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Seismic Evidence for Partial Lithospheric Delamination Model of Colorado Plateau Uplift

Lynda A. Lastowka[1] and Anne F. Sheehan[1]

University of Colorado, Boulder, Colorado

Jeffrey M. Schneider[2]

Enterprise Oil, Houston, Texas

Abstract. The lithospheric structure beneath the Colorado Plateau and Great Basin of the western United States is investigated using Pn and surface wave data from the Colorado Plateau – Great Basin broadband seismic experiment. Average Pn velocities of 8.0 km/s in the Colorado Plateau and 7.8 km/s in the eastern Great Basin are found. Teleseismic Rayleigh waves are also measured, and eastern Great Basin phase velocities are found to be 3-4% higher than Colorado Plateau phase velocities in the 20-35 s range, but indistinguishable at periods greater than 40 s. The apparent Pn/surface wave discrepancy is resolved with models that include a thicker crust and faster mantle lid for the Colorado Plateau than the eastern Great Basin. Models for both regions require a mantle low velocity zone. The slow mantle deep beneath the Colorado Plateau may suggest a thermal origin of Plateau uplift, which has not yet penetrated the mantle lid.

Introduction

The Great Basin and Colorado Plateau of the western United States are tectonically and physiographically distinctive provinces. Many outstanding questions remain concerning the high present day elevation of both the Colorado Plateau and Great Basin and the lack of deformation of the Colorado Plateau relative to the Great Basin and the adjacent Rocky Mountains. Models to explain the high elevation of the Colorado Plateau include crustal thickening and thermal expansion due to magmatic injection at the base of the crust [*Morgan and Swanberg*, 1985], mid-crustal flow from the Sevier hinterland into the Proto-Colorado Plateau [*McQuarrie and Chase*, 2000], or partial lithospheric delamination [*Beghoul and Barazangi*, 1989; *Spencer*, 1996].

Geophysical studies of the Colorado Plateau indicate moderate surface heat flow [*Bodell and Chapman*, 1982], crustal thickness ranging from 40-48 km [*Roller*, 1965; *Keller et al.*, 1976, 1979; *Sheehan et al.*, 1997; *Wolf and Cipar, 1996*], lower crustal and upper mantle seismicity [*Wong and Humphrey*, 1989], and upper mantle seismic velocities that range from slow [*Roller et al., 1965*] to normal [*Beghoul and Barazangi*, 1989]. The eastern Great Basin is characterized by areas of 100-200% extension, fault bounded mountain ranges, sedimentary basins, and Cenozoic volcanics. Previous studies show that the eastern Great Basin has thin crust [*Smith et al.*, 1989], high heat flow [*Morgan and Gosnold*, 1989], and slow upper mantle velocities [*Priestley and Brune*, 1978; *Keller et al.*, 1976].

In this study, the crustal and upper mantle structure of the Northern Colorado Plateau and eastern Great Basin are investigated using surface wave and Pn travel time data acquired by the Colorado Plateau - Great Basin (CPGB) PASSCAL experiment. Details of the CPGB deployment are given by *Jones* [1996] and *Sheehan et al.* [1997].

Surface Waves

The CPGB surface wave data set offers enhanced coverage over previous surface wave studies in the region. Rayleigh wave phase velocity measurements are made using the two-station (inter-station) technique [e.g., *Aki and Richards*, 1980]. A total of 41 Rayleigh wave inter-station phase

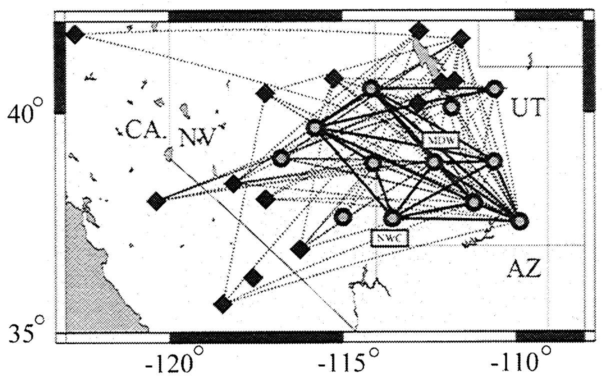

Fig. 1: Station locations and path coverage. Colorado Plateau - Great Basin PASSCAL seismic experiment stations shown as gray circles. USNSN stations used in Pn study shown as white diamonds. The solid paths were used in the inter-station surface wave study and the dotted paths were used in the inter-station Pn study. Paths between the five southeastern most stations were used for Colorado Plateau inter-station paths. The path between stations NWC and MDW is considered a TZ path. TZ also sample the eastern Great Basin and Colorado Plateau.

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[1] CIRES and Department of Geological Sciences, University of Colorado at Boulder, Boulder, CO.

[2] Enterprise Oil Services Inc., Houston, TX

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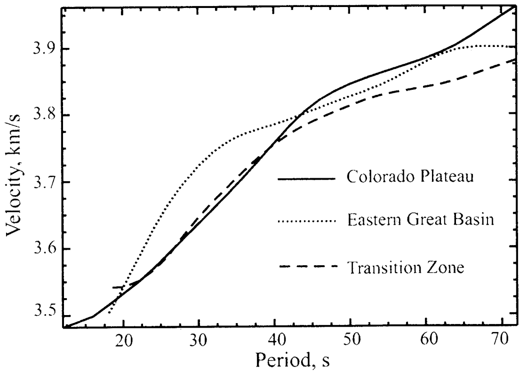

Fig. 2: Average Rayleigh wave phase velocity dispersion curves for the Colorado Plateau, eastern Great Basin, and TZ. Uncertainties are approximately ± 0.08 km/s.

velocity dispersion curves calculated from stations and sources within three degrees of being on the same great circle path were used in this study. The earthquakes used range from Mw 5.8 to 8.0, and were mostly from the southwest Pacific, the north Pacific, and Central America. Based on inter-station paths, curves were grouped into the eastern Great Basin (14 paths), the Colorado Plateau (19 paths), or the Transition Zone (TZ) between the two provinces (8 paths). An additional dispersion curve from the eastern Great Basin from *Sheehan* [1984] was added to the study. Paths measured are shown in Figure 1. To test the accuracy of the measurements, dispersion curves for paths with multiple measurements were compared, yielding agreement within 0.1 km/s.

Phase velocity dispersion curves for each province are obtained by averaging the suite of measurements over paths within the individual provinces Composite phase velocity curves for each province are shown in Figure 2. A comparison of the phase velocity curves shows that eastern Great Basin phase velocities are approximately 3% faster than Colorado Plateau phase velocities in the 20-35 s range, but are nearly indistinguishable from Colorado Plateau phase velocities at periods greater than 40 s. This result is consistent with thinner crust in the eastern Great Basin relative to the Colorado Plateau as indicated by previous studies. The standard deviation of the curves is approximately 0.08 km/s (~2%).

Pn velocities

Pn travel times provide constraint on the velocity structure of the mantle lid. Seismograms were collected from 101 events at epicentral distances from 250 to 1580 km from the CPGB stations. Most of the Pn arrivals came from southwest and northwest azimuths (California-Nevada border, Baja, and the California Coast) but there were also some events available from the north and northeast (Idaho and Idaho-Wyoming border). Unfortunately, there is little available seismicity from the east and southeast. Only events that contained a clear Pn arrival were selected using a waveform cross-correlation technique.

A two-station method was used to obtain inter-station Pn velocities [e.g. *Beghoul and Barazangi*, 1989]. Stations and sources that were within three degrees of being on the same great circle path were used. By using an inter-station technique, source mislocation effects are reduced. A total of 77 inter-station velocity measurements from 43 different events were used for final analysis (Figure 1).

Best fitting composite Colorado Plateau, Great Basin, and Transition Zone (TZ) Pn velocities were determined by a damped least squares inversion. In this study, the TZ is defined as the region approximately 100 km wide that separates the Colorado Plateau and eastern Great Basin, roughly centered on the Wasatch front. The portion of the inter-station paths east of the TZ are considered to be Colorado Plateau and the portions of the paths west of the TZ are eastern Great Basin.

Regional Pn velocities are 8.0 km/s for the Colorado Plateau, 7.8 km/s for the Great Basin, and 7.6 km/s for the TZ. The uncertainty in the velocities due to estimates in the travel times is .01 km/s. The results obtained for the Colorado Plateau are broadly consistent with those from the ISC data set used by *Beghoul and Barazangi* [1989].

Velocity Models

Inversions of the phase velocity data alone nearly always provide an excellent fit to the data, but without formulating a joint or constrained inversion, do not take into account any *a priori* knowledge of Earth structure. Therefore, in order to include constraints such as upper mantle velocity (from Pn), sediment thickness (from active source studies), and crustal thickness (from receiver functions), forward modeling was performed. Synthetic dispersion curves are calculated for a given Earth model following the methods of *Taylor* [1980] and *Rodi* [1975]. Since Rayleigh wave dispersion is most sensitive to variations in shear wave velocity, shear wave velocities and layer thicknesses are the only parameters treated independently in our modeling. Compressional velocities are calculated using assumed values of Poisson's ratio and densities are calculated from an empirical relationship between compressional velocity and density [*Berteussen*, 1977; *Ludwig et al.*, 1970].

Thickness and velocity of the sediment layer were held constant for all models. Sensitivity tests by *Schneider* [1997] show that an average sediment thickness of 1.5 km provides the best fit to the surface wave data in both the eastern Great

Table 1a – Colorado Plateau Model

Depth (km)	P velocity (km/s)	S velocity (km/s)	Density (kg/m^3)
0-1.5	3.7	2.1	1900
1.5-13.5	6.1	3.4	2700
13.5-42	6.7	3.8	2900
42-62	8.0	4.4	3300
62-102	7.5	4.2	3200
102-122	7.9	4.4	3300
122-	8.1	4.5	3400

Table 1b - Eastern Great Basin Model

Depth (km)	P velocity (km/s)	S velocity (km/s)	Density (kg/m^3)
0-1.5	3.7	2.1	1900
1.5-9	6.3	3.6	2800
9-35	6.7	3.8	2900
35-55	7.8	4.3	3200
55-95	7.5	4.2	3200
95-115	7.8	4.3	3300
115-	7.9	4.4	3300

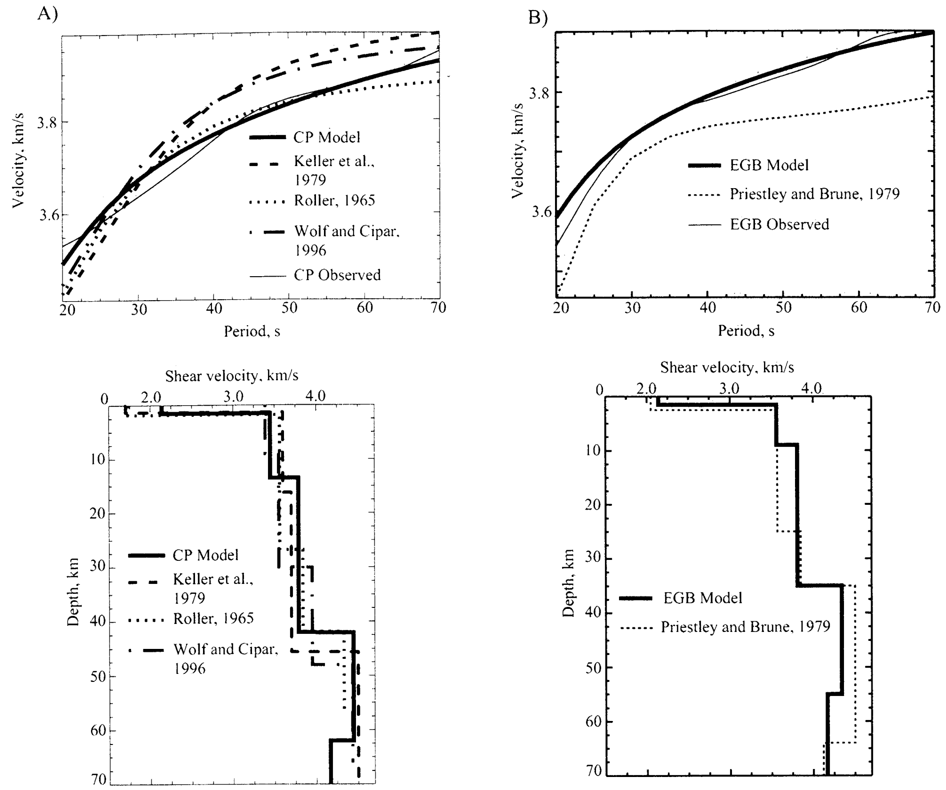

Fig. 3: The observed and modeled dispersion curves for a) the Colorado Plateau (CP) and b) the eastern Great Basin (EGB) along with our preferred model for each region. Other published models are shown for comparison. Models from refraction studies [*Roller*, 1965; *Wolf and Cipar*, 1996] converted to S-wave models using the scaling relationships used in this study.

Basin and Colorado Plateau, with sediment velocity Vp = 3.7 km/s and Vs = 2.1 km/s [*Benz et al.*, 1990; *Roller, 1965*; *Keller et al.*, 1979]. Crustal thickness values are held fixed for each tectonic province (42 km in the Colorado Plateau and 35 km in the eastern Great Basin) [*Sheehan et al.*, 1997]. The crustal Vp/Vs chosen is 1.77, consistent with the global crustal average [*Christensen*, 1996]. The velocity of the mantle lid is also held constant, using the values obtained from the Pn study presented here and assuming a Vp/Vs of 1.8. This value was chosen because Vp/Vs increases with increased pressure (depth) and mafic mineral content [*Christensen*, 1996, *Zandt, et al.*, 1995]. Comparison of our Pn results with the published Sn velocity tomography of *Nolet et al.* [1998] suggests an upper mantle Vp/Vs of 1.77 beneath the eastern Great Basin and 1.8 under the Colorado Plateau.

Our preferred seismic velocity model for the Colorado Plateau and the eastern Great Basin are shown in Table 1 and Figure 3. Our preferred model for each region is one that minimizes the misfit to the surface wave dispersion while also fitting the Pn velocity and crustal thickness constraints. After fitting these constraints it becomes apparent that a low velocity zone (Vs = 4.2 km/s) beneath a 20 km thick mantle lid is needed to fit the data.

Uplift of the Colorado Plateau

The thin crust and slow mantle velocities found for the Great Basin are characteristic of extensional regimes. However, the high elevations of the Colorado Plateau remain enigmatic. The seismic velocity models presented here allow us to assess the feasibility of various Colorado Plateau uplift mechanisms. *Morgan and Swanberg* [1985] presented a plateau uplift model with thermal expansion and magmatic crustal thickening, based on a relatively thick crust and a slow Pn velocity. This is inconsistent with a normal Pn velocity of 8.0 km/s and an apparently thin crust. Xenolith evidence presented by *Mattie et al.*, [1997] and *Condie and Selverstone*, [1999] implies there is not substantial magmatic underplating beneath the Colorado Plateau, which is consistent with out findings.

McQuarrie and Chase [2000] argue for intracrustal flow as a method for raising the Colorado Plateau and suggest that the crust is sufficiently thick to isostatically support the Plateau's current elevation. Following *Lachenbruch and Morgan* [1990], and using average crustal thickness and density values (41 km and 2853 kg/m^3, (*Christensen and Mooney*, [1995]) we calculated what mantle contribution to elevation is needed to produce the mean continental elevation of .825 km (*Turcotte and Shubert*, [1982]). Using this calculated typical mantle contribution and our crustal model of the Colorado Plateau results in an elevation of 1.5 km. This shows that a mantle with above average buoyancy is needed to support the Plateau's elevation of 2 km.

Uplift models involving delamination of the base of the mantle lithosphere (*Beghoul and Barazangi*, [1989]; *Spencer* [1996]) produce the mantle buoyancy needed for Colorado Plateau uplift while predicting a seismic velocity structure consistent with our Pn and surface wave observations. In the Spencer model, the lower 120-km of a 200-km lithosphere, (interpreted to be the Farallon slab), and a portion of the mantle lithosphere are delaminated at 30 Ma. We favor this model because it predicts a normal Pn velocity, preserves the petrologic signatures of the upper mantle, and also predicts asthenospheric material at depths consistent with the low velocity zone in our Colorado Plateau seismic model.

Conclusions

Seismic velocity models consistent with surface wave, Pn, and receiver function constraints are constructed for the eastern Great Basin and northern Colorado Plateau. The eastern Great Basin has a 35 km thick crust and a mantle lid velocity of 7.8 km/s, the Colorado Plateau has a 42 km thick crust and a mantle lid velocity of 8.0 km/s. We find that the source of the buoyancy may lie 20 km beneath the Moho as expressed by a low velocity zone. Our results support the lithospheric delamination hypothesis of *Spencer* [1996] for Colorado Plateau uplift. This model is consistent with the location of the mantle seismic low velocity zone in our Colorado Plateau velocity model, the normal mantle lid velocities that we find for the Colorado Plateau, as well as the low heat flow and deep seismicity of the Colorado Plateau.

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L.A. Lastowka, A. F. Sheehan, CIRES and Department of Geological Sciences, CB 399, University of Colorado at Boulder, Boulder, CO 80309 (email: lastowka@terra.colorado.edu)

J.M. Schneider, Enterprise Oil Services, Inc., Texaco Heritage Plaza, Suite 1800, 1111 Bagby, Houston, TX, 77002

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