Ancient Suture Zones Within Continents

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Summary. Ancient suture belts within continents are deformed regions which contain the remnants of former ocean basins. They form when two continents or island arcs that earlier were separated by an ocean basin converge and collide during plate tectonic activity. These belts provide the only record we have of deep oceanic crust and of ancient sea-floor processes for the first 94 percent of the earth's history, that is, prior to the oldest preserved crust in the oceans. Ten criteria for the recognition and interpretation of these ancient belts are discussed. A comprehensive program for the study of these belts should have great scientific and economic benefit for the United States and would be relatively cheap compared to other large national scientific efforts.

Over the last 15 to 20 years, earth science has undergone a first-order revolution occasioned by the discovery and application of the principles of plate tectonics. According to this new view of the earth, the outer 100 kilometers or so of the solid earth (called the lithosphere) is divided into a series of essentially rigid plates which are in motion with respect to one another. Three general kinds of boundaries are found: (i) divergent or constructive margins, where new lithosphere is formed, are principally represented by mid-oceanic ridges; (ii) convergent or destructive margins, where one plate dives beneath another, are found primarily in island (or continental) arc or deep-sea trench regions, such as Japan, the Aleutians, or the Cascades of the northwestern United States; and (iii) transform fault boundaries, where two plates slide past one another without creation or destruction of lithosphere, such as the San Andreas fault system.

This new mobilistic view of the earth resembles and is based in part on old ideas of continental drift. However, it is much more specific than the drift hypothesis and is supported by marine magnetic and heat-flow data as well as by seismic evidence. It has caused radical revisions in all the subdisciplines of earth science, such as the origin of volcanoes, the evolution of climate and of life, and the nature and occurrences of economic mineral deposits.

One consequence of the new mobilistic earth view is that continents are not permanent features; they break apart, drift about, and collide with each other in the normal course of plate tectonic activity. In this process previously existing ocean basins must disappear, except for scattered remnants, and the margins of formerly separate continents become joined together in a widely deformed, mountainous region.

The sites of former ocean basins and the collisional mountain belts which contain them are called sutures and suture belts, respectively (*1*). The Alpine-Himalayan mountain system provides a spectacular, currently active example of just such a suture belt formed by the convergence and collision of Eurasia with Africa and India, as a consequence of the opening, during the last 200 million years, of the Atlantic and Indian oceans.

Examples in the United States include (i) the Cordilleran mountain system, with numerous sutures of a variety of ages, some as old as 400 million years; (ii) the Appalachians, with sutures ranging in age from possibly 500 to 250 million years; (iii) the Ouachitas-Marathons belt, which may represent a suture 250 to 300 million years old between North America and South America; and (iv) various Precambrian terranes (greater than 570 million years) where possible sutures have been recognized in New York (Grenville Province), Arizona, Montana-Wyoming, and Minnesota-Wisconsin (Fig. 1).

As outlined above, plate tectonic theory has been spectacularly successful in explaining the present seismicity and processes of the earth. The application of this theory to the past is less certain, however, for a number of reasons.

Much of the observational basis of the present theory is seismic, based on the spatial distribution and mechanism of earthquakes. As we extrapolate back into the geologic past, we lose this seismic guide, and it becomes difficult to recognize the patterns of ancient plate boundaries. This difficulty of recognizing plate patterns becomes more and more of a problem as one goes backward in geologic time. It is possible, however, to make a fairly consistent analysis for most of the past 200 million years, that is, for the maximum total time for which oceanic crust has been preserved. Approximately 95 percent of earth history occurred prior to the oldest oceanic crust in the ocean basins themselves. Thus, even if we accept plate tectonic activity for the last 200 million years, we have no direct oceanic evidence for events before that time. What evidence there is exists solely on the continents.

The belts of seismicity that delineate the plate margins represent data collected only from the past 70 years or so. Furthermore, it is clear from the width of seismic belts that plates are not perfectly rigid; they can accumulate stress over time (*2*). Seismic belts on continents and in regions of collision are particularly diffuse spatially and are associated with much seismic activity within the crust. Simplistic plate tectonic models demanding perfect plate rigidity do not appear to apply to these areas, such as the Alpine-Himalayan region. Several recent workers (*3*) have proposed a rigid-plastic continuum approximation for these regions. Even if this approximation is instantaneously valid, it appears that the boundaries of rigid blocks may change or shift with time. The ultimate result of this process is that regions develop where nonrigid deformation has taken place. Nonrigid deformation features in fact dominate the geology of most suture belts; a key unresolved question is how this deformation is related to global-scale tectonic processes.

Examination of the geologic evidence reveals that rocks less than 600 to 700 million years old are similar to those rocks that are thought to form during present-day plate tectonic processes. Proterozoic terranes, ranging in age from 700 to 2500 million years, exhibit some rock sequences similar to present ones, presumably indicating plate tectonic pro-

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cesses, but other characteristic rock types are lacking, especially ophiolites and blue schists. Other rock suites present in Proterozoic terranes are uncommon or lacking in younger rock sequences, for example, anorthosites, rapakivi granites, and banded iron formations. Archean terranes, older than 2500 million years, differ significantly in nature from those presently observed. Presumably the tectonic processes in the early Precambrian also differed significantly from those found today.

Thus the study of ancient suture belts provides a means to understand the end product of processes of plate collision that are going on today. In addition, such studies are indispensable in any attempt to elucidate tectonic processes in times prior to that represented by the oldest oceanic crust, hence, to any study of the evolution of the thermal and tectonic regimes of the earth.

Ancient U.S. Suture Belts

Ancient suture belts of the United States provide excellent opportunities to study a wide range of tectonic features and processes. Phanerozoic belts (less than approximately 700 million years old) are particularly well developed, especially the Pacific margin belt (Cordillera) and the Appalachians and their correlatives to the south and west (Fig. 1). The Cordilleran belt has a history beginning with rifting in the late Precambrian, followed by development of a complex sequence of passive margins, consuming margins, collisions, ophiolite emplacement, and large-scale lateral movements extending to the present time. The Appalachian belt represents at least one continent-continent collision belt with a history beginning in the late Precambrian, culminating with collision of the North American and Gondwanan continents in late Paleozoic time. The Ouachitas system is of similar age, but its origin is less certain. Exposed Precambrian terranes in the United States are not as complete as some, yet they provide a number of features pertinent to a comprehensive understanding of the evolution of tectonic processes.

Criteria for Recognition

A number of features observed in mountain ranges and deformed belts may be used to infer the existence of a suture. Associated with each of these criteria are problems of interpretation, the solution of which would greatly enhance one's understanding of the criteria and their significance. These criteria and some related problems are as follows:

Ophiolite belts. Ophiolites are a pseudostratigraphic sequence of rocks, consisting from bottom to top of ultramafic rock, mafic intrusives, mafic extrusives, and deep-sea sediment. They commonly are interpreted as representing slices of oceanic crust formed in areas of spreading and emplaced on land by subsequent tectonism. Opinions differ on whether they represent mid-oceanic, back arc basin, or island arc lithosphere and on the mechanism of emplacement. A better understanding of ophiolites and their occurrence would aid significantly in inferring ancient spreading processes as well as the processes of subduction and collision (*4*).

Overthrust belts involving continental marginal sequences. These are of two types. The first comprises regions where deep-water or oceanic sequences are thrust over continental marginal sequences. Evidence of ophiolite complexes may be absent or only fragmentary. Examples of such occurrences include the Antler sequence in the Cordillera (*5*), the Taconic system of the northern Appalachians (*6*), and the Ouachitas system (*7*). The second type includes décollement-style fold and thrust belts of miogeosynclinal sequences over shelf deposits. Examples of this type of structure include the fold-thrust belt in the North American Cordillera, extending from southeastern California through Utah, western Wyoming and Montana, to northernmost Canada and the Appalachian Valley and Ridge Province, extending from Alabama to New York and beyond. Opinions differ on the tectonic significance of these features. The origin of some of these belts in response to collision seems certain (for example, the Appalachian Valley and Ridge belt and the Zagros fold-thrust belt in Iran), but other belts have not yet been related clearly to collisional events (for example, the Sevier belt of the U.S. Cordillera and the Andean fold belt) (*7*). A key factor in the interpretation of these belts is the environmental significance of the continental margin sequence itself, that is, whether it represents a passive, active, or transform margin. This interpretation is made by comparing the rocks in question with those forming today in the appropriate tectonic settings (*8*).

Varied or discrepant paleomagnetic directions in rocks of equivalent age in a given mountain belt. Such directions indicate that the rocks originated at different locations and were brought together by large-scale drifting movements. For example, the paleomagnetic inclination of Triassic basalts in "Wrangellia" in the North American Cordillera indicates that they formed in a latitude thousands of kilometers south of their present location (*9*). Similar results have been obtained from rocks within the Grenville belt, relative to older rocks of the Canadian shield. In addition, lower Tertiary rocks of the Pacific Northwest show magnetic directions at a large angle to those of rocks of similar age on the North American continent (*10*). A problem associated with the widespread application of this technique to most mountain belts is that rocks in suture belts generally are deformed or metamorphosed, or both; it is difficult to establish their age, and paleomagnetic directions are difficult to interpret (*11*). Paleomagnetic work on Precambrian rocks also currently is imprecise (*10*). Nevertheless, much more data from U.S. mobile belts, both Precambrian and younger, will be required.

Paired metamorphic belts and island arc sequences. The presence of adjacent blue schist and green schist belts of metamorphic rocks of the same age range implies the presence of a consuming plate margin. In theory, the polarity of subduction can be obtained from these sequences, but in practice the determination is complicated by polymetamorphism (superposition of one metamorphic assemblage over another), by changes in the polarity of subduction, and by the possible effects of collision (*12*). Compositional variations in volcanic sequences also are complicated by chemical mobility during metamorphism (*13*). So far, successful application of the composition versus depth-to-subduction zone relationship in ancient arc rocks is rare. Potentially, however, such studies, coupled with determination of the pressure-temperature conditions of the metamorphism and magma generation, will provide valuable comparisons with geologically young systems.

Shelf benthonic province boundaries. Present shelf benthonic provinces mirror the plate tectonic configuration of the world. The East Pacific Rise and the Mid-Atlantic Ridge represent lines corresponding to long-recognized faunal barriers. The Indonesian island arc system and the accompanying midplate islands to the east (Tuamotu Islands and Line Islands) represent faunal dispersal routes (*14*). Such relations are a potential tool for unraveling plate boundaries between continents in the past, for example, during Paleozoic time. Recognized faunal differences, such as the European-American distinctions of Ordovician age and the California-Nevada differences of Ordovician and Silurian ages, may reflect the presence of ridges or transform faults (which also may constitute faunal barriers) between the rocks in question at the time of their formation (*15*).

Boundaries between radiometric age provinces. In some cases where geologic relationships are appropriate, boundaries between igneous or metamorphic rocks of different ages may represent sutures (*16*). In other cases, however, such as in the Sierra Nevada or the Alps, such boundaries bear little or no relationship to recognized sutures. Thus this criterion must be used with caution.

Geophysical methods. A number of geophysical techniques have been used successfully to identify ancient sutures. Gravity and magnetic methods have been used to trace the Taconic suture in the northern Appalachians, and also to identify a possible suture in the southern Appalachians (*17*). Ophiolites in many parts of the world may be traceable on magnetic anomaly maps. The Consortium for Continental Reflection Profiling seismic lines in the southern Appalachians have been extremely successful in delineating a suture (*18*). European seismologists have identified old dipping slabs of lithosphere in the Alps and Apennines (*19*).

The principal contribution of geophysical methods to the recognition of suture zones is to enhance, or in areas of poor exposure to provide, the three-dimensional view otherwise obtainable from direct field observations. In ancient suture regions, however, the existing three-dimensional picture must be used with caution, as it represents only the final state in a long and complex evolutionary process. This situation is in contrast to that common in marine geophysics, which provides a three-dimensional view presumably reflecting presently active tectonic processes.

Structural discontinuities and shear zones. These features may be especially important indicators of suture zones. In particular, they appear to be essential for the identification of possible suture zones at substantial depths. Features that have been used include intersecting and strike-discordant trends of regional structures separated by a discontinuity, and fault and mylonite zones (mylonite zones are especially valuable when one is attempting to identify deep-level exposures of sutures). The direction and amount of movement on these fault zones often can be determined. Many fault zones experience separate and contradictory episodes of movement, however. Some zones may have an early dip-slip history overprinted by a later strike-slip history. If conditions are favorable, however, the rate of movement and of strain can be deduced from the fabric of the rocks, and the thermal conditions during movement can be estimated as well (*20*).

Melange complexes. These complexes, which constitute chaotic mixtures of unrelated or diverse lithologies, often are used to infer the existence of ancient sutures (*1*). The proposed origins of these complexes represent three broad tectonic environments: (i) by submarine sliding off submarine escarpments, particularly along rifted continental margins; (ii) by brecciation, tectonism, and landsliding along transform fault zones; and (iii) by deformation and possibly sliding associated with subduction zones. Critical outstanding problems of melanges include criteria for distinguishing between tectonic versus sedimentary deformation, between the three proposed origins, and the problem of renewed movements.

Stratigraphic differences across deformed zones. Two regions of crust within a deformed belt may exhibit rock sequences which differ so sharply from one another that they could not possibly result from facies changes. Such differences may indicate that one or both regions represent a discrete block or microcontinent separated from the other by a suture (*21*).

Proposed Plan of Study of Ancient Sutures

Although a great deal of work has been done on possible and recognized suture belts in the United States, much of it is outdated. This observation assumes great importance when one realizes that the quality of field geologic data available very much depends upon questions posed during fieldwork and thus upon the ideas in the mind of the geologist. Consequently, many investigators work-

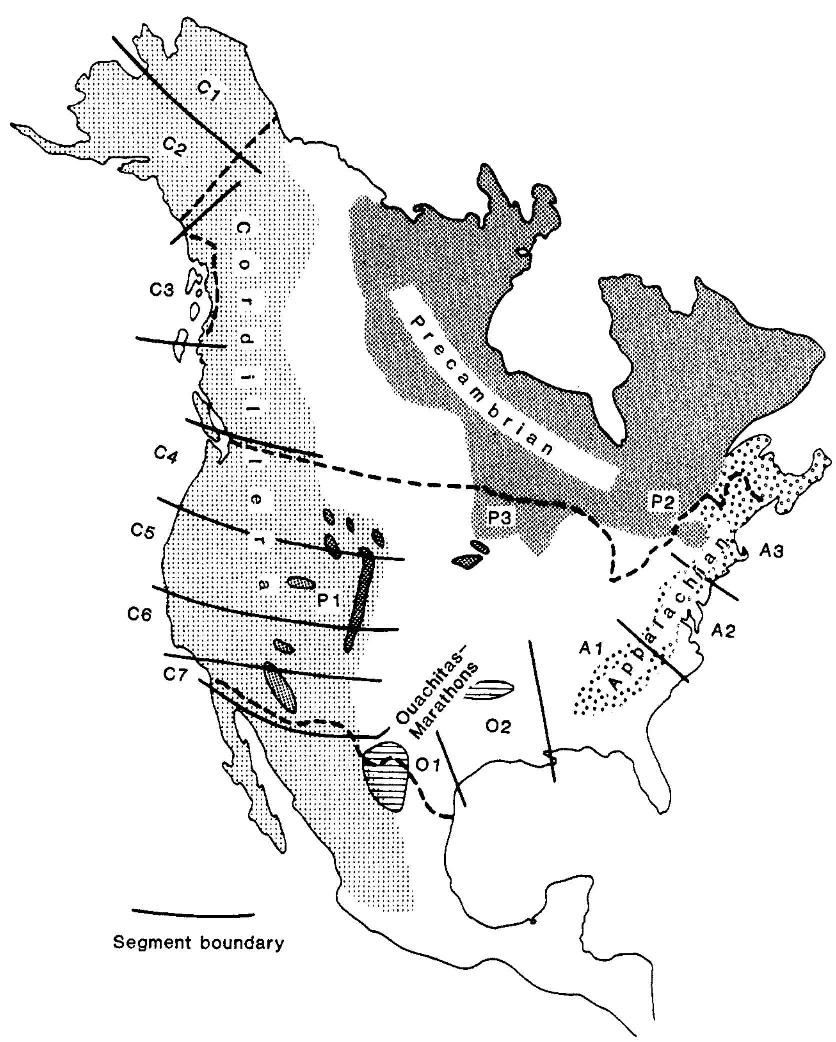

Fig. 1. Generalized map of North America showing suture belts and suggested division into segments. Modified after (*26*). Segment *A*, Appalachian; *C*, Cordilleran; *O*, Ouachitas-Marathons; and *P*, Precambrian.

ing before recent advances in petrology and paleogeography and particularly before the plate tectonic revolution did not make the kinds of observations required to allow modern interpretation. In addition, the United States never has benefited from a systematic, consistent, long-term regional program of geologic mapping such as that of the Western European countries, Canada, and Japan.

Thus a program for the study of ancient suture belts would have two parts: first, an assessment of existing data, and second, and more important, a rational plan for new work based on that assessment. For the first part, the plate margin cross sections constructed during the U.S. Geodynamics Program (published in the Geological Society of America Maps and Chart Series) might well serve as a good starting point. However, three limitations on these cross sections render them an inadequate base for new tectonic analyses of the type envisioned. First, they are two-dimensional, and a three-dimensional process is involved. Large-scale strike-slip faulting is apparently very important in the history of the Alpine-Himalayan system (*3*), in the Cordillera (*9*), and in the Appalachian-Hercynian system (*22*). Indeed, it may prove to be a more important tectonic process than the better recognized subduction and overthrusting. Second, coverage is not complete. The cross-sections project considered only the Ouachitas and Cordilleran systems. Neither the Appalachian system nor the Precambrian system was analyzed. Third, the cross sections are based upon existing data. In some cases, these data were collected almost a century ago by observers who had an entirely different frame of reference and who were not attempting to answer the same questions we now pose. Although in many cases the observations are valuable, even remarkably perceptive, many are not complete enough to satisfy modern needs. The construction of many of the cross sections has emphasized that we have outgrown the field data available for many of the deformed regions of the United States.

For these reasons, a massive new program of study is critically needed. The main aim of this proposed program should be to provide, above all, modern detailed maps and cross sections of the major suture belts in their entirety. These maps would provide the basis for numerous further multidisciplinary studies aimed at elucidating the tectonic history and processes recorded in the regions and the accompanying physical conditions.

Investigators could proceed either by considering each belt as a whole or by initially separating a particular belt into units for detailed treatment, to be followed by integration of all the information. From a practical standpoint, the latter approach may be more efficient. Hence, I suggest below initial separation of belts into segments representing regions along the strike of a suture belt that appear to display approximately uniform geometry and history. Other separations might be equally useful. A point to emphasize, however, is that such a separation should be for initial analysis only, to break up the regions into portions of manageable size. In view of the possible large-scale horizontal movements of terrane into, within, and out of the suture belts, a key element in such a program would be continued collaboration between work groups in separate segments and ultimately a synthesis of all the information from the entire belt. Suture belts, suggested segments, and possible questions to be addressed are listed below (Fig. 1).

North American Cordillera

General questions about the North American Cordillera include:

1) What was the age of inception of the Cordilleran system?

2) What is the relationship between various old sedimentary sequences in the Cordilleran system (for example, the Shoo Fly Formation of Sierra Nevada, together with equivalent rocks of the Klamath Mountains and Nevada), and what is their relationship to old (early Paleozoic) ophiolites?

3) What was the nature of the Antler orogeny, and what is its relationship to earlier deformation events present farther west?

4) What was the nature of succeeding orogenies, such as the Sonoma and Nevadan?

5) What are the number, timing, and origin of exotic terranes? What was the mechanism of their emplacement, and what tectonic events accompanied their accretion to North America? Can these tectonic events serve as a guide to analyzing older and less well-preserved possible accretionary belts?

6) What is the applicability to the North American Cordillera of tectonic models derived from southeast Asia and Indonesia, or the Alpine region, or southern Alaska?

7) What was the nature of the origin and emplacement of Cordilleran ophiolite terranes, in comparison with oceanic and Tethyan sequences?

8) What is the detailed intrusive and metamorphic history of the Cordilleran regions? What are the radiometric ages, compositional variations, or relation to deformation?

Suggested segments of the U.S. Cordillera and their approximate dimensions (in kilometers) are as follows (see Fig. 1): C1, Brooks Range–Seward Peninsula–Yukon region (1000 by 1500); C2, Alaska Range–Alaska Peninsula (500 by 1000); C3, southeast Alaska (300 by 1000); C4, southern Oregon to the Canadian border, Pacific Coast to the High Plains (500 by 1000); C5, southern Oregon–Klamath Mountains–northern Coast Ranges–Sierra Nevada to Nevada (650 by 1100); C6, central Coast Ranges, southern Sierra Nevada to the Colorado Plateau (500 by 650); and C7, southern Coast Ranges–Mojave Desert–Colorado Plateau (300 by 500). Work in the Cordillera should be closely coordinated with that in Canada, Mexico, and Central America.

Ouachitas

General questions about the Ouachitas region include the following:

1) What is the nature of the deformation? In particular, where is the suture, if any, and what are its characteristics?

2) What is the relationship of the Ouachitas belt to the Appalachians and the Cordillera, and to deformed belts of northwestern South America, western Africa, and Central America? This question clearly calls for international consideration and cooperation.

Suggested segments and their approximate dimensions (in kilometers) are as follows (see Fig. 1): O1, Ouachitas proper (250 by 650); and O2, Marathons–ancestral Rockies of New Mexico and Colorado (150 by 1000, discontinuous).

Appalachians

Possible general questions about the Appalachians include:

1) What are the number, ages, and geometry of Appalachian sutures?

2) What is the nature and continuity of the Brevard structure, across and along the strike?

3) Do the U.S. Appalachian ultramafic belts represent a continuation of sutures delineated in Newfoundland and Quebec by Canadian workers?

4) What are the relations of the Appalachians to their possible continuations in Europe, western Africa, northern South America, and Central America? Clearly, international coordination and cooperation is necessary.

Suggested segments and their approximate dimensions (in kilometers) include: A1, southern Appalachians to the North Carolina–Virginia boundary (500 by 700); A2, central Appalachians to the Pennsylvania–New York region (300 by 700); and A3, northern Appalachians (400 by 700).

Precambrian

The Precambrian era poses special problems. Although many structural and stratigraphic patterns in late Precambrian rocks resemble those of the Phanerozoic, older terranes present differences which make them difficult to compare with modern plate tectonic models. For example, ophiolites are unknown in most, if not all, deformed regions older than 1000 million years (*4, 23*). A key question is, What kind of evidence should one look for to detect the presence of sutures in older Precambrian terranes? The Precambrian record in the United States is incomplete. Exposures are spotty and do not lend themselves as well to segmental division as the Phanerozoic regions. Age divisions are known in the Precambrian, but in some cases these age boundaries define belts of intrusive activity rather than suture boundaries.

Precambrian terrane segments suggested for study and their approximate dimensions (in kilometers) include the following: P1, western Arizona–New Mexico to Montana (700 by 100, discontinuous); P2, Grenville Province (400 by 700); P3, the Minnesota-Wisconsin region; and P4, the midwestern region. Special problems for the P1 area include the relation of Wyoming province and younger rocks, possible sutures in Arizona and Wyoming, and their continuation. This latter region is one of proposed study in the Continental Scientific Drilling Program (*24*, pp. 77–79). The P2 region is not well exposed in the United States, except in northern New York. A special problem is whether a suture or sutures are present. The often cited "Grenville front" is a complex structural and metamorphic boundary, but continuity of sediments across the "front" suggests that it does not represent a suture. If present, the suture may be to the southeast, in a region of high-metamorphic grade. To solve this problem, one needs to see through the deformational and igneous and metamorphic history of the region (to recognize the suture, if present). For this area, close cooperation with Canadian workers is essential. In the P3 area, tectonic regimes similar to modern ones have been suggested by Van Schmus *et al.* (*25*). Again, close cooperation with Canadian workers is essential. This area also is one mentioned as a possible continental drilling target (*24*, pp. 64–69). Information on isolated outcrops in the midwestern and southwestern United States (P4) should be compiled and augmented for close comparison with other regions.

Recommended Procedures

1) The quality of field data should be assessed. Available detailed modern geologic and geophysical field data should be compiled on a scale of 1/100,000 to 1/250,000. This would be followed by detailed reconnaissance of poorly known areas. This phase of the project should take approximately 2 years, or perhaps longer.

2) After compilation of existing data and reconnaissance of the leftover regions, critical areas or topics in each segment should be selected for specific study. Studies should focus on multidisciplinary approaches to the understanding of a given problem and should include, but not be limited to, the following topics: (i) the areal distribution of rock types and the nature of the boundaries between rocks or terranes; (ii) the three-dimensional distribution of rocks derived from both direct and indirect (geophysical) means; (iii) precise dating of the rocks, achieved by the dating of stratigraphic sequences, using fossils where present (recent advances in Mesozoic and Paleozoic biostratigraphy of radiolarians are already causing a revolution in our ideas concerning the Cordillera and should be extended to other areas); by the dating of eruptive sequences by diverse radiometric means, for example, uranium-lead, rubidium-strontium, ^{40}Ar-^{39}Ar, and neodymium-samarium; and by determining the timing and sequences of metamorphism; (iv) petrography, petrology, and environmental significance of rock suites; paleogeography of sedimentary rocks, and pressure-temperature conditions and the tectonic setting of metamorphic and igneous rocks; and (v) detailed geometric, kinematic, and dynamic analyses of structural features.

Conclusions and Recommendations

1) The proposed program aims at a quantum leap in our knowledge of U.S. ancient suture zones, which will put knowledge of these regions on a level equal to that achieved in other advanced countries, such as Switzerland, France, Britain, Canada, Japan, or with that available from the oceans.

2) A key ingredient to understanding ancient suture belts is asking the right questions, which in turn requires familiarity with key concepts or areas. Summer field geologic institutes should be revived on a regular and systematic basis. The focus of this program would be to afford the opportunity for workers from various parts of the United States to examine other areas or, if appropriate, selected regions outside of the country for 1 to 3 weeks. Budget needs would include funds for minibuses with four-wheel drive, transportation, and subsistence for participants.

3) This project should encourage participation from academic, governmental, and industrial personnel. Special attention should be given to encouraging academic participation, in particular, the maximum possible participation of qualified students, who represent our future and from whom most of our good ideas derive. In this context, funds should be made available for adequate support of graduate students and of postdoctoral fellows. Recently an increasing amount of academic effort has gone into the application for and administration of grants. Every possible step should be taken to minimize the red tape necessary to obtain and use funds. In order to maximize their effectiveness, academic principal investigators need the ready availability of postdoctoral assistants.

Another desirable goal would be provision for increased short-term hiring of student assistants by U.S. Geological Survey personnel on the project. Funds also should be readily available to allow academic personnel to take a short course on topics such as new geophysical techniques, as appropriate.

4) To maximize the effectiveness of the project, it seems advisable to keep it relatively decentralized, within the constraints of the overall objective. Except for overall guidelines and policy, it might be advisable to handle funding on an individual basis. This approach would be directed toward attempting to maximize diversity and to hone ideas through friendly competition and would ensure maximum consideration of all possibilities. It might be useful, however, to require that any proposed work to be supported under the auspices of this project be demonstrably multidisciplinary in nature, either by establishing a project with two principal investigators in separate fields of earth science, collaborating on a single goal, or by designing the project so that the application of more than one discipline is clear-cut.

5) More than ever, geology is an inter-

national subject. Although the emphasis here is on U.S. terranes, clearly an essential ingredient of this kind of program is comparison with equivalent terranes and structures in other areas. International cooperation and coordination thus are necessary. A key ingredient in such international programs would be increased competence of American personnel in appropriate foreign languages.

6) Major unknowns include the nature of oceanic crust and the nature of processes in consuming margins. A valuable aid to this project would be a continued systematic program of scientific drilling in the oceanic crust and in active margin areas.

7) In a program of field geology, a critical need is funds and facilities for adequate publication and dissemination of detailed areal maps, many or most in color. This requirement is basic to any meaningful analysis, for what is needed is access to the primary field data, which can be illustrated adequately only on such maps and which are rarely shown at all on the small-scale sketch maps currently in vogue in most publications. Sadly, publication of such maps has grown progressively more difficult over the last few years and currently is limited in the United States primarily to the Geological Society of American Map and Chart Series. Although this series is satisfactory as far as it goes, it is not adequate at present for all the needs of the geologic community. Other avenues of publication, such as publications of the state geological surveys, need more emphasis. The expenses entailed in such a program are not insignificant, but they are not outlandish when compared with the laboratory budget requirements in other earth science branches, such as geophysics or geochemistry, or in the other physical sciences.

8) Implicit in this proposal is, of course, a "quantum jump" in the amount of financial support for interdisciplinary field studies in earth sciences. One can make, however, a rough calculation of the amounts necessary for this program, based on estimates of the amount necessary (say, $25,000) for one person-year of such field-oriented studies. These calculations indicate that the investment over the next 10 years of, say, the monetary equivalent of the *Glomar Explorer* Program would result in roughly 25,000 person-years devoted to the study of suture belts. This is not to suggest that such an investment is either necessary or desirable. Even if it were, it is doubtful that the personnel are available to absorb intelligently such funds in the time allotted. The important point is that fieldwork such as that proposed is comparatively cheap; a relatively modest investment of funds, even one-tenth as much as allotted to the *Glomar Explorer* Program, over the next 10 years would result in the sought-after quantum jump in our knowledge.

9) Finally, the economic implications of oceanic metal deposits presently forming at spreading ridges in the oceans have become common knowledge. As ancient sutures provide the only identifiable remnants of oceanic regions older than 200 million years, a better understanding of these zones in the United States clearly has potential economic benefits as well.

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