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# IMPLICATIONS OF VERY LONG BASELINE INTERFEROMETRY MEASUREMENTS ON NORTH AMERICAN INTRA-PLATE CRUSTAL DEFORMATION

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## ABSTRACT

Very Long Baseline Interferometry experiments over the last 1-3/4 years between Owens Valley, CA and Haystack, MA Radio Observatories suggest an upper limit of east-west crustal deformation between the two sites of 1 cm/yr over a distance of almost 4,000 km. In view of the fact that the baseline between the two sites traverses most of the major geological provinces of the United States, this low ceiling on the rate of crustal deformation has direct relevance to intra-plate crustal tectonics. The most active region traversed by this baseline is the Basin and Range province,which has been estimated by various researchers to be expanding in an east-west direction at rates of .3 to 1.5 cm/year. The Colorado Plateau and Rocky Mountain system also appear to be expanding, but at a somewhat lower rate. East of the Rocky Mountains, while the stress field is complex and not well understood, the predominant stress appears to be compressional, nearly horizontal, and east to northeast trending.

Possible explanations for this low rate of change of distance between the two VLBI observatories are:.

1. The North American Plate, as assumed by continental drift theory, is perfectly rigid.

2. The North American Plate is sufficiently elastic to absorb intra-plate regional tectonic motions but, overall, behaves as a nearly rigid plate.

3. Intra-plate crustal motions are episodic and this is a quiet period.

4. Motions in the various geologic provinces counteract one another.

While the available data are not sufficient to resolve the above explanations, it is suggested that the last one is the most plausible explanation and that opposing motions between various geological provinces do exceed the 1 cm/yr. limit.

## INTRODUCTION

Very Long Baseline Interferometry (VLBI) is a passive technique of utilizing celestial radio sources to locate accurately two radio telescopes separated by distances ranging from hundreds of meters to thousands of kilometers. The energy sources, usually extra-galactic quasars, are tape recorded at both sites and cross-correlated at a later time. A very accurate determination of the baseline vector between the two sites is achieved, since the time delay of the cross-correlation is dependent upon the position of the quasar relative to the two antennas and the distance separating the two sites. Details of the procedures can be found in Coates et al. (1975) and Ryan et al. (1979a).

Of the baseline components determined by VLBI, baseline length is more accurately determined than baseline direction because it is invariant under rotation (Shapiro et al., 1974) and not sensitive to errors in the Earth's orientation with respect to the radio source (primarily variations in rotation rate and polar motion). For this reason, this paper addresses only baseline length measurements and not direction.

Robertson et al. (1979) describe a series of VLBI experiments, beginning in September 1976, to determine the baseline between the Haystack Radio Observatory near Boston, MA and the Owens Valley Radio Observatory near Bishop, CA. The results of 21 months of experimentation are shown in Figure 1. The root-mean-square deviation about the weighted mean (rms) of single experiment baseline length values was originally about 7 cm. If the source coordinates are determined by the weighted mean of the 14 solutions and the baseline length determined from the mean coordinates, the rms scatter is reduced to about 4 cm.

Analysis of these data show that, to an accuracy of about 1 cm/yr, the baseline length did not appear to change (Ryan, 1979b). In other words, in a roughly east-west direction, the total intra-plate motion across central North American appears to be less than 1 cm/yr over the period of observations.

## DISCUSSION

Morgan (1968) pointed out that implicit in the concept of continental drift is the acceptance that all crustal blocks are perfectly rigid. That this concept is not applicable at the local level is well illustrated by the many regional tectonically active areas in the interiors of the various plates. However, there is not yet sufficient data to determine if the individual plates, as entire units, behave as rigid bodies.

The approximate trace of the almost 4,000 km baseline between the observing sites is shown in Figure 2. From the west it begins by crossing the active seismic zones of the Basin and Range Province in Nevada and Utah and the Intermountain Seismic Belt which marks the border between the Basin and Range and Colorado Plateau Provinces. The eastern terminus is near Boston, MA in the New England Province. The purpose of this paper is to examine broadly the tectonic activities expected in the various geologic provinces constituting the interior of the North American continent and assess the expected motions in light of the VLBI results. Obviously the crustal motions that will have greatest relative impact on changes in baseline length are local motions in the immediate vicinity of either receiver. In the central area of the U.S., at considerable distance from either observatory, shallow crustal disturbances may be insignificant. However, motions along major structural features, especially those extending down to, or into, the upper mantle, must be considered, particularly those that occur in the vicinity of the baseline.

Owens Valley, CA is located near the Nevada border approximately 300 km east of the San Andreas Fault system, well-removed from the active Pacific Plate margin. The site is within the Owens Valley Fault zone, but, as this is a left lateral fault trending roughly north-south, major motions along this system should have little or no affect on an east-west baseline. Continual local seismic observations of this complex system are being carried out, monitoring for small scale, localized motions around the observatory.

To the east of Owens Valley is the Basin and Range Province which, because of its active seismicity and close proximity to the observatory should presumably have the most impact on the baseline. This Province, which is laced with active, normal faults trending north or north-northwest, consists of sculptured, partially buried fault-bound blocks produced by crustal expansion during late Cenozoic time. It is an area of high heat flow, thin crust, low top-of-mantle seismic velocity and widespread volcanism, and is similar to other areas of active normal faulting such as the Rift Valleys of Africa or the Rhine Graben of Europe (Thompson and Burke, 1974). Thompson and Burke (1973) concluded that for the last 15 MY Dixie Valley, Nevada has been spreading in a N55$^{o}$W direction at an average rate of at least 0.4 mm/yr and for the last 12,000 years at an average rate of 1 mm/yr. Extrapolating this rate over the whole breadth of the Basin and Range Province suggests a total spreading of about 100 km (a 10% increase in crustal area), equivalent to an average motion of .7 cm/yr. This is in agreement with Gilluly (1970) who postulated a 7% to 16% increase in the original area in a nearly east-west direction. Likewise Stewart (1971) concluded that most of the expansion occurred over the last 17 MY or less at a rate of 0.3 to 1.5 cm/yr in predominately an E-W direction.

Further evidence of crustal extension in this region is presented by Davis and Burchfiel (1973) for the Garlock Fault, which they characterize as a major strike-slip fault with left-lateral displacement of at least 48 to 64 km. They believe this fault, which separates the Tehachapi-Sierra Nevada and Basin and Range from the Mojave Desert, is an intracontinental transform structure separating a northern crustal block distended by late Cenozoic Basin and Range faulting from a southern Mojave block much less affected by dilational tectonics. The westward extension of the northern block has been taken up by the westward bend of the San Andreas fault north of the junction of the two faults.

East of the Basin and Range the tectonics become more complex. The boundary between the Basin and Range and Colorado Plateau is a major crustal discontinuity that penetrates the upper mantle. In central Arizona, a seismic-refraction survey across the boundary indicates an abrupt increase of about 4 km in depth of the M (Moho) discontinuity as it passes under the Colorado Plateau (Warren, 1969). Similarly, Keller et al. (1975) and Smith et al. (1975) analyzed seismic refraction results along the western border of the Colorado Plateau in the region where the VLBI baseline crosses it. The thin Basin and Range crust of (about 25 km thick) increases to a thicker crust (approximately 40 km thick) under the Colorado Plateau. The transition zone along the front appears to consist of a mantle upwarp at least 50 km wide and extending at least 300 km N-S along the contact. Braile et al. (1974) detected this same zone further north along the Basin and Range/Middle Rocky Mountains contact. This zone coincides with a portion of the N-S trending Intermountain Seismic Belt investigated by Sbar et al. (1972). From studies of earthquakes in this region, they concluded that tectonic activity in the Rocky Mountain Province is sporadic and may vary considerably with time. In the Middle Rocky Mountains they identified normal faulting accompanying crustal expansion in an E-W direction. In central Utah, along the junction of the Basin and Range and Colorado Plateau, more nearly vertical motions occur on steeply dipping fault planes, possibly as a result of differential motion between the two Provinces.

Further seismic refraction evidence of rapid changes in crustal thickness was presented by Jackson and Pakiser (1965). Along the eastern edge of the Southern Rocky Mountain Province crustal thickness decreased from approximately 55 km to 40 km when going north from Colorado into Wyoming.

The southeast edge of the Colorado Plateau is bounded by the Rio Grande Rift--a N-S trending, horst and graben structure averaging about 150 km in width and extending from south-central Colorado, across central New Mexico and possibly into Mexico and Texas. Chapin and Seager (1975) describe this rift as "a 'pull-apart' structure caused by tensional fragmentation of western North America." The latest cycle of extension began about 29 MY ago with accelerated movement occurring 9 or 10 MY ago. Recent fault scarps (Chapin and Seager, 1975), abnormally high heat flow (Cook et al., 1978), and upwarping of the upper mantle (McCullar and Smithson, 1977) indicate that expansion is still continuing at an undetermined rate that is slower than during the Miocene/Pliocene acceleration.

Tectonics east of the Rocky Mountains are complex and not well understood because of the masking effects of recent surface sedimentation and relatively low levels of seismicity. However, it is clear that rifting of the continental crust during the last 1.5 to 1.6 MY has been important in the development of this area (Hinze et al., 1977). The general stress currently appears to be largely compressional, nearly horizontal and east to northeast trending (Sbar and Sykes, 1973). Such motion would counteract movements further west. 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 was complex with a single regional stress field not being applicable. In either case, in view of this area's lower seismicity, rates of motion should be less than in the provinces further west.

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). Fletcher et al. (1978) further point out that 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. Hence, their locations may be governed by deep-seated structures with, perhaps, lower crust or upper mantle expression. In respect to large tectonic features that might, at present, constitute areas of renewed crustal movements, in Iowa the VLBI baseline crosses the mid-continent gravity high, a major structural feature that, according to Burke and Dewey (1973), originated about 1,100 MY ago as a short lived, plume-generated triple junction. One arm of this feature progresses southwest from the west end of Lake Superior, one arm trends north into Canada, and one arm progesses southeast across the Michigan Basin (which the baseline also crosses). At present this structure consists of a deep-seated rift zone 50 to 100 km wide filled with basalts and intrusives of higher density than the host rocks (Chase and Gilmer, 1973). These areas are nearly aseismic, so any present motion probably is in the form of small scale aseismic creep.

The most active seismic area in the central U.S. is the Missouri, Arkansas, Tennessee and Kentucky area around New Madrid, MO., where one of North America's strongest earthquake series occurred in 1811 and 1812. The area is still active. 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 NW. 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 (Mitchell et al., 1977).

The baseline passes well north of New Madrid, and there is no evidence that horizontal motions in the New Madrid area affect the baseline distance between the observatories. However, the New Madrid area may be just the most active section along a much longer active tectonic trend. Fletcher et al. (1978) suggest that New Madrid may be part of a major fracture zone extending to the Gulf of Mexico and marking an ancient suture zone associated with the opening of the Gulf. Woollard (1969), among others, proposes that New Madrid is the southern anchor point of a seismically active tectonic zone extending NE to the St. Lawrence River Valley. The actual baseline crosses this proposed active zone in the Attica area of western New York, which is an area of low level seismicity.

A different viewpoint on the New Madrid area is presented by Heyl (1972) who identifies this area as the western end of an east trending zone of nearly continuous faults and intrusions, roughly following the 38th parallel of latitude from northern Virginia. He classifies this zone as a right-lateral wrench-fault extending deep into the crust and possibly the continental equivalent of the great oceanic fracture zones such as the Mendocino and the Kelvin.

The eastern most intra-plate seismic region that may influence the length of the baseline is the Appalachian seismic zone trending NE along the Appalachian Mountains and into the New England coastal area. Bollinger (1973) identified such a zone extending SW from Maryland to Central Alabama in the Valley and Ridge and Blue Ridge Provinces. Earthquake epicenters indicate this active zone continues NE into New England (Woollard, 1969). Gwinn (1964) argues that most of the folding in the central Appalachians is surficial and does not involve the deep basement rocks, so this zone may not extend deep into the crust.

Brown and Oliver (1976) analyzed existing eastern U.S. leveling data and identified large vertical motions apparently associated with recent tectonic structures. These motions are much larger than the average rates over the past 130 MY and are either episodic or oscillatory about long term trends. 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.

The Haystack Observatory is on the SW edge of an active NW trending seismic zone extending from Boston to NW of Ottawa. This zone may represent the landward extension of the Kelvin seamount chain (Sbar and Sykes, 1973). Seismic travel time residual anomalies in this area reveal a high velocity residual that extends at least into the upper mantle and that may be associated with an ancient suture zone (Fletcher et al., 1978). The proximity of this zone to the observing station makes it likely that even small, surficial crustal motions associated with this zone could impact the baseline length. For this reason seismic monitoring at this observatory is being carried out.

## SUMMARY

The Owens Valley-Haystack VLBI measurements place an upper limit on E-W crustal distance variations across central North America of less than 1 cm/yr. This rate appears to be on the low side in view of the many active tectonic areas traversed. The Owens Valley observatory is on the western edge of the seismically active Basin and Range Province which appears to be expanding in an E-W direction at a rate of .3 to 1.5 cm/yr.

The contact between the Basin and Range and the western edge of the Colorado Plateau is a major crustal break extending at least into the upper portion of the mantle. Extensional motion along these high angle normal faults is suggested by the coincidence of the zone with the Intermountain Seismic Belt. The N-S trending Rio Grande Rift may also be experiencing continued expansion.

Tectonics east of the Rocky Mountains are not well understood. The stress patterns are complex and have changed with geological time. In general, the present stress appears to be horizontal and compressional in generally an E-W direction. Strain release seems to be guided along older, unhealed crustal discontinuities. In this region several postulated N-S trending major features that could influence the baseline length are the Mid-continent gravity high, the St. Lawrence River-New Madrid seismic trend, and the Appalachian seismic zone. Motion may also be occurring along the E-W trending 38th parallel lineament and the Kelvin seamount-Boston-Ottawa seismic zone. Indeed, Lidiak et al. (1978) have listed more than 20 rifts in the central and eastern mid-continent, exclusive of late Precambrian and Triassic grabens. While seismicity in the eastern U.S. is much less than in the western U.S., eastern earthquakes in general appear to coincide with existing faults and are accompanied by motions along these faults. York and Oliver (1976) have found direct geological evidence of intra-plate eastern U.S. fault motion in Cretaceous and Cenozoic times, after the opening of the Atlantic Ocean.

## CONCLUSIONS

There are several possible explanations for the observed consistency of the VLBI baseline length.

1. The North American Plate behaves as a truly rigid body. This explanation is nearly impossible to support in view of the observed geological evidence of significant regional crustal activities and motions.

2. The North American Plate is sufficiently elastic to absorb regional crustal motions, but still behaves overall as a nearly rigid plate with continuous, ongoing motion of less than 1 cm/yr. In view of the width and length of

these active zones and the fact that many extend down to or into the upper mantle, it is hard to reconcile such behavior. These data would also seem to mitigate against continental motions being controlled by edge forces such as mid-ocean ridge expansion or subduction zone gravity pulling. A more reasonable explanation for continental drift would be frictional transfer of motion into the base of the crust from horizontal motions at the top of large mantle convection cells.

3. Intra-plate crustal motions are episodic and the VLBI measurements have occurred during a quiet time.

4. Motions in the various provinces are in different directions and tend to cancel one another.

The available data are not sufficient to favor either of the latter two possible explanations. The frequency of occurrence of North American Plate earthquakes does not indicate that we are presently in a particularly aseismic period, and it would be unusual if the individual provinces were all aseismic at the same time. The evidence, therefore, appears to favor the hypothesis that scalar horizontal intra-plate motions are greater than 1 cm/yr, but that the motions of the various provinces are in sufficient opposition to keep the total trans-continental motion to less than 1 cm/yr. Continued observations between the two observatories will extend the observing period and determine the present day rates of motion. Geodetic observations at further select intra-plate locations, using other fixed observatories or portable laser or VLBI systems, are under consideration and will obviously be required to help unravel the complex tectonics within the North American Plate.

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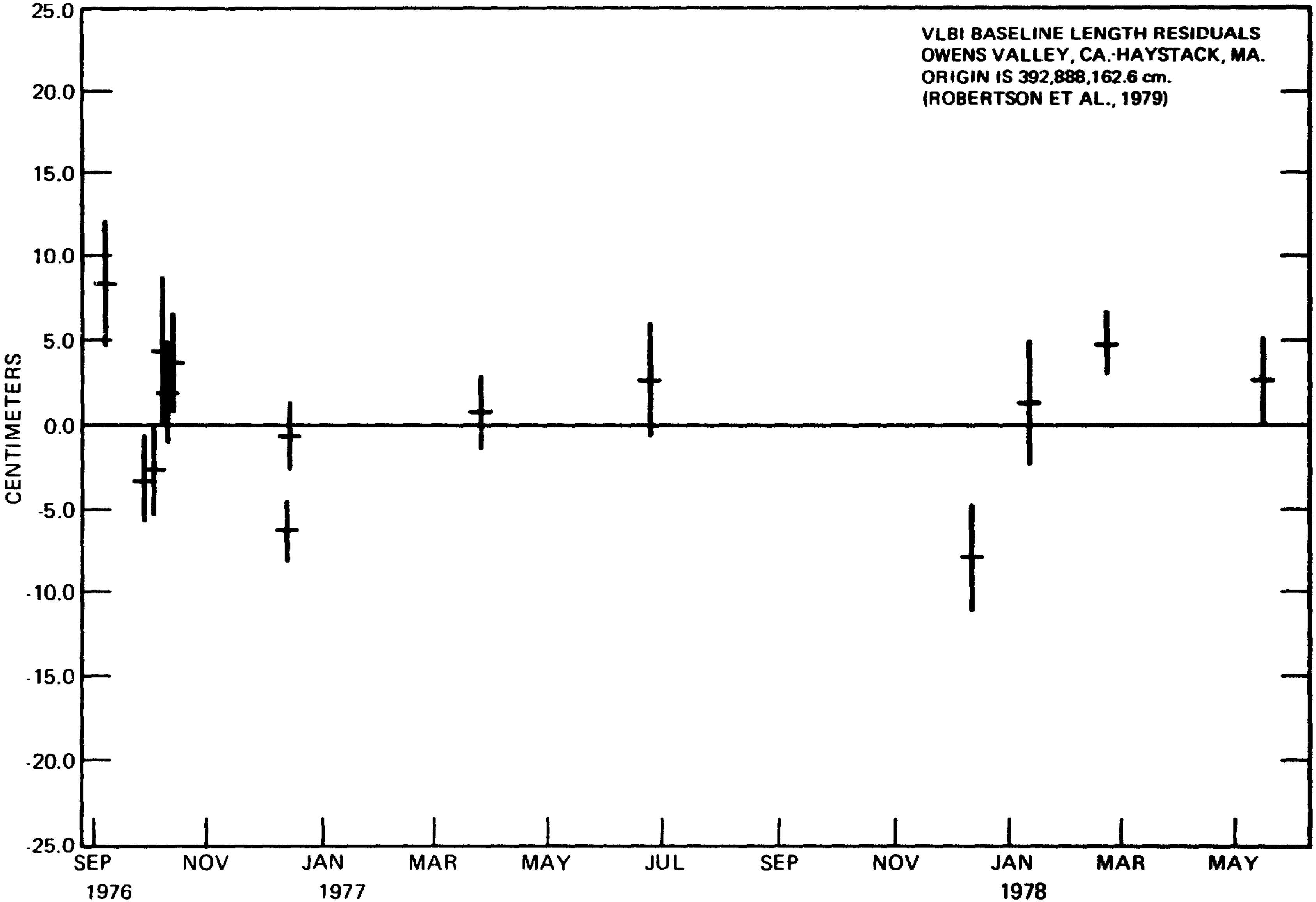
## FIGURE CAPTIONS

Figure 1: VLBI determined baseline lengths between Owens Valley, CA and Haystack, MA. Each source coordinate is kept fixed at the same value for all analyses. Weighted mean is 392,888,162.6 cm (from Robertson et al., 1979).

Figure 2: Major physiographic provinces of the United States and the approximate trace of the baseline between Owens Valley, CA and Haystack, MA.


VLBI BASELINE LENGTH RESIDUALS
OWENS VALLEY, CA.-HAYSTACK, MA.
ORIGIN IS 392,888,162.6 cm.
(ROBERTSON ET AL., 1979)
CENTIMETERS
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
SEP
NOV
JAN
MAR
MAY
JUL
SEP
NOV
JAN
MAR
MAY
1976
1977
1978


**VLBI BASELINE**
**OWENS VALLEY, CA. - HAYSTACK, MA.**