gabbros.	Early Proterozoic to Archean.

The theoretical basis for the representation on this map and its legend has been presented at length by Spizaharsky and Borovikov (1966). In brief, the earth's crust is considered to be heterogeneous, and to be divided into gross blocks along abyssal fractures; if so, each block would undergo its own independent history, and universal times of orogeny would be impossible. The tectonic cycle in each folded system began with a geosynclinal period; the supracrustal rocks that were formed during the period are divisible into a sequence of "structural stages" (rock-stratigraphic units like those on previous Soviet maps), and there is a parallel sequence of intrusive rocks (shown in an adjoining column in the legend). Folding was largely completed by the end of the geosynclinal period, but orogenic climaxes are not mentioned. In the folded systems the geosynclinal period was followed by an "orogenic" and "koilogenic" period, during which the crust was epeirogenically unwarped and downwarped. These authors use "orogenic" in a geomorphological rather than a tectonic sense—that is, for the formation of mountainous topography by uplift, rather than by deformation. In the geosynclinal systems, the "orogenic" and "koilogenic" period has not yet been attained.

According to the map legend, the geosynclinal period (and presumably also the periods of folding) ended in one folded system during the Cambrian, but in others during the Permian, the Triassic, the Early Cretaceous, and the Late Cretaceous; in the geosynclinal systems the geosynclinal period (and period of folding) has not yet ended. Were it not for the theoretical predilections of the compilers, the folding in these systems could be assigned, as on the "Tectonic Map of the U.S.S.R. and Adjacent Areas" and the "Tectonic Map of Europe," to the broadly defined Baikalian, Variscan, Mesozoic, and Alpine orogenies.

On the tectonic maps of Mexico and the U.S.S.R. the supracrustal rocks are thus subdivided in a manner like that on some of the tectonic maps hitherto considered, into a sequence of "structural stages" (although these are not so designated on the map of Mexico). Placing the intrusive and(or) magmatic units in a column in the legend adjacent to the supracrustal sequence is a worthy innovation, as it illustrates the parallel evolution of the two classes of rocks during the tectonic cycles in the foldbelts. The resulting legend is fairly simple on the "Tectonic Map of Mexico." On the Tectonic Map of the U.S.S.R." the great variety of features to be represented produces a legend vastly larger and more complex than on any tectonic map hitherto considered. This increases the difficulty of using the map and legend, but it certainly presents a truer picture of the local peculiarities and histories of each foldbelt; these are obscured by the generalizations made on other maps, where tectonic features from widely separated regions are grouped together and correlated.

REPRESENTATION OF SUBSEA AREAS

On most of the tectonic maps just reviewed only the sea-bottom configuration is shown, by topographic contours and bathmetric tints. Even by themselves, subsea topographic contours are more expressive of tectonics than topographic contours on the land, as the structures of the sea bottom have been less modified by erosional and depositional processes. Hence, fault scarps, fault blocks, upwarps, and downwarps are evident merely from their topographic configuration.

Although interpretation of features beneath the sea on tectonic maps cannot, as yet, be made with as much assurance as features on the land, recent oceanographic advances have encouraged proposals for more specific tectonic representation of subsea features. Such representation, especially by Soviet geologists and oceanographers, has appeared on some of the more recent tectonic maps. On the "Tectonic Map of Eurasia" (Yanshin, 1966b) the ocean bottoms are subdivided into first-order units shown by color patterns, as follows:

Structures of the Sea and Ocean Floors

Regions of pre-Cenozoic folding; continental platforms [=Continental shelves]:
1. Regions of epi-Mesozoic and older platforms.

Cenozoic folded and geosynclinal regions:
2. Folded and geosynclinal systems.
3. Regions of pre-Neogene folding.
4. Deep basins without granitic layer.
5. Deep ocean trenches.
6. Deep trenches of inland seas.

Regions of oceanic platform [= abyssal plains and ridges]:
7. Arched oceanic elevations of the basaltic crust; swells.
8. Marginal swells of oceanic platforms and Philippine basin.
9. Oceanic ridges of block structure.
10. Midoceanic ridges, and graben structures of Bay of Aden and Red Sea.
11. Old oceanic plates between zones of elevation (parts thickly covered by sediments shown by overprinted pattern).
12. Oceanic plates without granitic layer, originating in Paleozoic and Mesozoic.

Volcanicity:
Submarine volcanic ridges and plateaus (shown by overprinted patterns): a, basaltic; b, mixed composition, mostly andesitic.

Besides the first-order units, second-order symbols are used on the map to indicate morphological or tectonic boundaries, faults, folds, flat-topped seamounts, atolls and the like.

Many of the first-order units used on the map are merely morphological or descriptive, such as deep oceanic trenches, marginal swells, and mid-ocean ridges; these would probably be nearly as evident from detailed topographic contours alone. Other units imply rock composition, such as granitic or basaltic crust and thick sedimentary cover, and have been verified by geophysical measurements at least in places. Still others seem more speculative, such as units involving specific times of folding, as these times are not verifiable by present oceanographic methods.

Even more radical proposals for representing subsea tectonics have been made by Soviet geologists. These involve classification of areas by rock composition and ages of folding, placing heavy reliance on particular theories of oceanic origin and evolution.

Today, oceanographic and marine geological investigations are revealing not only subsea topography to considerable depths, but results are as yet available only in a few places. Accurate portayal of sea-bottom tectonics in the manner of the more radical proposals mentioned above must await a much wider extension of these investigations.

"THE TECTONIC MAP OF NORTH AMERICA"

COMPILATION OF MAP

Compilation of the "Tectonic Map of North America" was facilitated by the existence of tectonic maps of many of the areas or countries involved—some printed and available at the time the compilation began, others in progress at that time and printed subsequently, and others still in manuscript at the time of this writing. The maps in manuscript or in progress during the time of compilation were made available to the compiler through the courtesy of their authors.

A major source of information was the "Tectonic Map of the United States, exclusive of Alaska and Hawaii" (Longwell, 1944b; Cohee, 1962), but configuration of the surface of the basement rocks in this region was taken from the "Basement Map of North America Between 24° and 60° N.," compiled by a committee of the American Association of Petroleum Geologists (Flawn, 1967). The tectonics of the State of Alaska is shown on a manuscript map assembled in 1958 by George Gryc and his associates in the U.S. Geological Survey, but for the North American map the data shown there were greatly amplified by information obtained subsequently by these same geologists.

Canada is covered by a published tectonic map (Derry, 1950), but this is superseded by a new tectonic map compiled by the Geological Survey of Canada and a committee of Canadian geologists, under the direction of Clifford H. Stockwell (Stockwell, 1969). The new map, which was made available to the compiler in manuscript, is the chief basis for representing nearly half of the land area of North America. The part of this map covering the Canadian Shield was published first (Stockwell, 1965), the whole map in 1969. As will be seen later, the tectonic classification of the Precambrian used on this map was the principal basis for classification of the Precambrian used elsewhere on the North America map. Additional data on western Canada were obtained from a tectonic map of the western Cordillera in British Columbia and neighboring areas by William H. White (1966b, fig. 10–1).

All of Greenland is shown on a manuscript tectonic map by Asger Berthelsen prepared for the Geological Survey of Greenland. Eastern and northern Greenland are also shown on maps by John Haller of the Danish East Greenland Expeditions. Many of the latter maps have been published in various forms and on various scales (Haller, 1961b; Haller and Kulp, 1962, fig. 3 and pl. 4; Haller, 1968, maps 1–3), but others are still in press. The easternmost part of the U.S.S.R., lying within the area of the North America map base, is shown on a tectonic map by S. M. Tillman and his associates of the Siberian Section of the Academy of Sciences of the U.S.S.R. (Tillman and others, 1966), which was generously made available by its authors prior to publication.

Mexico is shown on a tectonic map compiled by Zoltan de Cserna (1961), which was the chief basis for representing that country on the North America map. In addition, as indicated below, the scheme of classification adopted by de Cserna in Mexico greatly aided the present compiler in working out a general tectonic classification for North America. South of Mexico, the next published tectonic maps are of Venezuela (Bucher, 1950; Smith, 1962). The tectonics of the intervening regions of Central America and the Antilles was filled in from geologic maps and miscellaneous data, both published and unpublished. For Central America, major assistance was obtained from Gabriel Dengo of the Organization for Economic Integration of Central America. A tectonic map of Cuba did not become available until after completion of the North America map but representation of the country on this map is much the same as on the present map (Puscharovsky and others, 1966).

The subsea topography surrounding North America was assembled from contour charts of the U.S. Navy Hydrographic Office, the U.S. Coast and Geodetic Survey, the U.S. Bureau of Commercial Fisheries, and the U.S. Geological Survey, extensively supplemented by publications of the staffs of Scripps Institution of Oceanography, Lamont Geological Observatory, and

Woods Hole Oceanographic Institution. These compilations were corrected by Henry W. Menard and Robert L. Fisher of Scripps Institution of Oceanography and by Bruce C. Heezen of Lamont Geological Observatory. The subsea topography of the Arctic Ocean and its surroundings was obtained from charts by the Marine Sciences Branch, Canadian Department of Mines, Energy, and Resources, which were furnished in manuscript through the courtesy of M. M. de Leeuw.

Preparation of the North America map was materially aided by the opportunity afforded to the compiler to view tectonic features in the field during many excursions, including excursions to such remote areas as Alaska, Newfoundland, southern Mexico, and Guatemala. The compiler also had several mutually helpful conferences with Clifford H. Stockwell and others at the offices of the Geological Survey of Canada, and with Zoltan de Cserna and others at the offices of the Instituto de Geología de México. He further benefited from attendance at conferences abroad which dealt with tectonic problems. Further, the compiler acknowledges with pleasure his rewarding association with Professor A. A. Bogdanoff of Moscow University, U.S.S.R., a world leader in the subject of tectonic mapping.

Finally, the "Tectonic Map of North America" could not have become a reality without the great and good help of Douglas M. Kinney, geologic map editor of the U.S. Geological Survey, first for his sage counsel and advice during the work of compilation, and second for his assistance in obtaining a printed product that faithfully reproduced the original specifications.

SPECIFICATIONS OF THE MAP

When planning the specifications of the "Tectonic Map of North America," the compiler considered the legends and the philosophical bases of the maps previously discussed, and adapted their best features to the new map. Rendering of second-order features on the North America map closely follows that on the "Tectonic Map of the United States" (Longwell, 1944b; Cohee, 1962), but many innovations are made in the rendering of the first-order features. All the land areas are subdivided into tectonic units, shown by color patterns, instead of being only partly colored. A practical reason for this change is that, whereas structural and tectonic data are complete enough within the conterminous United States for many features to be effectively represented by symbols alone, data are less complete elsewhere and many tectonic features in poorly known areas can only be blocked out by color patterns.

Clearly, the units to be shown by color patterns on the "Tectonic Map of North America" must differ from those on conventional areal geologic maps; they must be tectonic units, rather than stratigraphic units. But what are tectonic units? The preceding review of existing tectonic maps indicates a wide diversity of opinion among makers of tectonic maps as to what a tectonic unit should be—a diversity which reflects both philosophical and practical considerations.

In the judgment of the compiler, the ages of deformation of the rocks should not be the major criterion for distinguishing tectonic units. Many contrasting kinds of deformation can occur nearly simultaneously, in different rocks, and in different environments; these rocks and their environments are as significant as the times when they were deformed. Moreover, although specific ages of deformation can be determined in some local areas, regional ages of deformation are seldom clear-cut. Regional ages of deformation are seemingly clearest in the Precambrian rocks, which are readily divisible into gross provinces or foldbelts, but this is largely because of the great length of Precambrian time and the incompleteness of the record in these ancient rocks. Within the Phanerozoic rocks, many deformational events can be recognized, which not only can be more specifically dated than those in the Precambrian but which are more closely spaced in time. Differentiation of all such events on a tectonic map is of dubious significance, at least on a map of continental scope; the extent of many of the individual events is very local, or can be specifically proved only in local areas. Much more significant is the gross time (that is, the tectonic cycle) during which the structures in each foldbelt were created.

The units shown by color patterns on the "Tectonic Map of North America" should, then, combine several significant tectonic items. Within the deformed regions, the gross units should be the foldbelts, which evolved by continuing deformation during lengthy periods of geologic time and each of which had its own distinctive history and time span; these foldbelts should be distinguished by different colors. Subdivisions of each foldbelt should represent the kinds of rocks involved, which are, to a greater or lesser degree, products of this evolution—such as eugeosynclinal, miogeosynclinal, and other sedimentary rocks, and various metamorphic, plutonic, and volcanic rocks. These kinds of rocks can be differentiated by patterns of the prevailing colors. Finally, deformations of specific ages should be indicated only where they imply significant pulses in the evolution of the foldbelt as a whole; they can be shown by various tints of the prevailing color. These concepts correspond closely to the concepts that were the basis for the "Tectonic Map of Mexico" (de Cserna, 1961), and the present compiler acknowledges his indebtedness to those concepts in evolving specifications for the "Tectonic Map of North America."

These philosophical considerations are all very well, but they require modification in order to be represented on a map of North America on a 1:5,000,000 scale. Many tectonic items of theoretical significance are difficult or impossible to map at all, and others would require representation on a scale of 1:2,500,000, or even larger. The "structural stages" which adorn many recent tectonic maps are a case in point. The "stage" concept is valid in expressing the evolution of the foldbelts through time, and "stages" can be recognized in the rock sequences of the foldbelts of North America; to map them is another matter. Sequences of "stages" are generally best marked in strongly deformed areas, thus, both crowded outcrop patterns and crowded structural symbols would coincide on the map (figs. 5 and 6). The present compiler believes that the structures in such areas are more significant than the rock sequence, hence that representation of the latter must be sacrificed. Nevertheless, as will become apparent later, many of the subdivisions of the foldbelts used on the "Tectonic Map of North America" are gross "structural stages" in the sense of existing maps, but these are broad enough in scope to be represented clearly on the 1:5,000,000 scale.

A final disclaimer is in order: Tectonic classification will always be much more subjective than stratigraphic classification and will always be greatly influenced by the judgment and predilections of the map compiler. No two compilers will make identical tectonic classifications of the rocks of the same area—for example, as to what rocks are eugeosynclinal or miogeosynclinal, or as to what rocks are synorogenic or postorogenic. For the "Tectonic Map or North America," the present compiler has appraised the source data and the opinions of geologists that relate to each region, but judgment as to the final representation on the map was made by him alone. What he has shown on the map will differ more or less from what would be shown by another compiler, and may be erroneous in places; every feature shown on the map is controversial in some degree. Nevertheless, in making this map a single compiler has viewed North America in all its parts, and has compared the tectonic features of each part with each other part, thus hopefully arriving at a balanced judgment of the relative significance of each.

On the tectonic map, North America and its surroundings are divided into the following tectonically significant major units:

Platform areas:
- (A) Little deformed Precambrian deposits overlying more deformed earlier Precambrian rocks (Canadian Shield and elsewhere).
- (B) Platform deposits on Precambrian basement (cratonic area of central United States, western Canada, and the Arctic Islands).
- (C) Platform deposits on Paleozoic basement (Atlantic and Gulf Coastal Plains).
- (D) Platform deposits on Mesozoic basement (Arctic Coastal Plain of Alaska and northern Canada).
- (E) Volcanic rocks and associated sediments of North Atlantic province, on Precambrian and younger basement (Iceland, Greenland, and part of Baffin Island).
- (F) Icecaps of Quaternary age, on Precambrian and younger basement (Greenland and parts of Arctic Islands).

Foldbelts of Precambrian age:
- (G) Kenoran foldbelt (Canadian Shield and elsewhere).
- (H) Hudsonian foldbelt (Canadian Shield and elsewhere).
- (I) Greenville foldbelt (Canadian Shield and elsewhere).

Foldbelts mainly of Paleozoic age:
- (J) East Greenland foldbelt (northern east Greenland).
- (K) Innuitian foldbelt (Arctic Islands and north Greenland).
- (L) Appalachian foldbelt (southeastern North America).
- (M) Ouachita foldbelt (southern North America).

Foldbelts mainly of Mesozoic age:
- (N) Andean foldbelt (South America, in southeastern corner of map).
- (O) Cordilleran foldbelt (western North America).

Foldbelts mainly of Cenozoic age:
- (P) Pacific foldbelt (west coast of North America).
- (Q) Antillean foldbelt (Antilles, southern Central America, and Caribbean coast of South America).

Subsea areas.

On the map and its legend, these tectonic units and their subdivisions are indicated by colors that follow a prismatic scale, according to the ages of the geotectonic cycles during which they were formed—brown and red for Precambrian, purple for older Paleozoic, blue for younger Paleozoic, green for Mesozoic, and yellow and orange for Cenozoic. The units and their subdivisions are also indicated by symbols. Prefixes of the symbols are the capital letters in the preceding list. These letters are followed by numerals or letters which designate the subdivisions thereof—numerals for the sedimentary and metasedimentary subdivisions, Greek letters for the plutonic and volcanic subdivisions.[5]

However, some of these subdivisions occur in more than one of the foldbelts. For example, "thick deposits in structurally negative areas" are characteristic not only of the Cordilleran foldbelt, but also of the adjoining Pacific and Antillean foldbelts. Moreover, rocks of various Precambrian foldbelts come to the surface in

[5] Nine Greek letters are used in the legend, which are placed in conventional order (alpha, beta, gamma, delta, and so forth), reading from bottom to top of each column; however, certain letters in the sequence are omitted that would not reproduce clearly on the map (such as zeta, eta, kappa, and nu). The letters are used indiscriminately for whatever rock type appears in the sequence, so that granite, for example, is designated in one place as alpha, in others as beta, delta, and theta. This usage differs from that on some European maps where all granites are designated as gamma, all basalts as beta, and so forth, regardless of their place in the sequence.

the foldbelts of later ages. On many of the maps previously reviewed, such subdivisions are colored, patterned, and symbolized in an entirely different manner from one foldbelt to another, and it is difficult to observe their obvious kinships. In order to express such kinship on the "Tectonic Map of North America," the same colors and patterns are used for the subdivisions in all places but they are repeated in the legends of each foldbelt, only their symbols differing from one foldbelt to another.

PLATFORM AREAS

Platform areas are those parts of the continents in which flat-lying or gently tilted deposits, mainly sedimentary, are underlain at varying depths by a basement of rocks that had been consolidated, not only by earlier deformation, but in part by metamorphism and plutonism. This definition, while seemingly clear, is not everywhere easy to apply. In North America there is much debate among geologists and geophysicists as to which rocks should be called basement and which should not; in compiling the "Tectonic Map of North America" some arbitrary decisions have been made in places. The most extensive platform areas in North America are those with a Precambrian basement in the central craton and those with a Paleozoic basement in the Atlantic and Gulf Coastal Plains. The other platform areas are less extensive or otherwise less typical, but they can more appropriately be placed in this category than in any other.

The tectonic features of the platform areas are most effectively portrayed by means of contours on the upper surfaces of their underlying basements. These surfaces were produced by erosional truncation before the platform deposits were laid over them, but erosion ordinarily had advanced far enough so that any residual topographic features are scarcely apparent in the contours on a small-scale map. Most of the configuration of the surfaces is therefore the sum of all the deformations that were imposed on them after they were truncated. Contours on the surfaces of the underlying basements are available for all of the central cratonic area, for a large part of the Atlantic and Gulf Coastal Plains, and for the Greenland icecap; these are represented on the "Tectonic Map of North America." For the remaining platform areas configuration of the underlying basement is either unknown or is known only in small areas. These platform areas are relatively inconsequential and are not contoured.

(A) PLATFORM AREAS WITHIN THE PRECAMBRIAN

In parts of the Canadian Shield are areas of flat-lying or gently tilted sedimentary or volcanic rocks of Precambrian age, which lie on truncated surfaces of rocks that were strongly deformed during earlier Precambrian orogenies. These orogenies are of diverse ages, and the ages of the deposits that overlie the rocks deformed by them are probably equally diverse; on the map, these deposits are classed as of Early, Middle, and Late Proterozoic ages (A1, A2, and A3).[6] Most of these flat-lying or gently tilted rocks are now preserved in relatively small areas, but such rocks are very likely the last remnants of what were originally much more extensive platform deposits.

One well-known Precambrian platform deposit is the Keweenawan Series of the Lake Superior region—a very thick sequence of mafic lavas interbedded with and succeeded by red continental sandstones (A2). The series has been downwarped into a broad syncline, faulted, and invaded by thick sheets of gabbro (Aα) but it is unmetamorphosed and is tilted rather than folded, so that its structure contrasts with the underlying Precambrian which has undergone thorough orogenic deformation and moderate to strong regional metamorphism (James, 1955). Radiometric dating of the gabbro sheets indicates an age of about 1,100 m.y. (Goldich and others, 1961, p. 96), so that the part of the Keweenawan Series intruded by them is Middle Proterozoic; the higher parts of the series might extend into the Upper Proterozoic (Stockwell, 1964, p. 12). Other Precambrian continental and volcanic rocks which occur in more remote parts of the shield, such as the Athabaska, Dubawnt, and Coppermine River Groups, are even less disturbed than the Keweenawan Series, and like it form a platform cover over more disturbed earlier Precambrian rocks. Toward the northwest, on the shores of the mainland and in the southern parts of the Arctic Islands, the Precambrian platform deposits include marine carbonates and a few evaporite units (Blackadar and Fraser, 1961, p. 363–368). Many of these groups, like the Keweenawan Series, have been radiometrically dated as Middle Proterozoic.

Besides the extensive Middle Proterozoic platform deposits there are smaller areas of Precambrian platform deposits of earlier and later ages. No platform deposits of Archean age remain, if such ever existed. However, Lower Proterozoic supracrustal rocks extend in a few places as platform deposits (A1) over the deformed Archean, as in the region between Lake Huron and Lake Temiskaming. More commonly, they are eroded back to the edges of their foldbelts, where they form tilted sequences that lie against the deformed Archean (the "marginal homoclines" of Stockwell, 1965; here included in unit H5). The deformed rocks of the Middle

[6] Classification of the Precambrian used on the "Tectonic Map of North America" is discussed on pages 30–32.

Proterozoic Grenville foldbelt are overlain by a few small patches of flat-lying Upper Proterozoic deposits (A3), such as the Double Mer Sandstone near Hamilton Inlet; the Upper Proterozoic attains much greater bulk in parts of North America outside the shield, as will be seen later.

Included with the Upper Proterozoic platform deposits on the "Tectonic Map of North America" are the pre-Upper Cambrian rocks of the Wichita Mountains of Oklahoma. Most of the pre-Upper Cambrian rocks that are exposed are intrusive granites and gabbros, but subsurface data in surrounding areas demonstrate that these are not basement in the usual sense, but are sheets that intrude a thick and extensive terrane of lavas and graywackes (Ham and others, 1964, p. 21–37). Isotopic dating of the intrusives indicates ages of about 500 m.y. suggesting an Early Cambrian rather than a Precambrian age; the host rocks are of about the same age or slightly older. Regardless of an eventual decision as to the age classification of these pre-Upper Cambrian rocks, they are more closely related tectonically to the later Precambrian (A3) than to the Paleozoic, and are so treated here (see p. 64).

Shown on the "Tectonic Map of North America" by the same color patterns as the Middle and Upper Proterozoic platform deposits are strata of similar ages in parts of the Appalachian and Cordilleran foldbelts. These strata are properly geosynclinal rather than cratonic, yet they resemble the platform deposits in that they overlie deformed basements of earlier Precambrian rocks, and were themselves not materially deformed except by the Phanerozoic orogenies. They will be discused more specifically later.

(B) PLATFORM DEPOSITS ON PRECAMBRIAN BASEMENT

In the central craton of North America the exposed Precambrian rocks of the Canadian Shield are surrounded by areas in which they are covered by varying thicknesses of platform deposits of Paleozoic and younger ages. These platform deposits cover the interior lowlands south of the shield in the United States, from whence they extend northwestward through the plains of western Canada into the Arctic Islands and northern Greenland. A broad outlier of similar platform deposits covers the center of the shield southwest of Hudson Bay. Between the shield and the Appalachian foldbelt on the southeast, the platform deposits make only a discontinuous, narrow strip along the St. Lawrence River.

On the "Tectonic Map of North America" the upper surface of the Precambrian in the central craton is contoured on a 500-m (1,640-ft) interval, and its configuration is indicated by layer tints. During the last few decades the top of the basement in the craton south of the 60th parallel has been penetrated at numerous places by wells drilled for water, oil, or gas, so that control for contouring is excellent except near the centers of the deeper basins (Flawn, 1967); here, the basement configuration must be extrapolated from the structure of overlying strata. North of the 60th parallel, in Yukon Territory and the District of Mackenzie, very few deep wells have been drilled, but to complete the map, the sparse data from these wells have been used to extend the basement contours hypothetically to the Arctic Ocean.

The paleogeology of the buried Precambrian surface is of much tectonic interest, as it indicates the extensions of the Precambrian foldbelts away from their surface exposures, in the Canadian Shield and in outlying areas. The paleogeology can be deduced with much confidence in many places by means of well data. For the most part, however, it is not feasible to show the paleogeology on the "Tectonic Map of North America," except where exposed boundaries are extended for short distances beneath the cover as dotted lines. The paleogeology of the cratonic area in the United States is indicated on another map, so far as it can be deduced (Bayley and Muehlberger, 1968); data from that map, and from other sources, are summarized in figure 10.

The paleogeologic data show that in most places the Precambrian surface is a true basement of metamorphic and plutonic rocks. Nevertheless, in some areas the Paleozic cover is separated from the basement by moderately deformed younger Precambrian sediments and lavas—themselves ancient platform deposits like those in the Canadian Shield. Buried extensions of the Keweenawan Series and the related Sioux Quartzite occur in the states immediately south and southwest of Lake Superior, and there are areas of rhyolitic lava in Oklahoma, north Texas, and adjacent states (Muehlberger and others, 1966, p. 5422). At present, it is impracticable to represent the configuration of the lower surfaces of these Precambrian platform deposits, and the basement contours are perforce carried over their tops.

The basal deposits of the platform cover are Paleozoic, the earliest being mostly Late Cambrian in age, but the Cambrian is overstepped in many areas by younger strata. As indicated on the various geologic maps of North America, Paleozoic rocks also lie at the surface over extensive parts of the craton, especially toward the southeast, but they are covered westward, in the plains east of the Cordillera of the United States and Canada, by thick Mesozoic deposits and thinner Tertiary deposits.

The structure of the strata in the platform cover is of much tectonic interest and is known in detail, especially as a result of drilling for oil, gas, and water. Within each area the sequence of strata form a "layer cake." "Each layer is separated from the other by an unconformity; each layer of geology is completely independent of other layers above and below; there is no clue in the upper layer of either the existence or character of the next layer below; and each layer has its own oil and gas geology, completely independent from each of the other layers" (Levorsen, 1943, p. 912). Some of the unconformities between the layers are local; others extend over much or all of the craton, and the strata between them can be integrated into gross "sequences" (Sloss, 1963, p. 95). Four gross sequences have been recognized in the Paleozoic, the boundaries between them lying in the lower part of the Ordovician, the middle of the Devonian, and near the base of the Pennsylvanian; other gross sequences have been distinguished in the Mesozoic and Cenozoic (Sloss, fig. 6, p. 110).

On the tectonic maps of the United States (Longwell, 1944b; Cohee, 1962) and the "Tectonic Map of Canada" (Derry, 1950) the outcropping edges of some of these layers or sequences have been represented—on the former, the bases of the Pennsylvanian, the Cretaceous, the lower Tertiary, and the upper Tertiary. Similar usages have been followed on some tectonic maps of other areas or continents. Both the United States and Canadian maps also show structure contours on various strata within the platform cover. Contours on some of these strata can be extended over vast areas, as on the top of the Trenton Limestone (Ordovician) in the eastern United States, and on the top of the Dakota Sandstone (Cretaceous) east of the Cordilleran front from Kansas northward through Alberta. These contours usefully supplement the contours on the surface of the underlying basement and bring out details of the tectonics of the different layers or sequences in the cover.

Nevertheless, representation of structure within the platform cover has not been attempted on the "Tectonic Map of North America." To represent the extent and nature of the different layers or sequences in the cover would require many superposed lines or patterns, unsuitable on a map on this scale; their place is on maps of larger scales, or on a series of maps. Also, the differences between contours on the strata in the cover and those on the basement are of such a low order of magnitude that they are scarcely apparent on a map of small scale with a large contour interval; hence, only confusion would result from superposing them. Such contours would be much more meaningful on maps of larger scales and with smaller contour intervals.

Faults occur at different levels in the platform cover and its basement in the central craton and pose problems of three-dimensional representation. The faults are of three kinds: (1) those which displace units in the basement, but not the overlying strata; (2) those which displace the basement surface, but which may or may not extend upward to the ground surface; (3) those which displace the surface strata, but which may or may not extend downward to the basement surface. On the "Tectonic Map of North America," faults which displace units in the buried parts of the basement are mostly not shown; they are more appropriate as components of a paleogeologic map. Faults which displace the surface of the basement but which do not extend to the ground surface are shown by dotted lines (as concealed faults). Faults which displace the surface strata are shown by solid lines; some of these extend downward to the basement, some do not. Those which do not extend downward to the basement may be thought of as "floating" above the deeper lying structures that dominate the platform areas on the map.

The central craton as it existed during early Paleozoic time extended southwestward, well into the Cordilleran region, into what is now the Central and Southern Rocky Mountains, the Colorado Plateau, and parts of the Basin and Range province in Arizona and New Mexico. This part of the early craton has been reactivated or disrupted during later tectonic events.

In the Southern Rocky Mountains reactivation began during later Paleozoic time, but it was extended over much greater areas during the orogenies of Mesozoic and early Cenozoic time. During each of these times, the basement was raised into elongate uplifts or geanticlines, between which it was depressed into troughs of varying depth; during the later reactivations the basement and its cover were folded and faulted, and the weakened crust was penetrated by many intrusives—all of these events producing the modern structure of this part of the Rocky Mountains.

This record is reflected in the superincumbent Phanerozoic strata. During the early Paleozoic the region received thin cratonic deposits. During times of reactivation, as in the later Paleozoic and in the Paleocene and Eocene, thick marine or nonmarine deposits, largely clastics, accumulated in troughs or basins between the geanticlines. During pauses in reactivation, as during the later Mesozoic, sheets of sediments, some of geosynclinal proportions, were spread over the region from the mobile parts of the Cordillera to the west. These groups of strata are structural layers, or "stages," each of which has its own tectonic features that would deserve representation on large-scale maps. On a small-scale map of the whole continent, however, the dominant tectonic feature is the configuration of the deformed basement. Consequently, on the "Tectonic Map of North America," these areas are colored with the same relief tints as on the remainder of the platform, and contours on the Precambrian basement are extended to the western and southwestern edges of the Colorado Plateau—that is, up to the edge of the folds and thrusts of the Cordilleran miogeosyncline.

In that part of the Basin and Range province south and southwest of the Rocky Mountains, the former craton was mildly reactivated between late Paleozoic and early Cenozoic time, but it was strongly disrupted by block faulting later during the Cenozoic, producing the present pattern of ranges of older rocks and intervening basins deeply filled by late Tertiary and Quaternary nonmarine deposits (O12). Precambrian rocks form the surface of many of the ranges, especially in Arizona, and their cover rocks occupy correspondingly smaller areas. Configuration of the basement can be indicated by contours only in parts of this disrupted region.

(C) PLATFORM DEPOSITS ON PALEOZOIC BASEMENT

The Atlantic and Gulf Coastal Plains of southeastern and southern North America are formed of Mesozoic and younger platform deposits that were laid over the deformed Paleozoic and older rocks of the Appalachian and Ouachita foldbelts. The platform deposits thicken and slope seaward from the exposed parts of these foldbelts, the basement descending beneath them. The continental shelves which border these coastal plans are their submerged extensions. The Atlantic Coastal Plain is prolonged far southward in the Florida Peninsula, and extends thence, mainly submerged, through the Bahama Islands and up to the front of the Antillean foldbelt in Cuba. The Gulf Coastal Plain projects well into the central United States in the Mississippi Embayment, but it narrows southward into Mexico where it is partly interrupted by the outer folds of the Cordillera; it widens again farther south in the Yucatan Peninsula.

From New Jersey to the Llano uplift in central Texas the landward border of the "platform deposits on Paleozoic basement" is drawn on the tectonic map at the edge of the Cretaceous and(or) Tertiary deposits of the coastal plains, where they overlap on their basement. This border is used for practical reasons; alternatively, there is logic for placing the border farther coastward west of Alabama, at the fronts of the Appalachian and Ouachita foldbelts. Except in the Ouachita Mountains, this front is largely buried from Alabama to west Texas and is shown as a dotted line (or a concealed fault) on the tectonic map. Westward and southward from central Texas, the edge of the Cretaceous extends far inland from the Gulf Coastal Plain; here, the border of the platform is arbitrarily placed at the fronts of the Ouachita and Cordilleran foldbelts.

The platform as thus defined has a heterogeneous basement. The most characteristic parts are the deformed rocks of the Appalachian and Ouachita foldbelts—of both the external and internal (miogeosynclinal and eugeosynclinal) zones west of Alabama, of the internal zone alone to the northeast (the Piedmont province and its buried extensions). The internal zones are variably metamorphosed and that of the Appalachian foldbelt is invaded by plutonic rocks. Most of the deformed rocks are Paleozoic, but the internal zone of the Appalachian foldbelt includes probable Precambrian that has been reworked by the Paleozoic orogenies.

As the platform is defined, it must perforce also include less characteristic basement rocks. In the upper part of the Mississippi Embayment and in north-central Texas the Cretaceous and Tertiary deposits spread over the little disturbed Paleozoic rocks of the central craton, so that one layer of platform deposits oversteps another; contours on the Precambrian basement beneath the lower layer are mapped under the upper layer as dotted lines. Well to the southeast of the Appalachian foldbelt, in the Suwanee basin of northern Florida and southern Georgia, is another area of little disturbed Paleozoic strata, known only from drill data; the basin is bordered on the north and south by crystalline rocks, but its basal configuration is unknown.

Beneath the platform cover from the North Atlantic States southwestward to Texas are also Triassic rocks —or at least continental sedimentary rocks and mafic igneous rocks that are lithically identical with the Upper Triassic Newark Group of the inner zone of the Appalachians (L8). Some geologists have proposed that these form a "broad terrane" toward the coast, hence are the initial platform deposits (Spangler and Peterson, 1950, fig. 18, p. 87; McKee and others, 1959, pl. 10), but more plausibly these rocks are preserved in fault troughs like the exposed Newark Group (Durham and Murray, 1967, p. 432). The Eagle Mills Formation, from which a few Triassic plants have been recovered, has been penetrated in a trough-like belt that extends across southern Arkansas into Texas (Scott, Hayes, and Fietz, 1961). The Triassic rocks probably predate the platform sequence.

On the "Tectonic Map of North America," configuration of the Paleozoic basement (C) is indicated by 500-m contours and by layer tints in a manner similar to that of the Precambrian basement (B), but in a different color. These contours are drawn over the tops of all the heterogeneous rocks just described, whether they are characteristic basement or not. From Alabama eastward configuration of the basement is fairly well documented by drill penetrations out to the coast; near the coast, in the Bahama Islands, and on the continental shelves many additional data are afforded by seismic refraction surveys. From Mississippi westward through Texas the basement surface descends more rapidly seaward, so that all drill penetrations are within 150 km (100 miles) of the inner border of the coastal plain. Toward the coast the basement is far beyond reach of the drill, or even of very meaningful results from geophysical surveys. Nevertheless, hypothetical contours on the basement are shown as far as the coast and down to the 13,000-m contour on the tectonic map; these are derived from the "Basement Map of the United States" (Bayley and Muehlberger, 1968), whose authors compiled them from available geophysical data and by extrapolation from the structures of higher horizons.

The stratigraphy and tectonics of the segment of the coastal plain from Mississippi through Texas has been thoroughly documented by more than half a century of petroleum exploration. Many of the results have been presented on the two versions of the "Tectonic map of the United States" (Longwell, 1944b; Cohee, 1962), including not only faults and salt domes, but structure contours at many levels on the strata of the coastal plain sequence. Contours on the strata within the sequence are omitted from the "Tectonic Map of North America" because they obscure the regional picture on a 1:5,000,000 scale; admittedly, contours on these strata have a firmer factual basis than hypothetical contours on the basement, but contours on any single horizon can be extended over only a small part of the whole coastal plain—over long belts parallel to the strike where the strata are persistent, over short belts where they are not persistent (fig. 7). On the "Tectonic Map of the United States" of 1962, it was necessary to contour 24 different horizons in this part of the coastal plain to produce reliable results, 15 of which are in the later Tertiary of southern Louisiana alone.

In Mexico, south of this segment of the coastal plain, the Paleozoic basement again lies at relatively shallow depths, but drill penetrations are widely spaced and no regional contour maps on the basement were available to the compiler. Here, the "Tectonic Map of North America" shows contours on the top of the Lower Cretaceous, copied from the "Tectonic Map of Mexico" (de Cserna, 1961).

The oldest emerging strata of the platform cover are Lower Cretaceous from Mississippi westward, and Upper Cretaceous from Alabama eastward (except for the thin Lower Cretaceous Potomac Group north of the Potomac River). Still older components of the platform cover wedge in downdip beneath the surface—Jurassic from Mississippi westward, Lower Cretaceous from Alabama eastward. Probably the oldest components of the cover are the Werner Formation and Louann Salt, approximately earliest Jurassic, the latter being the source of most of the salt domes that penetrate the higher coastal plain strata from Mississippi westward.

The platform sequence extends upward through the Cretaceous and Tertiary into the Quaternary. In the Atlantic Coastal Plain, regional unconformities cause the Eocene to overstep the Cretaceous in places, and the Miocene to overstep both Eocene and Cretaceous in others. The sequence is relatively thin even near the coasts, but seismic refraction surveys indicate thicknesses as great as 4,500 m (15,000 ft) toward the edge of the continental shelf (Drake, Ewing, and Sutton, 1959, p. 176–184). The sequence is also thin in the northern part of the Florida Peninsula, but thickens rapidly toward its southern end to more than 7,000 m (23,000 ft) (Sheridan and others, 1966, p. 1983–1986). From Mississippi westward through Texas the sequence is more nearly complete and vastly thicker, especially near the coast. Along the coast of southern Louisiana and eastern Texas, the maximum thickness of sediments above the Oligocene is as much as 19,000 m (62,000 ft), the Pliocene as much as 1,800 m (6,000 ft), and the Quaternary as much as 2,400 m (8,000 ft) (Crouch, 1959), but these maxima are not all preserved in a single sequence. The thickness of the older part of the platform sequence near the coast is unknown but is undoubtedly also great.

The great thickness of sediments near the Louisiana and Texas coast, and the great depths of basement beneath, implies an extraordinary crustal subsidence. Some geologists attribute this subsidence to isostatic adjustment caused by loading of the crust by the voluminous sediments brought down by the Mississippi and other rivers, but it may have an ultimate tectonic cause in a postorogenic collapse of the interior of the Ouachita foldbelt in its great arc between Alabama and central Texas. Related to this collapse are the synthetic and antithetic faults in the coastal plain strata (shown on the map), which are concentric to the arc of the foldbelt.

Also shown as an area of "platform deposits on Paleozoic basement" (C) is a small enclave within the Cordilleran foldbelt in southern Coahuila immediately north of the Parras basin, where Cretaceous strata are more broadly folded and warped than in the surrounding ranges and where the basement lies so near the surface that it emerges in many places (for example, at Las Delicias; R. E. King and others, 1944, p. 25–31). Classification of this enclave as a platform rather than as part of the Cordilleran foldbelt must be made with

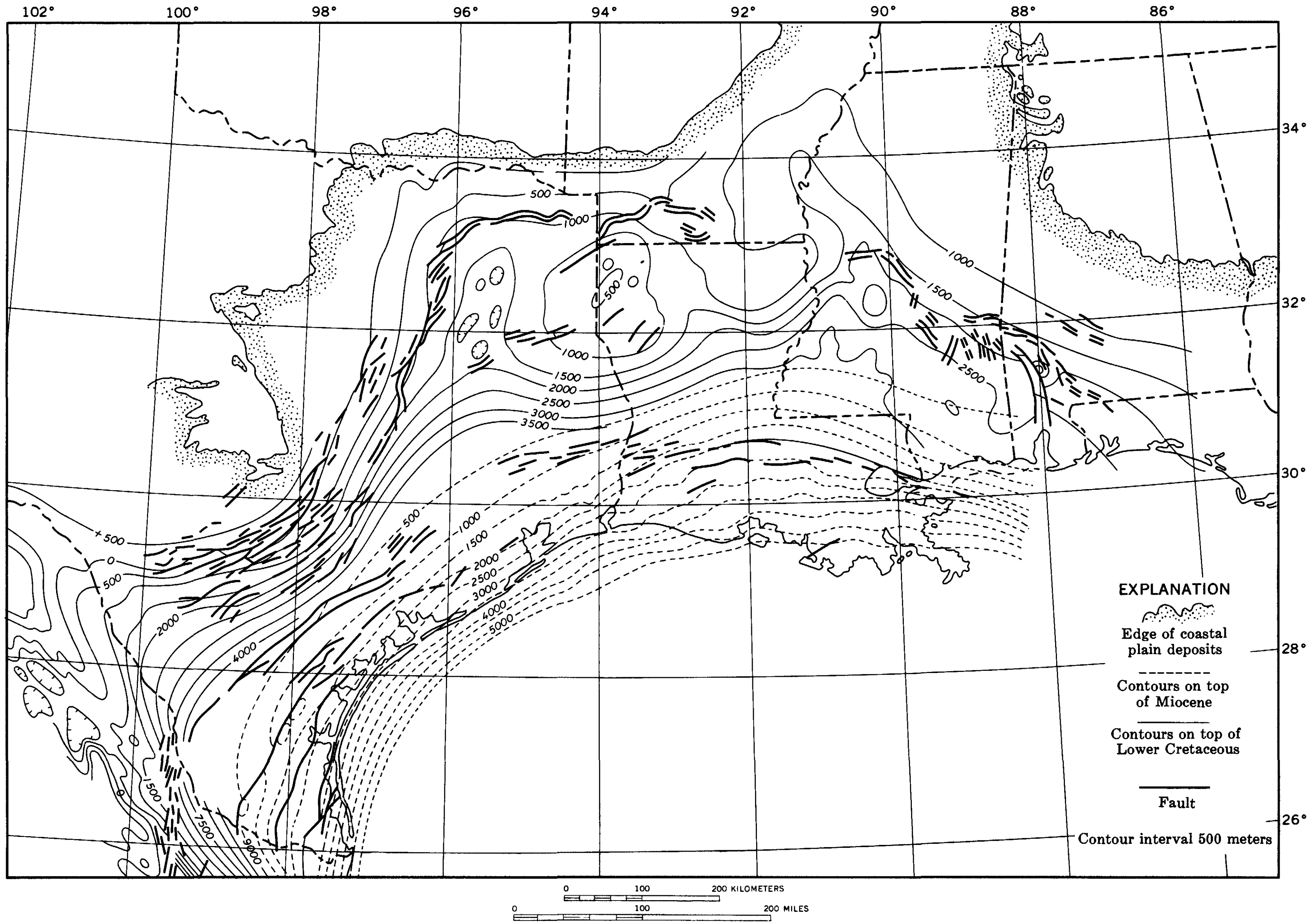


FIGURE 7.—Map of Gulf Coastal Plain in Texas, Louisiana, Mississippi, and adjacent States showing structure contours on two horizons in the strata of the platform cover, for comparison with the partly hypothetical contours on the top of the basement rock shown on the "Tectonic Map of North America." The contours on the top of the miocene are much generalized, as no horizons near this level persist far along the strike. Compiled from "Tectonic Map of United States" (Cohee, 1962) and other sources.

reservations; de Cserna (oral commun., 1964) has pointed out to the compiler that other ranges in the eastern part of the Mexican Cordillera have similar features, although perhaps to a lesser degree, so that distinctions are not absolute.

(D) PLATFORM DEPOSITS ON MESOZOIC BASEMENT

Classed as an area of "platform deposits on Mesozoic basement" (D) is the Arctic Coastal Plain a well-marked but somewhat discontinuous geomorphic feature that extends across northern Alaska, past the mouth of the Mackenzie River in Canada, and along the northwestern edge of the Arctic Islands nearly to Axel Heiberg Island. This coastal plain differs tectonically from those just discussed, and is more heterogeneous, so that its validity as a true platform is somewhat doubtful.

In northern Alaska the coastal plain lies between the front of the Cordillera (Brooks Range) and the Arctic Ocean, and extends from west of Point Barrow nearly to Yukon Territory, where the Cordillera impinges on the coast (Gryc, 1959, p. 107–110). Much of it is masked by Quaternary deposits, which lie in part on Upper Cretaceous, in part on marine Tertiary. Unlike the strata of the Atlantic and Gulf Coastal Plains, those of this coastal plain slope landward from the coast, and thicken into a foredeep along the front of the Brooks Range; basement is within 720 m (2,500 ft) of the surface near Point Barrow, and stratigraphic evidence suggests at least the ephemeral existence of a basement massif offshore beneath the present continental shelf. The structure of the base of the coastal plain deposits in northern Alaska is indicated on the tectonic map by partly hypothetical contours on a basement which may be equivalent to the metamorphosed lower Paleozoic rocks of the core of the Brooks Range.

On the Canadian mainland, in Yukon Territory and the District of Mackenzie, another segment of the Arctic Coastal Plain includes the delta of the Mackenzie River and some areas on either side, all mantled by Quaternary deposits. Here, the underlying bedrock and its basement slope steeply seaward, as attested by a single deep oil test well in the delta which failed to pass through the Lower Cretaceous at a total depth of 3,841 m (12,668 ft) (British-American, Shell, and Imperial Oil Companies, Reindeer D27 well, completed 1966).

In the northwest part of the Arctic Islands the Arctic Coastal Plain is formed by the Beaufort Formation (Craig and Fyles, 1961, p. 406–408) of preglacial Pliocene or earliest Pleistocene age—a deposit several hundred feet thick that was laid down by streams draining northwestward toward the Arctic Ocean. On Banks Island and part of Prince Patrick Island the Beaufort lies on Paleozoic platform deposits, but farther northeast on disturbed Mesozoic strata of the Sverdrup basin (a part of the Innuitian foldbelt).

(E) VOLCANIC ROCKS AND ASSOCIATED SEDIMENTS OF THE NORTH ATLANTIC PROVINCE

The plateau basalts and associated volcanics and sediments of the northeastern part of the area of the "Tectonic Map of North America" are part of an extensive petrographic province variously termed the North Atlantic, Brito-Arctic, or Thulean province, which includes some of the British Isles, the Faeroe Islands, and Spitzbergen, beyond the map area (Wenk, 1961, p. 279). Within the map area these rocks form Iceland, Jan Mayen Island, parts of the east and west coasts of Greenland, and a small part of the east coast of Baffin Island (fig. 8).

The basalts and associated rocks are not entirely comparable to the platform deposits previously discussed, but they do lie with little deformation on basements with more complex histories. The basalts and associated rocks of Greenland and Baffin Island were spread over continental crust—mainly metamorphic and plutonic rocks of the Hudsonian and earlier Precambrian foldbelts, but northward along the east coast of Greenland upon the diverse rocks of the Paleozoic East Greenland foldbelt. The basalts in Iceland and the other islands may have been erupted on oceanic crust.

Whether the basalts and associated rocks in the widely separated parts of the North Atlantic province were ever originally connected is a question which has implications as to the origin of the North Atlantic Ocean—whether by continental foundering, continental drift, or some other mechanism—but this question is beyond the scope of the present discussion. The occurrence of these rocks near the 70th parallel on both the east and west coasts of Greenland, as well as in Baffin Island, suggests former connections, even though they are now separated by the Greenland icecap and the waters of Davis Strait. The peculiar configuration of the base of the Greenland icecap near the 70th parallel may have some relation to the volcanic structures. Nevertheless, a connection across Greenland beneath the icecap has been questioned, because the sediments and lavas overlap inland from the coasts (Wager, 1947, p. 29; Wenk, 1961, p. 279).

The basal sediments in Greenland (E1) include both Lower and Upper Cretaceous on the west coast, and high Upper Cretaceous on the east coast; these are followed by Paleocene sediments with volcanic components that foreshadow the succeeding volcanic episode. Similar basal sediments occur on Baffin Island (Wilson and Clarke, 1965), but are not shown separately on the map.

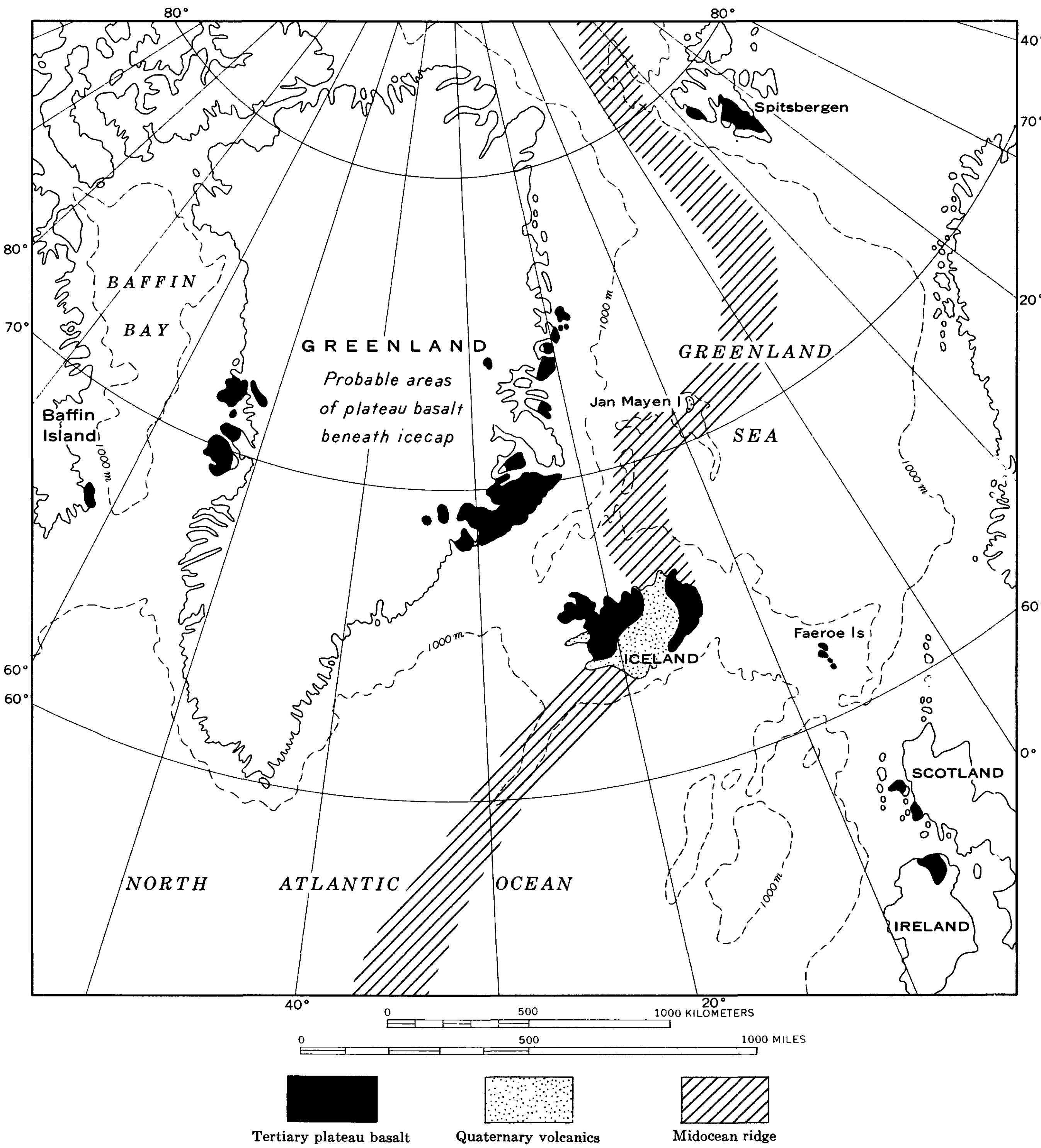


FIGURE 8.—Map of North Atlantic Ocean and adjoining lands, including areas beyond the limits of the "Tectonic Map of North America," showing plateau basalts of North Atlantic province, and related features.

The overlying plateau basalts (Eβ) have a thickness of nearly 8,000 m (26,000 ft) in east Greenland (Wager, 1947, p. 21) and are as thick or thicker in west Greenland (Rosenkrantz and others, 1942, p. 55). In east Greenland they are capped by remnants of late Eocene to Miocene marine sediments, a feature indicating that the eruptions were completed during Eocene time. Associated with the plateau basalts in east Greenland are plutons of various sizes and compositions (Eα), including the famous Skaergaard layered mafic intrusive (Wager and Deer, 1939), as well as alkali syenites and profuse dike swarms. Intrusives are inconsequential in the other areas and are not mapped.

In Iceland, sequences of plateau basalts as thick as 7,000 m (26,000 ft) are exposed, with thin sedimentary intercalations not shown on the map). The oldest radiometric dates are late Tertiary (about 16 m.y.), but plant remains in the sedimentary intercalations indicate various earlier ages back to the Eocene (Askelsson and others, 1960, p. 11–12). The basement on which the basalts were erupted is not exposed. On the "Tectonic Map of Europe" (Schatsky, 1962) it was assigned to "Precambrian of the marginal part of Laurentia", but this is very implausible. Seismic surveys indicate crustal layers beneath Iceland much like those elsewhere on the Mid-Atlantic Ridge—beneath the surface basalts an intermediate layer 16 km thick with a velocity of 6.7 km/sec, and a deep layer 10 km thick with a velocity of 7.4 km/sec. The velocity of the intermediate layer is between that of oceanic and continental crust and may be hydrated oceanic crust (L. C. Pakiser, oral commun., November 1967).

Extending across the center of Iceland is a broad belt of Quaternary volcanics (Eγ) of more varied composition than their predecessors, erupted along the trace of the Mid-Atlantic rift zone, and including several volcanoes still in vigorous eruption (Askelsson and others, 1960, p. 21–28, 32–45). Within the belt, special symbols are used on the map to express Quaternary volcanic features: (1) "mountains of volcanic rubble" ("moberg" or "palagonite mountains"), produced by eruptions under the Pleistocene icecap, and (2) "fractures", which are either rifts in very young lavas or alined clusters of cinder cones.

(F) ICECAPS

Glaciers, ice fields, and icecaps cover extensive land surfaces in the northern part of the area of the "Tectonic Map of North America," some being relics of Pleistocene time. Parts of this ice are truly platform deposits (although not composed of conventional sedimentary rocks) for they conceal, in places to great thickness, a deformed bedrock or basement whose varied structure and age is largely undetermined. The great icecap that covers the bedrock in all but the coastal parts of Greenland, and the smaller icecaps in the northeastern part of the Arctic Islands are therefore represented as platform deposits on the tectonic map. Most geographic maps overemphasize the ice-covered areas at the expense of the ice-free areas, but while the ice is geographically interesting not all of it is a platform cover in a tectonic sense. On the tectonic map, minor ice patches, valley glaciers, and ice areas with many rock ridges and nunataks are omitted; hence, the rendering of platforms covered by ice differs materially from the ice-covered areas shown on geographic maps.

Geographic maps show many ice fields and glaciers in the northern Cordillera, mostly near the Pacific Coast and north of the 56th parallel, but none of these can be classed as platforms in a tectonic sense. The most likely candidate is the great ice field of the St. Elias Mountains, near the common corners of Alaska, Yukon Territory, and British Columbia; to consider it a platform area is the more tempting because several major tectonic belts in the bedrock with uncertain mutual relations converge toward it. Nevertheless, large-scale geographic maps indicate that the ice field is by no means continuous and is interspersed throughout with rock ridges, many of which are still unexplored geologically.

On the tectonic map, the configuration of the basement beneath the Greenland icecap is represented by 500-m contours and by layer tints, in the same manner as the configuration of the basement in other platform areas. Data on the configuration of the basement of the other icecaps are not available, but this configuration is probably of less consequence. The configuration in Greenland is derived from variably spaced geophysical traverses across the ice. Many versions of the results of these traverses have been prepared; the latest is by John Haller of the Danish East Greenland Expeditions who generously made available his manuscript map for use in compiling the tectonic map.

These contours show vividly the extensive area in the center of Greenland where the basement beneath the ice descends below sea level—obviously in isostatic response to the load of the icecap. The ice above the basement is as much as 3,410-m (11,150 ft) thick, and its upper surface rises to a maximum altitude of 3,300-m (10,800 ft). Exceptional features of the basement configuration are the transverse ridges and troughs near the 70th parallel, which may have been shaped by local tectonic causes. The bedrock surface rises toward the coasts, where it emerges in bare plateaus and mountains a few kilometers to as much as 300 km (160 mi) wide. These attain imposing heights along the east coast, culminating in the plateau basalts south of Scoresby Sound at 3,700-m (12,150 ft). The eastern coastal mountains were raised, relative to the bordering sea, by upflexing and upfaulting during Tertiary time (Wager, 1947, p. 51–52); their western flank was depressed beneath the ice during Pleistocene time.

FOLDBELTS OF PRECAMBRIAN AGE

All the Precambrian rocks of North America (with the exception of the platform deposits already discussed) are parts of foldbelts that were formed during tectonic cycles embracing various parts of Precambrian time. Special problems are associated with the foldbelts of Precambrian age; hence, they are discussed separately from those of Phanerozoic age.

Precambrian rocks form the surface of vast areas in the northern and northeastern parts of North America, in the Canadian Shield and its extensions—into Greenland, the Arctic Islands, the Adirondack uplift, the Lake Superior region. Precambrian rocks also form the basement beneath the platform deposits in the surrounding parts of the craton, where they emerge in small inliers on the crests of some of the uplifts, and they extend beneath at least the edges of the younger foldbelts where they have been reworked by Phanerozoic orogenies and are brought to the surface in the cores of the ranges.

Because of the large area of Precambrian exposure in the Canadian Shield, this region offers the best opportunity in North America for determining a sequence of Precambrian rocks, the orogenies of Precambrian time, and the foldbelts produced thereby. Great progress in such determinations has been made in recent decades by the Canadian geologists; as a result of accelerated programs of geologic mapping and radiometric dating. The results obtained in the shield can, moreover, be extended with much success into the Precambrian rocks and foldbelts elsewhere in North America, so that these results are used as a basis for the stratigraphic and tectonic classifications on the "Tectonic Map of North America."

STRATIGRAPHIC CLASSIFICATION

Classification of rocks on a tectonic map is based ultimately on a stratigraphic classification, but the difficulties of making a meaningful stratigraphic classification of the Precambrian rocks are well known—difficulties resulting from the impossibility until recently of making any reliable correlations of rock sequences beyond local areas. Fossils of value for correlation are virtually lacking in Precambrian rocks, but the methods of radiometric dating that now exist have proved to be at least a partial substitute. These datings have not only opened the way for correlating Precambrian rocks over extensive areas, but have also shown the immense spans of Precambrian time during which these rocks were formed (James, 1960, p. 104–107).

Radiometric methods of dating are nevertheless still imperfect; the geochemical and geological limitations have been discussed at length in many publications. Radiometric methods, used in conjunction with geologic methods, can indicate broad correlations, but precise correlations are often elusive. A case in point is the relation between the original Huronian Series of Ontario and the Animikie Series of northern Michigan, nearby to the west (James, 1958, p. 33–34). Although traditionally the two have been correlated, and although they obviously lie within the same general age span, there is little evidence that they are actually contemporaneous and much geological evidence that they are not; conversely, if the two are not contemporaneous, there is little evidence as to which is the older and which the younger.

Many proposals for a general Precambrian classification have been made during the last century, but the earlier proposals are now obsolete and have only historical interest; they have been summarized in many publications (see, for example, Holmes, 1963). More to the present purpose are recent proposals, some of which are shown in table 1. Any classification that can be generally accepted must, however, await an international agreement among geologists. Such an international agreement cannot be made until several fundamental questions have been resolved, namely: Are Precambrian rocks and Precambrian time capable of subdivision into named systems and periods comparable to those of the Phanerozoic? Should these subdivisions be based on type sequences of rocks in one part of the world or another? Or should they be defined by means of clusters of radiometric dates which presumably express the times of orogeny that terminated such sequences? Could the existing terminologies of Precambrian rocks be retained and adapted to the radiometric dates that became available later, or should a new terminology be created?

As the "Tectonic Map of North America" has been completed before an international agreement on Precambrian classification has been reached, an interim classification must be used, but none of the existing classifications of the contributing geological surveys in North America are well adapted to this purpose.

The U.S. Geological Survey originally divided the Precambrian (or "Proterozoic Era") into the "Archean" and "Algonkian" Systems, presumably with time-rock connotations, but in actual practice in Geological Survey reports the systems were used empirically—for example, "Archean" for dominant plutonic rocks and "Algonkian" for dominant supracrustal rocks. The re-

TABLE 1.—*Comparison of various classifications of the Precambrian*

[In the table the rock terms "Lower," "Middle," and "Upper" are used, although some of the sources quoted use the time terms "early" ("earlier"), "middle," and "late" ("later")]

U.S. Geological Survey: Before 1933 (1)	U.S. Geological Survey: After 1933	Minnesota Geological Survey, 1961 (2)	Geological Survey of Canada: 1957, 1962 (3)	Geological Survey of Canada: After 1964 (4)	Baltic Shield (5)	Tectonic Map of North America (present report)
Cambrian	Cambrian	Cambrian	Cambrian	Cambrian	Cambrian	Cambrian
PROTEROZOIC ERA: Algonkian System Boundary not clearly defined Archean System	PRECAMBRIAN: Divided informally into: Upper, lower or Upper, Middle, Lower	PRECAMBRIAN: Upper: *Grenville orogeny* 1,100 m.y. *Penokean orogeny* 1,700 m.y. Middle	PROTEROZOIC: Divided into: Upper, Middle, Lower or Upper, Lower	PROTEROZOIC: Hadrynian *Grenville orogeny* ending 880 m.y. Neohelikian *Elsonian orogeny* ending 1,280 m.y. Paleohelikian *Hudsonian orogeny* ending 1,640 m.y. Aphebian	Sparagmite Series ("Eocambrian") Daslandian 850–1,200 m.y. Jotnian: Gothian 1,200–1,500 m.y.; platform deposits 1,300 m.y. Rapikivi granites 1,600 m.y. Karelian and Svecofennian 1,500–1,900 m.y.	PROTEROZOIC: Upper Middle Lower
		Algoman orogeny 2,500 m.y. Lower: *Laurentian orogeny* Age??	ARCHEAN	*Kenoran orogeny* ending 2,390 m.y. ARCHEAN	ARCHEAN: Belomorian 1,900–2,100 m.y. Saamian 2,150–2,900 m.y. Katarchean 2,770–3,950 m.y.	ARCHEAN

1. Wilmarth (1925, p. 42, 103, 127, and pl. 1).
2. Goldich and others (1961, p. 5).
3. Harrison (1957, p. 27); Stockwell (1962, p. 126 and fig. 3).
4. Stockwell (1964, p. 7–9; 1965; 1966, p. 33–34).
5. Compiled from Holtedahl and others (1964), Magnusson (1960), Simonen (1960), Polkanov and Gerling (1960), and other sources. The names used seem to apply interchangeably to rock units, to the tectonic cycle during which they were formed, and to the terminal orogenies; for the foldbelts created by the orogenies the suffix "-ides" is commonly substituted for "-ian." The Katarchean occurs only as relics in the Saamian gneisses of the Kola Peninsula. The Gothian and Daslandian infracrustal rocks occur only in the southwest part of the shield, and the Jotnian supracrustal rocks only in the central part.

sults had become so incongruous by 1933 that formal subdivisions of the Precambrian were abandoned, after which only informal subdivisions were used, described as "lower" and "upper" ("older" or "younger") or "lower," "middle," and "upper"; these have been applied locally, seldom with any implications of general correlation. The English language provides only three such relative descriptive terms, whereas modern knowledge demonstrates that the Precambrian contains four or more major subdivisions. Additional categories might be provided by expressions such as "lower upper" or "early late," but these are so offensive and confusing that they do not merit serious consideration.

In 1964 the Geological Survey of Canada adopted five named subdivisions of the Precambrian—"Archean," "Aphebian," "Paleohelikian," "Neohelikian," and "Hadrynian" (see table 1). The last four names, which are used for parts of an inclusive "Proterozoic," are derived from Greek words which indicate relative degrees of maturity (*aphebos*, *helikis*, and *hadrynes*, or past maturity, maturity, prematurity). The merits of these names and the acceptance which they will receive remain to be determined. The novelty of the names militates against comprehending either their meaning or the sequential relations of the units.

On the "Tectonic Map of North America" the interim classification of the Precambrian therefore reverts to the traditional terms "Archean" and "Proterozoic," which have been hallowed by long usage in geological textbooks and among geologists. The subdivisions thereof can be expressed by descriptive terms, and the Proterozoic is so divided into "Lower," "Middle," and "Upper" ("Early," "Middle," and "Late"); a similar subdivision of the Archean might be possible at a later time, but is not attempted on the map. These traditional terms are open to many objections it is true—ambiguities in their earlier definitions and how they were applied, and later questions as to how they could be redefined more precisely on the basis of radiometric dates. As suggested by table 1, there seems to be little agreement between North American and European geologists as to the age of the termination of the Archean. This interim classification, whatever its deficiencies, at least makes possible a subdivision of the Precambrian into more than the three descriptive categories available in the English language, and provides the subdivisions with names whose ages and sequential relations can be inferred by the geologist who uses the map.

Besides the general time-stratigraphic units just discussed, the captions in the legend of the "Tectonic Map of North America" mention the names of a few local Precambrian rock units (the Keewatin, Temiskaming, Huronian, Animikie, Grenville, and Keweenawan Series, the Sudbury Norite and Duluth Gabbro). These are included merely for mnemonic purposes and as examples; all are from the southern part of the shield in Canada and the United States, where the Precambrian is familiar to geologists. Their use does not imply that the names can be extended to rocks outside their typical areas, although such extensions have been proposed in the past. Elsewhere in the shield the rock units have properly been given other local names, but those in remote places and those recently proposed are less familiar to geologists. Many of the names for other rock units, and the probable ages of the units, have been tabulated in publications by Stockwell (1962, fig. 3; 1964, table 3) and by Goldich and others (1961, table 2).

TECTONIC CLASSIFICATION

Tectonic classification of the Precambrian rocks of North America on the basis of radiometric dating and other evidence is clearer than the stratigraphic classification. As more radiometric dates of Precambrian rocks become available, it is increasingly evident that they cluster during periods several hundred million years long, separated by periods as long or longer with few or no dates (for example, see Gastil, 1960, figs. 1 and 2; Stockwell, 1964, fig. 2). Most of the datings have been made on plutonic and metamorphic rocks, and the clusters of dates express times of plutonism and metamorphism. Inferentially, the clusters also express times of orogeny, of which the plutonism and metamorphism are partial manifestations. This is confirmed in places by structural unconformities between the rocks that yield the dates and overlying less deformed rocks. The times which yield clusters of radiometric dates are thus commonly interpreted by geologists as orogenic times, and they are so treated on the "Tectonic Map of North America."

Nevertheless, a qualification is needed. The clusters of dates have definite climaxes, but the whole spread of a cluster may be as great as 400 m.y.—or as long as all geologic time since the beginning of the Devonian. During Devonian and later time, geologists have distinguished many separately named orogenies, the number depending on the predilections of different geologists. Thus, the Precambrian "orogenies" are probably comparable, not so much to the orogenies within the foldbelts of later times, as to the tectonic cycles which created the foldbelts as a whole; probably the Precambrian "orogenies" themselves consisted of many such lesser orogenies, now blended together by imperfections of the record.

The nature of the Precambrian orogenies and tectonic cycles has been debated, opinions being colored by conflicting theories as to the origin and evolution of the earth's crust. Many geologists in the past have assumed that crustal behavior during much of Precambrian time differed substantially from that of Phanerozoic time. An ancient fallacy that has caused much mischief is an assumption of the universality of Precambrian orogenies; remnants of this fallacy persisted even into later times. Bucher (1933, p. 419) thus summarized the thinking of his day:

> The best evidence of the diminution in the course of geologic time of the areas occupied by the orogenic belts is the progressive decrease in the width of the zones of crystalline schists and gneisses produced in successive eras. * * * For Archeozoic time, crystalline schists and gneisses occupy apparently 100 percent of the folded belts so far as they are accessible to view today. For the Proterozoic, the percentage is still large, but much less than 100 percent. The contrast between the Proterozoic and the Paleozoic is still greater. * * *

A modern variant of these views is expressed by Stockwell (1966, p. 34–35):

> The orogens of the shield characteristically cover very broad regions quite unlike the mountain chains of later times. Another difference is the long time interval between deposition of sediments and their involvement in orogeny (about 400

m.y. in two instances), as contrasted with the close time sequence of geosynclinal deposition, sinking, and mountain building in younger rocks. Still another difference is the very extensive overlapping of a younger orogen on an older one and this occurs in regions not likely ever to have been the site of intervening geosynclinal deposition. On the whole, the thesis that the orogenic development of the shield differed from that of the younger rocks seems worth considering and, it may be suggested, resulted from deep crustal or subcrustal movements unrelated to the sinking of geosynclinal belts.

At least some of the alleged contrasts between Precambrian and Phanerozoic orogenies may be more apparent than real. The depth of denudation of a foldbelt is progressively greater the older the rocks; hence the exposed areas of crystalline rocks are also greater with age. Moreover, the universality of crystalline rocks in the Archean is probably not a product of any single world-wide orogeny, but results from the great length of Archean time during which many orogenies built foldbelts in different places. Also, if the foldbelts mentioned by Stockwell are actually products of gross tectonic cycles rather than single orogenies they are more comparable with those of Phanerozoic time; the Cordilleran foldbelt of western North America which was built during the last 150 m.y. of geologic time compares favorably in breadth and length to the Precambrian foldbelts, and likewise contains relics of earlier foldbelts that were reworked during the Cordilleran orogeny. Even allowing for probable changes in the nature and behavior of the earth's crust with time, it is reasonable to assume (as Sederholm did more than half a century ago) that the resemblances between the Precambrian and the Phanerozoic foldbelts are greater than the differences (see Holmes, 1963, p. xxi–xxii).

FOLDBELTS OF CANADIAN SHIELD

In the Canadian Shield, three great clusters of radiometric dates have been obtained in the Precambrian rocks, whose times probably express major orogenies; these times are so designated on the "Tectonic Map of North America," following previous usage. As explained earlier, the so-called orogenies of Precambrian time are more properly gross orogenic times or tectonic cycles in terms of Phanerozoic events, and this will be implicit in the discussion henceforth. The orogenies have been classified as shown in table 2.

These dates, and the orogenies which they express, occur in well-defined areas—the "provinces" of Canadian geologists—which are here considered to be the foldbelts produced by the orogenies (fig. 9). The provinces (or foldbelts) of each age are listed below, in order of increasing age:

- Grenville orogeny
  - Grenville province
- Hudsonian orogeny
  - Churchill province
  - Southern province
  - Bear province
  - Nain province
- Kenoran orogeny
  - Superior province
  - Slave province
  - Nain province (minor)

The restriction of orogenic effects during Precambrian time to specific foldbelts (provinces) is illustrated by the passage of deformed supracrustal rocks in the foldbelts into the platform deposits that extend over earlier foldbelts, as described under an earlier heading (p. 21–22). Platform deposits of Lower Proterozoic age (A1) thus define Kenoran foldbelts, those of Middle Proterozoic age (A2) Hudsonian foldbelts, and those of Upper Proterozoic age (A3) Grenville foldbelts. Such relations are most dramatically expressed during Middle Proterozoic time, when the rocks of the Grenville foldbelt in the southeastern part of the shield were subjected to deep-seated deformation and accompanying metamorphism and plutonism, whereas in the greater part of the shield to the northwest, supracrustal platform deposits (A2) were being laid down over rocks already consolidated by earlier orogenies—the deformed rocks and the platform deposits both yielding nearly contemporaneous radiometric dates.

TABLE 2.—*Classification of orogenies in Canadian Shield*

Rock sequence	Orogenies		Climax of orogeny [3]	Range of orogeny [3]
	Canada [1]	Minnesota [2]	Million years	
Upper Proterozoic (minor in shield).				
	(I) Grenville orogeny.[4]	Keweenawan igneous activity.	945	880-1, 000
Middle Proterozoic.	([5])			
	(H) Hudsonian orogeny.	Penokean orogeny.	1, 735	1, 640-1, 820
Lower Proterozoic.				
	(G) Kenoran orogeny.	Algoman orogeny.	2, 490	2, 390-2, 600
Archean.				

[1] Modified from Stockwell (1964, tables 1 and 2) and other papers.
[2] Modified from Goldich and others (1961, table 2; 1966, table 5).
[3] The climaxes and ranges of the orogenies are inferred from statistical summaries of recorded radiometric dates in Canada (Stockwell, 1964, p. 2–7); the climaxes and ranges of the orogenies are based on the abundance of the radiometric dates, the ends being assumed to be the mean minus the standard deviation.
[4] Pertinent objections have been raised by Gilluly (1966, p. 104–108) to such terms as "Grenville orogenic belt" and "Grenville orogeny." Rightly or wrongly, the terms are now so firmly entrenched in usage that it is undesirable to substitute some new and unfamiliar nomenclature.
[5] Stockwell distinguishes an additional Elsonian orogeny between the Hudsonian and Grenville; this is appraised on p. 35.

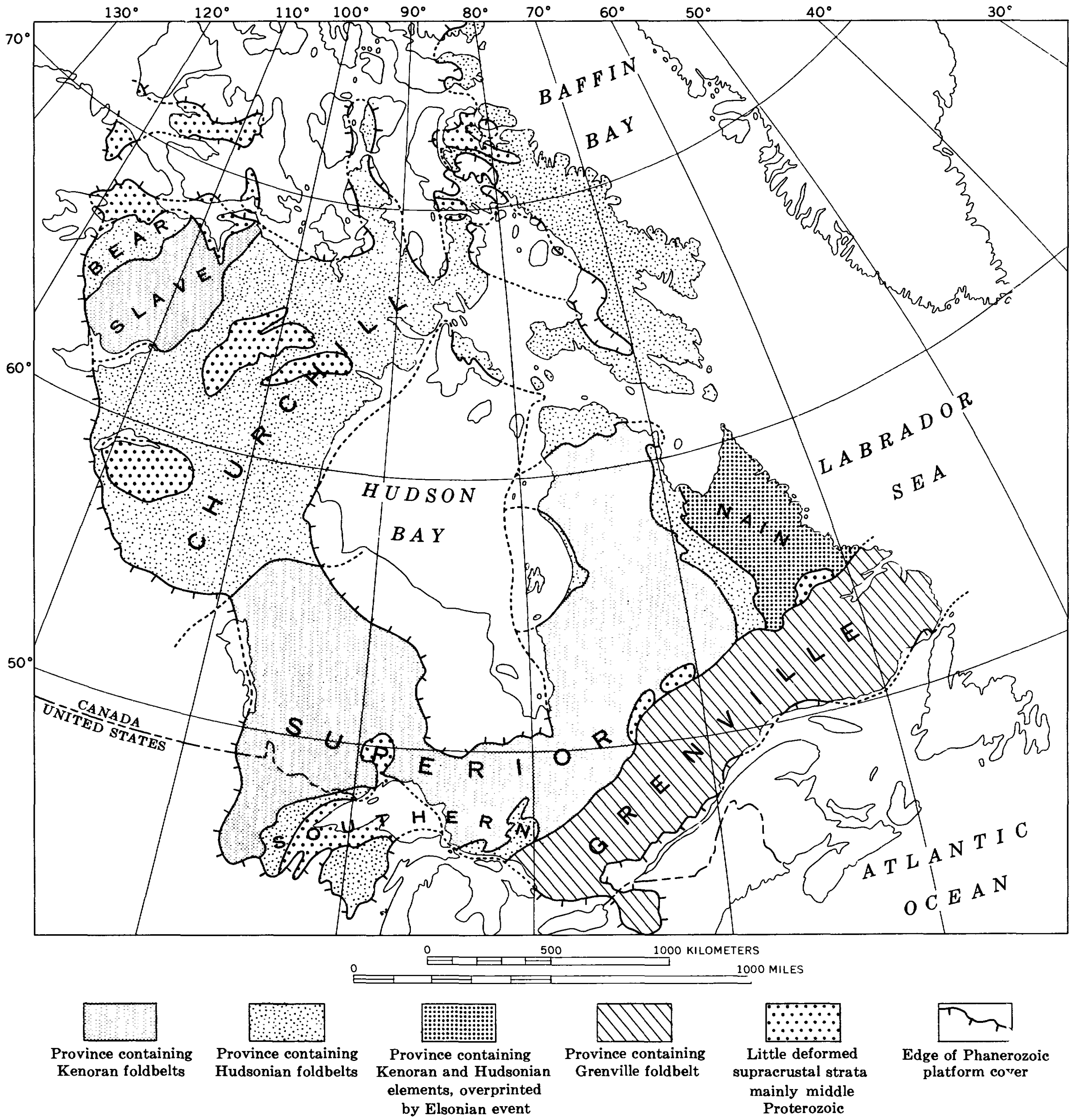


FIGURE 9.—Map of Canadian Shield showing provinces that contain different assemblages of Precambrian rocks. Modified from Stockwell (1964, fig. 1).

Besides the major orogenies, there are indications of other events of possible orogenic significance during Precambrian time in the Canadian Shield, two of which merit discussion:

Archean time was prolonged, and it is presumed that some or many orogenies occurred before the terminal Kenoran orogeny. One of these, the "Laurentian" orogeny is suggested by geological evidence in the Lake Superior region. As early as 1885, A. C. Lawson recognized that the Keewatin greenstones of the region were intruded by the so-called "Laurentian" granite (a misnomer, as the original "Laurentian" is in the Grenville province, and very much younger), and that the eroded surfaces of both were overlain by younger strata, now classed as later Archean (the Knife Lake); he ascribed to this event a major role in Precambrian history. Subsequent investigations indicate, however, that the younger Kenoran orogeny and the accompanying Algoman granites are much more prominent in the region, and the "Laurentian" has been relegated to a lesser rank (Goldich and others, 1961, p. 73–74). The age of the "Laurentian" event is still indeterminate, as no radiometric dates from it have survived; very likely they were overwhelmed by the Kenoran orogeny. Similar (but not necessarily contemporaneous) events may have occurred elsewhere in the Kenoran foldbelts during Archean time, as suggested by the occurrence of granite clasts in many of the sediments. Radiometric data indicate relics of a 3,550 m.y. event in the gneisses of the Minnesota River valley (Goldich, Lidiak, and others, 1966, p. 5395–5396), but their relation, if any, to the "Laurentian" event is unknown.

The record of pre-Kenoran tectonic events during the Archean is so imperfectly preserved that Stockwell (1965) was unable to map their effects in the Canadian Shield, and these effects are accordingly not indicated on the "Tectonic Map of North America."

Stockwell (1964, p. 2–3) proposed an "Elsonian orogeny" on the basis of a scattering of radiometric dates in the Nain province in the northeastern part of the Labrador Peninsula with a mean age of about 1,370 m.y. The area from which the dates were obtained is a terrane of gneisses and embedded granitic plutons, apparently not differing from the adjoining Hudsonian foldbelt except for the occurrence of bodies of anorthosite and gabbro like those in the Grenville foldbelt to the south ($I\beta$); Stockwell suggests that all the anorthosite and gabbro bodies are of Elsonian age, those in the Grenville foldbelt having been reworked during the subsequent Grenville orogeny. Credence in the existence of an "Elsonian orogeny" is enhanced by the occurrence of radiometric dates within the same age range elsewhere in North America outside the shield.

Nevertheless, the significance of the Elsonian event remains dubious. Even in the eastern part of the shield, radiometric dates within this age range are few, and have no prominent peak of abundance like those of the other Precambrian orogenies; radiometric dates within this age range are virtually lacking elsewhere in the shield, except in the Southern province (Michigan and Wisconsin). Besides the anorthosites and gabbros, there are no obvious geological manifestations of an orogeny and the event can hardly have produced a foldbelt in the usual sense. The compiler infers that the Elsonian is a minor event in the Canadian Shield that produced no more than an overprint on rocks already consolidated by the Hudsonian orogeny. On the "Tectonic Map of North America" the rocks of the Nain province are assigned to the Hudsonian foldbelt, the overprint of the Elsonian event being indicated, where appropriate, by a superposed diagonal ruling (H2).

Although the Laurentian, Elsonian, and other problematical Precambrian events have only minor significance in North America, they may reflect orogenies of greater significance in other continents. Thus, the Gothian deformation in the southwestern part of the Baltic Shield seems to be nearly contemporaneous with the Elsonian event in North America (table 1).

Subdivision of the rocks in the Precambrian foldbelts of the Canadian Shield on the "Tectonic Map of North America" largely follows the classification of Stockwell (1965). Within the Kenoran foldbelts little subdivision can be made, except to separate the supracrustal sedimentary and volcanic rocks (G2) from the granitic rocks ($G\gamma$); the migmatites (G1) probably represent partial conversions of the former into the latter. More complex classifications are possible in the Hudsonian and Grenville foldbelts, although even here it is necessary to show areas of undifferentiated rocks (H1 and I1), where the terranes are little mapped or poorly understood. It has been proposd that the closely accordant radiometric dates in each of these foldbelts indicates not only the ages of their climactic orogenies but also the general age ranges of all the rocks of each foldbelt (J. T. Wilson, 1950, p. 107–108). Stockwell's more detailed review indicates greater complexities. Each foldbelt includes not only geosynclinal supracrustal rocks that formed during the tectonic cycle that gave rise to the foldbelt, but also plutonic and supracrustal rocks which are relics of earlier cycles reworked by the later ones; these reworked earlier rocks are indicated on the tectonic map by superposed diagonal rulings. The Hudsonian foldbelts thus contain reworked relics of the Kenoran foldbelt (H3, $H\alpha$); the Grenville foldbelt contains reworked relics of both the Kenoran and Hudsonian foldbelts (I2, I3, $I\alpha$).

The famous "Grenville front," or prominent northwestern border of the Grenville foldbelt, truncates at high angles all the structures of the adjoining Kenoran foldbelt, and there has been much speculation as to its meaning. Certainly throughout its length it marks a significant contrast in style of deformation and metamorphism, and certainly through parts of its length it is a zone of major faulting and northwestward thrusting. Its actuality as a structural feature is confirmed by the occurrence through part of its length of a pronounced linear negative gravity anomaly (Canada Dominion Observatories, 1957). Nevertheless the "front" does not, as has sometimes been assumed, juxtapose a terrane of younger rocks in the Grenville foldbelt on the southeast against terranes of older rocks in the foldbelts to the northwest. Stockwell (1964, p. 18–21) has been able to trace relics of Archean and Lower Proterozoic rocks involved in the Kenoran and Hudsonian orogenies through the Grenville foldbelt (I2, I3), and he proposes that even the Grenville Series (I4) of the southern part of the foldbelt (from which the names of the foldbelt and the orogeny are derived) is not younger than the Early Proterozoic, and hence is not simply a geosynclinal precursor of the much later Grenville orogeny.

FOLDBELTS OF GREENLAND

The island of Greenland is obviously a detached northeastern extension of the Canadian Shield, with analogous Precambrian rocks and structures. Incomplete geophysical surveys suggest that the intervening Baffin Bay and Davis Strait are floored by oceanic crust, so that the detachment was more likely by drift than by foundering of shield rocks. Nevertheless, the geometry of the Precambrian rocks and structures does not match convincingly from one coast to another so that the original fit of the two shield areas is still uncertain.

Precambrian shield rocks underlie much of Greenland, but they are covered in small part by the plateau basalts and associated rocks (Eβ), and in much larger part by the central icecap (F), so that they only emerge near the coasts. Along the east and north coasts, besides, the shield is impinged by the East Greenland and Innuitian foldbelts (J and K), whose Precambrian components have been reworked by Paleozoic orogenies. Berthelsen and Noe-Nygaard (1965) have made an excellent summary of the Precambrian rocks of Greenland. Parts of these rocks are known in much detail, especially in the shield area on the west coast as far north as the 73d parallel (Berthelsen, 1961) and in the East Greenland foldbelt between the 70th and 80th parallels (Haller, 1961a, b; Haller and Kulp, 1962); some other parts are virtually unexplored, especially on the east coast, south of the 68th parallel. Less radiometric dating has been done on the Precambrian rocks of Greenland, compared with that of the Canadian Shield, but the available results are consistent with those of the shield.

The oldest clearly recognizable foldbelt in Greenland is the Ketilidian, which forms all the west coast as far north as the 63d parallel. Most of it consists of deep-seated metamorphic and plutonic rocks (G1) that have undergone long and complex histories. These have been divided into several named complexes of varying composition and metamorphic grade, which are separated in part by strike-slip faults. A few radiometric dates between 2,100 and 2,700 m.y. are available which indicate a correlation of the foldbelt with the Kenoran foldbelts of the mainland (fig. 10). Supracrustal rocks (G2) occur in a few places, notably in the Ivigtut area near the 61st parallel, where a sequence of sediments and volcanics as thick as 4,000 m (13,000 ft) is preserved. All the metamorphic and plutonic rocks of the east coast south of the plateau basalts at the 68th parallel are also probably part of the Ketilidian foldbelt (G1–H3a) but they are little known. Farther north, similar rocks form the autochthone of the East Greenland foldbelt at the head of Scoresby Sound and have yielded maximum radiometric dates of 2,300 m.y.

On the west coast at Søndre Strømfjord near the 67th parallel, rocks of the Ketilidian foldbelt are succeeded northward by other metamorphic and plutonic rocks of the Nagssugtoqidian foldbelt (H4), which have yielded radiometric dates of about 1,500 to 1,650 m.y., hence are correlative with the Hudsonian foldbelts of the mainland. The Nagssugtoqidian foldbelt, like the Ketilidian, is divided into named complexes of varied nature. Supracrustal rocks (H5), called the Agpatides, are reported around Umnak Fjord north of Disko Island, but they have been little studied.

In southernmost west Greenland the Ketilidian foldbelt has been overprinted by the Sanerutian event, so that all radiometric dates here are 1,600 m.y. or less, hence (like the Nagssugtoqidian) being correlative with the Hudsonian orogeny of the mainland. The area includes the extensive Julianehaab Granite (Hα), actually a heterogeneous complex of various granites with relics of sedimentary and volcanic suprastrata; although originally formed during the Ketilidian it was remobilized during the Sanerutian. The area also includes discordant bodies of postorogenic granite (H8) which yield Sanerutian dates. On the east coast the Ketilidian foldbelt is overprinted by the Sanerutian event as far north as Angmagssalik at the 66th parallel.

Southernmost west Greenland also contains the still younger Gardar Group—continental sandstones and volcanics (A2), block-faulted but otherwise little disturbed, and contemporaneous alkalic intrusives (Aα). These are platform rocks like the Keweenawan Series of the continental interior, and like them yield radiometric dates of about 1,000 m.y. They are not comparable to the infracrustal rocks of the Grenville foldbelt which strike out to sea on the opposing coast in Labrador, even though they yield similar dates, nor are they correlative with the remnants of Upper Proterozoic platform deposits (A3) that overlie the Grenville rocks. as was once proposed (Kranck, 1939, p. 30–32).

The age of the basement rocks of northern and northeastern Greenland is undetermined, but it is probably similar to that of the basement in Baffin and Ellesmere Islands, where a few Hudsonian dates have been obtained by the Geological Survey of Canada. Between Inglefield Land and Cape York, opposite Ellesmere Island near the 78th parallel, the basement is succeeded by the little disturbed platform deposits of the Thule Group (A2), which are overlain by a few remnants of the Cambrian and Ordovician (B). Although the Thule has not been dated, it is interpreted on the tectonic map to be of Middle Proterozoic age, like the comparable Precambrian platform deposits in the northern part of the Canadian Shield.

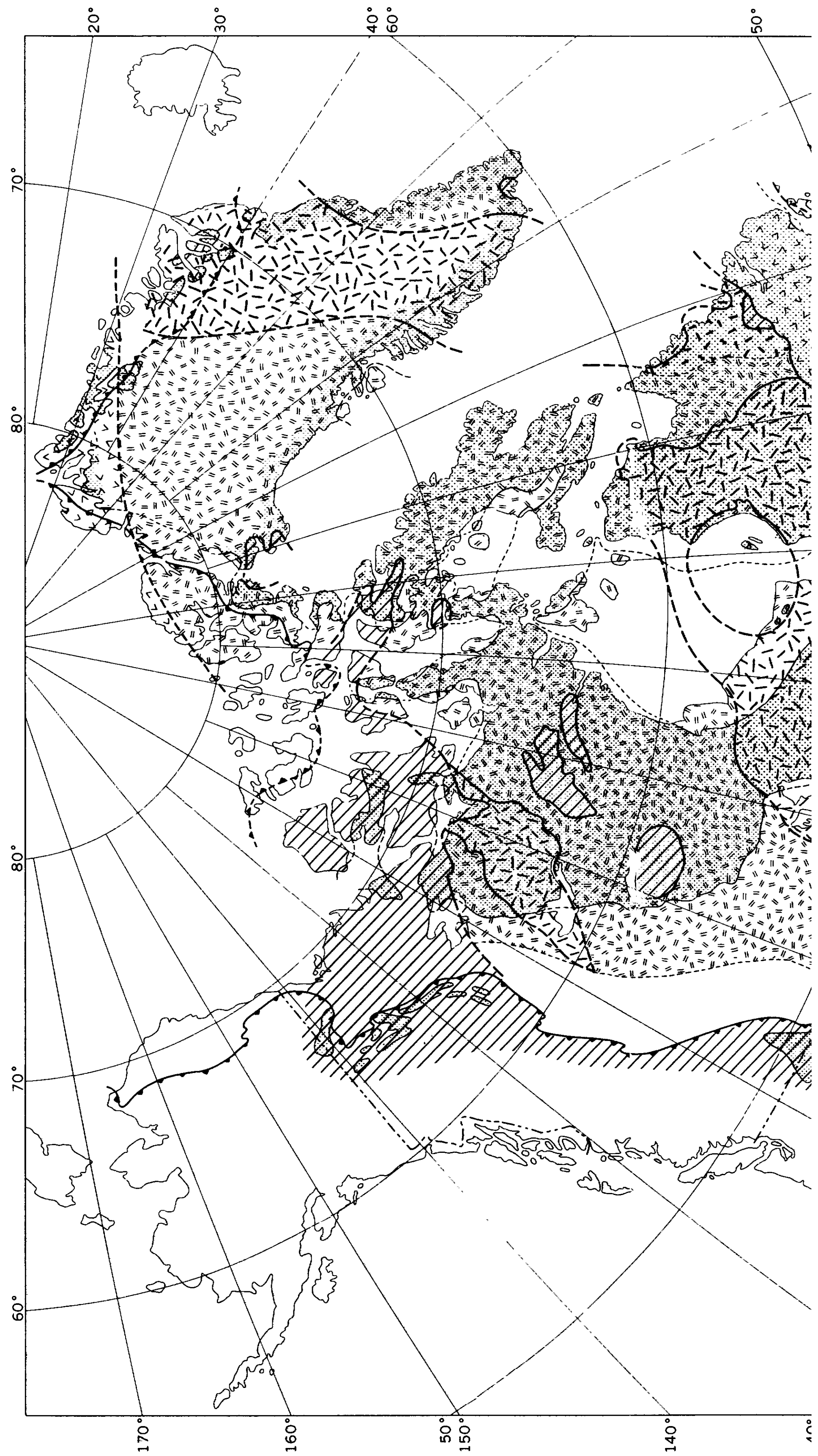
In northeast Greenland the Thule reappears from under the icecap around the head of Independence Fjord, where it is broadly folded and is overlain unconformably by the Upper Proterozoic Hagen Fjord Group (included with B on the map). Eastward in the East Greenland foldbelt, according to Haller (1961a), relations are even more discordant; the Thule is metamorphosed and plastically deformed (J1) by the Carolinidian orogeny, a precursor of the early Paleozoic orogeny that affects the succeeding rocks of the foldbelt (fig. 11). The Carolinidian orogeny has not been closely dated, but Berthelsen and Noe-Nygaard (1965) suggest its possible correlation with the Grenville orogeny, an interpretation adopted in the legend of the tectonic map. Within the East Greenland foldbelt this Carolinidian basement is followed by a pile of Upper Proterozoic geosynclinal deposits (included in J2) which are discussed on page 54.

FOLDBELTS SOUTH OF THE CANADIAN SHIELD

South of the Canadian Shield in the United States and Mexico, outcrops of the Precambrian are smaller, and are closely to widely separated by the cover of younger strata. In the central craton they emerge in a few of the higher uplifts—the Black Hills, the Sioux uplift, the St. Francois Mountains (in the Ozark uplift), the Arbuckle Mountains, and the Llano uplift. In the Appalachian foldbelt, metamorphic and plutonic rocks form some of the ranges near the central axis, but the remainder of the Precambrian here consists of younger supracrustal strata. In the northern part of the Cordilleran foldbelt only younger Precambrian supracrustal strata come to the surface, but in the Central and Southern Rocky Mountains metamorphic and plutonic rocks are extensive in the cores of the ranges. They reappear in the Basin and Range province west and southwest of the Colorado Plateau, in and near the edge of the Cordilleran miogeosyncline. They form the surface of large parts of the ranges of the province in Arizona and the desert region of southeastern California, whence they extend westward into the Transverse Ranges to within a few miles of the Pacific Coast. In most of Mexico, Precambrian metamorphic and plutonic rocks emerge only in small inliers on the crests of higher folds and fault blocks, but there is a larger area of uncertain dimensions in Oaxaca in the far south, as shown by radiometric dates in the metamorphic complex (O1). The occurrences in the Transverse Ranges and in Oaxaca are the only authentic Precambrian in the Pacific border region of North America.

These scattered outcrops of Precambrian metamorphic and plutonic rocks could not have been assembled into any kind of a coherent picture, were it not that similar rocks have been penetrated by many drill holes in the central cratonic area, and were it not that many radiometric dates have been obtained, not only from the rocks of the outcrops, but from the rocks of the drill holes. These have made it possible to construct paleogeologic maps of the surface of the buried part of the Precambrian, to connect rocks and structures in the outcrops, and to assign the Precambrian metamorphic and plutonic rocks over large parts of North America to provinces or foldbelts like those in the Canadian Shield.

For practical reasons it is not possible on the "Tectonic Map of North America" to represent the connections of these foldbelts where they are buried between the outcrops. For these, the reader should consult paleogeological maps, such as the map by Bayley and Muehlberger (1968). The general relations of the Precambrian foldbelts of North America, exposed or buried, are represented in the accompanying text figure (fig. 10). Radiometric datings south of the Canadian Shield are summarized in table 3, based in part on an extensive project of Goldich, Muehlberger, and others (Goldich, Lidiak, and others, 1966; Goldich, Muehlberger, and others, 1966; Muehlberger and others, 1966; Lidiak and others, 1966; Muehlberger and others, 1967).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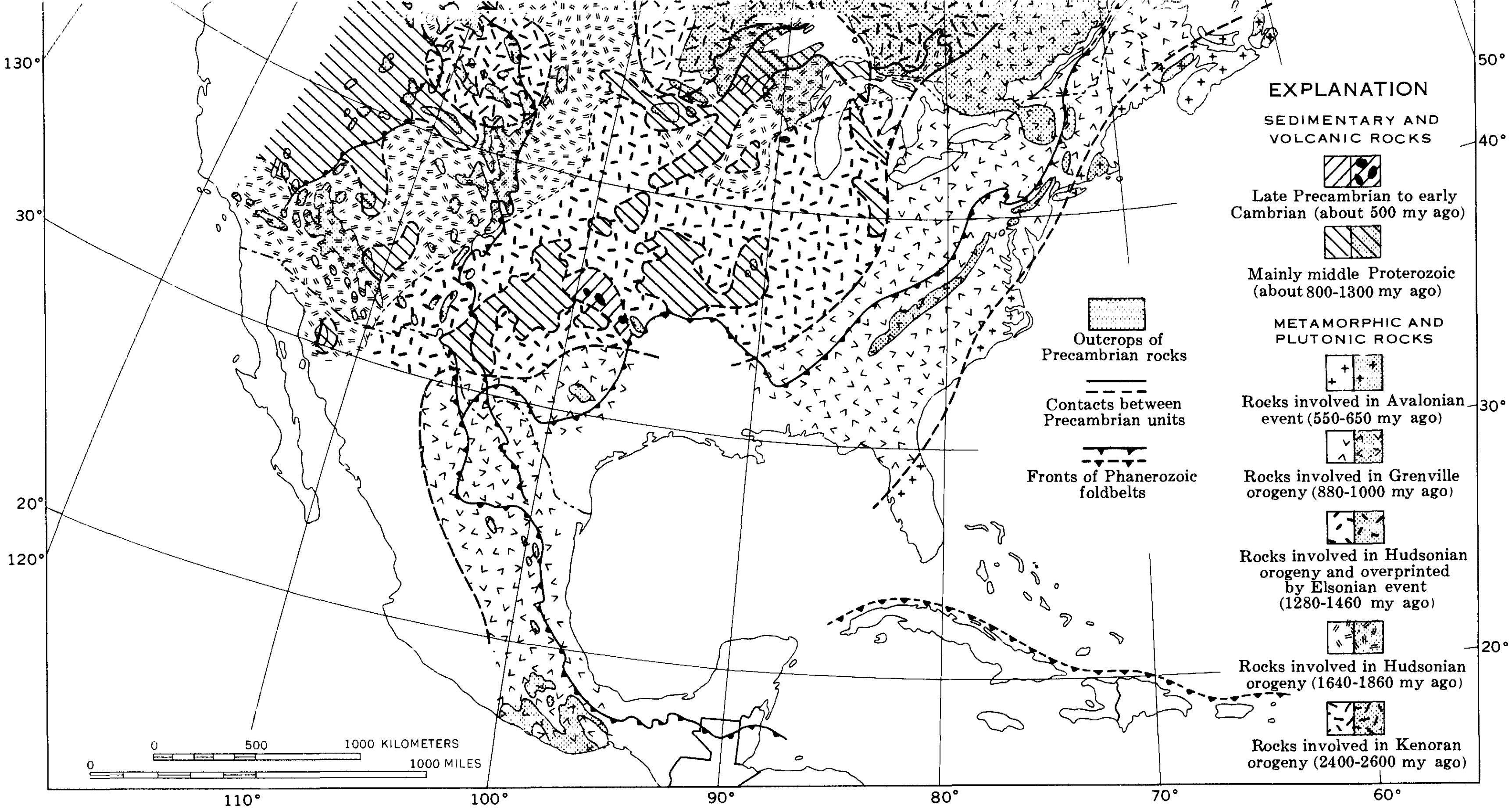

FIGURE 10.—Map of North America showing inferred extent of exposed and buried provinces of Precambrian rocks. Compiled from many sources, including Stockwell (1964, fig. 1), and Bayley and Muehlberger (1968).

TABLE 3.—*Summary of Precambrian rocks and events south of Canadian Shield*

Canadian Shield (Modified from Stockwell, 1964)	Appalachian foldbelt (Rodgers, 1967, and other sources)	Northeastern United States (Lidiak and others, 1966)	North-central United States (Goldich, Lidiak and others, 1966)	South-central United States (Muehlberger and others, 1966)	Western United States (Greatly generalized from many sources)	Mexico (Fries, 196[illegible]; Fries and Rincón-Orta, 1965)
PALEOZOIC				Wichita igneous activity 500 m.y.		
— 600 m.y. —						
UPPER PROTEROZOIC	Avalonian event (coastal region from Newfoundland southward) Holyrood granite 580 m.y.					Eastern Mexico (Tamaulipas) 710 m.y.
Grenville orogeny 880–1,000 m.y.	Grenville orogeny (in basement of interior Appalachians) 800–1,000 m.y.	Metamorphism east of "Grenville front," Ohio 800–1,000 m.y.	Keweenawan igneous activity, 1,000–1,200 m.y. Folding of Sioux Quartzite, 1,200 m.y.	Llano orogeny 1,000–1,150 m.y. Panhandle and Spavinaw igneous activities, 1,100–1,300 m.y.	Intrusives in Apache Group, 1,100 m.y.— Dates on Belt Series 900–1,300 m.y. Pikes Peak Granite, Colorado; Southern California plutonics, 1,000 m.y.	Southern Mexico (Oaxaca) 770–980 m.y.
PROTEROZOIC						
Elsonian event 1,280–1,460 m.y.	(No earlier dates recorded)	St. Francois igneous activity, 1,200–1,350 m.y. Plutonic complex of Iowa, 1,300?–1,500? m.y.	Apparent ages, 1,200–1,400 m.y. Event, 1,490 m.y.	Nemaha igneous activity 1,350–1,450 m.y. Granites, Arbuckle Mountains, 1,320–1,400 m.y. (No earlier dates recorded)	Sherman Granite, Colorado; younger granites of Arizona, 1,300–1,500 m.y.	Eastern Mexico (Hidalgo) 1,210 m.y.
MIDDLE						
Hudsonian orogeny 1,640–1,820 m.y.		Relics, 1,600–1,800 m.y.	Penokean and Black Hills orogenies 1,600–1,800 m.y.		Mazatzal orogeny, Arizona; final metamorphism in Front Range, Colorado, and pre-Belt basement, Montana, 1,650–1,750 m.y.	Northwestern Mexico (Sonora) 1,320–1,710 m.y.
LOWER PROTEROZOIC						
Kenoran orogeny 2,400–2,600 m.y.			Algoman orogeny 2,400–2,750 m.y.		Granites and metamorphics, NW. Wyoming, 2,400–2,600 m.y.	
ARCHEAN			Minnesota Valley relics 3,550 m.y.		Relics, NW. Wyoming 3,100 m.y.	

The oldest radiometric dates outside the Canadian Shield in North America have been obtained from Precambrian rocks in the mountains of northwestern Wyoming and adjacent Montana (Beartooth Mountains, Bighorn Mountains, Wind River Mountains, and other mountain ranges); they are consistently more than 2,400 m.y. old, with a few relics as great as 3,100 m.y. The dates obtained from the outcrops, and from drill samples in surrounding areas, define a province comparable in age to those produced by the Kenoran orogeny in the Canadian Shield; nevertheless, these provinces are not connected, as younger dates have been found in the intervening area. The rocks of the province are mainly granites and granite gneisses (Gγ), but they include the mafic Stillwater Complex of the Beartooth Mountains (Gα), and some schist and iron-formation in central Wyoming and elsewhere (G2). In the Black Hills, where most of the Precambrian is Lower Proterozoic, 2,500-m.y. dates have been obtained in the small Nemo district, from rocks probably representing an earlier basement.

The remaining Precambrian metamorphic and plutonic rocks of the western Cordillera all yield younger radiometric dates. Dominant dates from Montana to Arizona are between 1,500 and 1,800 m.y.; the rocks which yield them are classed on the tectonic map as Hudsonian (H5 or O2; Hγ or Oα), but this is a gross generalization of varied rock assemblages, all of which have had complex histories. In the north, the basement rocks below the Belt Series of Montana and comparable supracrustal strata in the Uinta and Wasatch Mountains of Utah have yielded dates within this age range (but relic earlier dates occur in the Little Belt Mountains, Mont.); the Belt Series itself has been dated by a variety of methods as between 1,300 and 900 m.y. old (Obradovich and Peterman, 1967), hence is Middle Proterozoic or somewhat younger.

In the south, the basement beneath the Grand Canyon Series and Apache Group, and beneath the Precambrian supracrustal strata near Caborca, northwestern Sonora, was deformed by the Mazatzal orogeny, dated as 1,650–1,750 m.y. ago (Wasserburg and Lanphere, 1965, p. 755), although it was once ascribed a younger ("Elsonian") age. Actually, two closely spaced events can be discriminated in the orogeny, one 1,650–1,715 m.y. ago, another 1,715–1,750 m.y. ago, the younger dominating toward the south (Silver, 1967). In several different parts of Arizona the rocks deformed and metamorphosed by the Mazatzal orogeny include sequences of sediments and volcanics as thick as 6,000 m (20,000 ft) (Anderson, 1966, p. 6–8). A basal unconformity has been observed beneath one of these sequences (Blacet, 1966), but its regional significance remains to be established. The supracrustal rocks of this region are probably Middle Proterozoic like the Belt Series in the north; diabase sills in the Apache Group have been dated at 1,100 m.y. (Shride, 1967, p. 76–77).

Special problems attend the Precambrian metamorphic and plutonic rocks of the Southern Rocky Mountains in Colorado and nearby Wyoming; clearly, they have had a complex history. The older paraschists and paragneisses (Idaho Springs Formation and other units) were originally laid down as geosynclinal sediments and volcanics and were afterwards deformed and metamorphosed. Still later, they were plastically folded, and another regional metamorphism was superposed; this event is dated at 1,750 m.y. ago (Pearson and others, 1966; Hedge and others, 1967, p. 554), or at about the time of the Hudsonian orogeny. These rocks, and associated plutonic rocks, are classed on the tectonic map as Kenoran reworked by Hudsonian orogeny (H3, Hα). Sequences of Lower Proterozoic supracrustal strata (H5) are preserved in places, as in the Medicine Bow Mountains of southern Wyoming and the Needle Mountains of southwestern Colorado, and there are several sets of younger plutonic rocks. Anorthosite (Iβ) like that in the eastern part of the Canadian Shield forms the central part of the Laramie Range, Wyo. (Newhouse and Hagner, 1957); extensive granites such as the Sherman and Silver Plume were emplaced 1,200–1,300 m.y. ago, and the less extensive Pikes Peak Granite was emplaced 1,000 m.y. ago.

Plutonic activity in the Southern Rocky Mountains thus extended well past the time of the Hudsonian orogeny, into the times of the Elsonian event and the Grenville orogeny. A similar situation obtains farther southwest, in Arizona, where granites emplaced at the close of the Mazatzal orogeny are dated at 1,650 m.y. ago, and are followed by later granites dated at 1,375 m.y. ago (Silver, 1966); various stray younger Precambrian dates reported in Arizona are probably an overprint related to these younger granites. The history implied by radiometric dates is also complex in the Transverse Ranges of southern California (Silver and others, 1963; Silver, 1968); gneisses and plutonics in the San Gabriel Mountains are dated at 1,650–1,700 m.y. ago (hence Mazatzal or Hudsonian); they were followed by a metamorphic event 1,420–1,450 m.y. ago, and later by intrusion of an anorthosite-syenite complex (Oβ) 1,220 m.y. ago. The Precambrian rocks were long afterwards invaded by Permian to Triassic and by later Mesozoic plutonic rocks.

Radiometric dates intermediate between the Hudsonian and Grenville orogenies have been determined in many of the Precambrian basement rocks penetrated by drilling east of the Cordillera, in the central craton

(Goldich, Lidiak, and others, 1966, p. 5384–5386). Some are merely apparent dates or an overprint, but others pertain to actual plutonic or volcanic events, as shown on table 3. Thus, rhyolitic volcanic rocks were spread widely in Missouri, Oklahoma, and northwestern Texas, and have been dated from place to place as 1,200–1,350 m.y., 1,150–1,300 m.y., 1,100–1,200 m.y., and 500 m.y. ago (Muehlberger and others, 1966, p. 5421–5422); there was also granite emplacement during some of these times. In the compiler's judgement, these events do not justify classing the basement rocks of the southeastern part of the craton as an extension of the proposed Elsonian foldbelt of the shield.[7]

The youngest Precambrian metamorphic and plutonic rocks south of the Canadian Shield are in the southeastern part of the United States, most of which are broadly correlative with those of the Grenville foldbelt. In the Appalachian foldbelt, rocks yielding dates of about 1,000 m.y. (L1) form the basement of the Paleozoic miogeosynclinal and eugeosynclinal sequences and, where present, that of the Upper Proterozoic supracrustal strata (L2) (King, 1969, p. 61–62); they emerge along the axis of the foldbelt in the Long Range of Newfoundland, the Green Mountains and other uplifts in New England, and in the Blue Ridge as far south as North Carolina. They can be extended westward by drill data to a well-defined boundary (probably a prolongation of the "Grenville front" of the shield) that is traceable southward from Michigan, through Ohio, into Kentucky (Bass, 1960).

Rocks affected by this event are recognizable again in Texas, where the Llano orogeny of the Llano uplift has been dated at 1,000 to 1,150 m.y. (Muehlberger and others, 1966, p. 5422–5423); comparable dates have been obtained from nearby drill samples and from west Texas outcrops (Wasserburg and others, 1962). Apparently the belt continues southward with much the same trend into eastern Mexico, although details are uncertain because of sparse outcrops (which are labeled O2 on the map, a symbol used elsewhere for rocks affected by the Hudsonian orogeny). Precambrian inliers in Tamaulipas have yielded a minimum date of 770 m.y., and those in Hidalgo a date of 1,210 m.y. The metamorphic complex in Oaxaca in the far south has yielded nine or more dates with a scatter between 700 and 1,100 m.y. (Fries and others, 1962, p. 45–52; Fries and Rincon-Orta, 1965, p. 81–87). The Precambrian age of the metamorphic rocks in Oaxaca is further attested by the recent discovery of unconformably overlying fossiliferous strata of Late Cambrian and younger Paleozoic ages (Pantoja-Alor and Robison, 1967).

There was thus a wide and lengthy belt along much of the southeastern edge of North America that was subjected to metamorphism, plutonism, and probably to orogeny about 1,000 m.y. ago, or at a time comparable to the Grenville orogeny and the formation of the Grenville foldbelt in the southeastern part of the Canadian Shield (fig. 10). This was during a part of Precambrian time when the remainder of North America to the northwest had been largely stabilized, and was receiving only supracrustal cratonic or geosynclinal deposits.

Some final Precambrian events deserve notice, although they are inadequately represented on the "Tectonic Map of North America" (data regarding them were received too late for inclusion). An Avalonian event (or orogeny) is now well documented in southeastern Newfoundland (Rodgers, 1967, p. 409–410; Poole, 1967, p. 14–17), where the Holyrood Granite (Lα) intrudes the Harbour Main Volcanics and these are succeeded by as much as 6,000 m (20,000 ft) of Upper Proterozoic strata that are topped by fossiliferous Lower Cambrian; the granite has yielded a radiometric date of 575 m.y. (McCartney and others, 1966). Comparable very late Precambrian events may have occurred in the basement rocks below the Lower Cambrian in the Maritime Provinces and possibly in southeastern New England (Isachsen, 1964, p. 812–816), although on the tectonic map these rocks are shown either as Grenville metamorphics (L1) or as Paleozoic plutonics (Lδ). Dates comparable to those of the Holyrood Granite have been obtained from drill samples near the Atlantic Coast in North Carolina (Denison and others, 1967), and perhaps in Florida (fig. 10). Farther northwest in North America, the only significant very late Precambrian to early Paleozoic events were the Wichita igneous activity (A3), referred to earlier (p. 22, 40) and the unconformity between the Belt and Windermere Series and their equivalents (O3 and O4) in the northern part of the Cordilleran foldbelt.

The Avalonian event, although scantily represented in North America, is of interest because it is nearly contemporaneous with the Pan-African or Damaran orogeny, dated at 450–550 m.y. ago, during which many foldbelts throughout Africa were deformed and metamorphosed (Kennedy, 1964; Clifford, 1967). An orogeny of about the same age is also reported in the Precambrian rocks of the Atlantic coastal area in Brazil.

PRECAMBRIAN OF NORTHERN SOUTH AMERICA

Brief mention should be made of the Precambrian of the Guyana Shield in Venezuela and adjacent countries of northern South America, whose edge projects

[7] W. R. Muehlberger has contributed a dissenting comment (written commun., April 1968): "All the events you cite are on volcanic rocks and their associated shallow granitic intrusives which are clearly younger than the basement on which they rest or into which they were intruded. This basement almost everywhere in the region from New Mexico eastward to Ohio has isotopic ages of 1,350–1,450 m.y. This basement I would include within the Elsonian of the exposed Canadian Shield. This is the event which we named the Nemaha to distinguish it from the Elsonian inasmuch as there is no clear connection between the two because of the later Grenville events."

into the southeastern corner of the "Tectonic Map of North America." The part of the shield shown in the map consists of metamorphic and plutonic rocks, from which radiometric dates of 2,000-2,500 m.y. have been obtained (McConnell and others, 1964), hence are classed as of Archean age and part of the Kenoran foldbelt on the tectonic map (G2 and Gγ). Other dates, both older and younger, have been reported from the crystalline rocks of various parts of the Guyana Shield, outside the area shown on the tectonic map. To the southeast, also outside the area shown on the map, the crystalline rocks are overlain unconformably by the nearly undeformed sandstones of the Roraima Formation, once thought to be of Paleozoic or Mesozoic age. However, mafic sills in this formation have yielded radiometric dates of 1,700 m.y. (McConnell and others, 1964), showing that it is likewise Precambrian and is of Lower Proterozoic age. The prolonged stability of the Guyana Shield, as indicated by these data, is noteworthy.

Northwest of the shield, in the Venezuelan Llanos, nearer the front of the Andes, small areas of crystalline rocks (N1 and Nβ) project near El Baúl, but are probably all of Paleozoic rather than of Precambrian age; Cambrian fossils have been found in some of the phyllites, and the intrusive granites have yielded radiometric dates of 270 m.y.

PHANEROZOIC FOLDBELTS

In North America, the foldbelts of Phanerozoic age lie farther away from the center of the continent than the Precambrian shield and its bordering platforms, and nearer the surrounding oceans. The continent is thus almost ideally symmetrical; however, this apparent symmetry may not be a valid generalization, as it is much less perfectly expressed, if at all, in other continents.

The Phanerozoic foldbelts evolved through time from early in the Paleozoic to the present, the evolution of some of them having been completed long ago, of others more recently, whereas in a few the evolution still continues. Their sedimentary and tectonic histories become plainer the younger their age, but the histories of all of them are better preserved than those of the Precambrian foldbelts. This makes it possible to classify their components in more detail than those of the Precambrian, but it creates correspondingly greater problems as to how to represent them on the "Tectonic Map of North America."

THE TECTONIC CYCLE

All foldbelts evolved through time, passing through what is here termed a tectonic cycle, consisting of preorogenic, orogenic, and postorogenic phases. These cycles consolidated originally mobile parts of the crust into cratons, the structures formed during successive phases changing from alpinotype to germanotype in the sense of Stillé. The orogenic phase was the climax of mobility in the foldbelt, when the folds, faults, and plutonic structures that were produced exceeded in magnitude and complexity any that were produced before or after.

The rocks that formed in the foldbelts during the tectonic cycles also changed with time. During the early, or preorogenic phase, the sites of most foldbelts were geosynclines, or tectonically unstable linear troughs in which sediments and volcanics accumulated, commonly to a greater thickness than in the adjoining cratons. Preorogenic and orogenic phases of the foldbelts overlapped; parts of the geosynclines were being orogenically deformed while other parts were still receiving deposits. The net effect of the orogenic phase was to reduce the areas of accumulation of supracrustal rocks and to break the earlier broad geosynclinal tracts into more localized basins, many of which were surrounded by areas of much topographic relief; localized deposition continued into the postorogenic phase, partly in fault-block depressions. In most foldbelts, marine deposition decreased progressively from the orogenic into the postorogenic phase, with a corresponding increase in nonmarine deposition. A still later phase occurs in the Phanerozoic foldbelts that formed earliest; they became so stable that their truncated surfaces were overspread by platform deposits.

During the tectonic cycle the foldbelts also underwent a magmatic evolution. During the preorogenic phase volcanics were erupted in submarine environments in parts of the geosynclines; during the orogenic and postorogenic phases the environment of volcanism became progressively more terrestrial; and during the later phases in many of the foldbelts the deformed bedrock was nearly or wholly concealed by broad sheets of volcanic products surmounted by chains of volcanic cones. Deep-seated crustal activity, of which the volcanism may be a surface manifestation, reached its climax during the orogenic phase, when various suites of plutonic rocks were emplaced, some in great volume. During the postorogenic phase plutonic rocks were emplaced in lesser volume, but they intruded both the original geosynclinal tracts and the adjacent disrupted parts of the original cratonic areas.

The foregoing paragraphs summarize the tectonic cycles that have been observed in many of the foldbelts of the world, details of the history and terminology being purposely suppressed so as to give the summary its widest possible application. More elaborate versions of the cycles have been proposed, but these obviously apply only in places; even the present version may be too particular. There are no "invariable laws" governing the evolution of foldbelts, as has sometimes been claimed; the histories of many of the foldbelts fail to conform, in a few or in many respects, to the classical concepts.

Nevertheless, tectonic cycles of the kind outlined occurred widely enough in North America, and are sufficiently similar from one foldbelt to another to serve as a frame on which to build the classifications adopted on the "Tectonic Map of North America." Although the cycles in each of the foldbelts are thus broadly similar, they and the rocks that formed during the cycles are sufficiently different from one to another to warrant listing them separately in the legend—rather than grouping map units together in foldbelts of the same general age, as has been done on some other tectonic maps.

TERMINOLOGY

Many tectonic terms are afflicted with confusing usage, and the terms "geosyncline" and "orogeny" used in the preceding summary are no exception, hence they require further explanation.

GEOSYNCLINE

The term "geosyncline" was first used in slightly different form by J. D. Dana in 1875, but the concept itself originated with James Hall in 1859. Since then, the term "geosyncline," the concept which it expresses, and the varieties of both, have undergone vast proliferation and mutation, as ably set forth by Glaessner and Teichert (1947). Of particular interest are the terms and concepts proposed by Stillé in several publications (1936b, 1940, and others), which were applied in expanded form to North America by Kay (1951); some of this terminology, especially the names "eugeosyncline" and "miogeosyncline" are discussed in the following section (p. 47–49).

The compiler regards geosynclines as tectonically unstable linear troughs in which sediments and volcanics accumulated, commonly to a greater thickness than in the adjoining cratonic areas, and the term is so used throughout this account. It is therefore applied to the "orthogeosynclines" of Stillé and Kay, and not to the "parageosynclines" of those authors, which are basins of sedimentary accumulation that formed in the cratons under conditions of greater tectonic stability.

Even the tectonically unstable linear troughs that are here considered to be "geosynclines" have a wide variety of characters and forms, some of which are mutually contradictory because they apply to different kinds or to different parts of geosynclines. Thus, a more precise definition of them would not only be difficult, but misleading and unduly restrictive. Some years ago the compiler (King, 1959, p. 56–57), rather than undertake a precise definition, listed ten "geosynclinal attributes," which were intended to encompass these variations.

In the preceding section (p. 43), it was stated that the preorogenic phase of the tectonic cycle in a foldbelt was also commonly a geosynclinal phase, and the inevitability of a geosynclinal phase as a prelude to orogeny has been proclaimed by many geologists, beginning with James Hall in his first statement of the concept. According to de Sitter (1956, p. 351), geosynclines are "those accumulations of sediments of great thickness which have been severely folded." Other geologists have attemped to set a critical limit to the thickness of sediments that could accumulate before the inevitable orogeny began—for example, about 12,000 m (40,000 ft) (Knopf, 1960, p. 132–133).

No such inevitability was intended by the compiler, in his outline of the geosynclinal concept presented above, and it appears to be unlikely; again, there are no "inevitable laws" governing the evolution of foldbelts. In the northern Cordillera the Middle and Upper Proterozoic Belt and Windermere Series accumulated to a thickness that far exceeds the figure cited, yet they remained virtually undeformed until the orogenies of Mesozoic time. The Mesozoic and Cenozoic sedimentary accumulation along the Gulf Coast likewise far exceeds this figure, yet the region remains one of very low mobility. Where accumulation of geosynclinal sediments did closely precede the orogeny in a foldbelt, neither the formation of the geosyncline nor the succeeding orogeny were a result of the sedimentary loading itself; instead, the creation of a trough capable of receiving a thick accumulation of sediments was an early phase of the mobility of the foldbelt.

OROGENY

Regarding the meaning of the term "orogeny," it is instructive to quote the views of several earlier geologists (see Dennis, 1967, p. 112–113, for summary of early literature). According to Gilbert (1890, p. 340), who was one of the earliest to use "orogeny" in a technical sense:

> The displacements of the earth's crust which produce mountain ridges are called orogenic. For the broader displacements causing continents and plateaus, ocean beds and continental basins, our language affords no term of equal convenience. Having occasion to contrast the phenomena of the narrower geographic waves with those of the broader swells, I shall take the liberty to apply to the broader movements the adjective epeirogenic * * *. The process of mountain formation is orogeny, the process of continent formation is epeirogeny, and the two collectively are diastrophism. It may be that orogenic and epeirogenic forces and processes are one, but so long at least as both are unknown it is convenient to consider them separately.

Soon after, the concept of "orogeny" and "epeirogeny" became encrusted with further connotations. According to Upham (1894, p. 385):

> Gilbert has recently supplied to our science the terms epeirogeny and epeirogenic, to designate the broad movements of uplift and subsidence which affect the whole or large parts of continents and the oceanic basins. Previously the terms orogeny and orogenic had come into use, denoting the process of formation of mountain ranges by folds, faults, upthrusts and overthrusts, affecting comparatively narrow belts and lifting them in great ridges, while epeirogenic movements of the earth's crust produce and maintain the continental plateaus and the broad depressions which are covered by the sea.

These early statements illustrate a fundamental dichotomy that has plagued the term "orogeny" to this day—between the processes which produced the rock structures within the mountain chains and the processes which produced the mountainous landscapes. It was not fully realized until later that most of the present mountainous landscapes were not caused directly by the processes that formed the rock structures, but were caused instead by the differential erosion of broadly uplifted masses of deformed rocks. Stillé (1936a, p. 850–851) has well expressed the resulting dilemma:

> As a matter of fact, orogeny in the tectonic sense generally fails as an explanation for the existence of the topographically great mountains of the earth, such as the Alps of Europe or the Cordilleras of North America. These mountains exist—or still exist—as a result of post-orogenic *en bloc* movements, for the most part still going on, and belonging to the category of epeirogenic processes. Thus arises the terminologic contradiction, that the mountains as we see them today owe their origin not to what is called orogeny, but to an entirely different type of movement that is to be strongly contrasted with the orogenic process. Orogeny and topographic mountains are indirectly connected in the sense that the orogenic units, at least in the beginning, coincide with the units of epeirogenic movement. Thus the Alps are a unit not only morphologically but also in relation to orogenic history.

Stillé's remarks reflect the conception of the term "orogeny" prevalent among geologists today, and in particular among the makers of tectonic maps. The futility of attempting to revert to Gilbert's sparse and uninformative definition is amply illustrated by the results which modern geologists have obtained when they applied his concept (Gilluly, 1966, p. 98). In this account, and on the legend of the "Tectonic Map of North America," "orogeny" is therefore used for the processes by which the rock structures within the mountain chains or foldbelts are created.

NAMES OF OROGENIES

The orogenic times in the foldbelts—that is, the times of formation of the rock structures—have been individually named, but here again there has been confusion of usage—whether these names should be applied to rather brief episodes, of deformation, or to times of prolonged orogenic activity that group together many episodes of shorter duration, or whether orogeny has been so nearly continuous through time in the foldbelts that specific names are unjustified.

According to common European usage (expressed, for example, on the "Tectonic Map of Europe," Schatsky, 1962), Phanerozoic time in that continent was marked by four orogenic times, or "eras"—the Assyntian (Baikalian), Caledonian, Variscan (Hercynian), and Alpine, which are, respectively, of late Precambrian to earliest Paleozoic, of early Paleozoic, of late Paleozoic, and of Mesozoic and Cenozoic ages. As a result of more detailed analyses, Stillé (see for example, Stillé, 1936b, p. 851–854; Knopf, 1948, p. 652–657) has distinguished 40 orogenies during Phanerozoic time, most of them being classed as phases of the broader orogenic times. While most of Stillé's orogenies were based on European field examples, he supposed that each was world-wide in its effects.

In North America, various major orogenies have been commonly recognized—for example, the Taconian, Acadian, Appalachian (more properly Allegheny), Nevadan, and Laramide, which are, respectively, of early Paleozoic, of middle Paleozoic, of late Paleozoic, of middle Mesozoic, and of late Mesozoic to early Tertiary ages. However, opinions have varied as to their meaning—whether they represent broad orogenic times like those in Europe, or specific episodes of short duration. Based on the latter concept, European geologists have regarded the North American orogenies as phases of their own orogenic eras. On the same basis, North American geologists have added other named orogenies not of the same age as the five mentioned, or named orogenies of the same age which occur far from the type areas of those mentioned; a formidable list of named orogenies could be assembled from the North American literature. Other North American geologists regard orogeny in the foldbelts as nearly continuous through large parts of Phanerozoic time, although probably episodic at any single locality (Gilluly, 1965, p. 21).

The compiler (1955b, p. 737–738) regards specific times of orogeny as episodes within the orogenic phases of the tectonic cycles which created the foldbelts. He doubts the correctness of the proposition that orogeny has been nearly continuous through the life of the foldbelts; instead, orogeny that produced actual rock structures (rather than ephemeral mountainous topography) was concentrated in a succession of episodes during each orogenic phase. Individual episodes were certainly not world-wide, and may not have been extensive even within the limits of a single foldbelt; names for such episodes are appropriate only for local purposes. Of broader interest are the orogenic times which are natural groupings of these episodes. The compiler believes that many of the traditional names for North American orogenies (like the Taconian and others, previously mentioned) apply most appropriately to such orogenic times, and has so used them on the legend for the tectonic map; they are thus comparable in scope, but not in age span, to the orogenic times in Europe (the Caledonian and others, previously mentioned, p. 45). Although such orogenic times, real or fancied, are no more than gross generalizations of many complex events, the names used for them are useful for expressing the general geological ages of the tectonic features.

SEDIMENTARY UNITS

GEOSYNCLINAL DEPOSITS

The older sedimentary units of the Phanerozoic foldbelts formed during the preorogenic phase of the tectonic cycle in geosynclines or troughs of accumulation that were much more extensive than those of the succeeding phases; various geosynclinal units are thus represented on the "Tectonic Map of North America." Nevertheless, the deposits and the troughs in which they formed are complex features; it is thus misleading to speak of a single Appalachian geosyncline or a single Cordilleran geosyncline. The nature of the deposits in one part of a geosynclinal trough varied with time, different segments of a single trough had contrasting histories, and quite different troughs developed through time in different parts of the longer foldbelts. Because of the small scale of the tectonic map, not all these complexities can be represented in the units that have been adopted.

In most of the foldbelts, a longitudinal subdivision can be made on the map between contrasting suites of deposits in the eugeosynclines and miogeosynclines. These terms, proposed by Stillé (1940), are now widely used for the features in question in Europe, North America, and elsewhere. They supplant the same author's earlier terms "pliomagmatic" and "miomagmatic" geosynclines (1936b), and correspond broadly to the terms "internides" and "externides" of some other authors—internal and external referring in this case to the parts of the foldbelts nearer to their central axes or farther away from them, rather than nearer to or farther away from the bordering cratons. (For a useful discussion of terms, see Knopf, 1960, p. 127–129; Kay, 1967).

As conceived by Stillé, the pliomagmatic or eugeosynclines were marked by strong volcanism during the early phases and by synorogenic plutonism during the later phases. Miomagmatic or miogeosynclines were more peripheral, with lesser magmatism and mobility, and were commonly little deformed until the orogeny in the adjoining eugeosynclines were nearly completed. The differences in magmatism and mobility have produced contrasting deposits—those of the eugeosynclines being principally submarine volcanics, cherts, slates, and graywackes; those of the miogeosynclines being principally carbonate rocks, quartzites, and shales.

Use of the terms "eugeosyncline" and "miogeosyncline" for these features creates the largely unwarranted implication that they were, in fact, separate geosynclinal troughs. This impression is enhanced by the fact that through lengthy segments of the foldbelts the two sets of deposits are separated by structural boundaries In many parts of the Appalachian foldbelt the two lie on opposite sides of a welt of basement rocks (the Long Range in Newfoundland, the Green Mountains and others in New England, the Blue Ridge farther south). In other places one set of deposits lies against, or is carried over the other set along major low-range thrusts (for example, the Taconic thrust in New York State, the Roberts thrust in Nevada), both sets consisting of sequences of nearly identical age span, but with radically different facies. In a few other places, however, transitional deposits can be traced from one into the other through the complex structures that were superposed on them later, relations which suggest that in general the two kinds of "geosynclines" were actually different parts of a single trough.

Many geologists have attempted to use the lithologic features mentioned as absolute criteria for distinguishing eugeosynclinal from miogeosynclinal deposits. In some areas the two kinds of deposits can be separated clearly by the lithologic criteria alone; nevertheless, the distinctions are blurred elsewhere, or deposits of the two kinds occur in different parts of the same sequence. Trümpy (1960, p. 899) describes the problems of nomenclature in the central and western Alps:

> Distinction between eugeosynclines and miogeosynclines * * * may be controversial. Volcanism cannot be used as the only criterion; the Triassic of the Dolomite Mountains is a good example of miogeosynclinal deposition with volcanic material, the Bündnerschiefer of the Prätigau exemplifies eugeosynclinal sedimentation without volcanism. Should Flysch formations be classed as miogeosynclinal or eugeosynclinal? They develop over mio- and eugeosynclines alike; they have no volcanic materials, but conditions of relief and of contemporaneous mobility approach those of true eugeosynclines.

Clearly, the lithologic criteria are simply manifestations of the respective tectonic environments. Thus, distinctions between eugeosynclines and miogeosynclines, and between their respective deposits, must be made in broadest terms, after considering the gross history and pattern of the particular foldbelt.

These considerations were used in classifying the eugeosynclinal and miogeosynclinal deposits on the

"Tectonic Map of North America"; hence, the classifications made rely heavily on the judgment of the compiler, not only as to the history and nature of the different sequences, but as to what extent these require generalization in order to be shown on a map of this scale. Even so, a few sequences seem not to be clearly assignable to either category, and are labeled simply as "geosynclinal deposits." Where differentiation is made on the map, the two kinds of deposits are shown in different shades of color, the stronger shades being used for the eugeosynclinal deposits.

During the orogenic phases the eugeosynclinal and miogeosynclinal rocks were subjected to contrasting styles of deformation, resulting from their differing environments and rock compositions; these are reflected by the different kinds of symbols that are needed to represent their structures on the tectonic map. The eugeosynclinal rocks were deformed in a deep-seated environment to the accompaniment of much metamorphism and plutonism, and generally as a mass because their monotonous sequences contain few units of contrasting competence. The miogeosynclinal rocks were deformed in shallower environments, where their stratified units of contrasting competence were deformed disharmonically. The deformation was accomplished mainly by lateral thrust from the internal or eugeosynclinal parts of the foldbelts, assisted in places by gravitational forces. Deformation terminated rather abruptly along a structural front, where the thick miogeosynclinal sequences gave place to the thinner sequences in the craton or foreland.

It has thus come about that large parts of the eugeosynclinal rocks were plastically folded, with little or no breakage and few contemporaneous faults; most of their breakage was along high-angle faults that were superposed later. On the tectonic map the pattern of the folding in the eugeosynclinal areas is indicated by trend lines, although their culminations into broader anticlinoria and synclinoria are indicated by axial symbols. The miogeosynclinal rocks, by contrast, were deformed piecemeal, according to the competence of their stratified units. They were thrown into long, nearly parallel anticlines and synclines, commonly asymmetrical away from the internal part of the foldbelt, and were broken by low-angle to high-angle faults that were thrust in the same direction, all the structures at a given stratigraphic level being based on a surface of décollement in one of the incompetent strata. On the tectonic map the structures of the miogeosynclinal areas are thus represented by variously crowded folds and thrust faults, the anticlines being shown by spindle symbols whose width and spacing expresses the intensity of the deformation.

EUGEOSYNCLINAL DEPOSITS

Eugeosynclinal deposits occupy large areas in both the Appalachian and Cordilleran foldbelts (L3, L4, L5; O6, O7), and they also occur in the Innuitian, Pacific, and Antillean foldbelts (K1, P1, P2, Q2, Q4a). In the Ouachita foldbelt the early Paleozoic (pre-Mississippian) deposits have many eugeosynclinal characters, but these are overlain by a thick body of late Paleozoic flysch; because of the small outcrop areas of each, they are not divided on the map (M). The East Greenland foldbelt seemingly lacks eugeosynclinal deposits at least within the present limits of exposure.

As already implied, deformation began in the eugeosynclinal areas during the geosynclinal phase itself, and a succession of pulses led up to the orogenic climax. Some of these pulses are sufficiently prominent to warrant indication on the tectonic map. In the northern part of the Appalachian foldbelt the Cambrian and Ordovician eugeosynclinal deposits that were deformed by the Taconian orogeny (L3) are separated from the Silurian and Devonian eugeosynclinal deposits that were deformed by the succeeding Acadian orogeny (L4). In the Cordilleran foldbelt a separation is made between older eugeosynclinal rocks that were deformed by several Paleozoic orogenies (O6) and the younger eugeosynclinal rocks that were deformed only by the middle Mesozoic (Nevadan) orogeny (O7). However, in parts of the eugeosynclinal areas regional metamorphism has been so great that the stratigraphic record is lost; here, the only indication of multiple orogenic pulses is afforded by a scatter of radiometric dates, and the rocks and areas affected by these pulses cannot be separately mapped.

MIOGEOSYNCLINAL DEPOSITS

The miogeosynclinal areas are those parts of the geosynclines nearest the cratons. The deposits of the miogeosynclinal and cratonic areas are much alike, except that the sequences in the former are thicker and more complete. In many places, the boundaries between the two sequences were suffiiciently fixed through time as to suggest that a hinge line of structural origin had been established there early in the tectonic cycle, and persisted later. Thus, the edges of the miogeosynclinal areas in many parts of the Appalachian and Cordilleran foldbelts are marked by a wedging out of the Lower and Middle Cambrian deposits, so that Upper Cambrian or even younger deposits were the first laid down on the adjacent craton; moreover the position of this wedge-out corresponds closely to that of the wedging out or thinning of many of the succeeding units. Nevertheless, the boundaries between the miogeosynclinal and cratonic areas fluctuated somewhat with time, making it difficult to draw a firm line between them or the tectonic map. On the map, the contact is arbitrarily shown in most places at the outer limit of strongly folded and faulted rocks, on the assumption that this change in style of deformation was caused by a change from a thick to a thin column of sediments. Boundaries drawn on such structural criteria do not necessarily correspond to boundaries indicated by stratigraphic criteria; very likely some miogeosynclinal rocks that escaped deformation are shown as cratonic on the map, and some cratonic rocks that were deformed are shown as miogeosynclinal.

The sequences in the miogeosynclinal areas are generally conformable. Most gaps in the record are along surfaces of disconformity; in only a few places are there angular discordances produced by significant deformation prior to the final orogeny. Nevertheless, miogeosynclinal deposition was much influenced by orogenic events that were taking place in the adjoining eugeosynclinal areas. In many miogeosynclines, initial quartzose clastics are followed by thick masses of carbonate rocks, indicative of general crustal quiescence. These are succeeded, however, by wedges of clastic rocks that taper away from the eugeosyncline, across the miogeosyncline and onto the craton, the first clastics being fine-grained and marine, the latter coarse-grained, largely continental, and partly coal bearing. The fine-grained clastics are probably related to the beginnings of orogeny in the eugeosynclinal area, the coarse-grained clastics to the orogenic climax or to postorogenic phases.

The successive units in the miogeosynclinal sequences are "structural stages" in the sense of European geologists, the upper clastic units corresponding to their "flysch" and "molasse." It has even been claimed that "flysch" and "molasse" are invariable sedimentary products of orogenies, hence that where they are absent there could have been no orogeny. However, the meanings of "flysch" and "molasse" in this broad sense are so ambiguous that in the present account the deposits which have been so called are mostly referred to in other terms. It would seem desirable to restrict "flysch" and "molasse" as far as possible to their original meanings.

Where first used in the Alps of central Europe, "flysch" and "molasse" apply to distinctive rock-stratigraphic units that are related to the tectonic evolution of the area. The original "flysch" is a sequence of distinctively interlayered sandstones, mudstones, and marls that seemingly accumulated in relatively narrow, deep, rapidly subsiding troughs. Nearly identical deposits occur elsewhere in the world (including the Appalachian and Ouachita foldbelts of North America), but large parts of the fine-grained clastic wedges of the miogeosynclinal sequences have few of the characteristics of "flysch." The original "molasse" is a less distinctive younger sequence of marine and brackish water sandstones, with some layers of gravelly or bouldery conglomerate ("nagelfluh"). Elsewhere, "molasse" has been used indiscriminately for almost any kind of postorogenic deposit, such as shallow-water marine sandstones and limestones, coal measures, red beds, or the terrestrial gravel filling of intermontane basins—thus depriving the term of any specific meaning.[8]

Many of the miogeosynclinal areas in North America have sequences of the sort described, although their age spans vary widely from one foldbelt to another. In the Appalachian foldbelt miogeosynclinal deposition (L6) began in the Cambrian or even earlier; carbonate deposits were succeeded by fine-grained clastics as early as the Middle Ordovician in some places and as late as the Silurian and Devonian in others. In the Rocky Mountains of Canada and in parts of the Great Basin of the United States, miogeosynclinal deposition (O9) began as early as in the Appalachians, but carbonate deposits were not succeeded by fine-grained clastics until Triassic time or later. In eastern Mexico the span of miogeosynclinal deposition (O9) was entirely in the Mesozoic; the carbonate deposits are Jurassic and Lower Cretaceous, and the fine-grained clastics are Upper Cretaceous.

Not all the miogeosynclinal deposits in North America have so ideal a sequence of units. In some, carbonate deposits and clastic wedges are repeated, in others clastic wedges overlie cratonic deposits with the first half of the geosynclinal sequence unrepresented, in still others the lithologies of all the subdivisions differ from any of those described. In the Great Basin of eastern Nevada, for example, Cambrian to Devonian carbonates are followed by a middle Paleozoic clastic wedge derived from the Antler orogenic belt to the west, which is topped in turn by upper Paleozoic carbonates.

Comment has already been made (p. 11, 20) on the difficulty of mapping "structural stages" or other rock units in strongly deformed areas, and this applies with special force to the miogeosynclinal belts. On the "Tectonic Map of Mexico" (de Cserna, 1961) on a scale of 1:2,500,000, units of miogeosynclinal deposits like those in the ideal sequence described above are separately mapped, but this is much less feasible of the "Tectonic Map of North America" on half the scale, either for Mexico or elsewhere (figs. 5 and 6). These difficulties are multiplied in the more complex sequences that have been cited. Consequently, on the "Tectonic Map of North America" the miogeosynclinal deposits in each foldbelt are shown as single units, thus grossly general-

[8] Some European geologists have attempted to provide for these alleged varieties of "molasse" by using the word in a plural form, but this has ridiculous connotations when transferred to American English. Thus, "intermontane basins filled with molasses" would mean, to us, filled with the thick sugary syrup with which we sweeten our corn bread or pancakes!

izing their many details of composition and age; however, some explanation of these details is given in the captions of the legend.

METAMORPHISM OF GEOSYNCLINAL DEPOSITS

In many of the Phanerozoic foldbelts of North America the geosynclinal rocks have been metamorphosed to varying degrees, especially in the eugeosynclinal areas; the rocks that are strongly metamorphosed are distinguished on the tectonic map by an overprinted pattern in red from those that are weakly metamorphosed or unmetamorphosed. In places, the strongly metamorphosed rocks pass along the strike into little metamorphosed rocks. Metamorphism thus increases southwestward in the eugeosynclinal rocks of the Appalachian foldbelt, and a boundary is indicated in northern New England that is determined by the garnet isograd; this is not a stratigraphic boundary, because units of equivalent ages extend across it from the little metamorphosed into the strongly metamorphosed rocks. Outside of New England, regional data on the metamorphic grades of the geosynclinal rocks are so incomplete that portrayal of the strongly metamorphosed rocks has had to be done on a relative basis, and is probably inconsistent from one area and from one foldbelt to another.

The regional extent of metamorphic rocks of different grades in North America is now being studied by geologists of the U.S. Geological Survey and Geological Survey of Canada, as part of a project for the "Map of the Metamorphic Rocks of the World," so that great improvements in representation of metamorphic rocks on tectonic maps can be anticipated at a later time.

In parts of the Cordilleran foldbelt additional units are distinguished as metamorphic complexes (O1). In the northern Cordillera of Canada and Alaska they generally occur in the median part of the foldbelt. In the far south they form much of the Sierra Madre del Sur along the Pacific coast of Mexico and extend eastward into Guatemala and Honduras. Earlier geologists interpreted these complexes as an Archean protaxis separating geosynclinal deposits on the two sides, but the ages of both the original rocks and their metamorphism have since been variously interpreted. Stratigraphic evidence indicates that some of the complexes are older than less metamorphosed Mesozoic or Paleozoic rocks, hence probably include Precambrian, yet they have yielded many radiometric ages as young as 150 m.y. or less, indicating a long-persistent plutonic and metamorphic activity, a late uplift and unroofing, or both. Whatever the ages of the original rocks in the metamorphic complexes, and their subsequent histories, they probably were formed by prolonged burial at great depths in the crust.

Metamorphic complexes are also indicated on the map in the Antillean foldbelt (Q1), especially in the islands of Cuba, Jamaica, and Hispaniola. These complexes are older than the oldest dated units of the Mesozoic stratified sequence, but they very likely include early Mesozoic eugeosynclinal deposits.

DEPOSITS OF SUCCESSOR BASINS

In the internal parts of many of the Phanerozoic foldbelts the eugeosynclinal deposits are succeeded by deposits that were laid down in more restricted basins, during the orogenic phase and the early part of the postorogenic phase; they generally overlie rocks that were much deformed by the first strong orogenies of the foldbelt. The extent and preservation of such deposits vary greatly from one foldbelt to another and from one segment to another. Originally, they were probably laid down widely in most of the foldbelts, but they have since been lost in many places by deep and prolonged erosion.

For the areas in which these deposits accumulated the term "successor basins" is used here and on the legend of the "Tectonic Map of North America." Some of them, notably the area of late Paleozoic deposits in the Maritime Provinces of southeastern Canada, were called "epieugeosynclines" by Kay (1951, p. 56–57), but this term seems overly complex, and elsewhere Kay has used it for features somewhat different from those here discussed. The "successor basins" of Alaska have been called "geosynclines" (Gates and Gryc, 1963, p. 269–272), but they are much less extensive and much more interrupted by nondepositional areas than the true geosynclines that preceded them.

In the Appalachian foldbelt the deposits of successor basins are late Paleozoic (chiefly Mississippian and Pennsylvanian) (L7), and are extensively preserved in the Canadian Maritime Provinces. Smaller outliers occur in Newfoundland and New England but they are unknown farther southwest. They were laid down after the climactic middle Paleozoic (Acadian) orogeny, but they were in part much deformed by later orogenies (L7a). Triassic deposits (L8) extend for much of the length of the foldbelt; they are postorogenic and were tilted and block-faulted rather than folded. In the Cordilleran foldbelt successor basins form nearly half of the interior of Alaska; they are large but more separated in Yukon Territory and British Columbia. Their deposits are late Mesozoic (latest Jurassic and Cretaceous) (O10), and although much deformed are younger than the climactic middle Mesozoic orogenies. In the western United States such deposits are preserved in the interior of the foldbelt only in patches too small to map, but extensive contemporaneous deposits occur to the east and west and are differently classified. In southern

Mexico the early Tertiary "red conglomerates" have tectonic affinities to the late Mesozoic deposits of successor basins farther north, but they are mapped with the younger basinal deposits (O11). The Innuitian foldbelt of the Arctic Islands is partly covered by upper Paleozoic, Mesozoic, and Tertiary deposits of the extensive Sverdrup basin (K3), and small basins of Devonian deposits occur in the East Greenland foldbelt (J3).

The deposits in the successor basins in many places attain thicknesses of 4,500–9,000 m (15,000–30,000 ft), but mostly represent localized, rapid sedimentation. All of them include fine to coarse debris derived from previously deformed older rocks of the surrounding highlands, and some of them include granite clasts from nearby plutons that were emplaced only a little earlier. Marine deposits are more restricted or intermittent than earlier, and brackish water or continental deposits are correspondingly more extensive. Some areas, such as the New Brunswick basin of the Appalachians and the Sverdrup basin of the Arctic, contain evaporite beds that have been deformed into domes and other diapir structures. Most of the sequence in the successor basins in Alaska is poorly sorted graywacke, with much volcanic debris and a few thin to thick interbedded lavas. The marine sequence is longest and least interrupted in the Sverdrup basin, but its deposits have many resemblances to those of a coastal plain; the basin was probably open on the northwest toward the Arctic Ocean (Tozer, 1961, p. 400).

YOUNGER BASINAL DEPOSITS

Several classes of younger sedimentary rocks are shown in some of the foldbelts on the "Tectonic Map of North America." Basinal deposits of Tertiary age, mainly marine and in part very thick, characterize the Pacific and Antillean foldbelts (P4, Q4). Most of them were moderately to strongly deformed by orogenies during the Cenozoic. The well-known Tertiary sequence of the California Coast Ranges presents a record of shifting basins and uplifts, and of many local episodes of deformation that culminated during a few times of more general orogeny, the last one in the Pleistocene. The records in some of the other sequences, especially in the Antilles, are equally complex. On large-scale maps it would be desirable to divide these sequences into "structural stages," according to their variations in lithologic facies and their times of deformation, but on the small scale of the "Tectonic Map of North America" few subdivisions are possible.

Eugeosynclinal deposits that are distinctly different in nature and origin from the other early Tertiary deposits form areas large enough to map separately along the south coast of Alaska, in the Coast Ranges of Oregon and Washington (P2), and in parts of the Greater Antilles (Q4a). In the Greater Antilles, where orogeny was largely completed during the early part of the Tertiary, postorogenic deposits (Q5) are shown in a separate category.

THICK DEPOSITS IN STRUCTURALLY NEGATIVE AREAS

Another class of younger sedimentary rocks includes the terrestrial deposits of Pliocene and Pleistocene age (O12) which attain great thicknesses in areas of late downwarping and downfaulting in the Cordilleran foldbelt. The class does not include river alluvium, terrace deposits, or glacial drift, which cover the bedrock thinly in parts of the foldbelt; such deposits have no tectonic significance and are not shown on the map.

In the Basin and Range province of western United States and northern Mexico the older rocks of the foldbelt and the adjacent craton were disrupted by blockfaulting during the latter part of Cenozoic time, and the basins between the ranges were filled with erosional debris. These deposits interrupt the continuity of the earlier structures in the adjacent ranges, and the bedrock beneath them is generally unknown and unmappable. Representation of the deposits on the map serves further to indicate the pattern of the very late ("neotectonic") deformation that was superposed on previous Cordilleran structures.

In central Alaska, much broader plains are interspersed between the mountain ranges, one of the largest being Yukon Flats on the upper course of the Yukon River. These are thinly to thickly mantled by Pleistocene and perhaps older Cenozoic deposits. The plains are partly of erosional origin, as indicated by bedrock hills that project through the cover here and there, but to some extent they are products of late crustal downwarping, hence deserve representation as tectonic features.

Other thick late Cenozoic deposits are shown on the map by the same pattern in the Pacific, Antillean, and Andean foldbelts (P5, Q6, N5). Some of those were laid down in intermontane basins like those in the Cordillera, others accumulated on narrow coastal plains. Parts of the deposits are terrestrial and resemble those in Cordillera, but they include marine units, especially near the coasts. In Central America and some other places the deposits include large volumes of pumice derived from surrounding volcanic areas, and in the coastal areas of the Antilles they include uplifted limestone reefs and banks.

VOLCANIC UNITS

Volcanic rocks form large and complex suites in all the foldbelts. During the early phases of the tectonic cycle thin to thick masses of submarine volcanics were erupted in the eugeosynclinal areas. Their presence here is implicit in the definition of eugeosynclines and they are not separated from the other eugeosynclinal deposits on the tectonic map, except for those of early Tertiary age in Oregon and Washington (P2a), which are areally extensive. Volcanic rocks that formed during the late phases of the tectonic cycle are mostly not preserved in the older Phanerozoic foldbelts, if they ever existed there, but they are areally extensive in the younger ones. During these late phases, terrestrial volcanic rocks were spread widely in the Cordilleran, Pacific, and Antillean foldbelts, over rocks that had been deformed during the climactic orogenies. Most of the volcanism in these foldbelts occurred during Tertiary time; it began during the Cretaceous in places and has continued through the Quaternary in others.

The later terrestrial volcanic rocks pose various practical problems of representation on the "Tectonic Map of North America." On the one hand, they are merely an inconvenient cover which interrupts the continuity of the older dominant structures of the foldbelts, and in the more extensive volcanic fields masks them entirely. In these more extensive volcanic fields, as in the northwestern conterminous United States and in western Mexico, they must be shown if only to indicate that the underlying rocks and structures are unknown. On the other hand, many small volcanic patches have been omitted. Between these extremes are numerous areas about which arbitrary decisions regarding representation have been made, as in medium-sized volcanic fields, and in the innumerable small remnants of once extensive fields that are now broken up by faulting, folding, and erosion.

These later terrestrial volcanic rocks also pose many problems of tectonic interpretation and subdivision. Certainly all of them have tectonic significance, but this significance is not always known or understood. A tectonic significance is most apparent for plateau basalts that were products of fissure eruptions, for ignimbrites (ash-flow tuffs) that were spread widely as clouds of incandescent glass, and for andesites that were built into eruptive mountain ranges and chains of volcanic cones, mainly near the continental borders. A tectonic significance is less obvious for the heterogeneous volcanic sequences that are extensive in many parts of the continent and are unclassifiable at present. Even when the theoretical significance of one of the classes of volcanic rocks is known, only fragmentary information on its areal extent is usually available.

However, the extent of the plateau basalts is well known in the Cordilleran foldbelt of Oregon, Washington, and British Columbia (Pγ), as well as in Greenland, Iceland, and Baffin Island (Eβ). The last three occurrences are here classed with the platform deposits and have been described under an earlier heading (p. 27–29). Aside from the plateau basalts, lack of data precludes differentiating the volcanic rocks as to kind or origin. Lack of differentiation is partly compensated by the use of symbols on the map to represent volcanic cones, calderas, and other volcanic structures.

The principal separation among the volcanics that is made on the Tectonic Map of North America is between the extensive areas that are mainly of Tertiary age (Oμ, Pδ, Qδ) and the more restricted ones that are mainly of Quaternary age (Oπ, Pϵ, Qϵ). The latter seemingly deserve differentiation on the map because they indicate volcanic activity along lines of very late crustal rupture. Rocks of Quaternary age form the volcanic fields of the Snake River Plain in Idaho and of the Transverse Belt of southern Mexico, both of which extend across the earlier Cordilleran structures. They also form volcanic chains parallel to the prevailing structure in the Cascade Range of Oregon and Washington, along the Pacific coast of Central America from Guatemala to Costa Rica, and in the island chains of the Aleutians and Lesser Antilles. As previously noted (p. 29), another belt of Quaternary volcanics extends across the center of Iceland (Eγ).

PLUTONIC UNITS

Embedded in the geosynclinal deposits of the Phanerozoic foldbelts are various kinds of plutonic rocks especially in the internal or eugeosynclinal zones that were deformed in deep-seated environments. They were emplaced by various combinations of magmatic, metasomatic, and tectonic activity as an integral part of the tectonic cycles that produced the foldbelts.

GRANITIC ROCKS

Granites and related felsic plutonic rocks occur in large volume in the internal zones of all the foldbelts, and are extensively exposed in most of them. They exhibit the widest variety of form, structure, and relation to the country rocks in which they lie—from migmatitic permeations, through discrete but still concordant bodies, to massive, thoroughly discordant bodies. The compiler regards all these as parts of a granite series in the sense of Read (1957, p. 374–375), or parts of a single evolutionary sequence resulting from progressive mobilization of crustal material during the preorogenic, orogenic, and postorogenic phases of the tectonic cycle. However, the subject of the granitic rocks has many more ramifications and problems then can be covered in this brief outline of the concept, and most of these are beyond the scope of this account. Moreover, some geologists have challenged the concept itself in many particulars (for example, Gilluly, 1963, p. 164–167; 1965, p. 23–25; Hamilton and Meyers, 1967, p. 17–23). On the "Tectonic Map of North America" it has not been possible to distinguish the different structural varieties of the granite series, partly because of the scale of the map, partly because of lack of adequate regional data.

Granitic rocks are extensively exposed in the internal zones of the Appalachian foldbelt (Lδ, Lϵ), and to a smaller extent in the East Greenland, Innuitian, and Antillean foldbelts (Jα, Kα, Qβ); none are exposed in the Ouachita foldbelt, whose internal zone is concealed, but there is some suggestion of their existence from subsurface data. By far the most extensive exposures (and probably also the greatest volume) of granitic rocks occur in the internal zone of the Cordilleran foldbelt throughout its length from Alaska to Central America (Oϵ, Oθ).

Most of the granitic rocks were emplaced during or shortly after the main orogenies of the foldbelts, but radiometric dating and some stratigraphic evidence indicates that the time of emplacement was more prolonged than previously supposed. In the Appalachian foldbelt the main emplacement was during the Devonian (Lδ), but some granitic bodies are as old as Ordovician and others as young as Carboniferous; the White Mountain alkalic rocks in northern New England are early Mesozoic (Lϵ), and the small hypabyssal intrusives of the Monteregian Hills in southern Quebec are Cretaceous (Lθ). In the Cordilleran foldbelt some granitic bodies in Alaska, Canada, and Mexico are of proved Paleozoic age, but the greater part is Mesozoic. The Mesozoic batholiths in the Cordillera have been shown by detailed study to be internally complex in both composition and age, and to consist of many discrete plutons that were emplaced over a long period. The rocks of the Sierra Nevada batholith in California vary from west to east from quartz diorite to granite and from Middle Jurassic to middle Cretaceous, but also include some late Triassic plutons on the east (Kistler and others, 1965). The Coast batholith of British Columbia has similarly been found to be a complex of plutons ranging from mafic to felsic and from early Mesozoic to Tertiary in age, with many included shreds and ghosts of the original country rocks (Roddick, 1966).

It is questionable whether representation of details of the age and composition of the granitic rocks would serve a useful purpose on the "Tectonic Map of North America," even were complete data available. These are facts of historical geology which are more appropriate on areal geologic maps, or on tectonic maps of larger scale. On the tectonic map, the granitic rocks shown separately from the rest are those of markedly different age, such as those of early Mesozoic age in northern New England (Lϵ), and those of Paleozoic age in the Cordillera (Oϵ).

However, in the Cordilleran, Pacific, and Antillean foldbelts intrusive and plutonic rocks of Tertiary age are separately shown (Oλ, Pβ, Qγ). They have a wide range of structures, composition, and age, but are generally of such small dimensions that a more detailed representation is not possible on the map. Many of them are plugs, laccoliths, and other hypabyssal bodies, but a few are deep-seated plutons that approach the dimensions of those of Mesozoic time. Most of the larger bodies were emplaced in the early part of Tertiary time, hence have been referred to as "Laramide," but a few of them in northern Washington, southern British Columbia, and elsewhere are as young as middle Tertiary.

The Tertiary intrusives of the Cordilleran foldbelt extend well to the east of the plutonic bodies of Mesozoic time, across the miogeosynclinal area, and into the reactivated parts of the craton beyond. Large granitic plutons of early Teritiary age occur, for example, in some of the uplifts of the Southern Rocky Mountains, where they have risen to their present position through the Precambrian basement. Plutons of this kind have had no apparent direct relation to any generation of magma in the eugeosynclinal area. Stillé has ascribed them to "allochthonous synorogenic plutonism fed by lateral migration of sialic magma" (Knopf, 1960, p. 131), but this seems inherently unlikely. They are more likely autochthonous, and were derived from deep levels of a crust that had been weakened and broken by many orogenic events.

MAFIC PLUTONIC ROCKS

Many of the granitic rocks of the foldbelts have more mafic phases, and there are occasional discrete plutons of gabbro, diorite, and other rocks which are either contemporaries of the dominant granitic plutons or of slightly earlier ages. On the tectonic map most of these are not separated from the granitic rocks, but a few in the Appalachian and Cordilleran foldbelts occupy sufficiently large areas to warrant separate representation (Lγ, Oδ).

ULTRAMAFIC ROCKS

A very different class of plutonic rocks from any of the others comprise the ultramafics—peridotites, dunites, and others, now widely serpentinized. They form small but numerous bodies in the Appalachian foldbelt (Lβ) and much larger masses in the Cordilleran, Pacific, and Antillean foldbelts (Oγ, Pα, Qα). The ultramafic bodies in the Appalachians are small pods and lenses that form clusters and chains in the metamorphic bedrock of the internal zones. Many of the large bodies in California and Cuba are thick, gently dipping sheets at the bases of thrust plates. Most of those in Guatemala and some in California are nearly vertical tabular bodies lying between high-angle transcurrent faults.

Most geologists have ascribed a significant role to the ultramafic rocks in the tectonic processes, but opinions as to what this role might be have fluctuated from year to year and from geologist to geologist. A formerly appealing interpretation was that they were intruded into the geosynclinal rocks near the central axis of the foldbelt during the first downwarping of the tectogene beneath it (Hess, 1939, p. 270–271), but this interpretation has lost plausibility along with the tectogene hypothesis itself. Many Mediterranean geologists are convinced that ultramafic rocks were extruded as magma on the sea floor of the eugeosynclines during their early phases, but no North American examples of such magmatic extrusions have been proved. It now seems clear that few, if any, of the ultramafic rocks in the North American foldbelts arrived as magma in the positions which they now occupy, rather that they were emplaced tectonically as cold, nearly solid bodies, their movement being facilitated by slippage along their serpentinized parts. Such bodies may originally have been intruded as magma into rocks at lower levels of the crust, or they may be wedges or slabs of the underlying mantle itself, carried tectonically high above their place of origin (Hess, 1966, p. 5–6).

DESCRIPTION OF FOLDBELTS

The tectonic features of the different foldbelts of Phanerozoic age in North America are reviewed below, in clockwise order around the continent, and in general from oldest to youngest. The descriptions deal solely with surface and near-surface rocks and structures of the kinds which can be shown appropriately on a tectonic map, and emphasis is given to the means of so representing them. The surface and near-surface rocks and structures of the foldbelts involve many other facts and problems which are not treated, and for which there is a voluminous literature. Further, no mention is made of the structure of the deeper crustal layers and their attendant geophysical problems, even though these would contribute greatly to a full understanding of the tectonics of the foldbelts; the place for these subjects is on other maps and in other publications.

(K) INNUITIAN FOLDBELT

The Innuitian foldbelt extends across the northern part of the Arctic Islands of Canada, and into Peary Land of northern Greenland (Thorsteinsson and Tozer, 1961, p. 346–349). Its eastern and western ends plunge beneath the Arctic Ocean, and its western end (in Prince Patrick Island) is also overlapped by Mesozoic and Tertiary strata. How much farther westward it continues is uncertain; it may be related to the early Paleozoic structures of the core of the Brooks Range in northern Alaska.

The Innuitian foldbelt developed from the Franklinian geosyncline (Thorsteinsson and Tozer, 1961). In the Arctic Islands, a miogeosynclinal belt borders the Canadian Shield and its platform cover, forming the Parry Islands (Melville and Bathurst Islands) and extending most of the length of Ellesmere Island. It contains a sequence as much as 6,000 m (20,000 ft) thick of Ordovician to Upper Devonian strata, mainly carbonates, but with minor clastics and evaporites (K2). In the Parry Islands these are thrown into long symmetrical east-west folds beautifully displayed on aerial photographs, the deformation being later than the Devonian and earlier than unconformably overlying Middle Pennsylvanian rocks (K3a).

The continuity of the miogeosynclinal structures is interrupted in Cornwallis and nearby islands, where the older miogeosynclinal strata (K2a) were folded between Silurian and Middle Devonian time, mainly along north-south axes that were probably draped over an extension of the Boothia uplift, which projects toward the area from the Canadian Shield (Kerr and Christie, 1965, p. 919).

A eugeosynclinal belt extends across northern Ellesmere Island and into the northern tip of Axel Heiberg Island. Its boundary with the miogeosynclinal belt is displayed only in eastern Ellesmere Island, where carbonates give place northwestward to graptolite shales and other clastics; elsewhere the boundary is concealed by the younger strata of the Sverdrup basin (see below). The eugeosynclinal rocks are as thick or thicker than the miogeosynclinal rocks, and in northern Ellesmere Island they are graywackes, shales, volcanics, with minor amounts of carbonates, all variably metamorphosed (K1 and K1a); they have yielded a few Ordovician and Silurian fossils. Schists and gneisses at the base may extend the sequence downward into the Proterozoic. The time of deformation of the eugeosynclinal rocks is uncertain; the deformation was earlier than the overlying Pennsylvanian, and it may have produced the clastics which occur in the Middle and Upper Devonian of the miogeosynclinal sequence. There are a few embedded granitic plutons (Kα), probably of Paleozoic age.

Less is known about the extension of the foldbelt into Peary Land, as it has been crossed by only a few ground traverses. Its rocks are clastics, with some carbonates and possible volcanics, that become increasingly metamorphosed northward; all are shown as eugeosynclinal (K1) on the tectonic map, but with doubt. Open folds at the edge of the craton are succeeded northward by more complex structures, including low-angle thrusts that are strangely directed northward, away from the craton. Some southward-directed thrusts occur in the western segment, which are thought to result from superposed Tertiary deformation (Haller and Kulp, 1962, p. 33). The time of deformation in Peary Land is uncertain, except that it is older than the overlying Middle Pennsylvanian. Long after the deformation, the foldbelt was split by longitudinal faults which raised the northern part as a horst.

In the northwestern Arctic Islands the core of the Innuitian foldbelt is concealed by upper Paleozoic, Mesozoic, and lower Tertiary (Paleocene or Eocene) strata in the extensive Sverdrup basin (K3a,-b-c)—one of the "successor basins" discussed above. These strata attain a thickness of 9,000 m (30,000 ft) in the eastern part of the basin, without any interruption by structural unconformities. The Pennsylvanian and Permian part of the sequence includes carbonates and evaporites, but the much thicker Mesozoic strata are mainly sandstones and shales. Sedimentation during Mesozoic time may have resembled that during Cenozoic time along the Gulf Coast, vast amounts of detritus being delivered by streams draining the continental interior—streams which were prograded toward the bordering sea, in this case the Arctic Ocean (Tozer, 1961, p. 400; Tozer and Thorsteinsson, 1964, p. 216–218). To complete the analogy, the evaporites in the lower part of the sequence have risen through the higher strata as domes and diapirs like those on the Gulf Coast (Thorsteinsson and Tozer, 1961, p. 355–356). The strata of the Sverdrup basin are little deformed in its western part, but are sharply folded and thrust in the eastern part, in Axel Heiberg and Ellesmere Islands; this deformation is a late feature, as it involves Tertiary beds at the top of the sequence. Many of the folds in this part of the basin trend north-south, and are perhaps on a posthumous extension of the older structures of the Boothia Uplift and Cornwallis Island.

Between Ellesmere Island and Greenland the Innuitian foldbelt is interrupted by the Kennedy and Robeson Channels whose straight-sided shores suggest a rift, probably produced by left-lateral faulting. The amount of lateral shift, if any, is difficult to prove, as the foldbelt crosses the channels at an oblique angle; nevertheless, the front of the foldbelt in Greenland is 225 km (140 miles) northeast of the front in Ellesmere Island.

(J) EAST GREENLAND FOLDBELT

The East Greenland foldbelt nearly converges with the Innuitian foldbelt at the northeastern corner of Greenland, and the two probably meet at an acute angle off the coast. From there the East Greenland foldbelt extends southward to Scoresby Sound at the 70th parallel, where it plunges under the Tertiary plateau basalts (Eβ); it does not reappear farther south, and presumably is cut off at the edge of the continental shelf. The exposed part of the foldbelt is 1,400 km (750 miles) long and as much as 300 km (160 miles) wide. The complex rocks and structures were deciphered by the staff of the Danish East Greenland Expeditions, under the direction of Lauge Koch, and have been ably summarized and interpreted by Haller in several publications (Haller, 1961a, b; Haller and Kulp, 1962, p. 31–61; Haller, 1968).

The East Greenland foldbelt, like the Innuitian foldbelt, is mainly an early Paleozoic feature, and both have been called "Caledonian" in a broad sense (Haller and Kulp, 1962, p. 68–73); however, details of their character and history differ. The main bulk of its geosynclinal accumulation is a mass of Upper Proterozoic sediments as much as 16,000 m (50,000 ft) thick (the Eleanore Bay and Tillite Groups in the south, the Hagen Fjord Group in the north), which are followed nearly conformably by much thinner Paleozoic strata, mainly Cambrian and Ordovician, but topped by Silurian in the north. On the tectonic map, the whole geosynclinal assemblage is shown as a single unit (J2). In the legend the accumulation is simply referred to as "geosynclinal," but all of it is broadly of miogeosynclinal type; no deposits of truly eugeosynclinal type occur within the width of exposure of the foldbelt. The geosynclinal strata overlie a crystalline basement (J1), which emerges widely between the 76th and 80th parallels and forms smaller inliers to the south. In the north, this is composed of Middle Proterozoic rocks deformed by the Carolinidian (Grenville?) orogeny (fig. 11); farther south, it is earlier Precambrian.

Both the geosynclinal rocks and their crystalline basement were strongly deformed; the Silurian is involved in the north, hence the orogeny was Caledonian in the classical sense. During deformation, the supracrustal strata were thrust westward over the Greenland Shield and its platform cover. Thrusting is prominently displayed in Kronprins Christian Land north of the 80th parallel, where westward movement was as much as 40 km (24 miles). Farther south, the frontal thrusts are largely concealed by the icecap, but they emerge for short distances, as in Dronning Louise Land (76th to 77th parallels) and in Gaaseland west of Scoresby Sound (70th parallel). Except along its western edge,

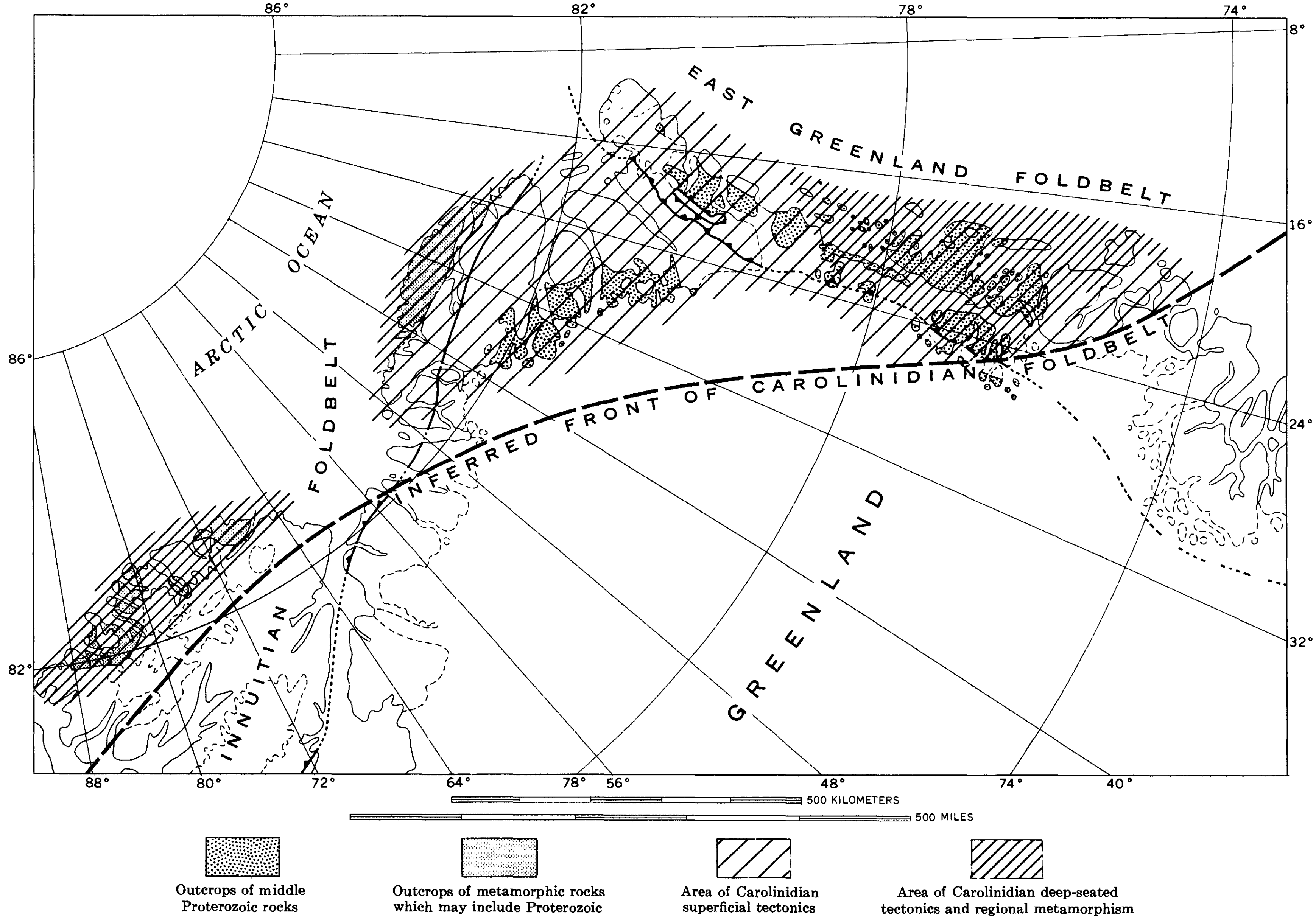

FIGURE 11.—Map of northeastern Greenland and adjacent areas showing inferred extent of the late Precambrian Carolinidian foldbelt, on which the Innuitian and East Greenland foldbelts were superposed during Paleozoic time. After Haller (1961b).

most of the foldbelt between the 70th and 76th parallels exposes deeper levels than farther north, and displays a highly mobile infrastructure (J2a), in which the Upper Proterozoic geosynclinal strata and their underlying basement have been migmatized and have flowed plastically into domes, recumbent folds, and mushroom-shaped bodies—all magnificently displayed on the steep walls of the fjords. It is surprising that such complex, deep-seated infrastructures should occur so near the foreland of the foldbelt.

Between the 72d and 74th parallels the Caledonian folded structures are overlain by Middle and Upper Devonian clastic deposits (J3), mostly red and continental and as much as 7,000 m (23,000 ft) thick; they have been called "molasse" and were deposited in "successor basins" as defined in this report. These strata were involved in a second orogeny at about the same time as the main deformation of the Innuitian foldbelt to the west; the orogeny has been called "young Caledonian," but it is contemporaneous with the Acadian orogeny farther south in North America. The surrounding pre-Devonian rocks, already thoroughly deformed by the Caledonian orogeny, were refolded and in part remobilized, along axes transverse to the earlier ones. On the tectonic map these younger superposed structures are shown as thin lines that extend across the earlier folds. Both the Devonian and the surrounding older rocks are invaded by late orogenic or postorogenic granite plutons (J*a*), which have yielded radiometric dates of 395 m.y.

Overlying all the earlier rocks and structures, especially near the coast, is a sequence of postorogenic Pennsylvanian, Permian, and Mesozoic formations (J4), capped in places by outliers of the Tertiary plateau basalts. The postorogenic formations have been little deformed, except by tilting and blockfaulting.

(L) APPALACHIAN FOLDBELT

The Appalachian foldbelt, which also formed mainly during Paleozoic time, is exposed for 3,700 km (2,000 miles) along the southeastern side of North America, from Newfoundland to Alabama. In the Canadian Maritime Provinces it is exposed to a width of 650 km (400 miles) and in Tennessee and North Carolina to a width of 400 km (250 miles); however, large parts of its original extent are now concealed by younger deposits, or submerged beneath the sea. Because of such concealment, it is nearly bisected near New York City. Northeastward, the Appalachian foldbelt runs out to sea along the coast of Newfoundland with no diminution in strength of deformation, and must surely continue to the edge of the continental shelf 100 km (60 miles) beyond. Its nearest counterparts in this direction are the Caledonian and Variscan foldbelts of the British Isles on the opposite shore of the Atlantic Ocean, from which it is separated by a wide expanse of oceanic crust. Southwestward, it plunges beneath the Mesozoic and Tertiary strata of the Gulf Coastal Plain in Alabama, again with no dimunition in strength of deformation. In the Atlantic Coastal Plain the southeastern part of the internal zone of the foldbelt is similarly covered by these younger strata.

The Appalachian foldbelt is notably more regular in plan than most of the others in North America, with fewer differences in structure from one part to another, and with fewer interruptions by superposed younger structures. Its longitudinal subdivisions maintain their identity for long distances. It pursues a sinuous course, and is divided transversely into a succession of salients and recesses, each salient being about 650 km (400 miles) long.

Nevertheless, as mentioned above, the exposed part of the foldbelt is nearly bisected at about mid-length near New York City; there are various contrasts between the two halves, some real, and some merely apparent. Geographically, the term "Appalachian Mountains" is thus commonly used only for the southern half, the highlands to the north being given other names. There is also a traditional belief that the northern half of the foldbelt is primarily an early Paleozoic feature and the southern half primarily a late Paleozoic feature. This has given rise to a concept, common in the European literature, of a "Variscan foldbelt" crossing westward over a "Caledonian foldbelt" near the place of bisection. The fallacy of this concept is now demonstrated by the nearly identical radiometric dates in the internal zones of both halves of the foldbelt (see p. 61). It has also been proposed (Drake and Woodward, 1963) that a fundamental zone of transcurrent faulting crosses the foldbelt near the place of bisection, extending inland from the line of Kelvin Seamounts in the Atlantic Ocean basin to the southeast. While there are geophysical indications of faulting along this trend in the ocean basin, neither geological nor geophysical data provide convincing evidence for through-going faults in the continent either at the surface or at depth—even though structural belts on the south are bent westward from corresponding belts on the north.

Whether superficial or fundamental, there are sufficient differences between the northern and southern halves of the Appalachian foldbelt to warrant separate treatment in the remainder of this account.

NORTHERN APPALACHIANS

In the northern Appalachians the front of the foldbelt nearly impinges on the Precambrian rocks of the Canadian Shield (or its outlier in the Adirondack uplift), with only a narrow foreland of Palezoic platform deposits (B) between. In southern Quebec the front of the foldbelt is the major low-angle thrust fault of Logan's Line, but frontal thrusts are discontinuous southward, and if present to the northeast are beneath the St. Lawrence Estuary.

Precambrian basement rocks (L1, Lα) emerge in the higher uplifts within the foldbelt itself, where they have been reworked by the Paleozoic orogenies. They are exposed in a chain of uplifts a short distance southeast of the front of the foldbelt, in the Long Range of Newfoundland, the Green Mountains and others of New England, and the Hudson River Highlands of New York State. They are exposed again in another chain of uplifts well to the southeast, in the Avalon Peninsula of Newfoundland, Cape Breton Island, southern New Brunswick, and perhaps in southeastern New England (although not there separated on the map from the Paleozoic plutonics, Lδ). The basement rocks to the northwest are extensions of the Grenville foldbelt and yield characteristic radiometric dates of about 1,000 m.y. Those to the southeast were all seemingly involved in the younger Avalonian event, and in Newfoundland at least yield radiometric dates of 600–550 m.y. The significance of the Avalonian rocks in the history of the northern Appalachians remains to be appraised, but in Newfoundland they may form the southeastern border of the Paleozoic foldbelt (Williams, 1964, p. 1155–1156; Poole, 1967, p. 19). In Newfoundland, the Holyrood Granite of the Avalonian basement is overlapped by fossiliferous Lower Cambrian, but in nearby areas a sequence of Upper Proterozoic strata (L2) as much as 12,000 m (40,000 ft) thick intervenes (Weeks, 1957, p. 145–147).

Miogeosynclinal deposits of Cambrian and Ordovician age (L6) are well displayed in western Newfoundland and from Vermont southward into Pennsylvania, but are absent, at least at the surface, through the central segment in Quebec. Although no more than 2,500 m (8,000 ft) thick, their sequence is thicker and more complete than that in the adjacent foreland; they are topped by younger Ordovician shales that are part of a clastic wedge which extends westward into the foreland, related to the late Ordovician Taconian orogeny. This orogeny is further expressed south of the Adirondack uplift by an angular unconformity between the Ordovician and the Silurian. Above the Silurian in the foreland to the west, from the Catskill Mountains southward, is a much thicker Devonian clastic wedge, coarse and continental toward the top, which reflects the Late Devonian Acadian orogeny within the foldbelt. Miogeosynclinal deposits of the same age as those on the northwest also occur on the southeastern side of the foldbelt in Newfoundland, where they are preserved in small patches on top of the Avalonian basement and the Upper Proterozoic strata, but both facies and faunas are more closely related to those in Europe than to those in the northwestern part of the Appalachian foldbelt.

Eugeosynclinal deposits of Cambrian to Devonian age form a large part of the remainder of the northern Appalachians. On the tectonic map they are divided into a Cambrian and Ordovician part (L3) and a Silurian and Devonian part (L4). They are further divided into an unmetamorphosed or weakly metamorphosed part which dominates to the northeast, and a strongly metamorphosed part (L3a, L4a) which dominates to the southwest, the boundary being placed at the garnet isograd.

Throughout the central segment in Quebec, Cambrian and Ordovician eugeosynclinal rocks extend to the front of the foldbelt, next to the shield and its narrow border of platform deposits. In the Taconic Mountains of New York State and in western Newfoundland, where Cambrian and Ordovician miogeosynclinal rocks form the front of the foldbelt, they are overlain with thrust contact by broad sheets of eugeosynclinal rocks of the same ages that were emplaced during early phases of the Taconian orogeny, probably by gravity sliding from the internal zone (Zen, 1967; Rodgers and Neale, 1963). Eugeosynclinal rocks of Cambrian to Devonian age form the central and greater part of Newfoundland, and are bordered not only on the northwest but on the southeast by Precambrian massifs with a thin miogeosynclinal cover (see above); (Williams, 1964). On the mainland of Nova Scotia, the eugeosynclinal rocks extend to the Atlantic coast, but probably formed in another depositional trough southeast of the belt of Avalonian basement (Poole, 1967, p. 18–19).

The eugeosynclinal sequences are generally thicker than the miogeosynclinal. In Vermont, they are dramatically so, the Cambrian and Ordovician changing from 2,500 m (8,000 ft) of miogeosynclinal deposits west of the Green Mountain uplift to 9,000–15,000 m (30,000–50,000 ft) of eugeosynclinal deposits east of it, where they are followed by 4,500–6,000 m (15,000–20,000 ft) of Silurian and Devonian (Cady, 1960, p. 541–544). Elsewhere thicknesses are variable; there may have been zones of uplift or volcanic chains along the sites of some of the present anticlinoria, although these are difficult to unravel because of subsequent deformation.

Parts of the Cambrian and Ordovician eugeosynclinal rocks were deformed during the Taconian orogeny before the succeeding strata were laid over them. Taconian folding seems to have been greatest along the northwestern border in Quebec, parts of which were not greatly deformed afterwards. These folded rocks are overlapped from the southeast by Silurian and Devonian shelf deposits (shown as miogeosynclinal, L6 on the map) which pass within a short distance into a thick eugeosynclinal sequence; here, the eugeosyncline had a two-phase history. A two-phase history is also evident in Newfoundland, where the Silurian, although containing volcanic components like the Ordovician, includes shallow-water arkoses, red beds, and conglomerates that contain clasts derived from the older rocks. Elsewhere in the eugeosynclinal part of the foldbelt, Taconian deformation is less obvious, and if present has been much obscured by later deformation; unconformities occur in places, and in New Hampshire the Silurian overlaps Ordovician plutons, but in places the sequence appears to be conformable from Ordovician into Silurian.

The greatest orogeny in the northern Appalachians was the Acadian, whose climax was during later Devonian time (Poole, 1967, p. 33–37). (There is no convincing evidence of a Caledonian orogeny in the classical sense, between the Silurian and Devonian.) From Maine northeastward, deeper downfolds preserve late Early Devonian continental plant-bearing beds lying conformably at the top of the eugeosynclinal sequence—beds which foreshadow the climactic orogeny. Deposits that succeed the orogeny are mostly Carboniferous, although in places they include the latest Devonian.

In Quebec and New England, Silurian and Devonian eugeosynclinal rocks are preserved in two deeply depressed synclinoria, separated by a median belt of anticlinoria that exposes the older Paleozoic—the Connecticut Valley-Gaspé synclinorium on the northwest and the Merrimack synclinorium on the southeast (not labeled on the map). Southwestward, the synclinoria become tightly compressed and the grade of metamorphism increases; in Connecticut schists and gneisses of the synclinoria and the intervening anticlinoria have been plastically folded into nappes of Pennine type. A third synclinorium forms most of the peninsula of Nova Scotia, southeast of the Precambrian massifs of Cape Breton Island and southern New Brunswick, but most of its rocks are Cambrian and Ordovician and the overlying Silurian and Devonian are minor.

Carboniferous deposits (with latest Devonian at the base in places, and some Permian at the top) (L7) accumulated in successor basins in many parts of the northern Appalachians, but most extensively in the Maritime Provinces. The largest, or New Brunswick basin, occupies more than half of that province, as well as Prince Edward Island and a large part of the floor of the Gulf of St. Lawrence. Farther southeast the basins are separated by massifs of Precambrian and older Paleozoic rocks, some of which stood as highlands during Carboniferous time. The first deposits of the basins (Mississippian) are partly marine, but the younger (Pennsylvanian) are largely continental, with workable coal measures. Degree of deformation varies. In the New Brunswick basin most of the surface rocks are nearly flat-lying, but there and elsewhere the sequence contains structural unconformities, and the degree of deformation increases downward; the rocks of some of the smaller basins are more folded, as shown by a separate symbol on the map (L7a). Configuration of the surface of the underlying basement that was consolidated by the Acadian orogeny is indicated on the map by 500-m contours.

Carboniferous deposits occupy smaller successor basins in western Newfoundland and southeastern New England, and while they overlie much deformed earlier rocks they are themselves more deformed than most of their counterparts in the Maritime Provinces. In the Narragansett basin of Rhode Island coal beds have been converted to graphite, and the southern end of the basin is intruded by late Paleozoic granite (Lϵ).

Upper Triassic rocks of the Newark Group (L8) form a downfaulted strip in the Connecticut Valley of New England, and another in the Bay of Fundy whose southeastern edge projects onto the shore of Nova Scotia; the latter strip extends southwestward into the Gulf of Maine, where its extent has been determined by geophysical means (the edge being shown by a dotted line on the map). The Triassic rocks are wholly postorogenic, unaltered, and merely tilted and block faulted; they are red beds and arkoses, with interbedded mafic lavas and related intrusives.

The Devonian and earlier eugeosynclinal rocks were little broken during the Acadian deformation, but they and the succeeding Carboniferous and Triassic rocks are traversed by many high-angle faults, most of which are grossly parallel to the grain of the foldbelt. These include the so-called Cabot fault of J. T. Wilson (1962), who proposed that this was a through-going fracture with left-lateral displacement, formed during Carboniferous time, that extended from Newfoundland through the Maritime Provinces into southeastern New England. It is true that there is an unusual concentration of high-angle faults of about this age in the places mentioned, but they form a zone as much as 100 km (60 miles) wide. None of the faults in the zone clearly persist for its whole length; some have proved left-lateral displacement, others right-lateral, whereas still others have only proved dip-slip displacement. The Triassic normal faults of the Bay of Fundy seem to be reactivations within the zone. The Triassic faults of the Connecticut Valley are a separate system farther west;

they include the Ammonoosuc normal fault of New Hampshire, once thought to be a west-dipping thrust.

Ultramafic rocks (Lβ) form pods and lenses in the Cambrian and Ordovician eugeosynclinal rocks on both the mainland and Newfoundland. In Newfoundland they lie in two belts, symmetrically placed on each side of a presumed central axis, but on the mainland they are concentrated in a belt on the northwest that extends, with interruptions, from Gaspé to southern New England. All of them are probably of Late Ordovician age; the thrust sheets of western Newfoundland that were emplaced as gravity slides during the Taconian orogeny contain ultramafic bodies that are rootless like the strata enclosing them.

Granitic rocks occupy parts of the site of the eugeosynclinal area, forming dispersed plutons to the northeast, but more extensive and more crowded plutons to the southwest. Both stratigraphic relations and radiometric dates indicate that they were emplaced during a prolonged period, from early Paleozoic into Mesozoic time. The earliest granitic rocks are pre-Silurian and probably mainly Late Ordovician. Early plutons have been identified in New Hampshire and Maine and others probably exist, but their known extent is too small to warrant separation from the younger Paleozoic granitic rocks on the map. The main assemblage of granitic rocks (Lδ) is of middle Paleozoic age, and yields radiometric dates of 350–400 m.y.; they are broadly contemporaneous with the Acadian orogeny, ranging from synorogenic to early postorogenic. A representative suite forms the New Hampshire Plutonic Series, but other series occur both in that state and elsewhere. Mafic plutonic rocks (Lγ), in part related to the dominant granitic rocks, form a few areas large enough to indicate separately on the tectonic map.

Younger granitic rocks are wholly postorogenic and are generally more alkalic than the earlier ones (Lϵ). They are exemplified by the White Mountain Plutonic Series of New Hampshire, which includes a spectacular array of ring dikes, some of which enclose remnants of supracrustal volcanics. The White Moutain Series is early Mesozoic, with radiometric dates of about 185 m.y., but the alkalic rocks farther south in New England are late Paleozoic. The oldest precede the Carboniferous deposits of the successor basins, but these deposits are themselves invaded by nonalkalic granite at the south end of the Narragansett basin.

The youngest intrusives of all, the Monteregian (Lθ), form a chain of stocks that extends eastward from Montreal (for which they are named) in the platform area into the outer edge of the foldbelt. They yield radiometric dates of about 110 m.y. and are of Cretaceous age.

SOUTHERN APPALACHIANS

South of its bisection near New York City, the Appalachian foldbelt is continuous on the surface to Alabama. Throughout this distance it borders the Paleozoic platform deposits of the craton to the northwest with a well-defined topographic and structural front, along which steep folds and prominent thrusts end abruptly, giving place to more open structures in the platform rocks beyond. On the tectonic map, this is shown as the edge of the miogeosynclinal deposits (L6), although stratigraphic data indicate that this edge is actually a broader, less well-defined zone.

Throughout the length of the southern Appalachians the miogeosynclinal rocks form a belt 65–130 km (40–80 miles) wide, expressed topographically by the Valley and Ridge province. The miogeosynclinal sequence, about 9,000 m (30,000 ft) thick, extends from Lower Cambrian to Pennsylvanian, the upper half (beginning as low as the Middle Ordovician in places) being largely clastic deposits derived from the southeast. Parts of the clastics (notably the Ordovician Martinsburg Formation) are typcial flysch laid down in deep longitudinal troughs (McBride, 1962, p. 87–88), but other parts are more varied and form wedges that taper across the miogeosyncline into the craton. Notable among the wedges is the great mass of Middle and Upper Devonian clastics in the northeastern half of the southern Appalachians, which are as much as 3,000 m (10,000 ft) thick at the apex, but which taper not only northwestward toward the craton, but southwestward along the trend of the foldbelt. Clastic deposits nearly as thick occur on the Middle and Upper Ordovician farther southwest, and in the Pennsylvanian of Alabama in the far southwest. Large parts of the clastics are marine, but they become continental higher up, especially in the Pennsylvanian.

The clastic deposits were derived from the erosion of uplifted and probably deformed parts of the interior of the foldbelt, and their maxima of different ages in different places suggest orogenic climaxes in adjacent segments of the internal zone; the Ordovician and Devonian maxima may be related to orogenies correlative with the Taconian and Acadian of the northern Appalachians. However, a large part of the thick Pennsylvanian clastics in the far southwest was probably related to orogeny in the impinging Ouachita foldbelt, now buried beneath the Gulf Coastal Plain to the south.

There are few breaks of any structural consequence within the miogeosynclinal sequence itself, and no strata lie unconformably above, hence the times of its deformation are inferential. The Pennsylvanian is preserved in places in the deeper downfolds in the miogeosynclinal belt, and the lowest Permian is conformable above the Pennsylvanian in the mildly folded part of the adjacent foreland, so that much of the deformation was late in Paleozoic time. This has been called the "Appalachian orogeny" (or "Appalachian Revolution"), but it is hardly Appalachian in a broad sense, and the more specific term "Allegheny orogeny" is more appropriate.

The structures of the miogeosynclinal belt—the classical "Appalachian structure" of American geology—includes long, parallel folds generally asymmetrical toward the northwest, which are broken by low- to high-angle faults that are thrust in the same direction (fig. 5*C*). Some of the thrust faults persist for great distances; the Saltville fault extends from Virginia to Alabama, and others are nearly as lengthy. Much of the structure is disharmonic so that the folds and faults overlie surfaces of décollement in various incompetent units low in the sequence; the underlying strata and the basement beneath are probably little deformed, or deformed in a different manner (Rodgers, 1953).

At the surface, the northeastern half of the miogeosynclinal belt contrasts with the southwestern, as the first is dominated by folds and the second by thrust faults—the faults so crowded in places that no intervening folds are preserved. Structures at depth are more alike in the two halves, surfaces of décollement being equally prominent in each. Wells drilled on the Nittany arch, the great culmination of miogeosynclinal folds in central Pennsylvania, passed through two or more thrusts within 1,500–3,000 m (5,000–10,000 ft) of the surface, and some of them ended in strata higher in the sequence than those in which they started.

Surfaces of décollement also extend out from the foldbelt into the adjoining platform deposits, and have determined much of the structure in this part of the craton or foreland. Near the common corners of Virginia, Kentucky, and Tennessee the Pine Mountain fault has moved a block of Carboniferous strata 200 km (124 miles) long and 40 km (25 miles) wide at the edge of the foreland for about 7 km (4 miles) northwestward along an incompetent shaly layer (Rich, 1934; and many later references). Less prominent but even more pervasive décollement surfaces of the same kind are now known from subsurface and outcrop data in the foreland of Pennsylvania, West Virginia, and Tennessee (Gwinn, 1964; Wilson and Stearns, 1958).

In Alabama, the miogeosynclinal rocks are separated from the crystalline rocks of the internal zone by the Talladega belt, a thrust slice about 200 km (125 miles) long made up of Paleozoic strata of a different facies, largely slaty below with fossiliferous Devonian cherts in the middle and plant-bearing Carboniferous above. This sequence is more like that in the Ouachita foldbelt (M) than any elsewhere in the Appalachians, and it is so represented on the tectonic map.

Through the remainder of the length of the miogeosynclinal belt northeast of Alabama, it is bordered on the southeast by the Blue Ridge uplift, which brings to the surface rocks beneath the Paleozoic miogeosynclinal deposits. The basement of the uplift is crystalline rocks that are outliers of the Grenville foldbelt (L1). Separating the basement from the Paleozoic are generally Upper Proterozoic supracrustal rocks (L2), mafic lavas to the northeast, nonvolcanic clastics to the southwest; the latter (Ocoee Series) are as thick or thicker than the adjoining Paleozoic miogeosynclinal sequence. The Upper Proterozoic rocks were little deformed before the orogenies of Paleozoic time.

At the boundary between the miogeosynclinal belt and the Blue Ridge uplift the structural style changes; the basement of the Blue Ridge is deformed with its cover and regional metamorphism is apparent. Toward the northeast the uplift is overfolded against the miogeosynclinal belt, but thrust faults develop southwestward along the border, carrying the basement and other rocks of the uplift northwestward over the miogeosynclinal rocks. In the Tennessee-North Carolina segment, much of the Blue Ridge uplift is allochthonous, as windows of the thrusts emerge as much as 65 km (40 miles) behind their leading edges. Southwest of Virginia the Precambrian basement rocks of the Blue Ridge uplift and their supracrustal cover are juxtaposed against the contrasting metamorphic and plutonic rocks of the Piedmont province to the southeast along the remarkably straight, narrow Brevard zone. Its principal structure is a high-angle fault, along which there are clear indications of a large component of right-lateral strike-slip displacement—including a nearly horizontal linear fabric, and inclusions of exotic rocks in the zone, far from any obvious sources (Reed and Bryant, 1964, p. 1192).

Besides the interpretation of the Brevard zone as one of strike-slip displacement, others are possible which are not necessarily incompatible. The compiler has compared the zone (and some similar ones in the same region) with the root zone of the nappes on the south flank of the Alps (King, 1950, p. 653), and has termed it a "dejective zone," thus implying a structure more fundamental than the mere surficial syncline postulated by earlier geologists (King, 1955a, p. 356). This interpretation has been further exploited by Burchfiel and Livingston (1967) who point out that the allochthonous Blue Ridge rocks northwest of it, like the nappes of the Alps, have no large, obvious source area; hence that this source area must have been pulled down and obliterated along the root zone. Credence is lent to this suggestion by the fraying out and disappearance of the Brevard zone to the northeast, at about the place where the Blue Ridge rocks cease to be allochthonous, and become part of an autochthonous uplift.

In the Piedmont province—the southeastern, eugeosynclinal part of the foldbelt—are supracrustal rocks younger than the Grenville basement, but their sequences and ages are enigmatic because of metamorphism, interruption by plutons, and a general absence of fossils. On the tectonic map they are indicated as undivided eugeosynclinal deposits, weakly to strongly metamorphosed (L5, L5a). In the Piedmont, the Grenville basement itself (L1) only comes to the surface in a cluster of mantled gneiss domes near Baltimore, Md.

So far as now known, the lower part of the sequence dominates in the northwestern part of the Piedmont province. It consists of very thick, nonvolcanic, clastic units, such as the Glenarm Series of Maryland and the Lynchburg Formation of Virginia; these much resemble the Ocoee Series of the southwestern part of the Blue Ridge uplift, and like it may be of Upper Proterozoic age (Hopson, 1964, p. 203–207). Higher units, many with large volcanic components, are infolded in the northwestern part of the Piedmont but dominate its southeastern part, especially in the Carolina Slate Belt; they contain a few Cambrian and Ordovician fossils at one place or another, and have yielded Ordovician radiometric dates elsewhere; whether other Paleozoic ages are represented is undetermined.

Most of the supracrustal rocks of the Piedmont province are regionally metamorphosed (L5a), and a metamorphic climax is attained (at least in North and South Carolina) in a sillimanite-almandine zone northwest of the slate belt (Overstreet and Bell, 1965, p. 54–57); this zone may have been the central axis of the foldbelt during some of the Paleozoic orogenies. Rocks of the Carolina Slate Belt itself are only weakly metamorphosed (L5) except near plutons, and similar weakly metamorphosed rocks may form a large part of the basement beneath the Atlantic Coastal Plain.

The supracrustal rocks of the Piedmont province have been disrupted by large volumes of plutonic rocks. Gabbros and diorites ($L\gamma$) occur in Maryland and North Carolina, and are seemingly of early Paleozoic or latest Precambrian age. A more extensive younger array of granitic plutonic rocks ($L\delta$) includes foliated concordant varieties, and more massive cross-cutting bodies.

Radiometric dates on plutonic and metamorphic rocks in the Piedmont province cluster near 450–500 m.y., 350 m.y., and 250 m.y., the first being more abundant to the northwest, the last to the southeast; they express times of plutonism, metamorphism, and presumably also of orogeny that extended through a long span of the Paleozoic (Hadley, 1964). These times invite comparison with the known events in the northern Appalachians (the Taconian, Acadian, and later Paleozoic orogenies), but the extent of the rocks involved in each is too vaguely known to make it possible to represent it on the tectonic map. Various considerations, including the record of clastic wedges in the miogeosynclinal belt, suggest that the earlier radiometric dates express a greater orogenic event than the later dates.

Extending through the Piedmont province from Pennsylvania to North Carolina are faulted strips and patches of the Upper Triassic postorogenic rocks of the Newark Group (L8), nearly identical in lithology and structure to the rocks of the same group in the northern Appalachians. They lie unconformably on the crystalline rocks of the Piedmont province, and in Pennsylvania overlap the edge of the miogeosynclinal belt. As shown on the tectonic map, mafic dikes related to the intrusives in the Newark Group extend long distances into the surrounding older rocks and have a systematic regional pattern (King, 1961). As already indicated (p. 24), faulted strips of Triassic rocks in the internal zones of the Appalachian and Ouachita foldbelts continue beneath the coastal plain cover at least as far southwest as southern Arkansas.

(M) OUACHITA FOLDBELT

The Ouachita foldbelt is, in many respects, a western continuation of the Appalachian foldbelt; nevertheless, its rock sequence and structure differ significantly, hence it evolved during a different tectonic cycle. The foldbelt extends more than 1,600 km (1,000 miles) across the southern United States, from near the last exposure of the Appalachians in Alabama to western Texas, where it passes into Mexico. However, it is only exposed for 510 km (275 miles) of this distance—in a large area in the Ouachita Mountains (Miser, 1929; and many later papers), and in the Marathon region and even smaller areas in western Texas (King, 1937). Through the remainder of its length it is covered by deposits of the Gulf Coastal Plain (C), but its position is indicated with varying degrees of precision by drill data (Flawn and others, 1961).

Because of the small extent of the exposed parts of the Ouachita foldbelt, its rocks are shown as a single unit (M) on the "Tectonic Map of North America" (fig. 12). The same symbol is used for inliers of deformed Paleozoic rocks in the eastern Cordillera of Mexico that were classed as parts of the Huastecan structural belt on the "Tectonic Map of Mexico" (de Cserna, 1961). In the Gulf Coastal Plain the front of the concealed part of the foldbelt is shown as a dotted line (or buried fault).

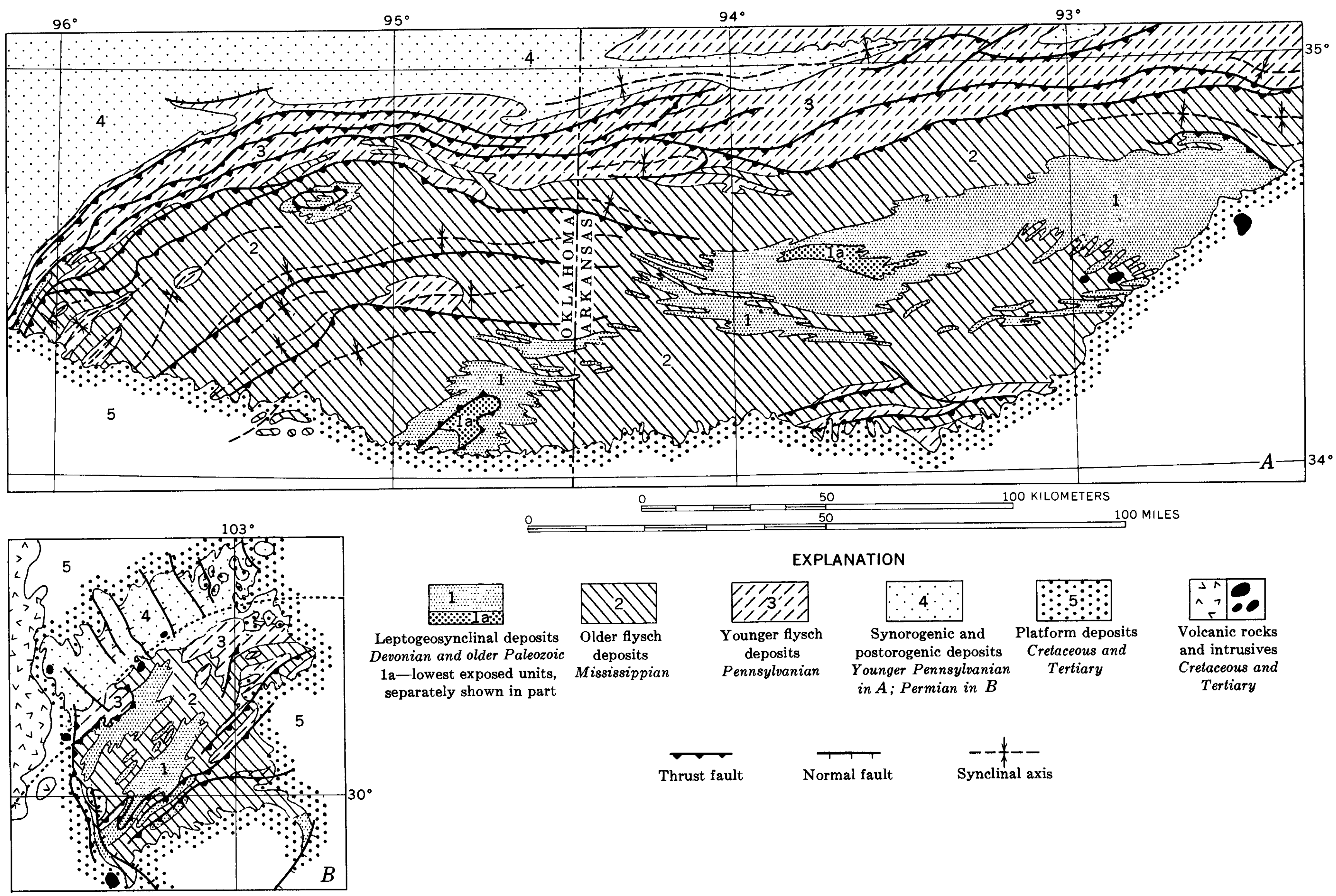

FIGURE 12.—Tectonic maps of the two larger areas of exposure of the Ouachita foldbelt showing the tectonic subdivisions of its rocks. These maps supplement the "Tectonic Map of North America," where the subdivisions are not shown because of the small scale. *A*, Ouachita Mountains of Oklahoma and Arkansas. *B*, Marathon region in western Texas. Compiled from geologic maps of Texas, Oklahoma, and Arkansas, with additions from other sources.

The course of the Ouachita foldbelt, like that of the Appalachian foldbelt, is marked by salients and recesses, but of even greater amplitude. The Ouachita Mountains are at the apex of one salient, the Marathon region at another; a deep recess lies between the Ouachita and Appalachian foldbelts in Mississippi and Alabama, and another adjoins the Llano uplift in central Texas. Throughout its course, the foldbelt lies against the central craton, whose Paleozoic rocks have a different character and structure, commonly with thrust contact; in part it is bordered by deep basins containing upper Paleozoic synorogenic clastic deposits—the Black Warrior basin of Alabama and Mississippi, the Arkoma basin of Arkansas and Oklahoma, and the Val Verde basin of western Texas.

The relation of the Ouachita foldbelt to the Appalachian foldbelt is incompletely determined. Trends of the two structures converge nearly at right angles, and drill data show that the frontal structures curve sharply from one trend to the other, but the manner of junction of the internal zones is unknown. The Ouachita foldbelt also meets the rocks and structures of the Wichita system nearly at right angles in southern Oklahoma; the junction is complexly faulted, but the Ouachita rocks are thrust over the Wichita rocks. In western Texas the Ouachita foldbelt again meets at right angles the younger Cordilleran foldbelt, which largely overwhelms it in Mexico.

The Paleozoic rock sequences of the exposed parts of the Ouachita foldbelt in the Ouachita Mountains and Marathon region are remarkably alike, especially considering their wide geographic separation and the very different nature of the contemporaneous rocks exposed in intervening and adjoining areas. The lowest exposed strata in both are high in the Cambrian. The remainder of the lower Paleozoic is dominantly slaty and cherty and is topped by a middle Paleozoic white chert or novaculite. These strata have many, but not all, of the characters of eugeosynclinal deposits. Their thickness is modest, generally no more than 900 m (3,000 ft), and they were probably laid down in a starved basin comparable to the leptogeosynclines of the Alps (Trümpy, 1960, p. 865–866). The only exception is the Silurian Blaylock Sandstone of the Ouachita Mountains, which wedges out rapidly northward and may be related to an early pulse of orogeny in the interior of the foldbelt.

Higher Paleozoic strata in both areas of exposure are dramatically different—a great mass of flysch that marks the orogenic phase in the foldbelt (Cline, 1960; Goldstein and Hendricks, 1962; McBride, 1966). Within the Ouachita Mountains the middle and upper Mississippian part (Stanley and Jackfork Formations) is 5,200 m (17,000 ft) or more thick, but both here and in the Marathon region this part wedges out almost entirely at the front of the foldbelt. The early Pennsylvanian part (Atoka Formation) is 6,000 m (19,000 ft) thick at the front of the Ouachita Mountains, and wedges out almost entirely near the Ozark uplift in the craton to the north. In west Texas a similarly great but younger flysch sequence occurs along the front, mainly in the Val Verde basin, and includes earliest Permian. Successive pulses of orogeny in the Ouachita foldbelt are thus suggested, progressing outward from the internal zones and westward along its trend—Mississippian and early Pennsylvanian pulses in both areas, a late Pennsylvanian pulse in the western area. Related to the younger pulses are structural unconformities in the higher Paleozoic foreland strata.

As a result of these orogenies, the exposed rocks of the Ouachita foldbelt were deformed in much the same manner as the rocks of the miogeosynclinal belt of the southern Appalachians, into asymmetrical folds overturned toward the north, with many low-angle to high-angle thrust faults. Thrusts are especially numerous and crowded in the western half of the Ouachita Mountains, near the impingement of the foldbelt on the Wichita system. The eastern half was formerly believed to be rather simply folded, even though the deepest parts of the structure and those parts farthest south were known to be conspicuously metamorphosed; it is now known that frontal thrusts extend across all this part to the Mississippi Embayment, and that the structures behind the front include major recumbent folds or nappes (Viele, 1966).

In the buried parts of the foldbelt, drill holes have penetrated deformed older and younger Paleozoic rocks that are recognizably like the formations in the exposed areas, but these formations, in both the outcrops and the buried areas, are only in the frontal zones. In Texas, drill holes have penetrated an internal zone of highly sheared, medium-grade metamorphic rocks of undetermined age (Flawn, in Flawn and others, 1961, p. 79–81); these nowhere come to the surface, except in a tiny outcrop immediately south of the Rio Grande in Coahuila, Mexico. Granitic and other plutonic rocks were penetrated in a few of the drill holes, but no large plutons have been found so far. East of Texas, the internal zones have not been reached by the drill, and are extensively blanketed by postorogenic deposits. Triassic redbeds (Eagle Mills Formation) occupy a long belt in Arkansas immediately south of the Ouachita Mountains. South of them a single well in northeastern Louisiana (Union Producing Co., No. 1–A Tensas Delta) penetrated undeformed Pennsylvanian strata, which perhaps were deposited in a successor basin, like basins in the Canadian Maritime Provinces, after the major orogeny in the interior of this part of the foldbelt had been completed.

STRUCTURAL SYSTEMS RELATED TO THE OUACHITA FOLDBELT

Before leaving the Ouachita foldbelt, discussion is desirable of other structural systems to which it is related in one way or another—systems which have been mentioned only incidentally hitherto.

Structures of Paleozoic age in the Wichita system extend west-northwest from their impingement with the Ouachita foldbelt for about 650 km (400 miles) across southwestern Oklahoma into the Texas Panhandle; they are vaguely connected thence northwestward through lesser structures with those of Paleozoic age in the Southern Rocky Mountains. Only a small part of the Wichita system projects to the surface, to form the Arbuckle and Wichita Mountains; the remainder is concealed by late Paleozoic postorogenic deposits, including extensive Permian redbeds to the west. On the "Tectonic Map of North America" the system is represented by its faults (mostly buried) and by contours on the surface of the Precambrian; its rocks are mapped as platform deposits on a Precambrian basement.

In the Wichita system the lower part of the Paleozoic sequence, through the Mississippian, is 3,700 m (12,000 ft) thick and mainly carbonate rocks; it much resembles that in the southern Appalachian miogeosyncline, except that it lacks most of the Cambrian components. The lower Paleozoic strata thin north, south, and west across the craton, where they lie on crystalline rocks consolidated during Middle Proterozoic orogenies. Within the system itself the Paleozoic strata lie on another body of rocks (Ham and others, 1964, p. 149–160). Where exposed in the Wichita Mountains these are primarily plutonic—gabbros, granites, and rhyolites (shown as A3 on the tectonic map)—but a few outcrops and extensive drill data demonstrate that the plutonic rocks are floored intrusives in the upper part of a supracrustal sequence 6,000 m (20,000 ft) thick, largely graywackes and volcanics. Radiometric datings on both the plutonics and volcanics yield surprisingly young ages of 500 m.y., thus placing them and at least part of the supracrustal sequence in the Cambrian rather than in the late Precambrian.

All these rocks and their basement were deformed during several stages of Pennsylvanian time, or broadly at the time of the orogenies in the nearby Ouachita foldbelt. Blocks of basement and supracrustal rocks were raised along high-angle faults, in part with lateral displacement, producing the massifs of the present Wichita and Arbuckle Mountains, and others still concealed. Their erosional debris was shed into deeply subsiding adjoining or intervening troughs—notably the Anadarko basin on the north flank of the Wichita Mountains—where another 4,500 m (15,000 ft) of later Paleozoic sediments accumulated, parts of which were severely folded and faulted during the final stages of the deformation.

Details of the deformation of the Wichita system, the related sedimentation, and the interaction of both with the growing Ouachita foldbelt have been described at length in other publications. Here, it is sufficient to observe that the history of the Wichita system has been germanotype, rather than alpinotype like the Ouachita foldbelt, yet that this history was characterized by a much greater mobility than in most of the cratonic areas of North America.

The Huastecan structural belt of eastern Mexico (de Cserna, 1960, p. 598–601; 1961) is virtually a continuation of the Ouachita foldbelt, but it is represented at the surface by only a few inliers of deformed Paleozoic rocks that emerge in the higher folds of the eastern part of the Cordilleran foldbelt (Flawn, in Flawn and others, 1961, p. 90–103), so that its structural pattern is largely conjectural. It is commonly assumed that the Huastecan belt (that is, the Ouachita foldbelt) extends southward along the trend of the present Cordillera, but this is by no means assured. Some of the most significant Paleozoic inliers occur near Las Delicias in southwestern Coahuila, 480 km (300 miles) south of the Marathon region, where a thick sequence of marine Permian with volcanic components has been steply folded along north-northeast axes and intruded by early Mesozoic granite (R. E. King and others, 1944, p. 25–27), suggesting that orogenic movements in the Ouachita foldbelt persisted later in Paleozoic time here than they did farther northeast.

At Las Delicias and elsewhere in western Coahuila, the Mesozoic cover is thinner than in adjacent parts of the Cordillera, over a largely buried massif termed the "Coahuila peninsula," around which the Cordilleran folds are strongly deflected on the south, part of this massif is shown as platform area (C) on the tectonic map (see p. 25–27). This buried massif probably is a consolidated part of the internal zones of the Ouachita foldbelt.

(O) CORDILLERAN FOLDBELT

The Cordilleran foldbelt extends for 8,000 km 5,500 miles) along the western side of North America, from Alaska to northern Central America, with a width of 650–1,600 km (400–1,00 miles). The foldbelt is sigmoid in plan, trending westward in the extreme north, meridionally in the main part, then eastward in the extreme south. Westward from Alaska it is separated by only a short stretch of shallow water from comparable foldbelts in Asia. Southeast of Guatemala and Honduras in Central America the rocks and structures differ from those to the north, and are described later as a part of the Antillean foldbelt (Q).

On its eastern side the Cordilleran foldbelt is bordered through most of its length by the central craton of North America, but in Alaska it fronts northward on the Arctic Coastal Plain, and in Mexico it fronts eastward on the Gulf Coastal Plain. On its inner side the Cordilleran foldbelt and the related Pacific foldbelt (P) are bordered for their entire length by the Pacific Ocean, without coastal plains and with only narrow continental shelves. In the northwest, the Pacific Coast is closely adjoined by the Aleutian Trench and in the south by the Middle America Trench, both with depths greater than 6,000 m (20,000 ft). In the more lengthy intervening area the ocean bottom next to the coast lacks trenches and lies at depths of 3,000–4,000 m (10,000–15,000 ft).

In the Cordilleran foldbelt, the climactic orogenies took place during Mesozoic time, but it had a long antecedent history of sedimentation and deformation. It arose from several geosynclines, some of which took form early in Paleozoic time, as in the Appalachian foldbelt, others as late as Mesozoic time. Early deformational features have been largely overwhelmed by the later ones, so that their patterns are seldom clear; some were probably precursors of the later structures, others seem to have been quite discordant. The postorogenic history of the foldbelt was much more eventful and complex than that in the Appalachians, with orogenic and epeirogenic events extending through most of the Cenozoic. In many places the imprint of these later events is so great as to disrupt or obscure the more fundamental Mesozoic structures.

These later events are also largely responsible for the present system of Cordilleran Mountains. Through most of the length of the Cordillera these events have produced two major mountain chains, one near the Pacific Coast on the west, the other fronting the continental interior on the east, with lower plateaus and less continuous ranges between. These are only indirectly related to the original Cordilleran foldbelt, and in much of the western United States the eastern mountain chain (Central and Southern Rocky Mountains) is actually a reactivated part of the original craton (see p. 23–24).

As might be expected from the great length of the Cordilleran foldbelt, its geology, tectonics, and history differ from one part to another, which makes generalization difficult, both on the tectonic map and in the present text; this is reflected by the large number of units into which the foldbelt is divided on the map legend, some of which occur only in one part or another. Nevertheless, a certain degree of unity is evident for long distances in the foldbelt, with rather abrupt contrasts in tectonic style across narrow transverse zones, so that the foldbelt is segmented (King, 1966, p. 2–3). How fundamental this segmentation may be is problematical, but it is a convenient basis for the ensuing descriptions, where the foldbelt is treated in terms of a northern Cordillera (Alaska and Canada), a central Cordillera (western United States), and a southern Cordillera (Mexico and Central America).

NORTHERN CORDILLERA

The Cordilleran foldbelt trends northwestward in Canada with a nearly constant width of about 800 km (500 miles). A little east of the Alaska-Yukon boundary the belt is constricted by a deep recess along its northeastern side. In Alaska the belt turns westward, widening and branching, one branch extending out to sea southwestward to form the Aleutian island arc. Despite the constriction and some tectonic differences on its two sides, the cross section of the foldbelt in both Canada and Alaska is much the same, and longitudinal strips of like rocks and structures extend through the whole segment, including a belt of miogeosynclinal rocks on the northeast and a belt of eugeosynclinal rocks on the southwest. In addition, a belt of younger rocks and structures fringing the Gulf of Alaska is distinguished as a part of the Pacific foldbelt (P) and described under a later heading. The segment extends a short distance southward across the 49th parallel into Washington, Idaho, and Montana, where it terminates against overlapping volcanic rocks and the transverse faults of the Lewis and Clark zone.

Easternmost Siberia, opposite Alaska, contains foldbelts that are the obvious extensions of the Cordilleran and Pacific foldbelts of North America into the continent of Asia. Indeed, the rocks and structures of the two continents are separated only by the very shallow northern part of the Bering Sea on the south and the Chukchi Sea on the north, underlain by continental crust. It is evident from published maps (notably Tilman and others, 1966) that rocks, structures, and orogenic times occur in Siberia which are analogous to those in Alaska; nevertheless, their positions and trends do not closely match. There has been much speculation as to precise connections by Soviet and American geologists (among the latter, Ostenso, 1968; Michael Churkin, Jr., unpub. data), but more precise comparisons are desirable. Further information will no doubt become available as a result of oceanographic investigations now in progress on the sea-bottom geology of the intervening areas.

Between the 46th and 60th parallels the outer, or miogeosynclinal, part of the northern Cordillera forms the Rocky Mountains, a bundle of parallel ranges with little curvature, about 120 km (75 miles) broad, which rise abruptly west of the plains of the continental interior, generally along a zone of thrusting (Bally and others, 1966, p. 340–345). The Lewis thrust near the 49th parallel carries Middle Proterozoic strata (O3) eastward at least 30 km (20 miles) over the rocks of the plains (Ross, 1959, p. 76–78); the similar but not identical McConnell thrust farther north carries Paleozoic strata eastward in the same manner. Behind the frontal thrust the rocks of the mountains are closely crowded into folds and thrust blocks, probably accompanied by décollement over the basement. East of the frontal thrusts the rocks of the plains are themselves intensely disturbed in a foothills belt 30 km (20 miles) wide.

North of the 60th parallel, the Rocky Mountains give place to the Mackenzie Mountains, also a bundle of ranges of folded and faulted rocks, but broader, more strongly arcuate, and offset a little to the east. An outer strand, the Franklin Mountains, deforms the rocks of the plains still farther east, nearly to Great Bear Lake and the edge of the Canadian Shield. Much farther northwest is the Brooks Range of northern Alaska, with a structure like that of the Rocky Mountains and Mackenzie Mountains, but trending nearly westward. Between the Mackenzie Mountains and the Brooks Range, the deep recess referred to above extends nearly to the Yukon River, into which structures curve from the ranges on either side. Within the recess are blocklike uplifts, such as the Richardson Mountains, separated by deep structural basins.

It should be evident from the "Tectonic Map of North America" that the Brooks Range is an integral part of the Cordilleran foldbelt (Gates and Gryc, 1963, p. 265–266), and is not an independent tectonic element, separated from the true Cordilleran foldbelt farther south by a "Yukon stable block," as has been claimed (Jeletzky, 1962, p. 62–66). The recess between the arcs of the Brooks Range and Mackenzie Mountains has features of a stable block, but this block does not extend indefinitely westward across Alaska. Large parts of the pre-Mesozoic rocks south of the Brooks Range are Paleozoic geosynclinal deposits, partly metamorphosed, which have participated in two or more of the Cordilleran orogenies.

No Precambrian crystalline rocks emerge anywhere within the ranges of the miogeosynclinal belt, nor apparently elsewhere in the northern Cordillera. However, younger Precambrian supracrustal rocks are extensively exposed in the higher uplifts in the miogeosynclinal belt and the adjoining part of the eugeosynclinal belt (Reesor, 1957, p. 152–162; Gabrielse, 1967, p. 271–275). They form significant "structural stages" in the lower part of the stratified sequence, hence are shown separately on the tectonic map (O3, O4).

The Middle Proterozoic part of this supracrustal sequence (O3) is exemplified by the Belt (Purcell) Series that is widely exposed near the 49th parallel, but whose equivalents also occur in the outer ranges as far north as Yukon Territory. The Belt is formed of shallow-water, fine-grained clastic rocks and interbedded carbonates; toward the east it overlies a Hudsonian (Lower Proterozoic) crystalline basement (H5, O2), but within the foldbelt its base is not visible even though it attains a thickness of 15,000 m (45,000 ft). It is everywhere unconformable beneath younger rocks, and in the interior of the foldbelt is succeeded by Upper Proterozoic supracrustal rocks (O4), exemplified by the Windermere Series near the 49th parallel, a sequence nearly as thick, but coarser and with some volcanic components, that is conformable or nearly so with the succeeding Paleozoic. The Upper Proterozoic includes the "grit unit" of the internal zones in Yukon Territory, a poorly sorted arkose, apparently derived from crystalline rocks farther southwest.

The Middle Proterozoic supracrustal rocks are geosynclinal deposits that formed in a trough antecedent to the main Cordilleran geosyncline, yet one which nearly corresponded in position to its successor. Most of its sediments were seemingly derived from the continental interior. This early geosynclinal phase was terminated by crustal movements, most of which were epeirogenic, but which attained orogenic proportions, at least in Yukon Territory. The succeeding Upper Proterozoic supracrustal rocks are more closely related to the main Cordilleran geosynclinal phase, and form its basal deposits where present. Their coarse sediments were derived from mixed sources, and part of them from lands farther in the interior of the foldbelt. Neither of these Proterozoic sequences was materially disturbed until the much later Cordilleran orogenies, and their metamorphic phases (O3a, O4a) date from that period.

On the tectonic map, strata shown as miogeosynclinal (O9) in the northern Cordillera extend from Cambrian to Jurassic in Canada, and from Upper Devonian to Jurassic in Alaska where the lower Paleozoic is shown separately (O5). The Cretaceous is generally excluded, but is mostly preserved in the adjoining platform area (B) rather than in the foldbelt. On the map, the boundary between the miogeosynclinal and platform area is thus commonly drawn at the contact between the Cretaceous and older strata, which in many places is also the outer limit of strong deformation. The deformed Paleozoic rocks in the outer strand of the foldbelt in the Franklin Mountains are therefore shown as miogeosynclinal, although they might, with much propriety, be considered as deformed platform cover. Also shown as miogeosynclinal are the pre-Cretaceous rocks in the recess between the Mackenzie Mountains and the Brooks Range, although not all of their complex sequence is truly geosynclinal (Jeletzky, 1962, p. 62–66). In places, miogeosynclinal rocks contrast greatly with adjacent eugeosynclinal rocks of the same ages (O6, O7), mostly where they are juxtaposed along faults. Elsewhere, the boundary is indefinite, different parts of the sequence partaking of one facies or the other, so that the contact is arbitrarily drawn.

In general, the Paleozoic miogeosynclinal rocks are dominantly carbonates, and the Mesozoic dominantly clastic wedge deposits, but the sequence varies greatly from one part of the belt to another (Bally and others, 1966, p. 361–369; Gabrielse, 1967, p. 275–283; Brosgé and others, 1962). Unconformities occur, especially in the upper part of the Devonian, but they were mostly produced by epeirogenic rather than orogenic movements, and angular discordances are local. The array of unconformities and the epeirogenic movements which they express is especially complex in the recess between the Mackenzie Mountains and the Brooks Range (Jeletzky, 1962, p. 62–71). However, true orogenic deformation seems to have occurred in the core of the eastern Brooks Range, where rocks below the Upper Devonian have been much metamorphosed (O5a); granites in the vicinity have been dated radiometrically between 370 and 220 m.y., hence are middle to late Paleozoic (Oϵ). A possible relation between these deformed rocks and the Innuitian foldbelt to the northeast has already been suggested (p. 53).

Most of the Mesozoic clastic wedge deposits of the miogeosynclinal sequence are related to orogenic activity in the eugeosynclinal part of the foldbelt, rather than in the miogeosynclinal area itself. Nearly all the deformation in the miogeosynclinal part of the foldbelt was late in the Cretaceous or still later, hence is Laramide in the broad sense; in the southern part of the segment Paleocene strata are deformed equally with the Cretaceous in the foothill belt east of the Rocky Mountains. In the Brooks Range, however, Laramide deformation was preceded by an Early Cretaceous (Aptian) time of orogeny and thrusting.

Much of the remainder of the northern Cordillera in both Canada and Alaska was a *eugeosyncline* during large parts of Paleozoic and Mesozoic time. Its supracrustal rocks and deformational events were as varied as those in other eugeosynclines, and at least the younger of these are well documented in many places. Volcanic rocks are common, especially in certain parts of the sequence—for example, from Devonian into Mississippian and from Permian into Triassic in some areas—but thick limestone bodies also accur, although they are mostly of local extent. Coarser clastic rocks, including conglomerate, attest the uplift and probable deformation of adjacent areas.

On the "Tectonic Map of North America," the eugeosynclinal rocks that were involved only in the Mesozoic orogenies, and which are primarily of Mesozoic age (O7) are separated from an earlier part, primarily of Paleozoic age (O6) which was involved in one or more previous orogenies and reworked later. Besides these, a still older unit of early Paleozoic age (O5) is shown in Alaska—a unit which was involved in middle Paleozoic or earlier orogenies, and not all of whose rocks are of eugeosynclinal character.

Rocks of the last-named category (O5) are extensive in the interior of Alaska, where they include phyllites and schists (O5a) that underlie little metamorphosed rocks of known Mesozoic age. On the flank of the Brooks Range the metamorphic rocks are traceable northward into unmetamorphosed formations beneath Upper Devonian conglomerates; elsewhere, their ages are known only from fossils in scattered limestone units. Clearly, these rocks have been involved in one or more orogenies during Paleozoic time, and perhaps early in that time. In the Seward Peninsula the metamorphic and partly fossiliferous rocks were folded along north-south axes during the Paleozoic, and were refolded along east-west axes during the Mesozoic or later (D. M. Hopkins, oral commun., 1966).

Southeast of Alaska older Paleozoic rocks are exposed only along the northeastern and southwestern edges of the eugeosynclinal area; those on the northeast are gradational into the miogeosynclinal deposits, those on the southwest (in the islands of the Alaska Panhandle) are more truly eugeosynclinal (Brew and others, 1966, p. 157–166). In the northeastern belt, where these rocks are not separated from the younger Paleozoic, significant orogeny near the close of the Devonian has been recorded in the Cassiar area and elsewhere (Wheeler, 1966, p. 34). Plutonic rocks of early Paleozoic age (Oϵ) occur in the southwestern area.

Later Paleozoic and early Mesozoic eugeosynclinal deposits (O6, O7) extend the length of the northern Cordillera, and many sequences attain thicknesses of more than 7,600 m (25,000 ft). Proportions of the different components—volcanics, chert, argillite, graywacke, and limestone—vary greatly from one place and from one part of the sequence to another, but the Mesozoic generally contains coarser clastics than the Paleozoic. Deposition was widely interrupted during early Triassic time, mostly by epeirogenic movements, but locally by moderate deformation (White, 1966a, p. 187).

Mesozoic time was one of nearly continuous orogeny from place to place in the eugeosynclinal area, and it is difficult to make any meaningful generalizations as to orogenic climaxes; the statement on the legend of the tectonic map that the eugeosynclinal deposits were deformed mainly during a middle Mesozoic (Nevadan) orogeny is a gross oversimplification (Misch, 1966, p. 119). In many areas all the Mesozoic, and even part of the Tertiary, is steeply folded. Nevertheless, a significant part of the deformation had been accomplished well before the terminal Mesozoic (Laramide) orogeny in the miogeosynclinal belt to the northeast. The younger Mesozoic and the Tertiary rocks (O10, O11), even where steeply folded, did not participate in many of the deformations that affected the older rocks; they are less metamorphosed and plutonized, and they contain larger volumes of terrestrial deposits and of coarse immature clastics.

During Mesozoic time granitic rocks were emplaced in the eugeosynclinal area on a vast scale (Oθ). The great Coast batholith of western Canada is nearly continuous for 1,800 km (1,100 miles), from the 49th past the 60th parallel, and is 80–200 km (50–120 miles) wide, but it is inhomogeneous internally and of several ages (Roddick, 1966, p. 76–79). Other sizeable but less continuous batholiths occur in Alaska to the northwest and in Canada to the east, especially in a belt along the northeastern side of the eugeosynclinal area (Cassiar Mountains southward to Monashee Mountains). Geologic relations and radiometric datings both indicate a prolonged time of emplacement—from 250 m.y. to less than 70 m.y., or through all of Mesozoic and into Tertiary time. By far the most extensive granitic emplacement, especially in the Coast batholith, occurred during Cretaceous. The batholiths of early Tertiary age are late phases of the Mesozoic plutonism, but a few near the 49th parallel are as young as middle Tertiary (Oλ). Radiometric dating suggests pulses of granitic emplacement during the Mesozoic at intervals of 30 m.y., but while the pulses lie within the general period of orogeny, they have little obvious relation to the known times of deformation in the supracrustal rocks (Gabrielse and Reesor, 1964, p. 127–128).

Parts of the eugeosynclinal rocks have been strongly metamorphosed, mainly in areas near granitic plutons, which were also areas of long-persistent heating and recrystallization. Metamorphic rocks thus lie within and around the Coast batholith, as well as in the plutonic belt along the northeastern side of the eugeosynclinal area, where they are more continuous than the granitic rocks themselves. Many of the metamorphic rocks in these belts can be identified as equivalent to less altered Proterozoic, Paleozoic, and Mesozoic formations, and have been so mapped (O3a, O4a, O6a, O7a). Other metamorphic rocks have been transformed by recrystallization and plastic flowage to such an extent that most indications of their original nature and relations have been lost, and they are therefore mapped as metamorphic complexes (O1). The complexes include the Birch Creek Schist of interior Alaska, the equivalent Yukon Group of Yukon Territory, the Shuswap complex of southern British Columbia, and various intervening bodies—all in the northeastern plutonic and metamorphic belt.

Earlier geologists interpreted the metamorphic complexes as an Archean protaxis that separated younger geosynclines on the two sides, but subsequent investigations reveal a much more eventful history, involving heating and recrystallization in place, penetrative flowage, and superposed deformations through prolonged periods of time. Most radiometric dates in the complexes are surprisingly young—150 m.y. or less—but those record only the latest thermal events and subsequent cooling, after burial at great depths in the crust. Parts of the complexes may be highly altered phases of Paleozoic or even Mesozoic supracrustal rocks, but other parts may once have been Proterozoic supracrustal rocks or an even earlier basement, now remobilized.

During Late Jurassic and through most of the Cretaceous time, the deformed eugeosynclinal rocks of the northern Cordillera were partly covered by deposits of successor basins (O10), which were themselves variably deformed later. The deposits are coarse clastics and interbedded volcanics, partly marine, partly continental, most of the clasts having been derived from surrounding uplifted areas; the deposits also include fragments from granite plutons that had been emplaced only a little earlier (Grantz and others, 1963, p. B58–B59). The successor basins are most extensive in Alaska (Gates and Gryc, 1963, p. 269–272), but the Bowser basin in central British Columbia is 200 by 320 km (120 by 200 miles) across (Souther and Armstrong, 1966, p. 178–180). Smaller basins of continental Tertiary deposits (O11) occur here and there in the interior of the northern Cordillera.

Parts of the eugeosynclinal rocks are broken by faults, some of which originated during the geosynclinal period itself, but extensive low-angle thrusts have been described only in the northern Cascade Range of Washington (Misch, 1966, p. 120–136). Of greater interest are the very lengthy longitudinal faults, which are commonly expressed as topographic trenches or valleys on the land and as fiords between the offshore islands. The fault zone of the Rocky Mountain Trench and its continuation into the Tintina Trench extends with a few offsets from south of the 49th parallel across Canada into Alaska, and the Denali fault zone extends through the high mountains of southern Alaska into the southeastern panhandle. The straight or gently curved courses of these and other fault zones, the interchange of apparent upthrown and downthrown sides along their courses, and the frequent absolute differences between rocks on the opposite sides all suggest major strike-slip displacements; strike-slip displacements have been proved in a few segments, but the actual displacement in much longer segments remains enigmatic. The Fairweather fault near the coast of Alaska is active today and has given rise to major earthquakes, but most of the remainder have long been dormant.

CENTRAL CORDILLERA

The Cordilleran Mountains occupy most of the United States west of the 104th Meridan, but the central segment of the Cordilleran foldbelt (O), as here defined, forms only part of them. The foldbelt is limited northward by the Lewis and Clark transverse zone near the 46th parallel, and southward by another transverse zone near the 34th parallel—the Transverse Ranges and the Texas Lineament of southern California and Arizona. The eastern part of the mountain system (Central and Southern Rocky Mountains and Colorado Plateau) is classed as a reactivated craton (B), and the western part (Cascade Range and Coast Ranges) is placed in the Pacific foldbelt (P). As here defined, the Cordilleran foldbelt is 1,100 km (700 miles) wide near the 42nd parallel, but it is much narrower to the north and south.

Even within the central segment of the foldbelt as thus restricted, the fundamental Mesozoic and older orogenic structures are greatly obscured by younger rocks and structures, so that their gross pattern is by no means as evident on the tectonic map as it is in the northern Cordillera. Superposed on the Mesozonic and older structures are Cenozoic volcanic fields and a system of block faults which trend in other directions, and on the tectonic map these varied features play against each other in counterpoint. In the northern part of the segment, the continuity of the Mesozonic and older structures is interrupted entirely by a transverse belt of volcanic rocks that extends from the Snake River Plain of Idaho into the Absaroka Mountains of Wyoming.

The eastern, or miogeosynclinal part of the foldbelt is poorly defined north of the transverse volcanic belt, in Idaho and Montana, where it is closely crowded between cratonic and internal elements. It widens farther south in the Great Basin, where it extends westward 400 km (250 miles) from the edge of the Colorado Plateau in Utah into central Nevada. In eastern California it extends as far west as the front of the Sierra Nevada, but in the Mojave Desert to the south its continuity is lost in the confused ranges of the southern transverse zone.

In western Wyoming and southeastern Idaho the frontal part of the miogeosynclinal belt consists of closely crowded folds and thrust slices, very much like those in the Canadian Rocky Mountains (Armstrong and Oriel, 1965). Southward in Utah, the frontal part is deflected into the eastern edge of the Great Basin, around the western end of the Uinta Mountains axis. The ranges of the eastern Great Basin contain low-angle thrust faults of great lateral displacement, many of which superpose strata near the base of the Paleozoic over Mesozoic strata; the thrusts can be correlated from one range to the next, through Utah into southern Nevada, in such a manner as to indicate that they are continuous features (Longwell, 1960; Crittenden, 1961; Armstrong, 1968, pl. 1). Behind the frontal belt in western Utah and eastern Nevada, the thrusts within the ranges differ; higher parts of the miogeosynclinal sequence have moved over the lower parts, and the whole has moved over a major décollement near the base of the Paleozoic (Misch, 1960). Correlation from one range to the next indicates that the décollement is a continuous feature like the frontal thrusts to the east. It is tempting to infer that the décollement is the root zone of the frontal thrusts, although there is some evidence that the former originated somewhat before the latter (Armstrong, 1968, p. 444). Frontal thrusts and décollement are exposed across nearly the whole width of the miogeosynclinal belt in this latitude, and if they are parts of the same feature there was an eastward transport of very broad sheets of miogeosynclinal strata over their basement—although for distances by no means as great as the observed breadth of exposure.

The crystalline basement (O2), probably part of the Hudsonian foldbelt, emerges near the eastern edge of the miogeosynclinal area in Utah, but it extends as far west as Death Valley in southeastern California. It is succeeded in places by Middle Proterozoic strata (O3), comparable to the Belt Series farther north and the Grand Canyon Series farther east, and more widely by Upper Proterozoic strata. The latter attain impressive thicknesses in the south (Noonday, Johnnie, Wyman, and other units), and like the Upper Proterozoic of the northern Cordillera are nearly conformable with the Paleozoic above; in this segment of the Cordillera their areal extent is not great enough to separate them from the higher miogeosynclinal strata on the tectonic map.

The miogeosynclinal sequence of the central Cordillera (O9) is largely Paleozoic, but includes remnants of lower Mesozoic (Triassic and Jurassic) at the top, as well as some infolded Cretaceous along the eastern edge. Farther back in the foldbelt, as at Eureka, Nev., the Cretaceous is postorogenic and continental, and was laid down in successor basins whose present remnants are too small to map. Throughout the Great Basin, the volume of the Paleozoic carbonate rocks is impressive. To the south, near Las Vegas, Nev., 5,500 m (18,000 ft) of dominantly carbonate rocks, extend from Cambrian to Permian. Farther north, near Eureka, Nev., carbonate rocks from Cambrian to Devonian alone are 4,500 m (15,000 ft) thick, but in this latitude they are succeeded by a Mississippian clastic wedge that expands westward toward the middle Paleozoic Antler orogenic belt in the eugeosynclinal area (Nolan and others, 1956); the thinner, higher Paleozoic, again contains carbonate strata. Further complications develop in the eastern part of the miogeosynclinal area in the same latitude, where the upper Paleozoic thickens to 9,000 m (30,000 ft) in the Oquirrh basin—nearly 10 times its value in nearby areas— in an exceptional area of extreme but transitory subsidence. On the other hand, in Idaho and Montana, ephemeral positive areas have caused large gaps in the Paleozoic sequence, and the Lower Cambrian is missing at the base.

The eugeosynclinal belt of the central Cordillera extends westward from the miogeosynclinal belt to the Pacific foldbelt (P) near the coast, which had a different tectonic history. In California the boundary with the Pacific foldbelt is along the western edge of the Sierra Nevada and Klamath Mountains, which in the latter area is a zone of east-dipping thrusts (Irwin, 1966, p. 33–36; Davis, 1968). In Oregon and Washington the boundary curves eastward in the Columbia arc (not labeled on the map), as shown by deflection of both structural trends and the quartz diorite petrographic boundary (Moore, 1959, p. 199). Whether the Columbia arc was indigenous, or whether it was created by oroclinal bending during the Cenozoic (Hamilton and Myers, 1966), is beyond the scope of this discussion.

As in the northern Cordillera, the eugeosynclinal supracrustal rocks of the central Cordillera are divided on the map into a unit of Triassic and Jurassic age (O7) deformed only during the Mesozoic orogenies, and a unit of Paleozoic age (O6) that was deformed during several earlier orogenies.

In Nevada, the eastern part of the eugeosynclinal belt is dominated by a lower to middle Paleozoic (Ordovician to Devonian) sequence of cherts and volcanics as much as 15,000 m (50,000 ft) thick that was deformed during the Antler orogeny of middle Paleozoic (Early Mississippian) time (Roberts and others, 1958, p. 2816–2821). The orogenic belt can be traced through the later structures that are superposed on it for a distance of 800 km (500 miles); its principal manifestation is an eastward transport along the low-angle Roberts thrust [9] of the eugeosynclinal sequence over a miogeosynclinal sequence of the same age (fig. 6 and 13). Windows and klippen of the thrust occur from one range to the next across a breadth of 95 km (60 miles), which is the minimum distance of transport. The known manifestation of the Antler orogenic belt involved only shallow parts of the crust, but its deep-seated origin is suggested by its influence on subsequent tectonic history. The orogenic belt was the site of lesser disturbances during succeeding Paleozoic time, and the upper Paleozoic and lower Mesozoic eugeosynclinal deposits were laid down only farther west (Silberling and Roberts, 1962, p. 7–25). The lower Mesozoic eugeosynclinal rocks (O7) pass eastward into near-shore shelf deposits toward the site of the orogenic belt.

Elsewhere in the western part of the Cordilleran foldbelt eugeosynclinal conditions were long persistent. Volcanic rocks as old as Silurian and Devonian have been identified in parts of the Klamath Mountains and the Sierra Nevada, and volcanic rocks are prominent in the remaining Paleozoic and the older Mesozoic, but the Klamath Mountains sequence contains several prominent Paleozoic carbonate formations (Irwin, 1966, p. 23; Clark and others, 1962). The Triassic and Jurassic contain great volumes of andesitic basaltic submarine lavas and pyroclastics (Dickinson, 1962). Partial sequences of eugeosynclinal rocks in various areas are 9,000 m (30,000 ft) or more thick; however, the total of the whole eugeosynclinal column is undetermined. Structural unconformities at various levels indicate pulses of orogeny from one place to another at various times during the Paleozoic and early Mesozoic, but their extent and magnitude is not as clearly defined as it is in the Antler orogenic belt.

The climactic middle Mesozoic orogeny in the Sierra Nevada has been dated as late in the Jurassic, and is the classic Nevadan orogeny; the climax may have been earlier or later in other parts of the eugeosynclinal belt (Gilluly, 1963, p. 146–150). Deformation was progressively younger eastward across the foldbelt, and in the miogeosynclinal area there is no clear separation between a middle Mesozoic orogeny and a terminal Mesozoic orogeny; most of the events were at intermediate times. At Eureka, Nev., deformed miogeosynclinal rocks are overlain by remnants of Lower Cretaceous successor basin deposits, but at the eastern edge in the same latitude the coarse synorogenic deposits are Upper

[9] Termed the "Roberts Mountains thrust" in many publications, but the shorter form proposed by Gilluly (1963, p. 141–142) is preferred by the compiler.

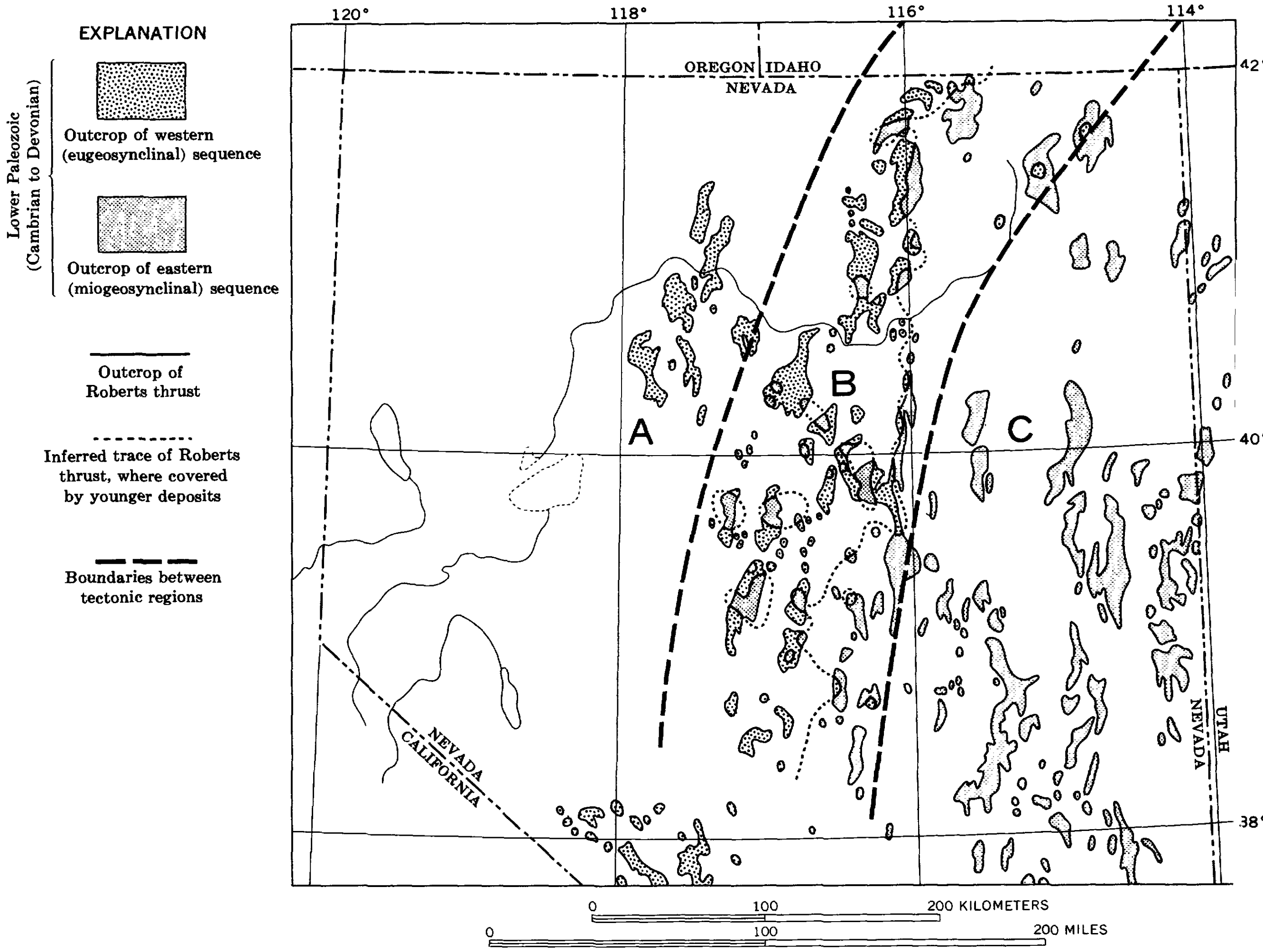

FIGURE 13.—Map of northern Nevada showing extent of Antler orogenic belt of middle Paleozoic time. The Paleozoic and Mesozoic rocks of northern Nevada are divisible into three tectonic regions with the following characters: Region A, Lower and upper Paleozoic eugeosynclinal deposits not affected by Antler orogeny, deformed by Sonoma orogeny during Permian time, overlapped from west by Triassic shelf deposits, and deformed by middle Mesozoic orogenies. Region B, Antler orogenic belt and area involved in Roberts thrust; lower Paleozoic eugeosynclinal deposits deformed by Antler orogeny in middle Paleozoic time and overlapped from east by upper Paleozoic shelf deposits. Region C, Lower Paleozoic miogeosynclinal deposits, upper Paleozoic clastic wedges derived from Antler orogenic belt, and minor Mesozoic deposits; deformed during late Mesozoic time, with development of thrusts and décollements. Compiled from many sources, including Roberts and others (1958).

Cretaceous (Spieker, 1946). Major thrusting in the miogeosynclinal belt in Utah was completed by the middle of Late Cretaceous time (Armstrong, 1968, p. 451). Farther north, in southeastern Idaho and western Wyoming, successive thrust blocks formed from west to east between Late Jurassic and Paleocene time (Armstrong and Oriel, 1965, p. 1857–1861). The classic Laramide orogeny of Paleocene time occurred primarily in the reactivated craton, east of the Cordilleran foldbelt as here defined.

Ultramafic rocks (Oγ) are prominent in the western part of the eugeosynclinal belt, especially in the Sierra Nevada and Klamath Mountains, where they form gently to steeply dipping tabular bodies, some of great thickness and extent. Commonly these bodies are along fault planes, and whatever their original history they clearly have been emplaced into their present positions by tectonic processes.

Granitic rocks (Oθ) are as extensive in the eugeosynclinal belt of the central Cordillera as they are in the northern Cordillera. They coalesce into two major batholiths—the Sierra Nevada batholith in the south and the Idaho batholith in the north, the latter offset eastward from the former in accordance with the curve of the Columbia arc (p. 70). Elsewhere, granitic rocks form smaller plutons in the eugeosynclinal terrane, or inliers in areas of younger rocks. Both of the larger batholiths are composite, being composed of many discrete plutons, and in the Idaho batholith including migmatized host rocks. The granitic rocks become more silicic eastward, changing from quartz diorite to quartz monzonite and granodiorite (Moore, 1959, p. 205–206). With some exceptions, they are also younger from to west to east; all are Mesozoic, but they yield radiometric dates between 180 and 80 m.y., or from late Triassic through the Cretaceous (Kistler and others, 1965, p. 162–164). Most of those west of the Sierra Nevada batholith are Jurassic or older, whereas most of the dated plutons in the Sierra Nevada and Idaho batholiths are of Cretaceous age. The Boulder batholith near the front of the foldbelt east of the Idaho batholith invades Late Cretaceous rocks. In the Great Basin Mesozoic plutons are mingled with smaller Tertiary intrusives (Oλ); the latter extend thence across the miogeosynclinal belt and into the reactivated craton east of it. The age range of the Mesozoic granitic rocks broadly coincides with the time of orogenic deformation of the eugeosynclinal rocks, but those of Cretaceous age are later than the orogenic climax; the Sierra Nevada batholith breaks into and shoulders aside eugeosynclinal rocks that had already been steeply upended and regionally metamorphosed.

During Cenozoic time, wide areas of the deformed geosynclinal rocks were covered by terrestrial volcanic rocks (Oμ, Oπ). The cover is largely intact through Oregon into southern Idaho, but farther south it is dismembered by block faulting and erosion. Volcanic history was prolonged; the older Tertiary volcanics are much deformed and mineralized, the more extensive middle Tertiary volcanics are block faulted, the Quaternary volcanics are merely tilted in the transverse Snake River downwarp. The varied compositions and origins of the volcanic rocks cannot readily be indicated on the tectonic map, and are therefore not differentiated in the generalized units adopted. Basaltic and andesitic volcanics are prominent to the north and west, but silicic volcanics cover large parts of the southern Great Basin, and include widely spread sheets of ignimbrite; where known, the calderas from which they were erupted are shown by smbols on the map.

During Cenozoic time also, large parts of the central Cordillera were disrupted by block faulting, caused by crustal distention. Block faulting has occurred in other foldbelts of the world late in the tectonic cycle, but its magnitude here is without parallel. Block faulting and volcanism partly coincide in time, but the faulting continued later; major faulting occurred during the early Pleistocene, and minor faulting continues today in places. In the Great Basin, the previously deformed terrane was split longitudinally into broad to narrow blocks, whose displacement produced the present topography of disconnected ranges and intervening basins; larger, longer fault blocks along the edge of the Colorado Plateau to the east and the Sierra Nevada to the west are more coherent manifestations of the same structure. The block faulting is a mountain-creating process, hence one of the few deformational events in the Cordillera to which the term "orogeny" can be applied in the narrow sense of Gilbert; in the broader sense of the term the block faulting is more properly postorogenic.

The faults at the edges of the mountain blocks are shown by normal fault symbols on the tectonic map, so far as they are known. Some of the known faults can be observed directly, the existence of others is proved by the even baselines of the mountains and the steep escarpments behind them. Other mountains may also have been fault blocks, but they were uplifted so long ago that the fault scarps have been destroyed by erosion, and the positions of the faults themselves are lost. The downfaulted blocks, or basins between the ranges, have been filled by debris eroded from the upfaulted areas, shown on the map as "thick deposits in structurally negative areas" (O12). Coarse fanglomerates were deposited near the edges of the basins and fine sands and silts near the centers, the whole accumulation of deposits attaining thicknesses of 3,000 m (10,000 ft) or more. On the tectonic map the distribution of these debris-filled basins suggests the pattern of latest deformation in the central Cordillera, even where faulting is not apparent.

SOUTHERN CORDILLERA

The southern Cordillera is separated from the central Cordillera by the so-called Texas Lineament (Albritton and Smith, 1957; King, 1965, p. 118), a transverse zone that extends east-southeast from the Transverse Ranges of coastal California, south of the Colorado Plateau and a little north of the United States-Mexican boundary, into western Texas. The zone is a strip of country as much as 160 km (100 miles) wide that separates two parts of the Cordillera with different topographies, geologic histories, and styles of deformation. South of the zone the Cordilleran foldbelt extends 800 km (500 miles) farther east than on the north side, and for long distances its deformed rocks closely adjoin little deformed rocks in the Colorado Plateau and the block mountains of New Mexico, which are reactivated or disrupted parts of the former craton. These contrasts have not been produced by transverse faulting, and the Texas Lineament is not a through-going fault zone, as has sometimes been assumed. It is true that the Transverse Ranges on the west contain eastward-trending high-angle faults, some with left-lateral displacement, but there are few faults parallel to the zone farther east, although it contains many faults trending in other directions (as elsewhere in the Cordillera).

The southern Cordillera includes all of Mexico except the Gulf Coastal Plain on the east, an area of platform deposits (C), and the parts of Baja California on the west which belong to the Pacific foldbelt (P). From southeastern Mexico it extends eastward into northern Central America, where it forms much of Guatemala, Belize, and Honduras. Except in the extreme south (see p. 74), most of the surface of the southern Cordillera is formed of Mesozoic and Cenozoic rocks, and older rocks emerge only as small inliers in the higher folds and fault blocks, so that the pre-Mesozoic structural pattern is largely undetermined or speculative. Very likely the Mesozoic and Cenozoic rocks and structures are superposed on a very different set of Paleozoic and older geosynclines and foldbelts, along with their forelands and backlands.

In the far northwest, in the Altar district of Sonora, are incomplete exposures of a geosynclinal sequence, very much like that in the Great Basin of the central Cordillera (O9), consisting of carbonate rocks that include Lower Cambrian and the higher Paleozoic systems, topped by Triassic and Jurassic marine shales; beneath are Upper Proterozoic supracrustal rocks like those in the Great Basin (O4), which rest on a crystalline (Hudsonian) basement (O2) (Cooper and Arellano, 1946; Damon and others, 1962). The relations of this geosynclinal sequence to rocks of surrounding areas in Mexico is unknown, and it is separated from its analogue in the Great Basin to the northwest by 650 km (400 miles), in which no trace of it is preserved.

Farther east, the front of the foldbelt of the southern Cordillera overwhelms the Ouachita foldbelt (M), whose characteristic rocks and structures are exposed in the Marathon dome and some other areas in western Texas. In northeastern Mexico the Coahuila peninsula notably distorts the Cordilleran folds, and is a massif that was evidently consolidated during the Ouachita orogeny. Inliers of Paleozoic and Precambrian rocks occur, both near the Coahuila peninsula and farther south along the Sierra Madre Oriental, but are too fragmentary to afford much of an idea of the true pre-Mesozoic structural patterns. The continuation of the Ouachita foldbelt (or Huastecan belt) within the southern Cordillera remains speculative. Some geologists (for example de Cserna, 1960, p. 598–601) have proposed that the late Paleozoic foldbelt follows the younger Cordilleran structures southeastward through Mexico into Central America.

Much of the southern Cordillera is a Mesozoic and younger feature. Its miogeosynclinal belt includes the present Sierra Madre Oriental, the Mesa Central on the west, part of the Sierra Madre del Sur on the south, and its extension into Central America. The miogeosynclinal rocks are dominantly later Mesozoic (mapped as O9, like the more heterogeneous miogeosynclinal deposits in Sonora). Jurassic and Lower Cretaceous carbonate rocks form most of the ranges, and are succeeded by Upper Cretaceous marine clastic wedge deposits. Beneath the carbonates are earlier Jurassic and Triassic red clastics, which include evaporites in some places and volcanics in others. In the interior ranges of central and southern Mexico the deformed Mesozoic miogeosynclinal rocks are overlain by thick accumulations of synorogenic and postorogenic coarse continental deposits of Eocene and younger age, the so-called red conglomerates (O10) (Fries, 1960, p. 91–101). In other ranges, fronting the Gulf Coastal Plain, marine lower Tertiary deposits, including Oligocene and even younger ages, are folded with the earlier rocks. Deformation of the miogeosynclinal belt of the southern Cordillera was thus primarily Late Cretaceous and early Tertiary, or broadly contemporaneous with the Laramide orogeny of the central Cordillera.

Deformation of the miogeosynclinal rocks produced a fine display of folds (Alvarez, 1949, p. 1330–1333), some long and closely crowded, others shorter and discontinuous; these are accompanied by few low-angle thrusts. The closely crowded folds formed over a décollement in the weak layers of the lower part of the Mesozoic sequence, especially where evaporites are interbedded; the more open folds involve the basement, which emerges in the cores of the uplifts. South of the 22d parallel the deformed miogeosynclinal rocks front the little disturbed rocks of the Gulf Coastal Plain in an abrupt mountain face, but farther north domical uplifts stand in front (shown by structure contours in the coastal plain rocks on the tectonic map)—the Sierra de Tamaulipas, the Sierra de San Carlos, the Sierranias del Burro, and the Marathon dome in Texas. The main bundle of folds is strongly deflected westward near the 25th parallel around the south end of the Coahuila peninsula, producing a prominent salient near Monterrey, Nuevo Leon. A lesser branch of the foldbelt, with open folds, extends northwest from Monterrey to the Big Bend of the Rio Grande (Weidie and Murray, 1967, p. 689). South of the 20th parallel the frontal folds bend eastward from Chipas into Guatamala and Belize, with a south-projecting recess in midcourse.

The Mesozoic miogeosynclinal rocks of the Mesa Central in Mexico pass westward beneath little deformed Tertiary volcanics ($O\mu$), including extensive sheets of ignimbrite, which form the broad dissected plateaus of the Sierra Madre Occidental. Relations between the prevolcanic external and internal zones of the foldbelt are thus largely concealed, and eugeosynclinal rocks are poorly known on the mainland. Metamorphic rocks of uncertain age (mapped as O6a) are exposed west of the volcanic plateau in Sinaloa. The prevolcanic rocks on the south coast of Mexico west of the 102d meridian (mapped as O1 and O9) are now known to include Mesozoic eugeosynclinal slates and volcanics and embedded ultramafic rocks (Zoltan de Cserna, written commun., 1968). The main occurrence of eugeosynclinal rocks is in Baja California, where they and their granitic plutons (O7, O7a, Oθ) form the backbone of the northern half of the peninsula and its southern tip. In the north they are submarine lavas, pyroclastics, and volcanic sediments, steeply upended and partly metamorphosed; they are known to include strata of Jurassic and Lower Cretaceous (Aptian) age, and may include older components (Allison, 1964, p. 12–15). Both the eugeosynclinal rocks and the plutons are overlain by nearly undeformed latest Cretaceous (Campanian) sediments (O10), indicating that the orogenic climax in the southern Cordillera was later than the classic Nevadan orogeny of analogous parts of the central Cordillera.

In the Sierra Madre del Sur of southern Mexico, and eastward into northern Central America, pre-Mesozoic rocks and structures are more widely exposed than elsewhere in the southern Cordillera. A sequence of Pennsylvanian and Permian carbonate rocks and their basal clastics extends from Chiapas across Guatemala into Belize; it was deformed by variable but undetermined amounts before the Mesozoic miogeosynclinal deposits were laid over it, hence is shown on the tectonic map as a lower "structural stage" (older miogeosynclinal deposits, O8). A much greater part of the pre-Mesozoic of this region is a metamorphic complex (O1), varying from paraschist with interbedded marble and amphibolite to highly migmatized gneisses (McBirney, 1963, p. 187–197; de Cserna, 1965, p. 15–19). It contains embedded granitic plutons that have yielded radiometric dates from 300–90 m.y., or from middle Paleozoic to late Mesozoic age (Oϵ, Oθ), thus indicating (as in the metamorphic complexes of the northern Cordillera) prolonged heating and plutonic activity. The complex itself is probably of heterogeneous ages. Much of it in Oaxaca is Precambrian, as it has yielded radiometric dates between 700–1,100 m.y. and is overlain unconformably by Cambrian strata (Fries and others, 1962, p. 45–52; Fries and Rincon-Orta, 1965, p. 81–87; Pantoja-Alor and Robison, 1967). In Guatemala and Belize the complex is unconformable below the upper Paleozoic strata, but may include earlier Paleozoic (Dixon, 1956, p. 13–17), whereas in southern Guatemala and Honduras it may include equivalents of the upper Paleozoic itself (Williams and others, 1964, p. 2–5).

The topographic Sierra Madre del Sur of southern Mexico trends east-southeast parallel with the Pacific Coast and the Middle America Trench immediately offshore, but the structures of both its miogeosynclinal Mesozoic rocks and its metamorphic complex extend southeastward across it to the coast, where they are remarkably truncated. In Guatemala and Belize the structures are alined more toward the east, and are traversed by a bundle of closely spaced high-angle faults with the same trend. The high-angle faults extend eastward into the faults that bound the Cayman Trench on the floor of the Caribbean Sea; their westward extension toward the Pacific is concealed. They enclose slices of diverse and contrasting rocks—Paleozoic, Mesozoic, and Tertiary sediments, metamorphic complex, granitic rocks, and ultramafic rocks (the latter possibly upthrust mantle material). To the compiler, this set of faults has every indication of being a zone of major strike-slip displacement, yet little tangible field evidenec for such displacement has been reported (Walper, 1960, p. 1312–1313; McBirney, 1963, p. 212–213).

Immediately north of the Sierra Madre del Sur the transverse Mexican volcanic belt (Oπ) extends from the Pacific to the Gulf of Mexico, and contains a dozen lofty volcanic cones (including Pico de Orizaba or Citlaltepetl, 5,698 m or 18,696 ft) and a host of lesser cones and craters, some still vigorously active. It originated late in Cenozoic time and no doubt follows a deep-seated line of weakness, but it is accompanied by little surface rupture and it does not perceptibly deflect the structures of the miogeosynclinal rocks that plunge beneath it from either side.

(P) PACIFIC FOLDBELT

Cenozoic orogenic activity is especially pronounced in that part of the Cordilleran Mountain System near the Pacific Coast, and on the tectonic map it is appropriate to separate this part from the main Cordilleran foldbelt (O) as a rather vaguely defined Pacific foldbelt (P). A similar distinction has been made in the Asiatic equivalent of the North American Cordillera, where Soviet geologists separate a "region of Cenozoic folding" (sometimes called "Kamchatkan") from a "region of Mesozoic folding" farther inland. The Pacific foldbelt is characterized by late orogenic, volcanic, and seismic activity, by Cenozoic rocks and structures, and by a basement of eugeosynclinal rocks that are younger than those of the main Cordillera. The Pacific foldbelt was a late accretion to the edge of the North American continent, and part or all of it may have formed on what was originally oceanic crust.

On the "Tectonic Map of North America" the Pacific foldbelt is shown as including the Aleutian Islands, the coastal mountains of southern Alaska, the Coast Ranges of Washington, Oregon, and California, part of the volcanic province of Washington and Oregon, and part of Baja California. Its boundary with the Cordilleran foldbelt is well defined in places, but indefinite in others, where it has been necessary to overlap the units distinctive of the two foldbelts. Thus, granitic rocks of the Cordilleran foldbelt (Oθ) are shown in the California Coast Ranges, and plateau basalt of the Pacific foldbelt (Pγ) is shown in the interior of British Columbia.

ALASKA

The characteristic rocks and structures of the internal part of the Cordilleran foldbelt extend westward across southern Alaska, south of the Alaska Range and into the Alaska Peninsula—Mesozoic eugeosynclinal rocks (O7) with their embedded granitic plutons (Oθ), and younger Mesozoic and Tertiary successor basin deposits (O10, O11). Between them and the coast, in the Chugach Mountains, Kenai Peninsula, and Kodiak Island, are younger eugeosynclinal deposits—a vast sequence of steeply upended and partly metamorphosed graywackes, containing granitic debris from the middle Mesozoic plutons farther inland, but themselves intruded by small plutons of Tertiary age (Pβ) (Miller, 1959, p. 20–21). Sparse fossils indicate that the greater part of this sequence is of Cretaceous age (P1), but it is overlain near Prince William Sound by similar deposits of Paleocene age (P2). The same sequence extends southwestward beneath the continental shelf off the Alaska Peninsula, where it reappears in the Shumagin Islands (Burk, 1965, p. 63–71). The base of the Cretaceous eugeosynclinal deposits is undetermined, and they may have been laid down off the edge of the original Cordilleran foldbelt, at oceanic depths at the foot of the continental slope. Overlying the eugeosynclinal deposits in their eastern segment is 7,600 m (25,000 ft) of younger Tertiary shallow water marine deposits (P4).

Northwest of the Cretaceous-Paleocene eugeosynclinal belt is the younger Aleutian volcanic arc (Coats, 1962), which extends 960 km (600 miles) through the Alaska Peninsula, ending northeastward at Mount Spurr in the Alaska Range. West of the peninsula, the arc runs out to sea for another 1,600 km (1,000 miles) through the Aleutian Islands; the islands surmount a submarine ridge between the deep Aleutian Trench on the south and the shallower Bering Sea on the north; the ridge continues westward through the Kommandorsky Islands to the coast of Kamchatka. The basement of the Alaska Peninsula is formed of Mesozoic and older rocks of the Cordilleran foldbelt, and is succeeded by Tertiary volcanics and volcanic-derived sediments (Pδ, P4), which are surmounted by young andesitic volcanic cones (Pϵ), some still vigorously active (Burk, 1965, p. 119–122). Very little of the pre-Tertiary basement (P1) emerges in the Aleutian Islands, and they are mostly formed of Tertiary and younger volcanics, the young andesitic cones lying on the northern side of the arc, away from the Aleutian Trench.

WASHINGTON AND OREGON

The northwestern States of Oregon and Washington differ both in geology and tectonic style from nearby parts of the Cordilleran region, for here Cenozoic volcanic rocks and structures dominate the scene nearly to the exclusion of all others (Waters, 1955, p. 704–713; Snavely and Wagner, 1963)—lava plateaus, volcanic cones, and eruptive ranges that were produced by upbuilding, and folded or block-faulted ranges that were produced by deformation of the volcanic materials. Cenozoic volcanic rocks, and the sediments associated with them, extend along the Pacific Coast for 480 km (300 miles) and extend inland for as much as 650 km (400 miles). Within the volcanic areas pre-Cenozoic rocks emerge only as occasional inliers, although they form most of its periphery.

The pre-Cenozoic rocks of the inliers and of the periphery of the volcanic area belong to the eugeosynclinal part of the Cordilleran foldbelt, whose structures are recessed eastward in the Columbia arc (see p. 70); the crust within the recess probably differs from that of the Cordilleran foldbelt, and may have been oceanic during its early history. On the site of the present Coast Ranges within the recess, eugeosynclinal deposits (P2) were laid down during Eocene time, and are interbedded with large volumes of submarine pillow basalt (P2a). During Miocene time the eastern part of the recess was covered by great floods of plateau basalt of the Columbia River Group (Pγ), and at about the same time andesitic lavas and pyroclastics (Pδ) accumulated along the site of the Cascade Range to the west. Building of the Cascade Range continued into late Tertiary and Quaternary time, when a chain of volcanoes (Pϵ) grew along its north-south axis. During Tertiary time, small mafic to silicic plutons (Pβ) were intruded in the volcanic rocks of the Cascade Range.

The structure of the volcanic area was produced by a combination of volcanic construction and of moderate deformation during Cenozoic time. The Coast Ranges on the west are an anticlinorium, openly folded except in the steeply upthrust Olympic Mountains at the north end. Between them and the Cascade Range to the east is a belt of downwarping expressed as a chain of lowlands extending from Puget Sound southward to the Willamette Valley, whose deeper parts are thickly covered by late Tertiary and Quaternary deposits (P5). The plateau basalts within the recess of the Columbia arc form a broad structural basin, little deformed in places, but in others crossed by anticlinal folds.

CALIFORNIA AND BAJA CALIFORNIA

The Coast Ranges of California extend south-southeastward along the Pacific Coast for 925 km (575 miles) from Cape Mendocino past San Francisco Bay to Point Conception, and are separated by the Great Valley from the Cordilleran foldbelt in the Sierra Nevada to the east. South of Los Angeles, the Peninsular Ranges extend south-southeastward into Baja California. In the intervening area are the eastward-trending Transverse Ranges. Cenozoic strata (P4), largely of marine origin, are thick and extensive in the Coast Ranges south of San Francisco Bay, as well as in parts of the Transverse Ranges and adjacent basins, and have undergone several periods of orogenic deformation.

In the coastal belt of California great thicknesses of clastic rocks accumulated from latest Jurassic through Cretaceous time, or mainly after the climax of the Nevadan orogeny in the Cordilleran foldbelt. To the east these rocks are fossiliferous shelf deposits (P3), but to the west they are a contemporaneous sequence of poorly fossiliferous eugeosynclinal deposits (P1)—the graywackes, shales, cherts, and pillow basalts of the Franciscan Formation and its kindred (Bailey and others, 1964). The Jurassic and Cretaceous shelf deposits are thrust to the west over the Franciscan deposits, and no transitional phases between them are known (Page, 1966, p. 268–272). The Franciscan deposits were probably laid down at oceanic depths at the foot of the continental slope, in a manner similar to the Cretaceous and Paleocene eugeosynclinal deposits along the south coast of Alaska.

Rocks similar to the Franciscan Formation probably extend southward along the continental shelf west of the Peninsular Ranges as far as southern Baja California, as they emerge in many of the offshore islands and coastal promontories of the peninsula, such as Catalina Island in the north and Sebastian Vizcaino Peninsula farther south (Allison, 1964, p. 14–15). Here, in contrast to farther north, they appear to be of about the same age as the eugeosynclinal rocks of the Cordilleran foldbelt to the east (O7), rather than younger as in California. Their sedimentary facies is decidedly different, and they contain no granitic plutons.

In other parts of the coastal mountains of California a basement of crystalline rocks emerges, not only in the Peninsular and Transverse Ranges, but also in a long strip of the Coast Ranges that extends northward past San Francisco Bay. The basement of the Transverse Ranges includes Precambrian plutonic rocks and Paleozoic metamorphic rocks (Oα, Oβ, O6a). In the Coast Ranges to the north are extensive granitic rocks (Oθ) and metamorphic rocks of probable early Paleozoic age (O6a); the granitic rocks have yielded radiometric dates of 80–90 m.y., hence are Cretaceous and are as young or younger than the Franciscan Formation, but they and the metamorphic rocks are everywhere faulted against the Franciscan, so that the original relations between them are unknown.

The Cenozoic strata of the Coast Ranges and Transverse Ranges have been described in many publications (Reed and Hollister, 1936, p. 1559–1596; Taliaferro, 1943, p. 135–149; Page, 1966, p. 263–268). On the tectonic map they are shown as a single unit (P4), although their record is so complex that they could be divided into a number of "structural stages" on a map of larger scale. Deposits of Miocene and earlier ages are extensive and mainly marine, but most of them grade eastward into continental equivalents. Pliocene marine deposits occur in more restricted coastal areas, such as the Los Angeles and Ventura basins, and in the southern part of the Great Valley. Marine Pliocene strata attain thickness of 4,500 m (15,000 ft) in some of the coastal areas, and nonmarine Pliocene in the interior basins is even thicker. In the coastal areas the marine Pliocene is succeeded conformably by thick lower Pleistocene marine and brackish water deposits, which are strongly unconformable beneath upper Pleistocene marine terrace deposits and alluvium.

The Cenozoic sequence of the Coast Ranges and Transverse Ranges records an eventful tectonic history, with times of deformation indicated at so many levels and with such varying magnitude from place to place that they are difficult to generalize into any orogenic climaxes. Nevertheless, a group of deformations during middle and late Miocene time appears to have been important, to have deformed the earlier Cenozoic strata widely, and to have restricted the areas of subsequent sedimentation. A final climax of deformation occurred during Quaternary time, mainly during the gap between the lower and upper Pleistocene deposits (Stillé, 1936, p. 867–868; Bailey, 1943, p. 1562–1564).

The sequence of Tertiary marine deposits along the western side of Baja California is nearly as complete as in California (Allison, 1964, p. 16–19), but neither they nor the late Cretaceous deposits beneath them have been as much deformed as farther north. In the southern half of the peninsula the upper Tertiary marine deposits pass eastward into a thick mass of terrestrial volcanics, pyroclastics, and volcanic sediments (Comondu

Formation, Pδ)—a mass which is broken off on the east by escarpments that face the Gulf of California.

The structure of the Coast Ranges, Tranverse Ranges, and northern Peninsular Ranges is confused by a multitude of faults. The widespread westward thrusting of Jurassic and Cretaceous shelf deposits over the Franciscan Formation has already been mentioned. Much more prominent and generally younger are the high-angle faults, many of which are of great length and have dominant components of strike-slip displacement (Crowell, 1962). The high-angle faults cross the grain of the ranges at an acute angle, mostly in a northwestward direction, but with a conspicuous east-trending set in the Transverse Ranges. Strike-slip displacement on the northwest-trending set is dominantly right lateral and on the east-trending set dominantly left lateral. The most lengthy high-angle fault is the San Andreas, which crosses all the coastal ranges from northern California to the United States-Mexican border with a nearly straight southeastward course, except for an eastward deflection in the Transverse Ranges.

Nearly every aspect of the high-angle faults of the coastal ranges has been diversely interpreted—the time of their inception, the magnitude and kind of their movements, and their role in the geologic history of the region (Hill and Dibblee, 1953; Oakeshott, 1966; Dibblee, 1966). The San Andreas fault has been variously estimated to have originated in early Cenozoic time or before and to have been displaced laterally as much as 560 km (350 miles), or to have originated during the Quaternary and to have been displaced less than 2 km (1 mile). In view of the marked contrasts between the rocks on the opposite sides of the San Andreas and most of the other high-angle faults, larger rather than smaller displacements seem likely; such movements probably account for the anomalous juxtaposition of the Franciscan basement against the crystalline basement in the Coast Ranges.

Along the San Andreas fault and many of the others are overwhelming indications of marked displacement during Quaternary time, and of continuing activity today. Modern activity is attested by the clustering of earthquake epicenters along the faults and by ground breakage along the faults at the times of earthquakes. Fault movements during the last few thousand years are indicated by characteristic landforms along the fault traces—fault trenches or rifts, pressure ridges, and sag ponds. Even more striking is the distortion of modern topography along the faults by offset of ridges and stream channels; stream channels crossing the San Andreas fault have been offset right laterally 100–1,500 m (325–4,500 ft). The record of displacement along the San Andreas and other high-angle faults indicates that movements were progressive, so that each topographic feature and each bedrock formation is more offset the greater its age.

The peninsula of Baja California, with eugeosynclinal rocks and granitic plutons in its basement, is a long sliver of continental crust, separated from the Mexican mainland by the deep water of the Gulf of California. The northern half of the gulf is thickly filled with sediments, but the southern half is floored by oceanic crust; the gulf is evidently a rift, across which the peninsula drifted northwestward from the continent during Cenozoic time (Rusnak and others, 1964, pp. 68–74). The faults which were formed during the drifting do not, however, extend directly down the gulf, and are not direct extensions of the high-angle faults of California. The latter trend southeastward into Mexico, each dying out on the Sonoran mainland. They are succeeded farther south by other faults, plainly indicated by the bathymetry of the gulf floor, which also trend southeastward, with an en echelon pattern. The northwestward drift of Baja California and the strike-slip displacement of the high-angle faults of California are not independent phenomena, but are parts of a single grand movement of the western coastal area of North America (Hamilton, 1961).

(Q) ANTILLEAN FOLDBELT

Another region of pronounced Cenozoic orogenic activity, here called the Antillean foldbelt (Q), lies between North and South America in the lands and islands surrounding the Caribbean Sea. On the tectonic map the foldbelt is shown as including the islands of the Greater and Lesser Antilles, and the mainland areas of coastal Venezuela and southern Central America. Southern Central America is included for convenience, but with equal propriety it could be classed as a southern prolongation of the Pacific foldbelt.

The Antillean foldbelt differs from those of North and South America, as it is an oceanic rather than a continental feature. Much of it is far from any large continental areas, and most of the emerged parts rise steeply from oceanic depths, making it one of the most rugged mountain systems of the Americas. The Puerto Rico Trench is 8,000 m (26,000 ft) deep 130 km (80 miles) north of the coast of Puerto Rico; the Cayman Trench is 7,000 m (23,000 ft) deep 40 km (25 miles) south of the coast of Cuba, and the Sierra Maestra rises another 2,000 m (6,500 ft) behind the coast. Peaks in the central cordilleras of Hispaniola and Costa Rica project above 3,000 m (10,000 ft), but the other land areas in the foldbelt are lower. As shown by the bathymetry on the tectonic map, the Caribbean sea floor is itself diversified by basins and trenches, with ridges and swells between, many of which do not project above sea level, and whose structure is largely conjectural. The land areas thus constitute only a fragment of the tectonics of the whole foldbelt, the remainder of which must be deduced from data obtained during oceanographic surveys.

Because of the fragmentary evidence, the origin and the tectonic history of the Antillean foldbelt are less certain than those of any of the foldbelts so far considered, and have been diversely interpreted. Many of the early hypotheses required extensive continental areas in the Caribbean region, which have now vanished by foundering or other causes. It is true that the crust of the Caribbean sea floor is somewhat thicker and less dense than normal oceanic crust, but it is by no means continental (Donnelly, 1964, p. 683–684); it was probably produced by hydration of normal oceanic crust, rather than by "oceanization" of continental crust. The tectogene hypothesis, which was at one time applied to the Antillean foldbelt (Hess, 1938) is discredited by newer geophysical data; as originally proposed, it involved downbuckling of a thicker and more sialic crust than is now known to exist.

Perhaps the Caribbean Sea was produced by the drifting apart of the North and South American continents, but most of the proposed reconstructions of drifting in the region involve implausible shifting, and even complete rotation of bits of continental crust to produce the present pattern of lands and islands. Other, more plausible reconstructions of the Caribbean by the drift hypothesis might be possible, but they are still in the formative stage. Hess writes (1966, p. 5), "It can be stated without question that the Caribbean existed during the whole of the Tertiary more or less with its present outlines, but how long before that was there a Caribbean?" Present evidence seems to indicate that, whatever may have been the origin and early nature of the Caribbean, the present lands and islands of the Antillean foldbelt were built up during Mesozoic and Cenozoic time on an original oceanic crust, by the addition of magmas from the mantle, followed by a complex tectonic evolution into the modern foldbelt (Dengo, 1962, p. 156–157; Donnelly, 1964, p. 689–695; Bowin, 1966, p. 15–17).

This tectonic evolution is most nearly completed in the large, massive islands of the Greater Antilles on the north and in the coastal area of Venezuela and Trinidad on the south, both of which underwent orogenic deformation during late Mesozoic and early Cenozoic time, and have now attained relative stability. It is less complete in Central America on the west, which is bordered on the Pacific side by a chain of active volcanoes and by the Middle America Trench (Dengo, 1967). Even less mature are the small islands of the Lesser Antilles on the east, which are mainly volcanic and rise individually out of deep water, with a trench extending at least part of the way around their Atlantic side.

Another item must be added to complete the tectonic picture—the great fault zones on each side of the Caribbean Sea, extending through Venezuela and Trinidad on the south and the Greater Antilles on the north. The Cordillera de la Costa in Venezuela and the North Range in Trinidad are a line of narrow ridges along the sea, composed of metamorphosed Mesozoic rocks (Q2a) unlike the unmetamorphosed Mesozoic rocks south of them. They have reached their present position by right-lateral displacement along a fault zone on the south side of the ridges (Rod, 1956, p. 474–476).

On the northern side of the Caribbean Sea the Cayman Trench extends diagonally through the Greater Antilles between Cuba and Jamaica, with steep infacing scarps on each side (Meyerhoff, 1962, p. 1–3). Farther east, and not in direct alinement, the Anegada Passage forms another, smaller trench between the Greater and Lesser Antilles. Both these features are certainly fault bounded, and at least some left-lateral displacement has occurred along them (or displacements opposite to those in Venezuela and Trinidad), but there are complications. The Cayman Trench is floored by an oceanic crust, much thinner than that beneath the islands and submarine rises on either side, suggesting that the trench is a rift, perhaps comparable to the rift in the Gulf of California, mentioned above (Ewing and others, 1960, p. 4095–4096). Whatever the nature of the fault movements north and south of the Caribbean Sea, they detached the more mature parts of the foldbelt from the unstable parts between, where tectonic evolution is still in progress.

No pre-Mesozoic tectonic units have been proved in the Antillean foldbelt, and their existence is doubtful in most of it. The last exposure of the pre-Mesozoic is in northern Central America where its metamorphic complex (O1) plunges southward beneath Tertiary volcanics (Q8) near the Honduras-Nicaragua border, and it is cut off eastward by the Caribbean coast. Farther south in Central America the basement is the Nicoya Complex (Q2), resembling the Franciscan of the Pacific foldbelt, and like it probably no older than Mesozoic (Dengo, 1962, p. 138–142). The pre-Mesozoic metamorphic complex seems to extend east of the coast beneath the Nicaraguan Rise and Cayman Ridge, but whether it emerges again in the Greater Antilles is undetermined. The basement of the Greater Antilles is also termed a metamorphic complex (Q1), but this is known only to be older than Late Jurassic. Most of it is probably older Mesozoic eugeosynclinal material, although pre-Mesozoic components have been proposed in Cuba (Khudoley, 1967, p. 672–674; Hatten, 1967, p. 780–782).

Mesozoic eugeosynclinal deposits (Q2), with large volumes of volcanics and volcanic-derived sediments, occur in all areas of the Antillean foldbelt. In southern Central America they are overlain by nonvolcanic Upper Cretaceous deposits (Q3), but in the Greater Antilles the eugeosynclinal sequence extends in most places to the top of the Mesozoic, and in southeastern Cuba into the Eocene (Q4a). In the Cordillera de la Costa of Venezuela, where all the eugeosynclinal rocks are regionally metamorphosed (Q2a), the largely nonvolcanic Caracas Group is bordered on the south by the structurally separated but probably older volcanics of the Villa de Cura Group. Mesozoic miogeosynclinal deposits, including thick carbonates, border the eugeosynclinal rocks on the north in Cuba (Q4), and on the south in Venezuela (N3), and are continuous with the platform deposits of the Bahama Islands and the Venezuelan interior. Succeeding older Tertiary deposits (Q4) are varied, largely clastic in many areas, but including volcanic components in southern Central America and thick carbonate units in parts of the Greater Antilles.

A significant Middle Cretaceous orogeny occurred in Cuba, but throughout much of the foldbelt the main orogenies occurred from Late Cretaceous through Eocene time. They were accompanied by emplacement of granitic plutons (Qβ) of middle Cretaceous to Eocene age, largely more mafic than those of the other foldbelts (diorites and quartz diorites). In Cuba the eugeosynclinal rocks were carried northward over the miogeosynclinal rocks in great thrust sheets or nappes of Alpine type (Hatten, 1967, p. 785–788), many of which have tabular masses of ultramafic rocks (Qα) along their soles.

In the more mature parts of the foldbelt, deformation was largely completed by Eocene or Oligocene time, so that the later Tertiary is postorogenic and little deformed (Q5). Deformation continued later in Hispaniola, and there was significant Miocene orogeny in Costa Rica, accompanied by emplacement of small granitic plutons in the central cordillera (Qγ) (Dengo, 1962, p. 143–147).

Young volcanic rocks are lacking in the more mature parts of the foldbelt, but they are important in the less stable intervening parts. Large areas in southern Central America are covered by late Tertiary lavas and pyroclastics, probably derived from fissure eruptions (Qδ). On these, on the Pacific side, younger volcanics (Qϵ) have been built, surmounted by a chain of volcanic cones that extends from the eastern border of Mexico to Costa Rica (Williams, 1952, 1960). An arcuate chain of volcanic cones also forms most of the islands of the Lesser Antilles to the east, but in the northern half of the arc the cones are bordered on the Atlantic side by half a dozen lower islands with a foundation of older Tertiary volcanics and diorite plutons, capped by later Tertiary limestones and other sediments (Q4).

(N) ANDEAN FOLDBELT

Many features like those in the North American Cordillera are repeated in the South American Cordillera, or Andean foldbelt (N). Most of the Andean foldbelt is outside the area of the "Tectonic Map of North America," but its northern prongs extend into it, in Colombia and Venezuela. The tectonic features of the Andean foldbelt are shown on the map down to the 6th parallel, mainly to provide a southern frame for the Caribbean Sea and its Antillean foldbelt (Q). The structures represented are copied from compiled maps, such as the "Geologic-Tectonic Map of Northern Venezuela" (Smith, 1962), and publications on the foldbelt have been studied only sufficiently to establish usable map units (see, for example, Jacobs and others, 196?; Mencher, 1963). The tectonics of the foldbelt and its map units will be shown more authoritatively on the "Tectonic Map of South America," which is now in preparation by geologists of the South American countries.

In Colombia, the Andes Mountains split northward into a Cordillera Occidental, a Cordillera Central, and a Cordillera Oriental. The first two plunge northward beneath the lowlands of the Rio Magdalena and its tributaries, but the third extends northeastward into Venezuela, bifurcating in turn into the Sierra de Perijá and the Cordillera de Mérida, which enclose the Maracaibo Basin. The Sierra Nevada de Santa Marta along the Caribbean coast in Colombia is an independent massif. The various cordilleras and sierras are composed of Mesozoic and older rocks, and the lowlands between them are underlain by Cenozoic rocks.

Pre-Mesozoic rocks, largely metamorphosed (N1, Nα), form much of the Cordillera Central and Sierra Nevada de Santa Marta, and emerge in smaller inliers in the Cordillera Oriental and Cordillera de Mérida. They include fossiliferous rocks of various Paleozoic ages, and probably also Precambrian rocks; the pre-Mesozoic basement of the Cordillera Oriental includes reworked parts of the edge of the Precambrian Guyana Shield. Orogenies at various times during the Paleozoic are suggested in places by unconformities or gaps in the sequence, but they are too imperfectly known to give much of an idea of the resulting structures. Embedded in the metamorphic rocks are granitic plutons (Nβ), primarily Mesozoic but possibly including Paleozoic. Recent radiometric determinations in Colombia show that they are dominantly Mesozoic, the large pluton in the Sierra Nevada de Santa Marta is dated at 160–170 m.y. (Jurassic) and the large pluton near Medellín in the Cordillera Central is dated at 70 m.y. (Late Cretaceous).

Tectonic history becomes plainer in the Mesozoic. The Cordillera Occidental and the lower ranges along the Pacific coast are formed of Mesozoic eugeosynclinal deposits (N2)—submarine lavas and associated sediments that are largely of Cretaceous age, but which may also include Jurassic. The Cordillera Oriental and its extensions into Venezuela is formed of Mesozoic miogeosynclinal deposits (N3), including thick sequences of Cretaceous carbonates. Beneath them, however, are continental red clastics (Girón Group), which are largely of Jurassic age.

The Andean cordilleras were deformed and shaped into much their present outlines by several orogenies between Late Cretaceous and Eocene time. The miogeosynclinal rocks of the Cordillera Oriental and Sierra de Perijá were thrown into closely crowded, east-directed folds and thrust slices, but the cordilleras of metamorphic and plutonic rocks were raised mainly as block uplifts bordered by high-angle faults, some with strike-slip displacement. The Boconó fault, which extends the length of the Cordillera de Mérida, has a large component of right-lateral displacement, and may be still active (Rod, 1956, p. 463–468).

Basinal deposits of Eocene and younger Tertiary ages (N4), partly marine and partly continental, and both synorogenic and postorogenic, fill the depressions between the cordilleras, and have been extensively explored for petroleum. In deeper depressions along the Magdalena River in Colombia, and in the Maracaibo Basin in Venezuela, these deposits are covered in turn by late Tertiary and Quaternary deposits (N5). The configuration of the pre-Tertiary basement beneath the Maracaibo Basin is shown on the map by 500-m contour lines.

SUBSEA AREAS

On the "Tectonic Map of North America" the terrain beneath the seas and oceans surrounding North America is represented by 500-m (1,640-ft) topographic contours, with the first 200-m (656-ft) contour added, and by bathymetric tints for each 1,000-m (3,280-ft) interval. The many sources from which the contours have been compiled were summarized earlier (p. 18–19). In addition, a special symbol is used to represent prominent faults or fracture zones on the ocean floor, whose existence is indicated by topographic scarps, and in part by geophysical evidence. The treatment of the subsea areas adopted on the North America map corresponds to that on most tectonic maps previously published.

The topography of the sea bottom is clearly more expressive of tectonics than the topography on the land, because the original structural surfaces have been much less modified by subsequent erosion and deposition. Hence, fault scarps, fault blocks, upwarps, and downwarps are evident merely from their surface configuration. Moreover, the internal structure of the topographic features on the sea bottom cannot, as yet, be deciphered with as much assurance as on the land. The features are not available for field inspection, but must be probed indirectly by various kinds of oceanographic surveys. These surveys are still incomplete in the areas surrounding North America, and some of the methods of survey are still being perfected.

On the North America map, as on many others, the subsea areas are not classified into tectonic units like those on the land. However, subsea tectonic units are shown on some of the newer tectonic maps, such as the "Tectonic Map of Eurasia" (Yanshin, 1966) discussed earlier (p. 17–18). Many of the tectonic units shown on such maps are merely morphological or descriptive, and correspond to the physiographic provinces which have been mapped on the sea bottoms around North America (for example, Heezen and others, 1959, p. 20), and include such features as continental slopes, continental rises, and abyssal plains. Most of these provinces are evident in the subsea topography itself. Other tectonic units shown on such maps indicate the surface or subsurface composition of the sea bottom, such as areas of oceanic crust or continental crust, and areas with thick sedimentary cover. Many data on the composition of the sea bottom have been obtained around North America, but no maps have been published of large areas which show instrumentally verified compositions. Other tectonic units on such newer maps are of more questionable value, as these imply ages of the units or ages of the deformation, which cannot be verified by existing oceanographic methods, and which imply a choice between several possible theories of oceanic tectonics.

Some of the existing survey methods offer more possibilities than others for refining the tectonic classification of the subsea areas. Continuous seismic reflection profiling provides information on the structure of reflecting surfaces more than 1,000 m (3,300 ft) below the bottom surface, revealing features that can be interpreted as flat-lying, tilted, or folded sedimentary beds, as well as faults and unconformities. Many profiles have now been made on the continental shelves and slopes around North America—for example, off the Atlantic Coast of the United States (Uchupi and Emery, 1967).

These surveys will aid materially in an eventual tectonic mapping of the shelves and slopes around the continent, areas which are shown without symbols on the present map.

Magnetic surveys also have tectonic implications. A total intensity magnetic survey has been made of a large area off the Pacific Coast of the United States (Vacquier and others, 1961; Raff and Mason, 1961) which, although incomplete, has revealed a remarkable pattern of narrow, parallel belts of positive and negative anomalies, offset along the subsea fracture zones. Similar parallel belts of magnetic anomalies have been found on each flank of the Mid-Atlantic and other mid-ocean ridges (Vine and Matthews, 1963), and it has been proposed that all these anomaly belts are products of sea floor spreading (Wilson, 1965a; Vine and Wilson, 1965). Parallel anomaly belts, apparently of a different kind, are known on the continental shelf and slope off the Atlantic Coast (Drake and others, 1963), but the western Atlantic Ocean basin between Bermuda and the continental slope is reported to be magnetically featureless (E. R. King and others, 1961; Heirtzler and Hayes, 1967). Magnetic surveys, when more complete, will have an important influence on the tectonic mapping of the subsea areas around North America.

FAULT ZONES

Further discussion is desirable on the only subsea structural features specifically shown on the tectonic map—the faults or fracture zones. The most notable of these are off the Pacific Coast of North America; the zones have been described and interpreted by Menard and others in various publications (for summary, see Menard, 1964, p. 41–53). From north to south, those shown on the map are the Mendocino, Pioneer (minor), Murray, Molokai (incompletely represented by the Shirley Trough), Clarion, and Clipperton. Still other fracture zones extend westward from the coast of South America, beyond the map area (fig. 14).

The fault zones on the Pacific Ocean floor are remarkably evenly spaced, about 1,000 km (600 miles) apart, and trend nearly westward from the coast along great circle courses for distances of many thousands of kilometers. All of them are expressed topographically by escarpments or lines of ridges and troughs, and at least some of them form the borders of ocean bottoms of different depths; thus, the ocean bottom south of the Mendocino zone is at least 1,000 m (3,300 ft) lower than north of it. The areas between the zones also differ in tectonic behavior, as shown on the map by the nearly featureless surface between the Mendocino and Murray zones, contrasted with the abundant seamounts north and south of them. Seismic surveys show that these express differences in crustal thickness in the areas between the zones. The age of the faulting is undetermined. In view of the fact that few ages older than Cretaceous have been verified in the oceanic areas, they cannot be very ancient, yet no earthquake epicenters occur along them except near their intersections with other features.

Despite the strong expression of the faults on the Pacific Ocean floor and their close approach to the coast of North America, remarkably little indication of them can be discovered on the land. The only zone directly traceable to the land is the Mendocino, which offsets the edge of the continental shelf right laterally about 80 km (50 miles), but even it is not identifiable in the surface rocks farther inland. It has been proposed on geological or geophysical evidence that the zone extends long distances eastward across North America (Gilliland, 1962; Fuller, 1964); however, the proposals are as yet unconvincing. The Murray zone disappears near the foot of the continental slope, perhaps beneath a sedimentary cover. It may be related to the faults with left-lateral displacement in the Transverse Ranges of southern California; these, in turn, are at the western end of the Texas Lineament, which is not a fault zone. The Clarion zone disappears far west of the coast, but is alined with the Trans-Mexican volcanic belt, which again is not a fault zone. The Clipperton zone disappears far west of the coast, but is alined with minor transverse structures in Costa Rica, and these in turn with the lengthy faults on the north coast of South America. A broken, zig-zag connection between the Clipperton zone and the transverse faults of Guatemala can also be imagined through the northeast-trending Tehuantepec fracture zone. The vagueness of all these relations strengthens the belief that the faults of the Pacific Ocean floor are structures in the oceanic crust, and that if they extend eastward into the North American continent, it is beneath the upper crust, whose surface has been affected indirectly at most.

Where the Mendocino fracture zone leaves the coast it is expressed by a northward-facing scarp, but 120 km (75 miles) farther west the topography reverses to a southward-facing scarp as much as 3,000 m (10,000 ft) high, which continues to the termination of the zone, showing that displacements on the zone have been complex. This complexity is more strikingly demonstrated by matching magnetic anomalies across it. The anomalies indicate that west of the coast there has been an astonishing left-lateral offset of 1,170 km (785 miles), as compared with an 80 km (50 miles) right-lateral offset of the continental shelf along the same zone. Similarly, matching the anomalies across the Murray zone indicates as much as 640 km (395 miles) of right-lateral offset at sea, decreasing eastward, whereas the faults in

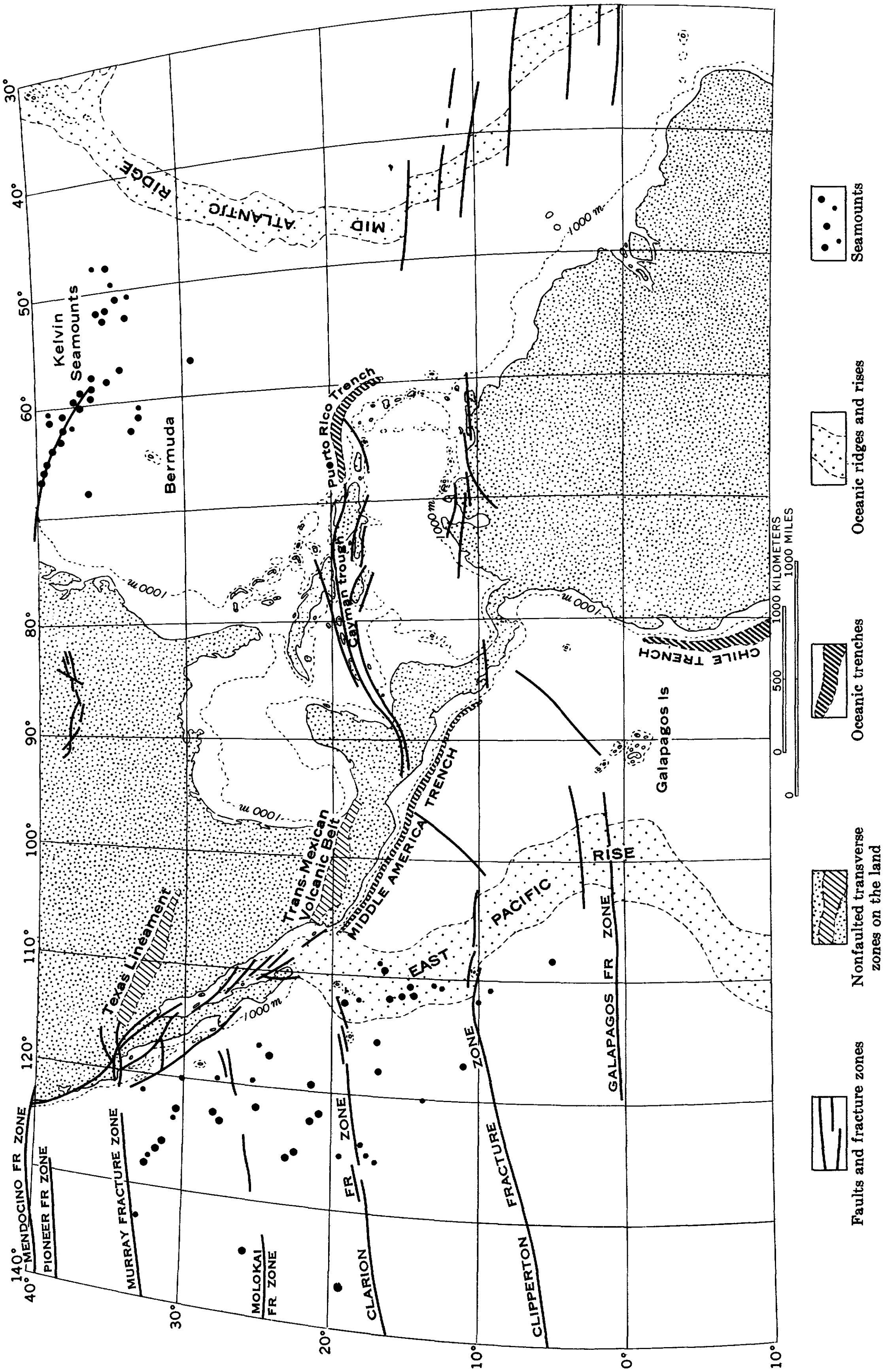

FIGURE 14.—Map showing transverse structural features on the lands and beneath the seas in the southern part of the area of the "Tectonic Map of North America," and in adjacent regions. Compiled from "Tectonic Map of North America," and from publications of H. W. Menard, B. C. Heezen, and others.

the Transverse Ranges on the land are offset left laterally.

These paradoxes seemed inexplicable until J. T. Wilson (1966) proposed the concept of "transform faults," along which lateral displacement has occurred in opposing senses on the two sides of a zone of oceanic spreading. The zone of spreading in this case is the East Pacific Rise, which is supposed to extend northward from the ocean beneath the continent in the Gulf of California and to emerge again in the ocean floor north of the Mendocino fracture zone. The oceanic spreading along the East Pacific Rise, and the accompanying transform faulting, if these exist, had a major influence on the creation of the younger tectonic features of the Cordilleran and the Pacific foldbelts of the North American continent.

The existence of lengthy fracture zones on the Pacific Ocean floor has implications on the origin of the fault zones on the north and south sides of the Caribbean Sea (p. 78), especially since east-west fracture zones, also transform faults, are now known to cross the Mid-Atlantic Ridge between the equator and lat 15° N. (Heezen and Tharp, 1961). The faults in the Caribbean Sea may therefore not be local features produced by a movement pattern in the Antillean foldbelt alone, but may be parts of a circumglobal fracture system in the oceanic crust (fig. 14).

Aside from the subsea faults in the Caribbean Sea, only one other is shown on the tectonic map on the eastern side of North America. This is supposed to follow the arc of the Kelvin Seamounts ("Bermuda-New England seamount arc" of Northrop and others, 1962) onto the continental shelf and slope near the 40th parallel. The existence of the fault on the shelf and slope is suggested by a 145-km (94-miles) right-lateral distortion or actual offset of sedimentary basins and belts of magnetic anomalies that have been determined by oceanographic surveys (Drake and Woodward, 1963, p. 53–55). A landward prolongation of the fault across the Appalachian foldbelt has been proposed on seemingly tenuous evidence, although there is admittedly a discontinuity at about this latitude between the northern and southern Appalachians, so that the structures of the former lie eastward of those of the latter (p. 56).

GLOSSARY

This glossary defines the tectonic terms used in the text, not all of which are familiar to the non-specialized reader. The initial sentences under many of the items are abstracted from the "International Tectonic Dictionary" (Dennis, 1967). Succeeding sentences are explanations or qualifications by the compiler. Some of the terms are discussed at greater length at appropriate places in the text. French equivalents of some of the terms are included to facilitate comparison with the legend of the "Tectonic Map of Europe" (Schatsky, 1962). For brevity, sources and authorships of the terms are seldom included; for literature references and for history of usage the reader should consult the "International Tectonic Dictionary."

Allochthone.—A mass of rocks which has been moved by tectonic forces from its original site of origin, as in a thrust sheet or nappe. Opposite, *autochthone.*

Alpinotype tectonics.—The tectonics of alpine mountain belts, which are produced from orthogeosynclines. Characterized in the internal parts by deep-seated plastic folding and plutonism, and in the external parts by lateral thrusting, which has produced nappes, thrust sheets, and closely crowded folds.

Antithetic structures.—Structures produced by minor movements that oppose the prevailing larger movements in the area; for example, faults which are downthrown in a sense opposite to the general uplifting or arching. Opposite, *synthetic structures.*

Autochthone.—A mass of rocks which, though variably deformed, has remained at its original site of origin, where it is still rooted to its basement. Opposite, *allochthone.*

Basement rocks.—Rocks beneath the platform areas and the foldbelts that were consolidated during earlier deformations, which are overlain by a less deformed younger structural layer or cover. Ideally, basement rocks are metamorphic and plutonic, and contrast strongly with their cover, but parts of the basement are composed of intermediate rock types so that distinctions are blurred in places. In the central part of the continent the basement rocks are Precambrian, but they are of younger ages elsewhere. French, *socle.* (See p. 21.)

Batholith.—Traditionally used for large, subjacent and discordant plutonic bodies, supposedly floorless in contrast to other intrusive bodies; most batholiths are formed of granitic rocks but presumably could be of other compositions. In the western Cordillera of the United States and Canada the term is used specifically for regionally extensive aggregates of granitic rocks, complex internally, and consisting of many individual *plutons* of varied compositions and ages; the "Tectonic Map of North America" and the present text defer to the latter usage. Examples, Sierra Nevada batholith, Idaho batholith, Coast batholith. (See p. 51–52.)

Block faulting.—The breakup of a previous more homogeneous terrane into blocks as a result of faulting that is mainly normal or tensional. The resulting structure is an array of uplifted mountains (preserving their block forms in the early stages), separated by down-faulted depressions. Block-faulting is primarily a postorogenic feature and disturbs terranes with varied prior histories, ranging from those which have undergone little earlier deformation to those of thoroughly deformed rocks. Example, the Basin and Range province of the southwestern United States. (See p. 24, 72.)

Craton.—A part of the earth's crust which has attained stability, and which has been little deformed for a prolonged period. As originally defined, the cratons included parts of both the continents and the ocean bottoms, but the proposed examples of the latter are unproved or dubious. In the present text the term is used only in the continental areas, where it includes both *shields* and *platforms.*

Décollement.—Detachment of rocks along a stratigraphic surface, resulting in independent styles of deformation in the rocks above and below. The term is merely descriptive, and the detachment could have been produced by any one of a number of tectonic forces, including lateral thrusting and gravity sliding.

Diapir.—A fold or dome which contains a core of more mobile rock that has pierced and intruded the overlying less mobile rock. Ordinarily the more mobile rock has a lower density than its cover, but it may be of many kinds, including salt (as in salt domes), other evaporites, or clay.

Disharmonic folding.—Folding in which there are notable differences in kinds of structures between adjacent rock bodies, resulting from bedding-plane slip along sedimentary layers. This type of deformation is characteristic of stratified sequences and is, in fact, demanded by the geometry of their folds. In extreme form, bedding-plane slip produces *décollement*, and the two structures are commonly associated.

Disrupted areas.—Used specifically in the text for previously stabilized or cratonic areas that have been broken up by block-faulting and related processes. Example, the part of the Basin and Range province in southern Arizona and New Mexico. (See p. 24, 72.)

Epeirogeny.—Broad uplift and subsidence of the crust, primarily by vertical movements, which has affected large parts of the continents. Epeirogeny occurs both in the cratons and in foldbelts during the final stages of their tectonic cycles. It has produced the present mountainous topography in many of the foldbelts, and thus would be "orogeny" as some geologists have defined the term (but not the present compiler). Even as here defined, epeirogenic and orogenic structures grade into each other in detail, although most of them differ distinctly from each other. Counterpart, *orogeny.* (See p. 44–45.)

Epieugeosyncline.—A sedimentary trough or basin on the site of a former eugeosyncline. Nearly synonymous with *successor basin*, the term preferred in the present text.

Eugeosyncline.—The internal part of a geosyncline (orthogeosyncline), away from the craton, characterized by strong volcanism during its early phases and by synorogenic plutonism during its later phases. Deposits of eugeosynclines include submarine volcanics, cherts, slates, and graywackes. Counterpart, *miogeosyncline.* (See p. 46–47.)

Event.—A noncommittal term used for any incident of probable tectonic significance that is suggested by geological, radiometric, or other evidence, whose full implications are unknown. Used especially for minor clusters of radiometric dates whose relations to geologic structures or processes have not been precisely determined.

Externides.—The external or outer part of a foldbelt, nearest the craton or foreland, commonly the site of a miogeosyncline during its early phases and subjected to marginal deformation later. Opposite, *internides.* The terms externides and internides express relative positions of units within the foldbelts, and not their relation to adjacent parts of the continents. In relation to the central craton of North America, the externides of the Phanerozoic foldbelts would be internal, and the internides external. (See p. 46).

Flysch.—A sequence of distinctively interlayered sandstones, mudstones, and marls believed to have accumulated in relatively narrow, deep, rapidly subsiding troughs. The term originated in the European Alps, but nearly identical deposits occur in many other foldbelts of the world. Flysch is commonly interpreted as a synorogenic deposit, and hence the term has been used improperly by many geologists for any clastic sediment that was laid down during the time of the orogeny. (See p. 48).

Foldbelt.—A linear belt that has been subjected to folding and other deformation during the orogenic phase of a tectonic cycle. Each foldbelt evolved during a time span different from that of any of the others, and details of their histories differ, although they can be grouped broadly according to generalized worldwide times of orogeny. Individual foldbelts, and the tectonic cycles which created them, are used as fundamental units on the "Tectonic Map of North America." Synonyms, *mobile belt*, *orogenic belt*, and (less properly) *mountain belt.* French, *region de plissement.*

Foredeep.—The part of the foreland or craton next to a foldbelt that was deeply downfolded and thickly filled with sediments during the climactic orogeny.

Foreland.—A stable area marginal to a foldbelt, toward which its rocks were thrust or overfolded. The area is commonly continental, and is a *craton* or *platform area.*

Germanotype tectonics.—Tectonics of the cratons and the stabilized foldbelts, derived from the structures in Germany north of the Alps. The milder phases of this type of tectonics are epeirogenic, but it also includes broad folds dominated by vertical uplift and high-angle faults, block-faulted terranes, and sedimentary basins deformed within a frame of surrounding massifs.

Infrastructure.—Structure produced at a deep crustal level, in a plutonic environment, under conditions of elevated temperature and pressure, which is characterized by plastic folding and by granitic and other migmatitic and magmatic rocks. This environment occurs in the internal parts of most of the foldbelts, but the term is used especially where the infrastructure is clearly contrasted with a less disturbed or altered higher layer, or *suprastructure.*

Internides.—The internal part of a foldbelt, farthest away from the craton, commonly the site of a eugeosyncline during its early phases, and subjected later to plastic folding and plutonism. Opposite, *externides.*

Koilogenic.—A term used by Spizaharsky and Borovikov (1966) for broad downwarping or subsidence of the crust, of a sort that would be classed as a negative epeirogenic movement in the present text.

Leptogeosyncline.—A part of a geosyncline (orthogeosyncline) in which the water was of great depth, but which received only small thicknesses of sediments over prolonged periods; a form of starved sedimentary basin.

Massif.—A massive topographic and structural feature in a foldbelt, commonly formed of rocks more rigid than those of its surroundings. These rocks may be protruding bodies of basement rocks, rocks consolidated during early deformations in the foldbelt, or younger plutonic bodies.

Miogeosyncline.—The external part of a geosyncline, where there was little or no magmatic activity during its depositional phase, and which was little deformed except during the closing phases of the orogeny. Deposits of miogeosynclines include carbonate rocks, quartzites, and shales; these are identical with those laid down on the cratons, but they were laid down to a much greater thickness and in a more complete sequence. Counterpart, *eugeosyncline.* (See p. 47–49.)

Miomagmatic geosyncline.—A term proposed by Stillé in 1936, but superseded by his later term *miogeosyncline.* (See p. 46.)

Molasse.—A term used in the European Alps for a Tertiary sequence of marine and brackish water sandstones, with some layers of gravelly to bouldery conglomerate. As the molasse was laid down after the climax of the Alpine orogeny the term has been used widely throughout the world for any kind of postorogenic deposit. Because of the great variety of alleged molasse deposits the term is not considered useful outside its original area in the present text. (See p. 48).

Neotectonics.—The youngest tectonics of the earth, which was produced during the later part of the Tertiary, during the Quaternary, as well as the tectonics in process of formation at the present time.

Oroclinal structure.—An arcuate structure supposed to have been formed by bending of the crust in a horizontal direction, or by "deformation in plan". Some geologists propose that deformation of this kind produced many or most of the arcuate patterns of the foldbelts.

Orogenic phase.—The median part of the tectonic cycle in a foldbelt, characterized by the climax of crustal mobility and orogenic activity, and by the formation of *alpinotype structures.* The orogenic phase is commonly shorter than the *preorogenic* and *postorogenic phases* which precede and follow it, and may be less than a geologic period in length, although it is usually prolonged by a succession of orogenic *pulsations.* Rocks formed during the orogenic phase are termed *synorogenic.*

Orogeny.—The processes which create the rock structures within the mountain chains or foldbelts. The word orogeny actually means "the formation of mountains," which implies not only the formation of the rock structures in the mountains but also of the mountainous landscapes. When the term first began to be used a century ago, these were supposed to be parts of the same process and the distinction between them was only recognized later. Most geologists today use the term orogeny as here defined, and consider the formation of the mountainous landscapes to be a postorogenic or epeirogenic process. (See p. 44–45.)

Orthogeosyncline.—A major linear sedimentary trough lying outside the craton, generally divisible into eugeosynclinal and miogeosynclinal parts. The term is synonymous with *geosyncline* as originally defined and as used here; it was proposed in order to distinguish it from sedimentary troughs and basins in the cratons which were called *parageosynclines*, but these are not accepted as geosynclines in the present text.

Overprint.—The superposition of a younger event on a dominant earlier event, as indicated by a minor scatter of young radiometric dates in a terrane dominated by earlier dates. Where valid, the younger dates can sometimes be ascribed to renewed orogeny or to recurring plutonic activity, but the reasons for many of them are obscure.

Paleogeographic map.—A map which purports to show the extent and outlines of lands, seas, and other geographic features at a given time in the geologic past. (See p. 2.)

Paleogeologic map.—A map which shows the areal geology of the surface beneath an unconformity, which has been covered by younger strata. (See p. 2.)

Paleotectonic map.—A map which represents the tectonic features as they existed at a given time in the geologic past. (See p. 1.)

Parageosyncline.—A sedimentary trough or basin in the craton. Although different varieties of parageosynclines have been recognized and separately named, none of them are considered to be true geosynclines in the present text. Counterpart, *orthogeosyncline.*

Pennine-type structure.—Structure like that in the Pennine Alps of central Europe, characterized by plastic deformation of the crystalline basement and its cover, and by the formation of large recumbent folds or nappes.

Platform.—That part of a continent which is covered by flat-lying or gently tilted strata, mainly sedimentary, which are underlain at varying depths by basement rocks that were consolidated during earlier deformations. A part of the *craton* of the continent. French, *plateforme.* (See p. 21).

Pliomagmatic geosyncline.—A term proposed by Stillé in 1936, but superceded by his later term *eugeosyncline.* (See p. 46.)

Pluton.—Originally proposed as a noncommittal term for a body of intrusive igneous rock of any shape or size, hence including batholiths and many other varieties. However, in the western Cordillera of the United States and Canada the term is commonly used for the individual, relatively restricted bodies of particular composition and age which are components of the larger aggregates, or *batholiths.*

Plutonism.—Processes which take place at depth in the earth's crust under conditions of elevated temperature and pressure, which produce *plutonic rocks*—that is, metamorphic, migmatitic, and magmatic rocks. In the present text the term plutonic rocks is used specifically for the migmatitic and magmatic varieties, especially the granitic types. Plutonic processes are prominent in the internal parts of foldbelts, and the plutonic environment can be termed *infracrustal.*

Postorogenic phase.—The final phase of the tectonic cycle in a foldbelt, following the climatic orogeny. In some foldbelts the postorogenic rocks and structures are minor and do not obscure the orogenic structures, in others they nearly overwhelm them; in all foldbelts, the postorogenic events have produced the present mountainous landscapes. Postorogenic structures are *germanotype* and *epeirogenic.* Postorogenic sediments are varied; by common European usage they are called *molasse*, but this term has little utility. Postorogenic plutonic bodies include discordant granitic plutons and a wide variety of hypabyssal intrusives. In many of the foldbelts, terrestrial volcanic rocks were spread widely over the deformed terrane during this phase.

Preorogenic phase.—The initial phase of the tectonic cycle of a foldbelt, prior to the climactic orogeny. The phase is the time of formation of geosynclines, most of which are clearly divisible into eugeosynclinal (internal) and miogeosynclinal (external) parts, the first characterized by abundant submarine volcanism, the second by little magnatism and by carbonate-quartzite sedimentation. The plutonic rocks of the preorogenic phase include ultramafic bodies and rare early granitic plutons.

Protaxis.—An antique term for the central axis of a mountain chain, supposedly consisting of the oldest rocks and structures. (See p. 49.)

Pulsation.—A minor time of deformation which is one part or phase of a more prolonged epoch of orogeny.

Reactivated areas.—Used specifically in the present text for the parts of a previously stabilized craton that have been involved in one or more renewed deformations. Example, Southern Rocky Mountains. (See p. 23–24.)

Reworked structures.—Structures that were formed during an earlier time of deformation or orogeny, which have been involved in later deformation that has refolded or otherwise modified them.

Shield.—A large area of exposed basement rocks in a craton, commonly surrounded by sediment-covered platforms; the term is virtually restricted to exposed areas of Precambrian basement rocks. French, *bouclier.*

Structural stage.—A rock-stratigraphic unit or layer in a foldbelt, characterized throughout by a common facies related to the tectonic evolution of the foldbelt. As originally conceived, successive structural stages are supposed to be separated by unconformities, but this is dubious. Rocks of a single stage may vary considerably in age span from place to place, hence a structural stage is not a stratigraphic stage, or time-stratigraphic unit. French, *étage structuraux.* (See p. 10–11.)

Successor basin.—A sedimentary basin of relatively restricted extent in the internal part of a foldbelt, formed during the orogenic phase or early part of the postorogenic phase. Its deposits overlie geosynclinal rocks that were deformed by the climatic orogenies of the foldbelt, but they themselves have been variably deformed during the later phases of the orogeny. Includes *epieugeosynclines.* (See p. 49–50.)

Supracrustal rocks.—Sedimentary and volcanic rocks of the suprastructure in a foldbelt, which have been subject only to near-surface deformational processes, and not to deep burial, plutonism, or metamorphism.

Suprastructure.—The upper structural layer in a foldbelt, subjected to relatively near-surface deformational processes, in contrast to an underlying and differently deformed *infrastructure.*

Synorogenic rocks.—Rocks formed during the orogenic phase of the tectonic cycle of a foldbelt. Synorogenic sediments are preserved mainly in the external parts of the foldbelt; they include *flysch* as strictly defined, as well as broad sheets of deposit spread far from their orogenic sources. Synorogenic plutonic rocks include concordant granites which have disrupted or replaced the rocks of the internal parts of the foldbelt.

Synthetic structures.—Structures produced by minor movements that are in harmony with the major movements of the area; for example, faults which are downthrown in the same sense as the general uplifting or arching. Opposite, *antithetic structures.*

Tectonic cycle.—The interval of time during which an original mobile area has evolved into a stabilized foldbelt, passing through preorogenic, orogenic, and postorogenic phases, each characterized by distinctive structures and by distinctive suites of sedimentary, volcanic, and plutonic rocks. Called a *geotectonic cycle* by some geologists. (See p. 43–44.)

Tectonic map.—A map which portrays the architecture of the upper part of the earth's crust, or the features produced by deformation and other earth forces, and represents them by means of symbols, patterns, and colors. (See p. 1–2.)

Transform fault.—A term applied to a class of faults on the ocean floor; no valid equivalents have been demonstrated on the continents. They are transverse to mid-ocean ridges (and rises), which are commonly offset geographically across them (see fig. 14). The axes of the ridges are inferred to be loci of the addition of new crustal material, which results in spreading of the ocean floor and of strike-slip displacement of the transform faults on the two flanks. However, the geographic offsets of the ridges themselves are only indirectly related to such displacements. As a result of spreading of the ocean floor from the ridge the strike-slip displacement on the faults is in opposite senses on the two flanks. The displacements can be inferred in places from offsets of sea-bottom topography, but they can be demonstrated even more conclusively by offsets of narrow parallel belts of magnetic anomaly. At each end, the transform faults lose displacement and die out on the ocean floor at variable distances from the ridge axes.

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