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Proposed Satellite Laser Ranging and Very Long Baseline Interferometry Sites for Crustal Dynamics Investigations

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PROPOSED SATELLITE LASER RANGING AND VERY LONG BASELINE INTERFEROMETRY SITES FOR CRUSTAL DYNAMICS INVESTIGATIONS

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PREFACE

The Crustal Dynamics Project under consideration by NASA will unify a number of space-related geodetic measurement techniques. This program will entail major expansion of the number of measurements by the various techniques, and consequently require selection of many additional sites for laser ranging or Very Long Baseline Interferometry (VLBI). To provide some basis for discussion of selection of these sites, the authors have studied the application of these new techniques to earthquake-related tectonic problems and proposed a global and regional network. This report, though extensively documented, represents only the opinions of the authors, and is intended solely to serve as a starting point for a site selection process to which several organizations and many interested scientists will contribute.

INTRODUCTION

In the near future, satellite laser ranging and very long baseline interferometry (VLBI) will achieve geodetic baseline accuracies in the 2-4 cm range over distances of several thousand kilometers. Such accuracy will for the first time permit the direct measurement of global plate motions and intraplate deformation, thus introducing a new epoch in geodynamics analogous to that resulting in geodesy from the application of satellite tracking data (Henriksen and Mueller, 1974).

The purpose of this report is to propose sites for a global network using satellite laser ranging or VLBI (with fixed or mobile systems) for tectonic studies. The network of sites proposed is analogous to the 45-station network of satellite triangulation sites described by Schmid (1974), but is specifically oriented towards research in crustal dynamics. It is designed to furnish: (1) detailed data on Pacific-North American plate motions in California, (2) less-detailed information on crustal motions in the North American cordillera, (3) reconnaissance data on intraplate motions in the central and eastern U.S., and (4) reconnaissance data on major global tectonic problems.

A general plan for NASA crustal dynamics research in the 1980-85 period has been published in draft form (OSTA, 1978), and forms the basis for the present report, although regional nets proposed in that plan for some areas such as New Zealand have been omitted here. General plans for crustal dynamics research with space techniques have also been published in "Outlook for Space, NASA SP-386" and Lowman (1976).

It should be mentioned here that the measurements proposed, although based on a five-year program, should be continued into the indefinite future.

SCIENTIFIC BACKGROUND

Plate tectonic theory forms the conceptual foundation of the recommendations presented here. This theory holds that most horizontal crustal motions can be described as rotations of rigid spherical lithospheric caps bounded by spreading centers, subduction zones, or transform faults. The theory was originally based on evidence from ocean basins, and has proven extraordinarily successful in explaining the dynamics of the oceanic crust and active continental margins. However, as pointed out by Minster et al. (1974), plate tectonic theory has not been, except locally, demonstrable by direct geodetic techniques, and has so far been unsuccessful in mathematically describing continental intraplate tectonic deformation. Laser ranging and VLBI techniques appear uniquely suited to these problems, by providing precise long-distance measurements of the following aspects of crustal motion and deformation.

Plate Velocities

The motion of a rigid plate on a sphere is, by a theorem proven by Euler, a rotation about a pole. Plate "velocities" are thus angular velocity vectors, and unless stated otherwise are relative to other plates. Relative plate velocity vectors have been computed by Le Pichon (1968), Chase (1978), and Minster and Jordan (1978) on the basis of marine magnetic anomalies, earthquake slip vectors, and transform fault azimuths. Typical relative motions at spreading centers range from about 2 cm/yr in the Atlantic to 18 cm/yr in the Pacific. These rates are derived from geophysical and geological data spanning millions of years, and are thus long-term averages. Present-day "instantaneous" plate velocities have not been measured directly because of the long distances and large areas involved. Furthermore, "absolute" plate velocities (Minster et al., 1974) are difficult to determine, the most promising technique being the mapping of hot spot traces, such as the Hawaiian Island chain, over a network of mantle plumes assumed fixed in the lower mantle. Both relative and "absolute" velocity determinations to date have been largelv restricted to oceanic crust. Because of these limitations, direct measurement of plate velocities, especially plates with large proportions of continental crust, is a major objective of the proposed NASA crustal dynamics program.

Plate Identification

Although to a first approximation global tectonics can be described in terms of six plates (Le Pichon, 1968), the actual number of such plates is difficult to determine. This is another way of saying that active plate boundaries (ridges, trenches, and transform faults) are not completely known. For example, there is no obvious line of seismicity to mark the boundary between the North and South American plates. However, as shown by Minster and Jordan (1978), such a boundary (and several others) seems implied by their model, which is derived by inversion of magnetic anomalies, earthquake slip vectors, and fault trends. Satellite laser ranging and VLBI measurements can permit a direct approach to the problem of identifying the smaller plates by providing actual measurements of plate rotations and intra-continental crustal deformation.

Plate Rigidity

As first pointed out by Morgan (1968), the assumption that gives the plate tectonic theory mathematical rigor is that the plates are "perfectly" rigid. Morgan and others have, of course, realized that this assumption is not valid for many continental orogenic areas, and the theory could still be generally sound even without perfect rigidity. However, recent studies, such as that of Sykes (1978), imply significant intraplate deformation in nominally inactive regions and along "passive" continental margins. It is clearly important to determine just how rigid the plates are, i.e, to test the fundamental assumption of plate tectonic theory. For this reason, a number of cratonic sites outside zones of obvious tectonic activity are proposed.

Measurement Strategy

It will be helpful to summarize some principles on which our recommendations for sites have been based. First, the network of sites is designed to take advantage of the unique characteristics of VLBI and satellite laser ranging techniques, particularly their great accuracy in horizontal baseline measurements over long distances. Although a few areas have been recommended for networks of closely-spaced stations, following the OSTA report, highest priority has been given to long baseline sites. Specific features that are of great tectonic interest, such as the Garlock fault, but which can be studied by conventional ground based techniques, have generally not been recommended for VLBI or laser ranging measurements.

The baselines have been planned so that measurements are made as nearly parallel as possible to the probable direction of tectonic motion. For measurements across oceanic plate boundaries, the ideal baselines are parallel to the nearest transform faults, which are generally assumed to give the direction of sea-floor spreading or plate movements. Some ridges with oblique spreading directions are suspected, and may eventually dictate relocation of baselines.

Baselines have been planned to seek unambiguous answers to tectonic questions. For example, measurements across more than one plate boundary have in general been avoided, since data obtained on crustal motion could not be assigned to either boundary uniquely.

Finally, sites and baselines have been planned with varying degrees of redundancy to permit verification of measurements.

NORTH AMERICAN TECTONICS: WESTERN U.S.

Recommended sites and baselines in the United States have been planned to address specific tectonic problems. Beginning with the western U.S., these can be outlined as follows.

San Andreas Fault Zone

This fault, a prominent feature of the boundary between the Pacific and North American plates, is of major importance for seismic risk assessment and scientific reasons. The San Andreas fault itself is but one member of a zone of sub-parallel strike-slip faults, many of which are active. This is particularly true of California south of the Transverse Ranges, where activity is distributed among the San Jacinto, San Andreas, Imperial, and other faults in and bordering the Salton Trough. Motion across the San Andreas fault itself has been measured by ground survey methods (Mead, 1971; Savage and Buford, 1973), and is between 3.2 and 3.5 cm/yr in central California. To the south, a rate of 5.0 cm/yr has been measured by trilateration across the Salton Trough (Savage, et al., 1979). However, Gergen (1978), using ground surveys along the U.S.-Mexico border, computed a motion of 11.1 cm/yr. Smith et al. (1979), using satellite laser ranging between Otay Mountain (in the Peninsular Ranges) and Quincy (in the Sierra Nevada) as part of the San Andreas Fault Experiment, obtained a rate of 9.5 cm/yr across the baseline (which included several active faults beside the San Andreas). For comparison, the Minster and Jordan (1978) RM2 model, based on marine magnetic anomaly data covering some 3 million years, predicts a relative motion rate in central California of 5.6 cm/yr between the Pacific and North American plates.

The most general problem associated with the San Andreas fault zone is the nature of regional strain accumulation, since strain accumulation is the immediate cause of earthquakes. Since almost any fault in southern or western California must be considered potentially active (including the reverse faults of the Transverse

Ranges), regional measurements are clearly called for. A related problem is the distribution of aseismic motion along the San Andreas and other faults. A very general problem to which geodetic measurements can be applied is the nature and extent of the plate boundary; this will be discussed below.

Basin and Range Province

It is generally realized (e.g., Atwater, 1970) that the boundary between the North American and Pacific plates is, in the United States, a broad one. Much of this boundary consists of the Basin and Range Province, a globally unique broad zone of Cenozoic block-faulting characterized by sesimic activity, high heat flow, and thin crust. Although the bedrock geology of the Basin and Range Province has been intensively studied for many years, the origin of the Cenozoic faulting is not understood. As summarized by Stewart (1979), four major schools of thought include: (1) regional wrench faulting, (2) back-arc spreading, (3) subduction of the East Pacific Rise, and (4) up-welling mantle plumes. The wrench fault theory, in which the Basin and Range Province is considered to be a regional megashear zone bounded by the Lewis and Clark lineament on the north and the San Andreas system on the south, has much to recommend it and is particularly susceptible to investigation by VLBI and satellite ranging techniques. A specific concept testable by these methods is the proposal of Wright (1979) that two stress fields are involved, one producing shearing in the western part of the province and the other producing tension in the central part. Crustal extension across the Basin and Range has been estimated at 0.3 to 1.5 cm/yr for the last several million years (Stewart, 1971).

Intermountain Seismic Belt

This feature is a well-defined but poorly-understood zone of seismicity extending northward along the Wasatch Range into Idaho and Montana (Smith, 1978). A number of damaging earthquakes, such as that at Hebgen Lake in 1959, have occurred in this belt. However, there are a number of seismic gaps of potential seismic danger. The sporadic distribution of earthquakes, and the shortness of the instrumental record, make regional seismic hazards difficult to understand. Geodetic measurement of regional strain accumulation and deformation in the seismic belt should greatly increase our knowledge in this area. Furthermore, the belt marks a major transition in crust and upper mantle properties between the Basin and Range Province and the ranges and plateaus to the east, and as such is of considerable scientific interest.

Colorado Plateau

The Colorado Plateau, the southernmost of a cratonic zone extending south from Wyoming (the "Eastern Ranges and Plateaus" of King (1976)), is an outlier of the stable North American craton separated from it by the southern Rockies and the Rio Grande rift. Despite its spectacular scenery, the plateau has been marked by tectonic stability since the Cambrian period. The structure is largely undisturbed except for jointing and minor faults. Tectonically, the Colorado Plateau is of interest in the crustal dynamics program for several reasons. One is that it provides a relatively stable base against which to measure deformation in more active provinces such as the Basin and Range. A more speculative aspect of the plateau is the possibility that it may be undergoing regional rotation as part of the megashearing expressed in the Basin and Range Province.

Snake River Plain

This feature, a tectonic depression floored with Quaternary and Recent basalts, has been interpreted in various ways. One popular concept (Armstrong, 1979) holds it to be the trace of a hot spot over-ridden by North America, with the Yellowstone Park volcanic area representing the present expression of the hot spot. An opposing view (Christiansen and McKee, 1979) considers it to be of fundamentally tectonic origin, representing a zone of northwest-southeast crustal extension. One problem with the latter view is that although the Snake River Plain has undergone volcanic activity within the last few hundred years, it is nearly aseismic, and thus it is not clear if the feature has essentially stopped opening or is doing so by means of aseismic creep. Geodetic investigations will obviously be of value in answering these questions.

Columbia Plateau

The Columbia Plateau is one of the world's great occurrences of tholeiitic basalt, chiefly erupted during the Miocene Epoch in repeated eruptions covering thousands of square kilometers. It is apparently petrologically related to the Snake River Plain, but is much less active seismically. No baselines have been proposed specifically to investigate crustal deformation on the plateau.

Puget Sound Area

The Pacific northwest of the U.S. is underlain by an eastward-dipping subduction zone (Figure 3a), which is currently being thrust under the Coast Ranges of Oregon and Washington. This subduction accounts for both volcanic activity in the Cascades and moderate seismic activity under Puget Sound. Leveling data have been reviewed by Ando and Balazs (1979), but there are no comparable surveys of horizontal deformation. Such horizontal deformation should be apparent, since the Olympic Mountains appear to be a volcanic pile being thrust under the continent.

A baseline across Puget Sound would clarify the structure of the subducting plate and the Coast Ranges (particularly the Olympic Mountains), and the origin of seismicity in the Seattle-Tacoma area.

Lewis and Clark Lineament

This structure, also called the "Lewis and Clark line," is a zone of northwest-trending faults, expressed by valleys crossing the Cordillera. It is marked by low-level seismicity and several major mineral deposits. The faulting is believed to have a substantial right-lateral strike-slip component, and the lineament thus forms the northern member of the megashear couple referred to earlier whose movement is responsible for the Basin and Range Province faulting. However, this interpretation is most tentative.

Proposed measurements between the northern Great Plains (a cratonic area) and the Cascades and Coast Ranges should, if carried out long enough, test the strike-slip fault concept of the lineament. If verified this would support the interpretation of the Basin and Range Province as tension faults complementary to the previously-described megashear.

Rio Grande Rift

This rift, a discrete structure although physiographically continuous with the Basin and Range Province, appears to be analogous to the East African rift valleys. It is the immediate result of tensional faulting, accompanied by high heat flow, crustal thinning, and minor seismic activity (possibly diminished by high crustal temperatures that promote creep instead of stick-slip movement). Representing as it does an accessible example of incipient continental fragmentation, the Rio Grande Rift has been intensively studied in the 1970's by geological, geophysical, and geodetic techniques, thus providing a test area with abundant "ground truth" for crustal dynamics project investigations, although the present rate of crustal extension appears extremely low.

Rocky Mountains

The southern and central Rocky Mountains (from Montana south) are not well-understood tectonically. Their location, separated from the rest of the North American Cordillera by the cratonic Green River Basin and Colorado Plateau, is anomalous, and they do not fit easily into the plate tectonics concept. It is also not clear what the relationship is between the Rocky Mountains, the Rio Grande Rift, and the Basin and Range Province, although they share some structural characteristics. The Rockies are only mildly seismic, and horizontal deformation in this region relatively slow. However, a regional geodetic study of the Cordillera must include some measurements across the Rockies.

NORTH AMERICAN TECTONICS: EASTERN U.S.

Tectonic Problems of the Eastern United States

In addition to the western sites proposed above, a reconnaissance program involving a small number of new central and eastern U.S. sites is suggested. Tectonics east of the Rocky Mountains are complex and not well understood because of the masking effects of recent surface sedimentation, relatively low levels of seismicity and, until recently, incomplete data bases. Sbar and Sykes (1973) suggest that the general stress in the east currently appears to be largely compressional, nearly horizontal and east to northeast trending. However, Street et al. (1974), as a result of focal mechanism solutions of earthquakes occurring in the general area of New Madrid, MO from 1962 to 1973, found that the stress field there was complex with a single regional stress field not being applicable.

There is mounting evidence that tectonic zones presently active in the eastern U.S. are controlled by the existence of unhealed fault zones subjected to high stress levels (Sbar and Sykes, 1973). As Fletcher et al. (1978) point out, many of the earthquakes located east of the Rocky Mountains occur in zones several hundred kilometers in width and do not appear to be related to single, continuous faults. This fault pattern is confirmed by surface geology and geophysics. Evidently the east contains no long, continuous, easily-identifiable faults comparable to major western faults such as the San Andreas.

The well established patterns of low level seismicity existing in the east do indicate that crustal motions are occurring. In addition to this seismicity, further evidence of tectonism is furnished by offsets of drill holes used for highway blasting. By this means, Block (1979) detected contemporary horizontal motions of .28 cm/yr in Connecticut, and Schafer (1979) measured horizontal motions of up to and greater than 3.8 cm/yr in areas of the Appalachian Plateau and Valley and Ridge Province. Some, or all, of these bore hole motions might be due to the effects of road grading or blasting, but the large masses of rock involved suggest larger forces at work. It is not known if these tectonic motions are sufficiently cumulative to constitute significant intraplate motion, or whether the local motions are absorbed by plastic deformation in the neighboring crust. Based on nearly two years of VLBI observations, the baseline length between Owens Valley, CA and Haystack, MA is changing at a rate of less than 1 cm/yr (Allenby, 1979). In view of the active crustal expansion in the western U.S., this suggests that large scale counteracting contraction may be occurring in the central and eastern U.S.

In consideration of the large historical eastern earthquakes and this area's potential for further devestating upheavals, further intensive geodynamic studies are clearly justified. However, because the extent and locus of the motion is so uncertain, we propose initially only a limited reconnaissance program supported primarily by existing or approved VLBI sites but augmented by three new sites (Meade's Ranch, Ozark Plateau, and Interior Plateau). These sites provide sufficient baselines to cover the active seismic zones discussed below and will provide data on the magnitude and direction of present motions.

New Madrid, MO

In this area one of North America's strongest earthquake series occurred in 1811 and 1812. It is the most active seismic area in the central and eastern U.S. Recently 330 local earthquakes with magnitudes of 1 or greater were detected in a 21 month period (Stauder et al., 1976). The pattern of these events indicate several linear trends, presumably corresponding to active faults. The dominant patterns trend NE, parallel to the axis of the Mississippi Embayment, while subordinate patterns trend N-S and N-W. Within these zones the faults appear to offset one another with the linear dimensions of the individual faults varying from about 25 to 100 km in length. Analysis of travel time residuals at seismic stations in the area suggest a deep, roughly cylindrical zone of low-velocity material, possibly associated with a mantle plume. As discussed below, this area is the focus of many postulated eastern U.S. tectonic zones.

Mississippi Embayment

This may be part of a major fracture zone extending from New Madrid to the Gulf of Mexico and marking an ancient rift zone associated with the opening of the Gulf. While active subsidence has occurred in the embayment from cretaceous time to the present, the extent or direction of present day lateral motions are not known. However, this embayment is very similar to East African Rift Valleys in its subsidence, alkaline magmatism, and seismicity, and might be active.

Thirty-Eighth Parallel Lineament

Heyl (1972) identifies the New Madrid Area as the western end of an east-trending zone of nearly continuous faults and intrusions, roughly following the 38th parallel of latitude. According to Heyl the zone consists of an interconnected line of at least 800 miles of faults, monoclines, igneous intrusions and local stratigraphic facies changes running westward from the Stanley fault in north-central Virginia. He classifies this zone as a right-lateral wrench-fault extending deep into the crust and possibly the continental equivalent of great oceanic fracture zones such as the Mendocino and the Kelvin. However, Lowman et al. (1979) found no evidence of this zone in eastern West Virginia, so it may not be a single continuous tectonic zone.

Boston-Ottawa Seismic Zone

Sykes (1978) also suggests that some major eastern onshore fracture zones may be continuations of major offshore transform faults formed during the opening of the North Atlantic. A small circle passing along the offshore New England seamount chain continues onshore along an active seismic trend running north-west from Boston through Ottawa, Canada. The Haystack VLBI observatory lies at the south-east edge of this seismic zone. While baselines between U.S. and foreign observatories are not shown on the enclosed U.S. baseline map, a baseline between Haystack and our proposed site at Churchill crosses this seismic zone.

St. Lawrence Valley-Missouri Seismic Trend

Still another focus for New Madrid seismic activity is a northeast trending seismic zone extending NE from southeastern Missouri through Indiana and Ohio to the St. Lawrence Valley (Woollard, 1969). It has been suggested that this system is a rift zone initiated in Mesozoic time that, judging from the seismicity, is still active today. Gaps in this seismic trend indicate either areas of slow creep, locked zones, or that the trend is not continuous.

Appalachian Fold Belt

A continuing NE-SW zone of low seismic activity coincides roughly with the Appalachian fold belt from New England to Alabama. Extending from the Atlantic Coast and intersecting this Appalachian trend are two active siesmic zones crossing Central Virginia and South Carolina-Georgia (Bollinger, 1973). Data from ground leveling lines suggest that considerable vertical movement is occurring in this area (Brown and Oliver, 1976). For example, the Appalachian Highlands are rising relative to the Atlantic Coast at rates of up to .6 cm/yr, while western Illinois is rising at a rate of 1.6 cm/yr with respect to central Ohio. Motions involving such large vertical movements presumably include horizontal components as well, but the lower accuracies of horizontal land surveying lines preclude detecting motions of this magnitude.

Atlantic Oceanic Crustal Deformation

Geophysical data indicates that the mobility of large continents may be reduced by the lack of an upper mantle decoupling zone or asthenosphere under old continental cratons. In this case, deformation may be occurring along the Atlantic Ocean-N.A. continental interface as the result of spreading along the Mid-Atlantic Ridge. Baselines between the continental U.S. and Bermuda will address this problem.

OTHER NORTH AMERICAN SITES

Alaska

Alaska is a geologically complex region of high seismic activity with the Pacific Plate being thrust, at about 5 cm/yr, under the Aleutian archipelago along the Aleutian trench. A well-developed Benioff zone extends northward under the Aleutian Arc and Bering Sea. Large vertical motions in this area are well-documented. For example, initial coseismic vertical deformation following the 1964 Prince William Sound earthquake amounted to over 5 meters with continuous smaller vertical motions since (Brown et al., 1977).

A problem in Alaska is being assured of a stabilized location on the mainland. Lathram (1973) characterizes Alaska as not a conglomerate of drifted segments of other continents, but as a continental mass accreted between the Canadian and Siberian shields by the interaction of these shields, with ancient, Precambrian oceans. The northern and southern borders are compressionally distorted by thrusting from the down moving Pacific plate in the south and compression across the Brooks Range in the north. In between lie at least four major zones of right-lateral strike-slip faulting with activity beginning in the Paleozoic and probably in some cases, extending into the present (Grantz, 1966). Allen (1978), utilizing Landsat images, classifies the Denali fault as presently active based on displacements across Quaternary terraces.

These faults constitute major orogenic belts and are, from north to south, the Kaltag-Yukon faults, Iditarod-Nixon Fork fault, the Denali fault, and the Castle Mountain fault (Lathram, 1972).

Five of the six recommended sites are those suggested in the OSTA (1978) report. The additional new site (number 60, Wiseman) has an airfield, is between the Yukon Flats fault and the Brooks Range thrust zone, and lies on undifferentiated Paleozoic metomorphic rocks. It perhaps will be the Alaskan site least affected by intraplate deformations.

The proposed network will not only furnish data on current intraplate activity in Alaska, but will also guard against localized site motions contaminating global interplate measurements. Because of the weather, all these should be VLBI sites.

Gulf of California

Baja California is separated from the Mexican mainland by the Gulf of California, which is being formed by a series of large en echelon transform faults extending from the East Pacific Rise at the mouth of the Gulf. Baja California is on the Pacific Plate, while mainland Mexico is on the North American Plate. The Gulf of California apparently represents incipient ocean basin formation that began about four million years ago, as dated by magnetic anomalies. These same anomalies indicate an average spreading rate over this time period of 6 cm/yr (Larson et al., 1968). This right-lateral strike-slip motion is transferred up the Gulf of California, through the Salton trough of Southern California and, eventually, into the San Andreas fault zone.

Atwater (1970) has suggested that all the Gulf of California motion may not be transmitted into the San Andreas system, but some may be transmitted into the Basin and Range Province. In such a case the western U.S. would be a megashear representing a wide, slushy boundary between two large moving plates. The proposed stations at La Paz and Mazatlan should determine present slip rates up the Gulf. U.S. stations as discussed earlier will determine the distribution of this motion in the western U.S..

Caribbean

As described by Jordan (1975), the Caribbean Plate is the center of an extremely complex and poorly understood plate tectonic area involving five major plates (Caribbean, North American, South American, Cocos and Nazca) and four triple junctions (Cocos, North American, Caribbean; Cocos, Nazca, Caribbean; Nazca, South American, Caribbean; and South American, North American, Caribbean). In general, the plate is moving eastward in respect to the North American and South American plates. The northern plate boundary consists of a series of left-lateral strike-slip faults crossing Guatemala (Motagua fault zone) and progressing almost due east between Cuba and Hispaniola. The eastern and western borders are subduction zones along the West Indies arc (east) and Middle American trench (west). The southern boundary in Venezuela, Colombia and Panama is characterized by a broad deformation zone consisting of a number of fault-bounded blocks with complex patterns of both strike-slip and thrusting movements. These blocks may be engaged in a complex pattern of relative motion (Jordan, 1975).

The OSTA (1978) report proposes 15 Caribbean sites. Our recommended sites at Vera Cruz, Oaxaco, British Honduras, Nicaragua, Grand Turk, Puerto Rico and the Northern Antilles follow the OSTA recommendations. However, we do not recommend the eight OSTA sites located in the complex southern plate border area, because this network appears to support a special detailed regional study at variance with an initial goal of studying broad global problems. We suggest that a detailed geodynamic program in Costa Rica, Panama, Colombia and Venezuela can best be initiated at a later date when the present day major plate motions in the region are better understood.

GLOBAL TECTONICS

The scientific basis for the global network of sites recommended can also be discussed in relation to some of the specific tectonic problems that can be investigated, in addition to the general ones of plate rigidity, velocity, and identification previously discussed.

Atlantic Ocean

The Atlantic Ocean basin is central to all concepts of plate tectonics and continental drift. Its concordant coastlines and the similar geology of opposing coastlines were the basis for the Wegener's original theory of continental drift. Studies of transform faults, deep-sea sediments, and magnetic anomalies of the Atlantic were similarly fundamental in establishing the theory of plate tectonics. For these reasons, direct measurements of plate motions in and across the Atlantic will have major implications for tectonic theory.

Several specific questions can be approached using VLBI and laser ranging. Perhaps the most general is that of whether continental drift is actually occurring. Despite the widespread acceptance of this concept, as a corollary of plate tectonics, there has not to date been a direct geodetic demonstration of drift over intercontinental distances. Such a demonstration may require several decades if, as Anderson (1975) suggests, stress propagation is slow; nevertheless, it is in principle now possible. Another question is whether South and North America are on different plates, as implied by the studies of Minster et al. (1974). Direct measurement of the rotation vectors at different latitudes across the Atlantic are one approach to this problem. Finally, the recurring question of why earthquakes occur along supposedly passive (i.e., Atlantic-type) continental margins may be partially answered by measurement of plate rigidity across such margins.

Africa

Apart from particular tectonic features such as the East African Rift system, which will be discussed elsewhere because of its close relation to the Red Sea, the continent of Africa as a whole is of tectonic importance for several reasons. First, in many continental drift reconstructions, starting with that of Wegener, Africa lies at the center of Pangea, appearing to be the nucleus from which the other continents moved away (particularly those of the southern hemisphere). Furthermore, it has been suggested, by Burke and Wilson (1973), that Africa has in fact been fixed with respect to the mantle for the last 20 million years, on the basis of the absence of hot spot trails. Tectonically, Africa appears to be, except for the rift system, remarkably stable tectonically, and thus offers an excellent site for testing the basic assumption of plate rigidity.

In summary, Africa is the continental analogue of the Atlantic Ocean in being central, theoretically and perhaps literally, to global tectonic theories, and measurements both within and to it appear fundamental to any attempt to measure global tectonic plate movements and deformation.

Aleutian Subduction Zone

The subduction zone being thrust northwestward under the Aleutian Islands is one of the best-studied and fastest-moving. Furthermore, it is largely responsible for the frequent strong earthquakes of southern Alaska. Consequently, this feature is of prime importance for our understanding of the relations among plate movement, seismic activity, and even volcanism. It will be of great interest, for example, to find the relation between motion of the Pacific plate at the Hawaiian Islands and the subduction of the plate at the Aleutian trench.

East Pacific Rise - North American Plate

It was suggested by Menard in the 1960s that the Basin and Range Province was the result of the intersection of North America by the East Pacific Rise. This concept has largely fallen out of favor, and it is now generally thought that the Rise breaks up into a series of transform faults in the Gulf of California. Nevertheless, it can hardly be coincidence that such a uniquely wide and active zone of tension faulting as the Basin and Range Province lies just north of the place where the East Pacific Rise meets the continent. Better knowledge of plate motions in southwestern North America should clarify regional relations in this area.

Nazca Plate Subduction

The Nazca Plate is probably the simplest and best-documented of all major plates. Furthermore, it is one of the fastest-moving, having half-spreading rates of up to 9 cm/yr (Minster, et al., 1974) away from the East Pacific Rise, and its subduction under South America is responsible for frequent devastating earthquakes. These characteristics, coupled with its relatively moderate size, suggest that the Nazca Plate is an ideal site for study of both plate motions and intraplate deformation.

Davis Strait

Marine geophysical data indicate that the crust under Davis Strait and Baffin Bay is oceanic, and dating of magnetic anomalies suggests that Greenland and North America separated during the mid-Cenozoic. This separation is thought to have stopped long before the present time, but there is still persistent minor seismic activity under Baffin Bay and adjacent Arctic islands. This may be the result of reactivation of older faults; nevertheless, a full understanding of the tectonic history of the North Atlantic will require investigation of possible movement across Davis Strait and Baffin Bay.

Alpine-Himalayan System

The young orogenic system reaching from the Atlantic Ocean (in Morocco) to the Indian Ocean (in Burma) is extraordinarily complex and active, and appears to represent a zone of plate convergence. However, it has proven extremely difficult (Dewey et al., 1973) to apply plate tectonic theory to this belt; Minster et al. (1974), for example, explicitly omitted Asiatic data from their mathematical model of plate motions. Knowledge of the actual crustal deformation in this belt is necessary to set limits on models of plate movements elsewhere. In addition, the Alpine-Himalayan system is one of extremely dangerous seismicity. It is obvious that accurate regional measurements across the system are a necessary first step for several reasons. These should eventually be supplemented by denser networks of baselines.

Red Sea

The Arabian Plate is analogous to the Nazca Plate in being unusually well-defined tectonicaly, with rift, subduction, and transform fault boundaries. The plate appears to be moving northward as a consequence of sea-floor spreading in the Red Sea. The latter is itself of interest as an example of a young ocean basin (Stage 2 in the Wilson Cycle), and because it grades into the spreading centers of the Gulf of Aden and the Indian Ocean. Movement of the Arabian Plate will therefore, if measured accurately, permit another evaluation of the relation between plate motions as inferred from marine magnetic anomalies and as measured directly.

East African Rifts

The African rift valleys are the classic example of this type of structure, and are of great interest in plate tectonic theory as an incipient ocean basin. There was for some years debate as to whether they were formed by tension or compression, but it was found that the rifts are clearly bounded by normal faults, indicating tension. This has also been verified geodetically and geophysically. However, it has been found impossible to model the tectonics of east Africa with rigid plates (Minster and Jordan, 1978); one result of such a model implies compressive motion across the rifts at 1 cm/yr. Despite their apparent simplicity, therefore, the East African Rifts remain a first-order problem, whose solution requires accurate regional measurements.

Indian Ocean Tectonics

A problem related to that of east Africa is the overall dynamics of the Indian Ocean. One particular question is whether the Australian Plate (called the Indian Plate by some) is one plate or two, or if it is one plate undergoing internal deformation (Minster and Jordan, 1978). There is considerable diffuse seismic activity roughly coincident with the Ninety East Ridge south of Indonesia, and Stein and Okal (1977) have interpreted this feature as a wrench fault zone resulting from the differing resistance to subduction of the Himalayas and the Indonesian island arc. Another specific problem of the Australian plate is the origin of the intra-continental stresses described by Sykes (1978), analogous to those in other continents.

Alpine Fault Zone

The Alpine fault zone of New Zealand is of particular interest for several reasons. First, it is part of the boundary between the Pacific and Australian plates. Furthermore, it is one of the few places where a transform fault is exposed on land. Unlike the San Andreas fault, however, there is no movement at this time on the Alpine fault itself; the movement instead appears to be continuously distributed over a zone 70-100 km wide, as indicated by conventional geodetic surveys. In summary, the Alpine fault zone is both similar to and different from the San Andreas fault zone to make it an excellent structure for investigation by laser and VLBI techniques.

Australian - S.W. Pacific Plate Boundary

It is generally believed that Australia is drifting northward as part of the motion of the Australian plate. However, there are no good estimates of the rate, only of the direction (from earthquake slip vectors), and the boundary is a complex one probably consisting of several micro-plates with an unknown strike-slip component of movement. Precise measurements of the motions across this boundary will be an important constraint on models of the Australian Plate, and will provide valuable information on internal deformation of the Australian and possibly the Pacific plates.

Baikal Rift

The valley occupies by Lake Baikal is characterized by sesimic activity, high heat flow, and associated volcanic activity, and appears to be a typical rift valley representing crustal dilation or, in plate tectonic theory, the incipient formation of an ocean basin. Measurements across the Baikal rift are thus of obvious importance by themselves. But in addition, knowledge of the Baikal rift dynamics is necessary for understanding of the motion and rigidity of the Eurasian plate as a whole.

North-east Siberia

A long-standing problem in global plate tectonics is the location of the northwest boundary of the North American plate. The obvious choice, Bering Strait, is almost certainly not the true plate boundary, since the geology of Alaska and Siberia is essentially continuous. The present consensus, following Churkin (1972), is that the boundary is the rift zone in the Cherskiy Mountains, which is probably the continental extension of the Nansen Ridge (itself an extension of the Mid-Atlantic Ridge). However, the seismicity is diffuse and low-level, and further data are needed to define the plate boundary.

SITES AND BASELINES

Table I (Appendix A) lists the existing and recommended VLBI and laser sites for the continental United States, North America, and the globe. These sites are displayed on three maps: Figure 1 (continental United States), Figure 2 (North America) and Figure 3 (world). Representative baselines connecting selected sites in the continental United States and over the globe are shown in Figures 1b and 3b, respectively. Each observing site is designated by a unique number, given in the first column of Table I. This same number is used to locate the site in Figures 1-3. Column 2 of the Table lists those Figures on which the site appears (some stations appear on more than one map). The third column provides the approximate geographic location of the site, followed by a three letter identification code. The fifth column of the Table designates the kind of site, as follows: existing VLBI sites (or existing radio astronomy observatories that could be used as VLBI sites) are shown by squares ( ). Triangles ( ) represent existing laser sites (whether or not presently occupied). Locations equipped for both VLBI and laser observing are shown by a nested triangle within a square ( ). Proposed sites are indicated by a circle; if the proposed site is recommended for VLBI observing, then a square is nested inside the circle ( ). If a laser site is proposed, a triangle is included inside the circle ( ). The _type_ of observing system, fixed (F) or mobile (M), is given in the sixth column, and additional remarks are included in the last column.

The maps in Figures 1-3 use the same symbols and numerical designation found in Table I. Representative baselines in Figures 1b (continental United States) and 3b (globe) are coded as follows: solid lines indicate global plate motion baselines (between stations on different plates). Baselines for intraplate deformation are shown by dashed lines. The special case of baselines for study of deformation in the western United States is represented by dotted lines. In both Figure 1b and 3b only selected representative baselines are drawn; there has been no attempt to include all possible station-station combinations. In Figure 3b large two headed arrows between continents indicate the multiple combination baselines already being measured between existing VLBI or laser sites.

WESTERN UNITED STATES

Forty-four sites are listed in Table I within the lower 48 United States. Fifteen of these are in California and an additional 16 are located in the western half of the country. These sites are proposed principally for studies of deformation within the western United States, addressing the particular tectonic problems described above. Ten of the fifteen California sites already exist. Three of these have or will shortly have both VLBI and laser capability (8--Goldstone, 11--Owens Valley, 14--Quincy). Six of the California locations are designated ARIES sites for mobile VLBI systems (2--La Jolla, 4--Palos Verdes, 5--Malibu, 6--JPL, 7--Pearblossom, 13--San Francisco). In addition, we recommend a site clearly on the Pacific Plate (3--San Clemente Island), and two others on the western side of the San Andreas Fault Zone (9--Vandenberg Air Force Base and 12--Monterey). Two sites on the eastern side of the San Andreas which provide good measurement geometry are also recommended (10--Lake Isabella and 15--Trinity County). An existing laser facility is located at Otay Mountain (1) and Quincy (14).

Existing facilities elsewhere in the western United States include mobile laser sites at Bear Lake, Utah (22) and Tucson, Arizona (Mt. Hopkins--28). The very large array (VLA) at Magdalena, New Mexico is an established radio astronomical observatory and Fort Davis, Texas will be equipped for both VLBI and laser ranging.

Fourteen additional sites are recommended to address the tectonic problems described above. Four of these are east of the front of the Rocky Mountains, located on the presumably stable great plains (19--Shelby, Montana; 24--Ft. Morgan, Colorado; 31--Abbott, New Mexico; 32--Roswell, New Mexico). Three sites on the Colorado Plateau are suggested (25--Dirty Devil Creek, Utah; 27--Flagstaff, Arizona; 30--Chaco Canyon, New Mexico). Within the Rocky Mountains are two proposed sites (20--Lowman, Idaho; 23-Muddy Creek, Wyoming) in addition to the Bear Lake, Utah (22) facility. We suggest two sites within the Basin and Range (21--Tuscarora, Nevada; 26--Duckwater, Nevada). One location in Oregon (16--Scottsburg) and two in Washington (17--Sequim; 18--Skykomish) provide the necessary tie points to address the tectonic problems described above. The baselines recommended are detailed below:

San Andreas Fault Zone

Maximizing the geometry for motion of the Pacific Plate past the North American Plate along the San Andreas fault zone suggests the following baselines (see Figure 1b):

15 (Trinity County) to 12 (Monterey), 9 (Vandenberg), 3 (San Clemente) or 2 (La Jolla)

1 (Otay Mountain) to 10 (Lake Isabella) or 14 (Quincy)

2 (La Jolla) to 8 (Goldstone) or 11 (Owens Valley).

The Otay Mountain (1) - Quincy (14) line has already been measured using mobile lasers. The La Jolla (2) to Goldstone (8) or La Jolla to Owens Valley (11) combinations presumably would involve VLBI systems for which those sites have been equipped. Additional baselines of interest across the San Andreas Fault Zone system are provided by 3 (San Clemente Island) or 2 (La Jolla) to either 1 (Otay Mountain), 28 (Tucson, Arizona) or 33 (Ft. Davis, Texas). Here the geometry is not as well suited for measuring the expected motion. Other interplate baselines shown in Figure 1b that cross the San Andreas Fault Zone range from the interior of the North American Plate to the California coast:

24 (Ft. Morgan) to 3 (San Clemente Island) and 9 (Vandenberg)

34 (Meades Ranch) to 3 (San Clemente Island)

41 (Haystack) or 38 (Green Bank) to 2 (La Jolla)

39 (Goddard) to 1 (Otay Mountain).

Basin and Range

Measurements of possible extension within the northern Basin and Range are provided by the following baselines:

14 (Quincy) to 21 (Tuscarora), 22 (Bear Lake) and 23 (Muddy Creek)

21 (Tuscarora) to 22 (Bear Lake) and 23 (Muddy Creek).

In the southern Basin and Range, measurement of crustal extension is possible along the 25 (Dirty Devil Creek) to 11 (Owens Valley) and 26 (Duckwater) baselines. Possible shearing can be examined along the 11 (Owens Valley) to 27 (Flagstaff) and to 28 (Tucson) tielines. Baseline measurements between 1 (Otay Mountain) and 28 (Tucson) could monitor possible extension in the extreme southern portion of the Basin and Range.

Intermountain Seismic Belt

Baselines suitable for measuring possible deformation in this region include

22 (Bear Lake) to 20 (Lowman) and 21 (Tuscarora)

25 (Dirty Devil Creek) to 26 (Duckwater) and 11 (Owens Valley).

Note that these baselines have also been discussed above under the Basin and Range.

Colorado Plateau

Internal deformation within the plateau can be monitored with the triangular network of stations 25 (Dirty Devil Creek) - 27 (Flagstaff) - 30 (Chaco Canyon). Little motion is to be expected along these lines if the block is indeed tectonically stable, as described above. The possibility of regional rotation can be tested with the following baselines:

24 (Ft. Morgan) to 25 (Dirty Devil Creek)

29 (VLA) to 27 (Flagstaff) and 30 (Chaco Canyon).

The first of these connects the stable interior of the United States with the Plateau. Other checks on regional rotation, but using baselines which tie to plateau to regions of possible tectonic activity, are possible from

26 (Duckwater) to 27 (Flagstaff) and 25 (Dirty Devil Creek)

22 (Bear Lake) to 27 (Flagstaff) and 30 (Chaco Canyon).

If the Plateau is indeed a stable block, then it becomes an important tie point for baselines to other less stable regions, making possible the measurement of deformation affecting sites such as 8 (Goldstone), 11 (Owens Valley) and 26 (Duckwater).

Snake River Plain - Columbia Plateau

The question of possible crustal extension in this region is addressed by baselines tied to the site 20 (Lowman, Idaho): from 15 (Trinity County) which also crosses the northern Basin and Range, from 16 (Scottsburg) which crosses the Cascades, from 21 (Tuscarora) and 22 (Bear Lake). The site at Lowman (20) is tied to the stable interior of the United States through 19 (Shelby).

Puget Sound Area

The recommended baseline here is 17 (Sequim) to 18 (Skykomish) for measurement of possible horizontal deformation.

Lewis and Clark Lineament

Baselines between 19 (Shelby) and the two in the Puget Sound area (17--Sequim, 18--Skykomish) maximize the possible deformation along strike of the faults in this zone.

Rio Grande Rift

There are several suggested baselines shown in Figure 1a for measuring east-west crustal extension across the Rio Grande Rift. These include:

28 (Tucson) to 32 (Roswell)

29 (VLA) to 32 (Roswell) and to 31 (Abbott)

30 (Chaco Canyon) to 31 (Abbott).

These are spaced along the north-south strike of the rift. Two other baselines may be affected by extension within the rift. In the extreme south, the long 1 (Otay Mountain) to 33 (Ft. Davis) baseline across the southern Basin and Range will also cross the rift, as will the long tie line at the northern end between 25 (Dirty Devil Creek) and 34 (Meades Ranch). Because the 29-31 and 29-32 strike at angles to the presumed east-west extension, it will also be possible to check for components of motion along strike.

Rocky Mountains

Although motions within the Rocky Mountains are expected to be slight, several baselines are suggested which may place some limits on the deformation between this and adjacent regions. In particular, 23 (Muddy Creek) to 24 (Ft. Morgan) and 22 (Bear Lake) to the Colorado Plateau sites 27 (Flagstaff) and 30 (Chaco Canyon) are such baselines. Deformation <u>within</u> the Rocky Mountains is addressed by 22 (Bear Lake) to 23 (Muddy Creek).

CENTRAL AND EASTERN UNITED STATES

Sites numbered 34-44 are in the eastern half of the United States. Except for those mentioned above as relevant for global plate motion studies (e.g., 38-Green Bank, 39-Goddard, 41 Haystack) these sites are designated principally for intraplate studies. Existing sites include the radio astronomy observatory at Danville (37) and Maryland Point (40) and two laser stations, one at Patrick Air Force Base in Florida (42) and one on the island of Bermuda (44). A proposed VLBI site at Richmond, Florida (43) and three proposed sites at Meades Ranch, Kansas (34), Ironton, Missouri (35) and Franklin, Kentucky (36) complete the United States sites in Table I. Baselines appropriate to individual tectonic problems are discussed below.

General Intraplate Deformation

It is generally assumed, as mentioned previously, that the interior portions of large tectonic plates are rigid. Testing of this assumption is an important part of the Crustal Dynamics Project measurements. We recommend a number of baselines which should determine an upper limit to intraplate deformation in the central portion of the North American plate. These include a number of ties to 34-Meades Ranch, a central U.S. geodetic benchmark. For example, the baselines between 34 and

19 (Shelby), 24 (Ft. Morgan), 32 (Roswell), 33 (Ft. Davis) and 38 (Green Bank).

The first four of these are sites used for western United States studies. The Green Bank station (38) provides a tie to the eastern portion of the United States.

East-west stability can be measured by the long baselines 19 (Shelby)-41 (Haystack), 33 (Ft. Davis) to 43 (Richmond), 42 (Patrick Air Force Base) and to 44 (Bermuda). The last of these is also discussed below. North-south stability is addressed by the lines connecting 41 (Haystack) to 43 (Richmond) and 39 (Goddard) to 42 (Patrick Air Force Base).

Cross ties are provided by connecting the sites

33 (Ft. Davis) to 42 (Haystack) and to 38 (Green Bank)

37 (Danville) to 19 (Shelby), 38 (Green Bank) and 41 (Haystack)

32 (Roswell) to 35 (Ironton)

36 (Franklin) to 43 (Richmond) and 44 (Bermuda)

24 (Ft. Morgan) to 43 (Richmond).

Several of these are also discussed below in the context of specific tectonic problems.

New Madrid, Missouri

Within the area of active seismicity no individual baselines are planned, as deformation on this scale is better studied by high density geodesy techniques. This area is, however, likely to be the focus of many tectonic regimes in the eastern United States, as described above. These larger scale regions are discussed below:

Mississippi Embayment

The baseline 35 (Ironton) to 36 (Franklin) is suggested for measurement of east-west extension in this failed rift system. Because of the proximity to New Madrid and the possibility of deformation in directions other than east-west, these two sites are tied to 37 (Danville) forming a triangular network for study of this region.

Thirty-Eighth Parallel Lineament

Strike-slip motion along this proposed feature, if large enough, could be measured by the 36 (Franklin) to 38 (Green Bank) line. Although not shown in Figure 1b, other possibly useful baselines might be 35 (Ironton) to 38 (Green Bank) or 35, 36 to 39 (Goddard). The problem with these is that they cross several tectonic elements, and little is known about the nature of possible deformation within the individual regions, as described above.

Boston-Ottawa Seismic Zone

None of the baselines shown in Figure 1b crosses this zone, but such potential baselines as 41 (Haystack) to 67 (Algonquin Radio Observatory, Canada), may provide some information on deformation in this area.

St. Lawrence Valley - Missouri Seismic Trend

Baselines from 37 (Danville) to 91 (Haystack), 38 (Green Bank) and 36 (Franklin) should provide measurements covering the seismic zone.

Appalachian Fold Belt/Atlantic Ocean Crustal Deformation

Intraplate deformation along the Atlantic continental shelf and coast into the Appalachians, in directions roughly perpendicular to the coast, can be monitored by baseline measurements from Bermuda (44) to several sites. In particular, deformation in the Atlantic is addressed by the baselines

44 (Bermuda) to 42 (Patrick Air Force Base), 39 (Goddard) 41 (Haystack).

Baselines crossing the Appalachians include

44 (Bermuda) to 36 (Franklin) and 38 (Green Bank)

43 (Richmond) to 36 (Franklin).

NORTH AMERICA

Proposed VLBI or laser sites in addition to those described above but also located in North America are designed to provide measurements relevant to the complex tectonic motions in Alaska, Baja California and the Caribbean. These sites, as well as the 44 described above, are shown in Figure 2. The new sites are numbered 60-78 in Table I. Six of these already exist; 61 (Fairbanks, Alaska) will be a fixed VLBI site; radio astronomy observatories are found at 67 (Algonquin, Ontario, Canada), 69 (Penticton, British Columbia, Canada) and 77 (Arecibo, Puerto Rico). A CTS antenna at 68 (Prince Albert, Saskatchewan, Canada) makes this a likely and desirable VLBI site. Both mobile laser and mobile VLBI facilities exist at 76 (Grand Turk Island). Thirteen additional sites are recommended as follows:

Alaska

The problem of finding a stable site for baseline measurements as well as the great complexity of the tectonics in this region suggests a number of sites located on separate blocks. Accordingly we suggest 60 (Wiseman) may be the most stable location in Alaska (see above). The other five recommended sites are at Fairwell (62), Dillingham (63), Seward (64) and Cordova (65). Measurements between all the seven proposed sites should provide a relatively complete picture of the intraplate deformation occurring in this region of high seismic risk, including motion along the major faults.

Canada

Principally for studies of intraplate deformation within North America and for providing relatively stable sites well within the continental portion of the North American Plate we suggest four locations in Canada. To the already existing facilities a site near Churchill, Manitoba (66) is recommended. Baselines from these stations are shown in Figure 3b and discussed under global baselines.

Mexico and Baja California and the Caribbean

The desire to measure deformation in the Gulf of California and into the Salton Trough dictated the locations 70 (La Paz, Baja California) and 71 (Mazatlan, Sinaloa). In fact it may be useful at some future time to add several stations to the north of these to monitor the spreading and deformation in the northern end of the Gulf of California.

The sites located at 72 (Vera Cruz, Vera Cruz), 74 (Belmopan, British Honduras) and 75 (Waspan, Nicaragua) provide ends for ties to 76 (Grand Turk) and 77 (Arecibo, Puerto Rico) which cross the major tectonic elements in the Caribbean. The Northern Antilles (78) site is also useful in this regard, especially when linked with the Mexican sites described above.

Finally, several of these sites, especially 73 (Oaxaca, Oaxaca, Mexico), should become important for global plate motion study. The baselines between these and Pacific sites (see below) cross the offshore subduction zone of the Middle America Trench.

GLOBAL SITES AND BASELINES

VLBI and laser sites outside of North America are numbered 90-141. Of these 52 sites, 24 already exist. Existing or already planned laser sites include:

90--Maui, Hawaii	118--Kootwick, Netherlands
91--Samoa	119--Wetzel, Germany
98--Arequipa, Peru	120--Southern India
101--Natal, Brazil	133--Yarragadee, Australia
110--Helwan, Egypt	134--Orroral, Australia
115--Madrid, Spain	136--Kwajalein Island

Of these facilities five are fixed, the remainder are mobile systems. Their locations are shown in Figure 3a.

Eighteen VLBI or radio astronomy observatories exist, and are also shown in Figure 3a. These are:

90--Maui, Hawaii	120--Onsala, Sweden
94--Quito, Ecuador	121--Helsinki, Finland
99--Santiago, Chile	122--Torun, Poland
102--Sao Paulo, Brazil	123--Bologna, Italy
109--Johannesburg, South Africa	124--Belgrade, Yugoslavia
115--Madrid, Spain	125--Crimea Radio Observatory, U.S.S.R.
116--Chilbolton or Jodrell Bank, England	134--Parkes, Australia
118--Westerbork, Netherlands	136--Kwajalein Island
119--Bonn, Germany	138--Kashima, Japan

Most of these are radio astronomy observatories and not presently set up for mobile VLBI operations.

We have recommended 28 additional sites, located both on islands in the ocean and on the continents. Within the Pacific Ocean lie five new sites (92-Marquesas Island or Tahiti; 93-Galapagos Islands, 95-Sala-y-Gomez Island, 96-Easter Island and 97-Juan Fernandez). Of these 95 and 96 are similar except that Easter Island is much closer to the ridge of the East Pacific Rise. Newly proposed South American sites number only two (100-Paramaribo, Surinam and 103-La Plata, Argentina) as this area already has five existing facilities.

To the west of the Mid-Atlantic Ridge are 104 (Ascension Island) and 105 (Godthab, Greenland). Immediately on the eastern side of the Ridge is 117 (Hofn, Iceland).

No new sites are proposed for Europe, because of the large number of existing facilities.

Africa is of great importance in plate tectonic studies. One laser and one radio astronomy observatory already exist (110-Helwan, Egypt and 109-Johannesburg, South Africa). For the baselines discussed below, sites at Sidi Ifni, Morocco (106), Libreville, Gabon (107), Walvis Bay, Namibia (108), Mecca, Saudi Arabia (111), Nairobi, Kenya (112) and Malakal, Sudan (113) are appropriate.

Ankara, Turkey (114) may be a useful site in the Middle East.

In Asia only first order study of plate rigidity and plate motion is likely to result in the next decade. Six proposed sites are spread over the continental land mass. Four of these are in the Soviet Union (126-Nukus, 127-Krasnoyarsk, 128-Chita and 141-Cape Schmidt), one is in Tibet (129-Lhasa) and one (130) in either China (Shanghai) or Korea (Seoul). It remains questionable that all these locations will indeed be used as the tie points for the baselines described below, but if they do become available their contribution to understanding crustal deformation in Asia will be significant.

Heard Island (Australia) or Kerguelen Islands (French) (132) is a very important location in terms of the baselines described below.

One additional site in Australia, perhaps near Darwin (135) is desirable for minimum study of intraplate deformation of this continent as well as for plate motion study. Two stations, one on either side of the Alpine Fault in New Zealand are proposed (139-Auckland, 140-Dunedin).

Representative baselines connecting these stations and appropriate to the tectonic problems described above are shown on Figure 3b. Only a small sample of the possible or desirable baselines have been displayed. Many already existing ties between operating sites on separate continents are collected in "cluster-cluster baselines," where broad arrows indicate all the possible ties between existing sites on two separate plates. For example, the North American sites already involved in plate motion studies are Haystack (41), Green Bank (38), Goddard (39), Ft. Davis (33) and, in the near future, Richmond (43), Patrick Air Force Base (42) and Fairbanks (61). Baselines between these and corresponding European cluster stations (115-Madrid, 118-Kootwick and Westerbork, 119-Wetzel and Bonn, 120-Onsala, 122-Torun) are shown by broad grey (VLBI) or cross-hatched (laser) arrows, rather than as individual baselines. Stations in a so-called "cluster" may be recognized by the line-dash symbol connecting VLBI stations or laser stations. These baselines are themselves useful for intraplate deformation studies and are so defined in Figure 3b.

Atlantic Ocean

Baselines crossing the Mid-Atlantic Ridge, designated to show the motion of Europe and Africa with respect to North and South America, are many. In the North Atlantic, cluster baselines between North America and Europe were described above. In addition to these 35 or so baselines, we recommend the use of additional ties. For example, excellent geometry across the Mid-Atlantic spreading ridge is obtained with 66 (Churchill) to 115 (Madrid) and 119 (Wetzel or Bonn). Numerous other baselines likewise provide good geometry over the northern Mid-Atlantic Ridge, especially those from 105 (Godthab) to 120 (Onsala), 122 (Torun), 119 (Wetzel or Bonn) and 115 (Madrid). Likewise ties from Godthab (105) to almost any European site will provide the same information.

Intraplate deformation baselines in the Northern Atlantic and adjacent coasts are shown as dashed lines in Figure 3b. Of special importance here is Höfn, Iceland (117), which may be linked with any of the above described stations (115, 119, 120, or 122).

The Central Atlantic spreading and crustal deformation may be addressed by cluster baselines between South America and Europe (although the geometry is not optimum) and by baselines linking the eastern United States stations with Africa. For example,

43 (Richmond) to 106 (Sidi Ifni), 113 (Malakal) and 107 (Libreville)

41 (Haystack) to 106 (Sidi Ifni) and 107 (Libreville).

Other choices are of course possible between the two continents. The recommendations above maximize the geometry by having baselines nearly parallel to the transform fault direction; that is, the best baselines for <u>detecting</u> spreading-related motion are those perpendicular to the spreading axes. It is also desirable to seek components in other directions to investigate possible rotation of plates.

The South Atlantic is the classical area for plate tectonic theory, and motion between South America and Africe is addressed by baselines such as:

101 (Natal) to 106 (Sidi Ifni), 107 (Libreville), 108 (Walvis Bay) and 110 (Helwan)

102 (Sao Paulo) to 107 (Libreville) and 108 (Walvis Bay)

103 (La Plata) to 110 (Helwan), 107 (Libreville) and 108 (Walvis Bay).

The geometry varies greatly with respect to the spreading axis, so good determination of the rotational motion should be possible if observations are carried out over a long enough time base.

Most of the observations assume central and west Africa is a relatively rigid plate, but the dashed baselines between sites in Africa are designed to address this problem directly. A similar set of intraplate deformation baselines for South America is also shown in Figure 3b. If these plates indeed prove to be rigid to the level of measurement capability, then additional sites in the continental interiors can also be used to study the gross plate motions.

Aleutian Subduction Zone

A portion of this tectonic problem is addressed by cluster baselines: between Fairbanks (61) and the Pacific cluster stations Maui (90) and Kwajalein (136). Ranging to Marcus Island (137) would also be useful.

Pacific Plate - North American Plate

Baselines showing the relative motion between these two plates are also part of an existing larger cluster, between 90 (Maui) and stations in California (8-Goldstone, for example). The geometry here is not optimum, however, as the baseline crosses the plate boundary nearly perpendicular to the direction of motion. Futhermore, most of the California stations are very close to the plate boundary. Although not explicitly shown in Figure 3b, baselines connecting the Pacific stations 90 (Maui), 91 (Samoa), 92 (Marquesas or Tahiti), 136 (Kwajalein) and 137 (Wake Island) with interior North America sites (e.g., 33-Fort Davis, 19-Shelby, 66-Churchill, and 68-Prince Albert) might be the most appropriate choices. For some of these the baseline geometry is improved over the Maui-California tie; one such favorable line is from 92 (Marquesas) to 19 (Shelby) or 68 (Prince Albert).

Additional study of the East Pacific Rise and its associated spreading is provided by the baselines connecting Pacific stations with those on the Nazca Plate:

90 (Maui) to 93 (Galapagos), 97 (Juan Fernandez) and 95 (Sala-y-Gomez)

91 (Samoa) to 93 (Galapagos) and 95 (Sala-y-Gomez)

92 (Marquesas) to 96 (Easter) or 95 (Sala-y-Gomez) and 97 (Juan Fernandez).

Internal deformation within the Pacific Plate can be monitored with the baselines shown as dashed and dashed-lined lines in Figure 3b. That is, baselines connecting 90 (Maui), 91 (Samoa), 92 (Marquesas), 136 (Kwajalein), 137 (Wake Island), 70 (La Paz) and 1 (Otay Mountain) can be used to determine the rigidity of the plate.

Nazca Plate Subduction

The triangular distribution of stations 93 (Galapagos)-95 (Sala-y-Gomez)-97 (Juan Fernandez) provides measurements for intra-plate deformation on the Nazca Plate. The same stations, when tied to sites in South America, can be used to measure the convergence and subduction of the ocean plate along the Peru-Chile Trench. Because of possible deformation along the Andes it is also advisable to employ baselines reaching to the continental interior. Such recommended baselines include:

97 (Juan Fernandez) to 99 (Santiago) or 103 (La Plata) and to 102 (Sao Paulo)

95 (Sala-y-Gomez) to 98 (Arequipa), 101 (Natal) and possibly 102 (Sao Paulo)

93 (Galapagos) to 94 (Quito) or 101 (Natal).

These baselines provide samples both perpendicular to the plate boundary (along strike for the subduction) as well as at some angle to the subduction.

Intraplate deformation within South America may be monitored as shown by the dashed lines and dash-lined baselines in Figure 3b. The distribution of existing and proposed stations provides a good network for this study.

Davis Strait

The recommended baseline here is 66 (Churchill) to 105 (Godthab). Additional ties not shown in Figure 3b might include 67 (Algonquin) to 105 and 68 (Prince Albert) to 105.

Alpine-Himalayan System

Only a few of the possible baselines crossing this convergent zone are shown in Figure 3b. The 111 (Mecca) to 126 (Nukus) and 127 (Krasnoyarsk) and the 131 (India) to 126, 127 and 129 (Lhasa) are appropriate choices. The great complexity of the Alpine system in Europe makes selection of baselines difficult, and a denser network of stations may be required to unravel the crustal deformation in this area. In principle, 110 (Helwan) could become an important tie for several baselines into eastern Europe (e.g., 114-Ankara, 125-Crimea Radio Observatory, 124-Belgrade, 122-Torun).

Plate rigidity in Eurasia should also be studied, as shown by the dashed lines connecting stations at Onsala (120), Helsinki (121), Crimea (125), Nukus (126) and Krasnoyarsk (127).

Red Sea

Spreading in this newly opening ocean can be measured by baselines connecting 111 (Mecca) with 113 (Malakal) or 107 (Libreville), if the African Plate itself is rigid. In principle 111 to 106 (Sidi Ifni) is also a reasonable baseline but the geometry with respect to the spreading is not as favorable.

East African Rifts

A denser network than shown in Figure 3 is probably justified for this prototype continental rift structure. First order measurements are recommended between Nairobi (112) and 113 (Malakal).

Indian Ocean Tectonics

This large and complicated region requires a number of measurement baselines to address the variety of tectonic problems found here. Heard Island or the Kerguelen Islands (132) becomes a major tie point for many of the recommended baselines. Spreading across the SW Indian Ridge, or motion between the African Plate and the Antarctic Plate, uses the following:

132 (Heard) to 107 (Libreville), 108 (Walvis Bay) and 112 (Nairobi).

Relative motion between the Australian Plate and the Antarctic Plate measures spreading in the SE Indian Ridge as follows:

132 (Heard) to 133 (Yarragadee), 134 (Orroral) and 135 (Parkes).

The baseline 132 (Heard) to 131 (India) ties the motion of the Antarctic Plate to India.

Motion between Africa and Australia and between India and Africa is monitored with baselines such as:

112 (Nairobi) to 131 (India)

112 (Nairobi) to 133 (Yarragadee).

These as well as 108 (Walvis Bay) to 135 (Darwin) all cross the Carlsbad Ridge, providing data on the spreading there.

The line between 131 (India) and 133 (Yarragadee) crosses the Ninety-East Ridge and may provide measurements relevant to the question of whether or not this represents a plate boundary between India and Australia. The geometry is not ideal for determining motion, however.

Deformation within the Australian continent is well addressed by the triangular distribution of stations shown in Figure 3. Because many of the baselines described here are tied to sites in Australia, it is important to determine how rigidly this plate behaves.

Alpine Fault Zone

For simple first order measurements the baseline connecting 139 (Auckland) on North Island with 140 (Dunedin) on South Island provides good geometry along the Alpine Fault. Because of the geologic similarity to the San Andreas, it may be advisable to provide a more dense network that we have suggested.

Australian - SW Pacific Plate Boundary

Laser cluster baselines between Australia (133-Yarragadee and 134-Orroral) and the Pacific sites 90 (Maui), 91 (Samoa) and 136 (Kwajalein) form the basis for those measurements across the convergent boundaries. Additional lines we recommend include the ties from 134 (Orroral) to Wake (137) and Marquesas (92). All of these trend nearly perpendicular to the presumed plate boundary in this region, providing favorable geometry for measuring the relative motion of the Australian and Pacific Plates.

Baikal Rift

Extension in this isolated intra-continental rift is addressed by the 127 (Krasnoyarsk) to 128 (Chita) line.

Northeast Siberia

Measurement across the possible plate boundaries in this area of the world are provided by the baseline 127 (Krasnoyarsk) to 141 (Cape Schmidt).

ACKNOWLEDGEMENTS

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TABLE I

EXISTING AND PROPOSED VLBI AND LASER SITES

(Frey, Allenby and Lowman, August 1979)

SITE NO.	FIGURE NUMBER	LOCATION	ID	SYM	TYPE	REMARKS
1	1,2,3	CALIFORNIA, Otay Mountain	OTY	△	M	
2	1,2	CALIFORNIA, La Jolla	LAJ	□	M	
3	1,2	CALIFORNIA, San Clemente Island	SCI	○		
4	1,2	CALIFORNIA, Palos Verdes	PVS	□	M	
5	1,2	CALIFORNIA, Malibu	MAL	□	M	
6	1,2	CALIFORNIA, Pasadena (JPL)	JPL	□	M	
7	1,2	CALIFORNIA, Pearblossom	PRB	□	M	
8	1,2,3	CALIFORNIA, Goldstone	GDS	$\boxed{\triangle}$	F,M	□-Fixed; △- Mobile
9	1,2	CALIFORNIA, Vandenberg Air Force Base	VAN	○		
10	1,2	CALIFORNIA, Lake Isabella	LKI	○		
11	1,2,3	CALIFORNIA, Owens Valley	OVO	$\boxed{\triangle}$	F,M	□-Fixed; △- Mobile
12	1,2	CALIFORNIA, Monterey	MNT	○		
13	1,2	CALIFORNIA, San Francisco	SFO	□	M	
14	1,2	CALIFORNIA, Quincy (Hat Creek)	QCY	$\boxed{\triangle}$	M,M	
15	1,2	CALIFORNIA, Trinity County	TRC	○		
16	1,2	OREGON, Scottsburg	SCT	○		
17	1,2	WASHINGTON, Sequim	SQM	○		
18	1,2	WASHINGTON, Skykomish	SKY	○		
19	1,2	MONTANA, Shelby	SHL	○		
20	1,2	IDAHO, Lowman	LOW	○		
21	1,2	NEVADA, Tuscarora	TSC	○		
22	1,2	UTAH, Bear Lake	BLK	△	M	

SITE NO.	FIGURE NUMBER	LOCATION	ID	SYM	TYPE	REMARKS
23	1,2	WYOMING, Muddy Creek	MUD	○		
24	1,2	COLORADO, Ft. Morgan	FMR	○		
25	1,2	UTAH, Dirty Devil Creek	DRT	○		
26	1,2	NEVADA, Duckwater	DCK	○		
27	1,2	ARIZONA, Flagstaff	FLG	○		
28	1,2	ARIZONA, Tucson (Mt. Hopkins)	TUC	△	M	
29	1,2	NEW MEXICO, Magdalena (VLA)	VLA	□		Radio Observatory
30	1,2	NEW MEXICO, Chaco Canyon	CCN	○		
31	1,2	NEW MEXICO, Abbott	ABT	○		
32	1,2	NEW MEXICO, Roswell	ROS	○		
33	1,2,3	TEXAS, Fort Davis (McDonald Observatory)	FDS	□△	F,F	
34	1,2	KANSAS, Meades Ranch	MDR	○		
35	1,2	MISSOURI, Ironton	IRN	○		
36	1,2	KENTUCKY, Franklin	FRK	○		
37	1,2	ILLINOIS, Danville (Vermillion Observatory)	VRO	□		Radio Observatory
38	1,2,3	WEST VIRGINIA, Green Bank (Nat'l Radio Observatory)	GBK	□	F	
39	1,2,3	MARYLAND, Greenbelt (Goddard Space Flight Center)	LTF	△	F	STALAS
40	1,2	MARYLAND, Maryland Pt.	MDP	□		Radio Observatory
41	1,2,3	MASSACHUSETTS, Westford (Haystack)	HAY	□△	F,M	□-Fixed; △-Mobile
42	1,2,3	FLORIDA, Melbourne (Patrick Air Force Base)	PAT	△	F	
43	1,2,3	FLORIDA, Richmond	RCH	○□	F	
44	1,2,3	BERMUDA	BDA	△	M	

SITE NO.	FIXED NUMBER	LOCATION	ID	SYM	TYPE	REMARKS
60	2,3	ALASKA, Wiseman	WSM	○		
61	2,3	ALASKA, Fairbanks	FRB	□	F	
62	2	ALASKA, Fairwell	FRL	○		
63	2	ALASKA, Dillingham	DIL	○		
64	2	ALASKA, Seward	SWD	○		
65	2	ALASKA, Cordova	COR	○		
66	2,3	CANADA, Manitoba (Churchill)	CHR	○		
67	2,3	CANADA, Ontario (Algonquin)	ARO	□		Radio Observatory
68	2,3	CANADA, Saskatchewan (Prince Albert)	PRA	□		CTS Antenna
69	2,3	CANADA, British Columbia (Penticton)	PNT	□		Radio Observatory
70	2,3	MEXICO, Baja California (La Paz)	LPZ	○		
71	2,3	MEXICO, Simaloa (Mazatlan)	MAZ	○		
72	2,3	MEXICO, Vera Cruz (Vera Cruz)	VCZ	○		
73	2	MEXICO, Oaxaca (Oaxaca)	OXA	○		
74	2	BRITISH HONDURAS, Belmopan	BLM	○		
75	2	NICARAGUA, Waspan	WSP	○		
76	2	GRAND TURK ISLAND	GRT	$\boxed{\triangle}$	M,M	
77	2	PUERTO RICO, Arecibo	ARI	□	F	
78	2	NORTHERN ANTILLES, Antigua (St. Johns)	ANT	○		

SITE NO.	FIGURE NUMBER	LOCATION	ID	SYM	TYPE	REMARKS
90	3	HAWAII, Maui	MAU	$\boxed{\triangle}$	F,F?	△-Fixed; □- ?
91	3	SAMOA	SMA	△	M	
92	3	MARQUESAS ISLAND or TAHITI	MQS	○		
93	3	GALAPAGOS ISLANDS	GAL	○		
94	3	SOUTH AMERICA, Ecuador (Quito)	QUI	□	F	
95	3	SALA-Y-GOMEZ ISLAND	SYG	○		
96	3	EASTER ISLAND	ETR	○		Move to 95? △?
97	3	JUAN FERNANDEZ ISLAND	FRN	○		
98	3	SOUTH AMERICA, Peru (Arequipa)	ARE	△		
99	3	SOUTH AMERICA, Chile (Santiago)	AGO	□		
100	3	SURINAM, Paramaribo	PMO	○		
101	3	SOUTH AMERICA, Brazil (Natal)	NAT	△		
102	3	SOUTH AMERICA, Brazil (Sao Paulo)	SPO	□		
103	3	SOUTH AMERICA, Argentina (La Plata)	LAP	○		
104	3	ASCENSION ISLAND	ACN	○		
105	3	GREENLAND, Godthab	GDT	○		
106	3	AFRICA, Morocco (Sidi Ifni)	IFN	○		
107	3	AFRICA, Gabon (Libreville)	LBR	○		
108	3	AFRICA, Namibia (Walvis Bay)	WAL	○		
109	3	AFRICA, South Africa (Johannesburg)	JOH	□		Radio Observatory
110	3	AFRICA, Egypt (Helwan)	HEL	△	F	
111	3	SAUDI ARABIA, Mecca	MEC	○		
112	3	AFRICA, Kenya (Nairobi)	NAI	○		
113	3	AFRICA, Sudan (Malakal)	MLK	○		
114	3	TURKEY, Ankara	ANK	○		
115	3	SPAIN, Madrid	MAD	$\boxed{\triangle}$	F,M	□-Fixed; △-Mobile

SITE NO	FIGURE NUMBER	LOCATION	ID	SYM	TYPE	REMARKS
116	3	ENGLAND, Chilbolton or Jodrell Bank	CHL	□		Radio Observatory
117	3	ICELAND, Hofn	HOF	○		
118	3	NETHERLANDS, Kootwick or Westerbork	KTW	⧋	F,F	△-Kootwick; □-Westerbork
119	3	GERMANY, Wetzel and Bonn	WET	⧋	F,F,	△-Wetzel; □-Bonn
120	3	SWEDEN, Onsala	ONS	□	F	
121	3	FINLAND, Helsinki	HLS	□	F	
122	3	POLAND, Torun	TRN	□		Radio Observatory
123	3	ITALY, Bologna	BLO	□		Radio Observatory
124	3	YUGOSLAVIA, Belgrade	BEL	□		Radio Observatory
125	3	USSR, Crimea Radio Observatory	CRO	□		Radio Observatory
126	3	USSR, Southern (Nukus)	NUK	○		
127	3	USSR, Eastern (Krasnoyarsk)	KRS	○		
128	3	USSR, Asiatic (Chita)	CHT	○		
129	3	TIBET, Lhasa	LHS	○		
130	3	CHINA, Shanghai or KOREA, Seoul	SHA	○		
131	3	INDIA	IND	△		
132	3	HEARD ISLAND or KERGUELEN	HRD	○		
133	3	AUSTRALIA, Yarragadee	YAR	△	M	
134	3	AUSTRALIA, Orroral and Parkes	PRK	⧋	F,F	△-Orroral; □-Parkes
135	3	AUSTRALIA, Darwin	DAR	○		
136	3	KWAJALEIN	KWJ	⧋	F,M	□-Fixed; △-Mobile
137	3	WAKE or MARCUS ISLAND	WKE	○		
138	3	JAPAN, Kashima	KSH	□	F	
139	3	NEW ZEALAND, North Island, Auckland	AUK	○		
140	3	NEW ZEALAND, South Island, Dunedin	DUN	○		
141	3	USSR, Siberia (Cape Schmidt)	SCH	○		

NOTES:

□ VLBI SITE

△ LASER SITE

⧈ VLBI & LASER SITE

F = FIXED SITE

○ PROPOSED VLBI OR LASER SITE

◎ PROPOSED VLBI SITE

◬ PROPOSED LASER SITE

M = MOBILE SITE

FIGURE CAPTIONS

Figure 1a: Tectonic map of U.S., from U.S. National Atlas, with physiographic provinces and recommended or existing VLBI and laser ranging sites superimposed.

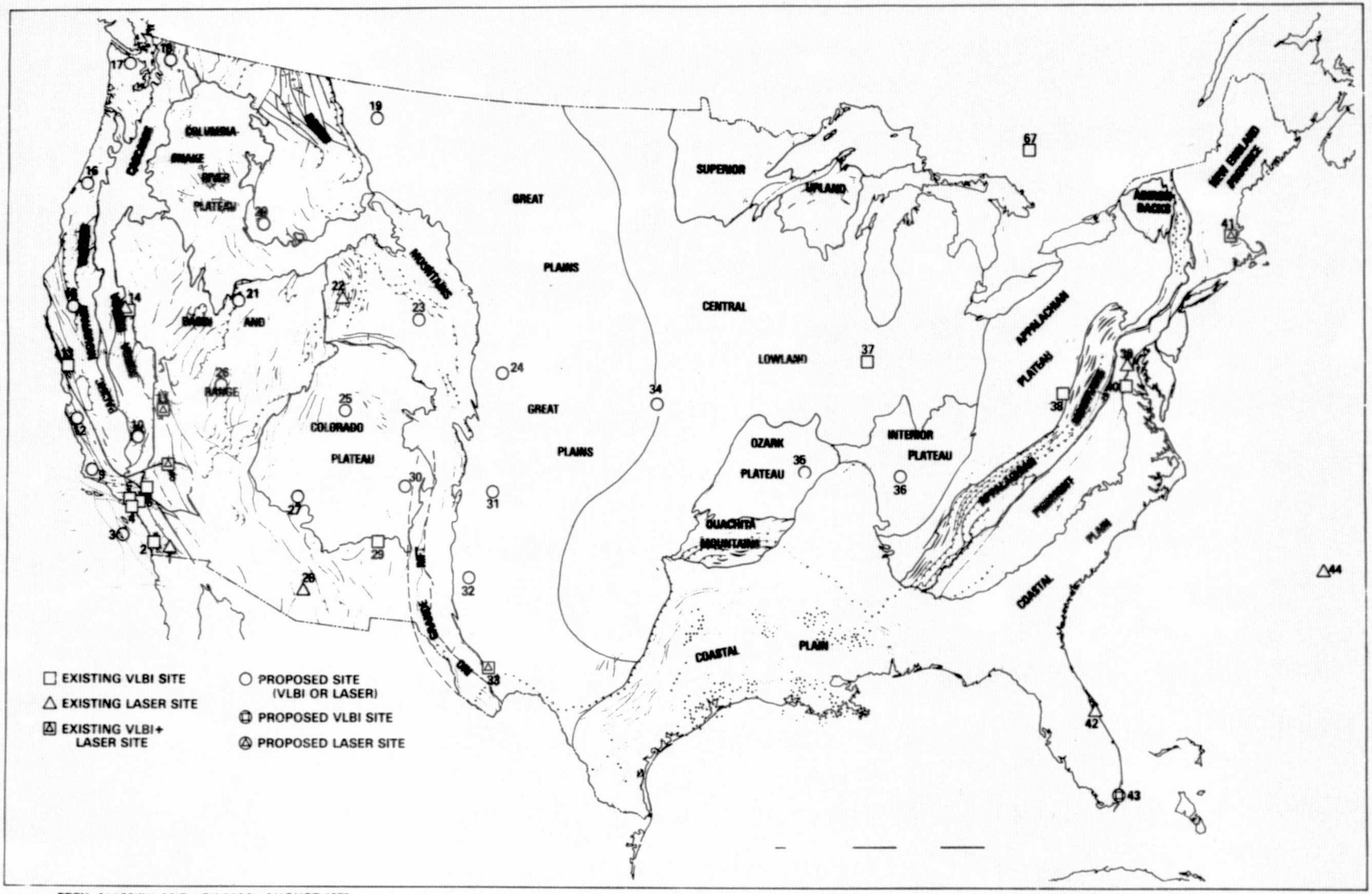
Figure 1b: Tectonic map of U.S., as in Figure 1a, with recommended or existing sites and representative baselines superimposed.

Figure 2: Tectonic map of North America (P.B. King and G.J. Edmonston, U.S. Geological Survey Map I-688, 1972), with recommended or existing sites superimposed.

Figure 3a: Tectonic activity map of the world, showing tectonic features active now or within the last one million years, with recommended or existing sites superimposed.

Figure 3b: Tectonic activity map, as in Figure 3a, with sites and representative baselines superimposed.

CRUSTAL DYNAMICS PROJECT - U.S. VLBI/LASER SITES



FREY, ALLENBY AND LOWMAN, AUGUST 1979

Figure 1a

CRUSTAL DYNAMICS PROJECT - U.S. VLBI/LASER SITES
REPRESENTATIVE U.S. BASELINES

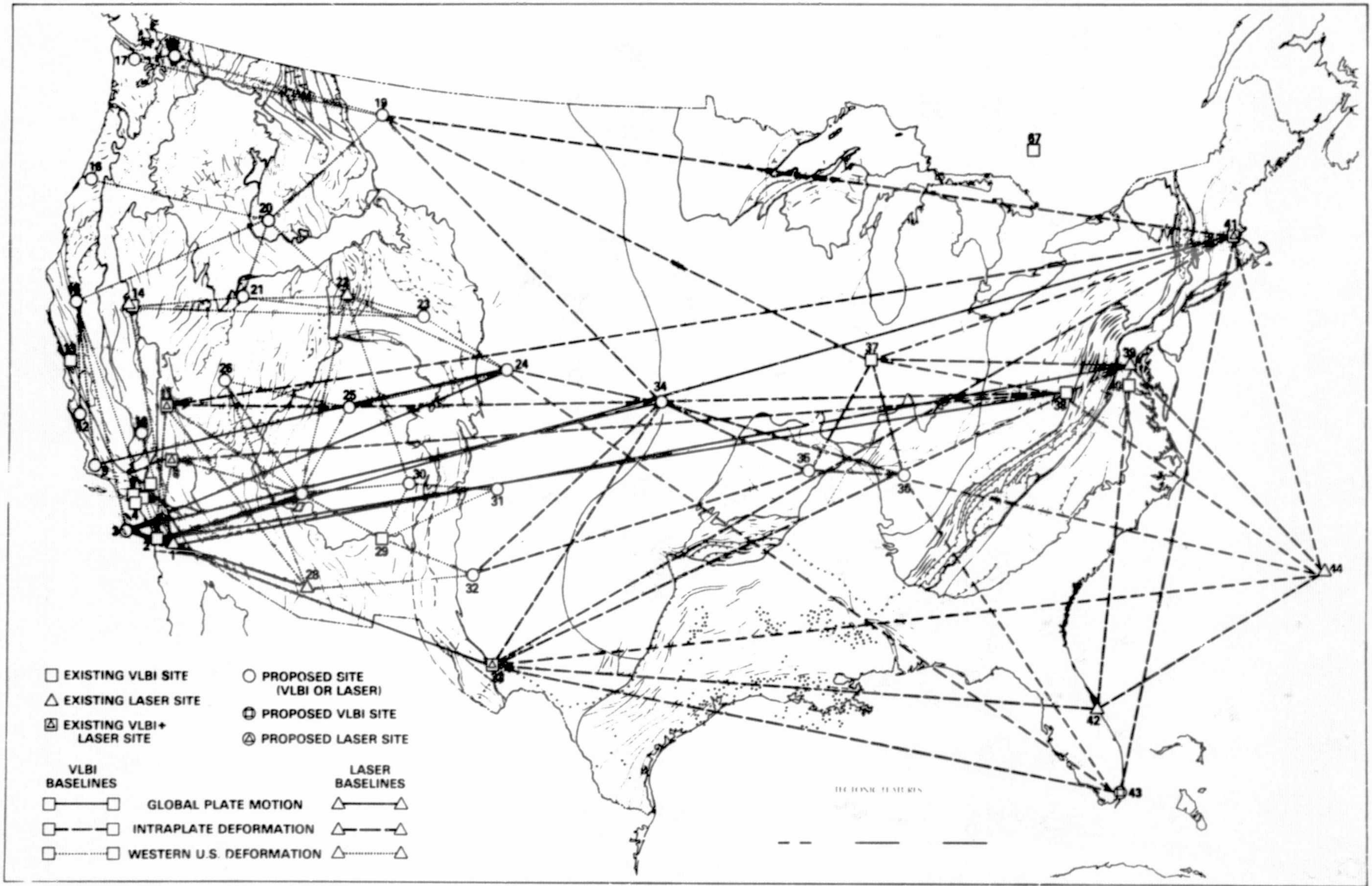


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Figure 1b

CRUSTAL DYNAMICS PROJECT - NORTH AMERICAN VLBI/LASER SITES

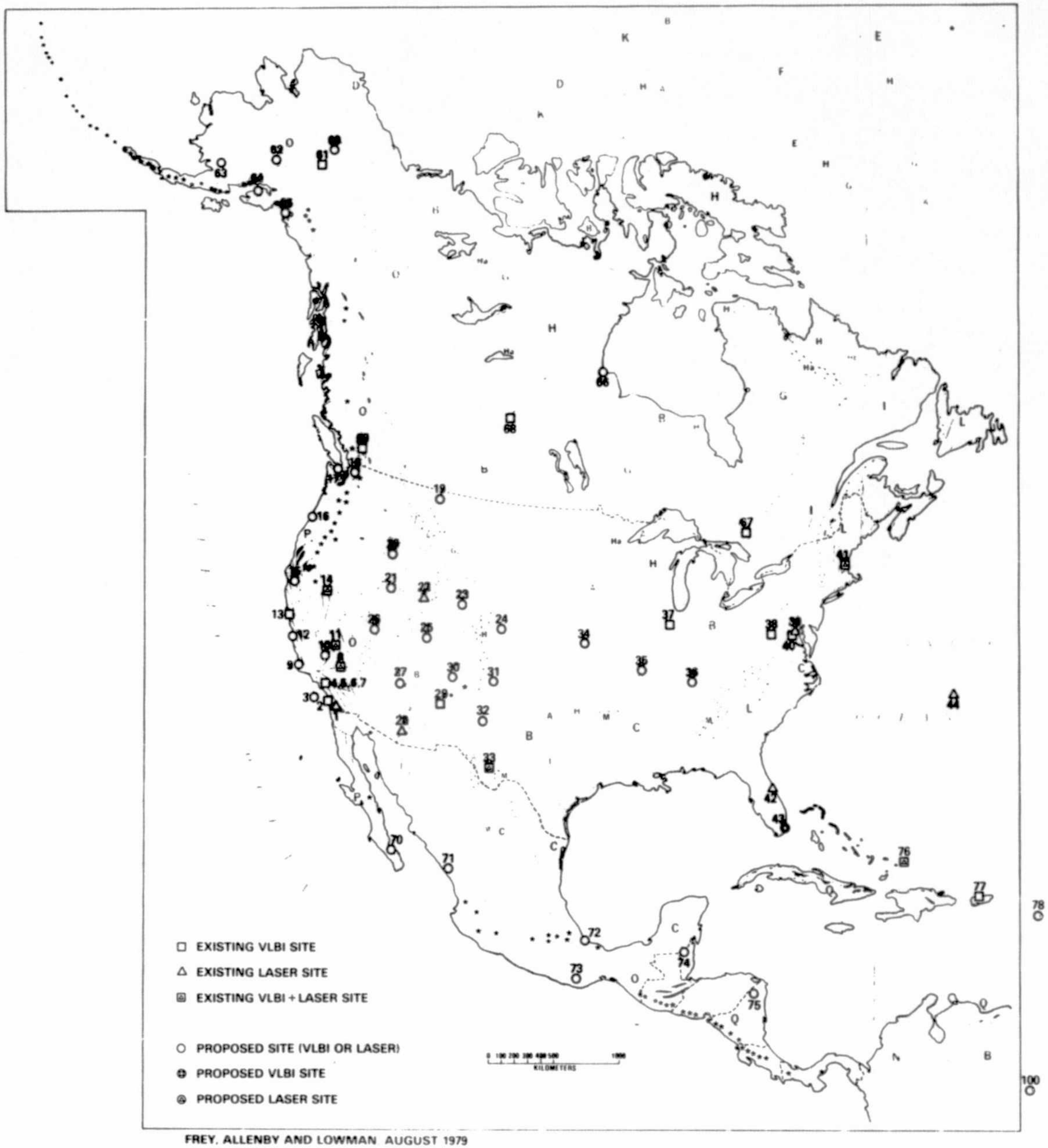

Figure 2

CRUSTAL DYNAMICS PROJECT - GLOBAL VLBI/LASER SITES

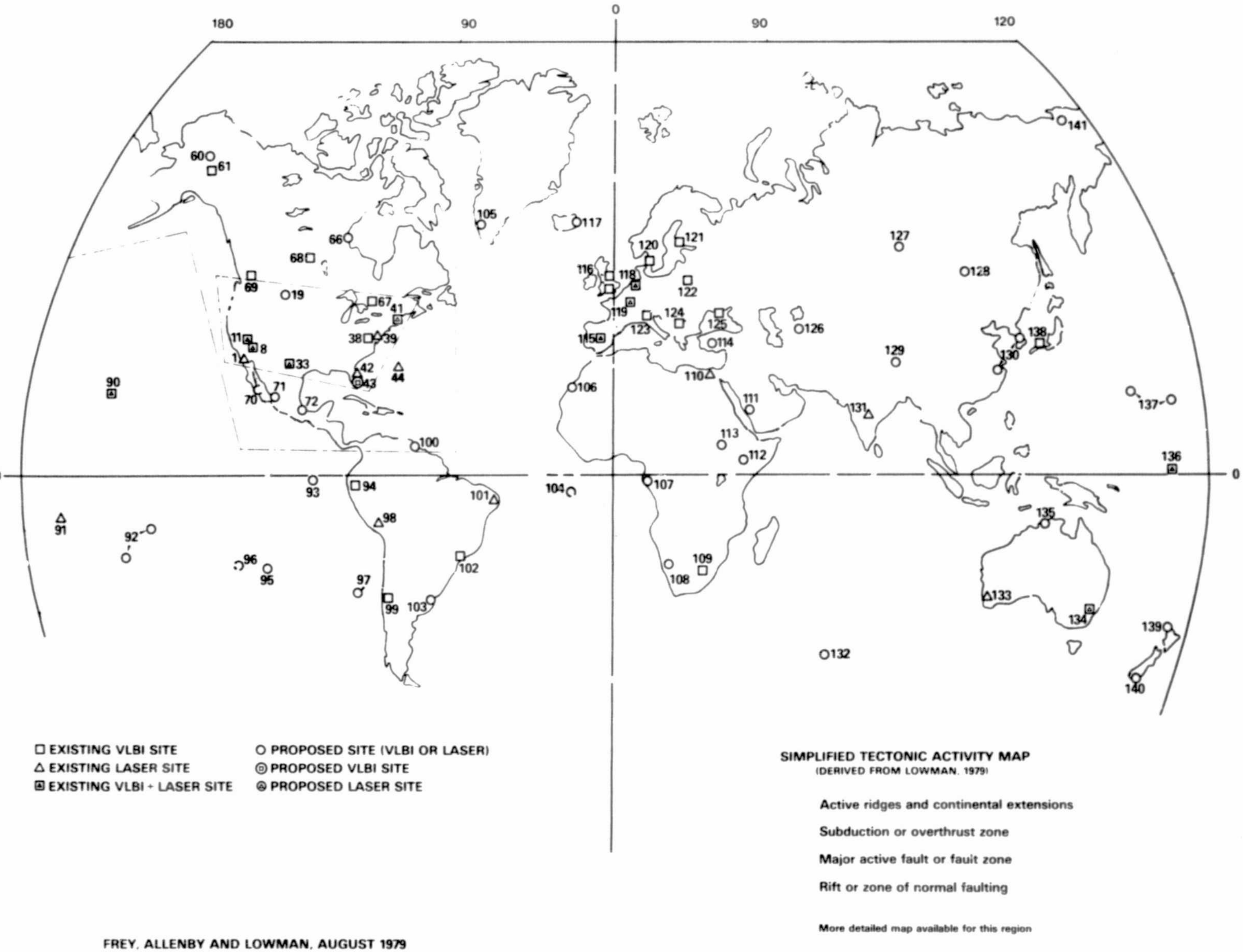

Figure 3a

CRUSTAL DYNAMICS PROJECT - GLOBAL VLBI/LASER SITES
REPRESENTATIVE GLOBAL BASELINES

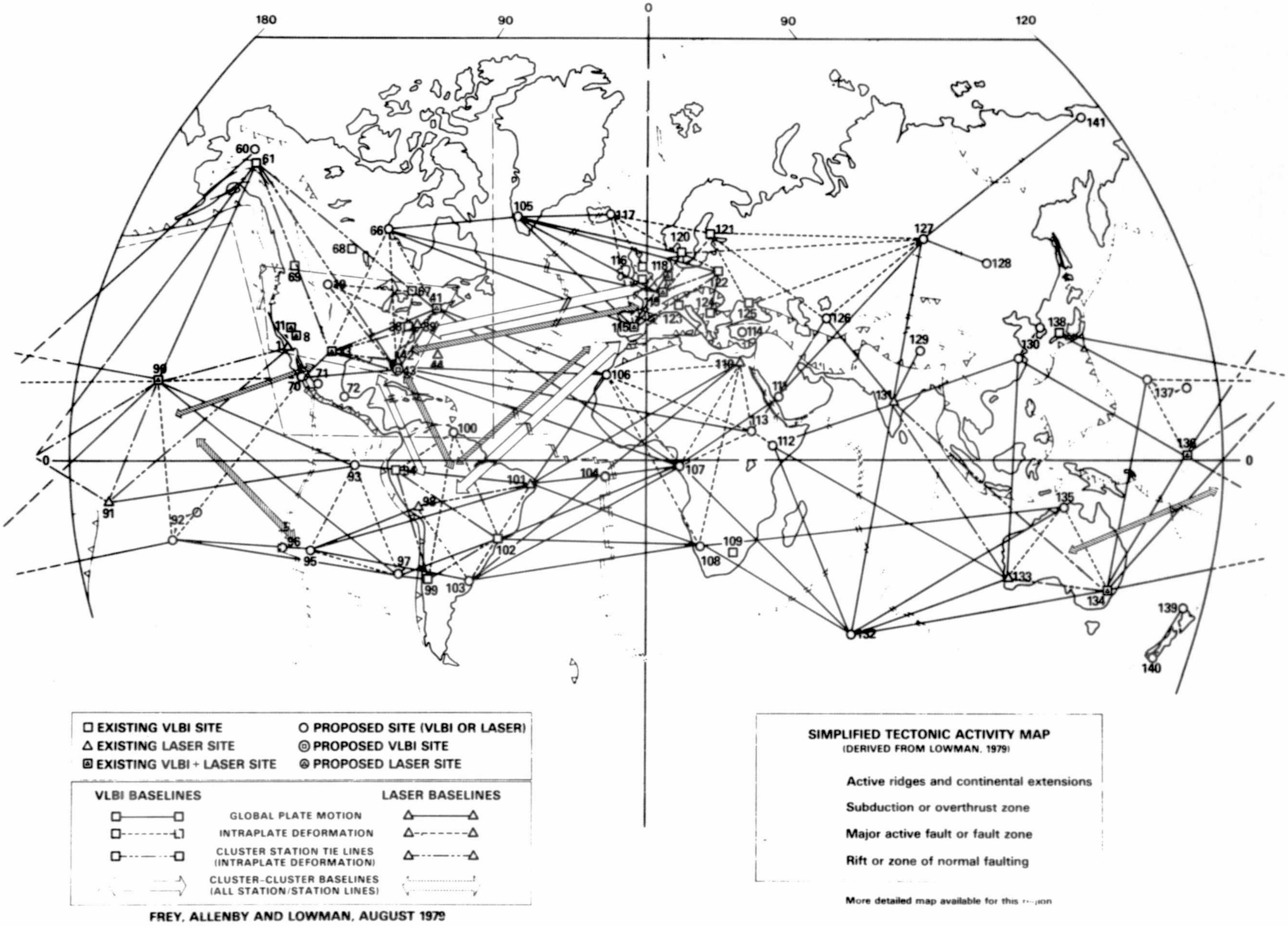

Figure 3b