Tilting of the Great Plains

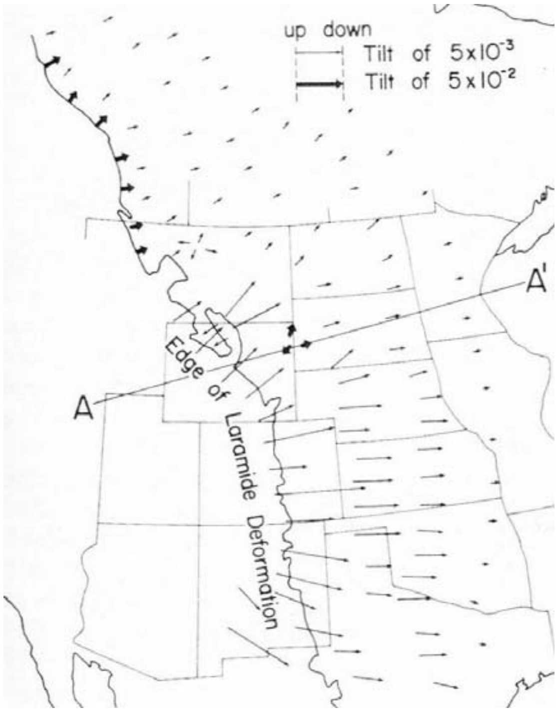

Fig 1: The tilting of the Great Plains spans the continent from central Texas to northern Alberta (from a 1989 paper by Jerry Mitrovica, Christopher Beaumont and Gerry Jarvis).

The tilting of the Great Plains up to the Rockies is a subject that has long fascinated geologists. For example, here in Alpine the top of the Cretaceous Formation is about 3,500 feet above sea level, at Kent 4,640 feet and near El Paso, 4,700 feet. Meanwhile, the same horizon at Killeen in central Texas is about 800 feet above sea level. I use the top of this formation because at the time it was created, around 80 million years ago, it was slightly under the sea level at the time. Sea levels were higher in the Cretaceous period but only by a few hundred feet, so the uplift towards the Rockies took place sometime in the last 80 million years. The same phenomenon is found all the way up the Great Plains into Canada as shown in the map above by Mitrovica, Beaumont and Jarvis.

Tectonics Background

The uplift is bound up with the tectonics of the western United States and the following two pages give some background in tectonics for those unfamiliar with the subject. Tectonics deals with the broad architecture of the outer part of the earth, particularly the movement of continental and oceanic plates and the effects of their contact and collisions on the structure of the crust.

The great discovery in earth science in the twentieth century was of plate tectonics. By a combination of surveying of the ocean floor for submarine warfare purposes and improved analysis of earthquake shock waves, it was discovered that the Earth's outer layer, the *lithosphere*, is divided into a number of *plates*, 6 large and at least 14 small ones, that move

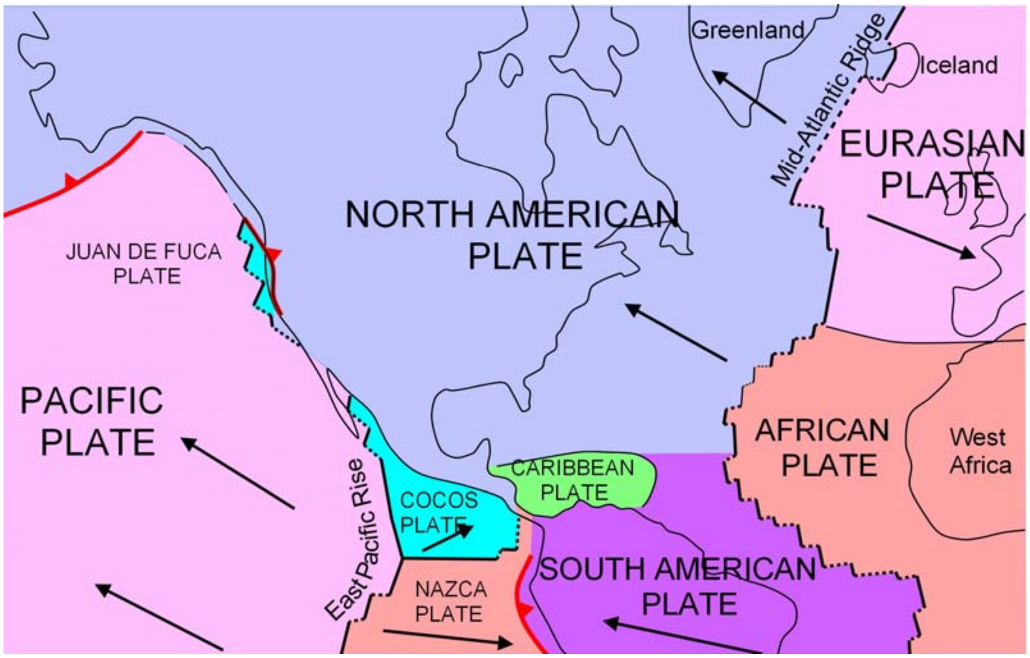

Fig. 2: The North American plate is bounded on the west by the Juan de Fuca and Cocos remnants of the Farallon plate, and the Pacific plate. The latter intersected the North American plate about 29 Ma. The red lines are present-day subduction zones with barbs showing the direction of subduction. Ridges are shown as solid black lines, transform faults as dotted black lines. Black arrowed lines show the direction of plate travel today (adapted from Windley).

slowly around the planet at rates of up to several inches per year. New lithosphere is generated at *spreading centers* in mid-ocean ridges such as the mid-Atlantic Ridge. These ridges circumnavigate the entire globe, 300 to 600 miles wide, and standing up from 6,500 to 10,000 feet above the neighboring ocean basins. They are made up of segments connected by transform faults in a zigzag fashion. In a transform fault, rocks on either side of the fault slide past each other horizontally.

Since the earth is not expanding, the newly created crust is accommodated by plates overriding one another at what are called *subduction zones*, in which the oldest and coldest plate is subducted under the other at roughly 45 degrees, creating enormous stresses, earthquakes and volcanism as it does so.

The lithosphere is rigid with a thickness that is proportional to its age; as it gets older it thickens. Under the oceans, its average thickness is about 40 miles, under continents, 70 to 90 miles. It is underlain by the much weaker *asthenosphere*, which reacts to stress like a fluid, and extends down to a depth of 280 miles.

The upper part of the lithosphere is called the Earth's *crust*. It can be oceanic or continental. Oceanic crust underlies the oceans and is 5 miles thick on average. Continental crust, which makes up the continents, is rather less dense than oceanic crust and is 12-40 miles thick, the thicker parts lying under large mountain ranges such as the Andes. Seismic waves change speed at the base of the crust, a surface called the Mohorovicic discontinuity or *Moho*, after its discoverer. Most plates are made up of both oceanic and continental crust.

The North American plate includes North America plus about half of the north Atlantic (Fig. 2). On its east, it meets the Eurasian and African plates at the mid-Atlantic ridge. On its west, it began overriding the Farallon plate in a subduction zone at 175 million years ago (Ma).

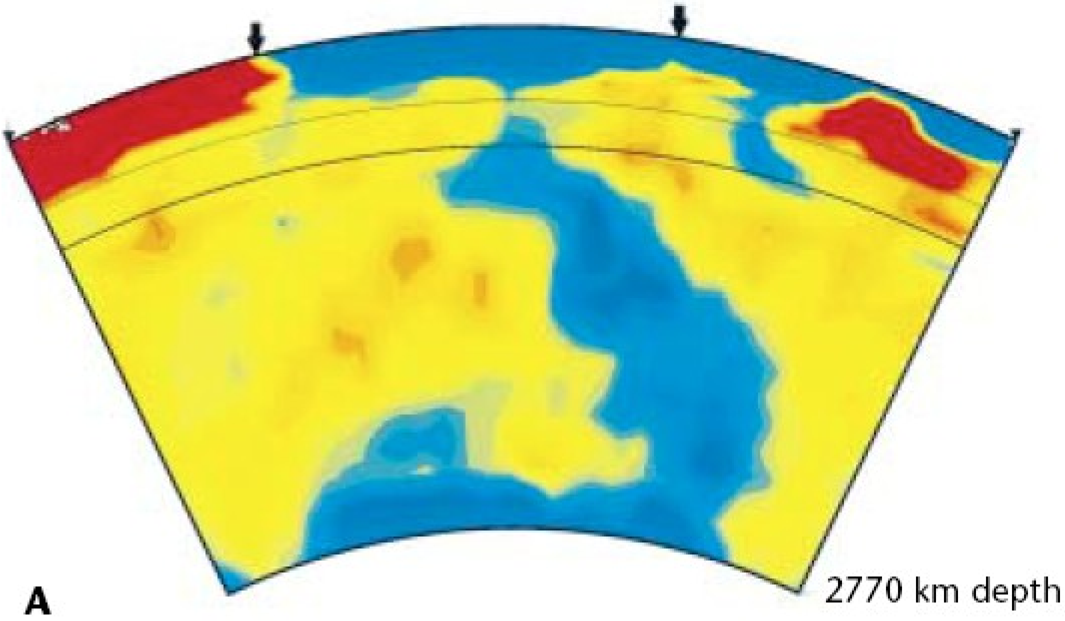

Fig. 3: In this cross-section of the earth's structure down to the core at 2,770 kilometers (1,700 miles), blue areas are those in which shock waves travel faster than normal, red areas are where they travel slower than usual. Blue areas are interpreted as ones that are colder than usual, red area hotter (from Grande 1997).

At 29 Ma, the trailing edge of this plate, the East Pacific Rise spreading center, collided with the North American plate and subduction ended on the west coast south of San Francisco. Only fragments of the Farallon plate remain on the surface, the Cocos and Juan de Fuca plates, but in a breakthrough resulting from increased computer processing power, images of the plate dangling below North America were produced for the first time in 1997 by a method known as seismic tomography (Figure 3). In this method, waves generated by earthquakes are detected by sensors throughout the world, and the speed and distance they have traveled can be computed. The above image shows a section of the earth's outer layers across North America from 30.1°N, 117.1°W to 30.2°N, 56.4°W. In the Alpine area, the section crosses Highway 118 about 25 miles south of town.

The blue area sloping diagonally to the right is thought to be the remains of the Farallon Plate. Its upper part is midway in the section, about Mobile, Alabama. Its base is 700 miles east of Jacksonville, Florida, southeast of Bermuda. The base is farther east because the North American plate moved west northwest over the Farallon plate since subduction began 140 million years ago. The left arrow on the diagram, which marks the boundary on the surface between hot material to the west and cold material to the east, is at about 103.7°W, i.e. about 14 miles west of Highway 118, and the red bulge below maxes out at 101.2°W, on the Devil's River north of Comstock and just west of Del Rio. Alpine is therefore also on the hot-cold boundary.

Most of the tectonic activity in western North America over the past 150 million years is now attributed to the Farallon plate subduction. This first showed up in the Rocky Mountain area as a mountain-building episode or *orogeny*. Although two names are used, the Sevier and Laramide Orogenies were really one continuous episode that created fold and thrust belts from Utah east to Colorado and from Canada south into Mexico as shown in Figure 4.

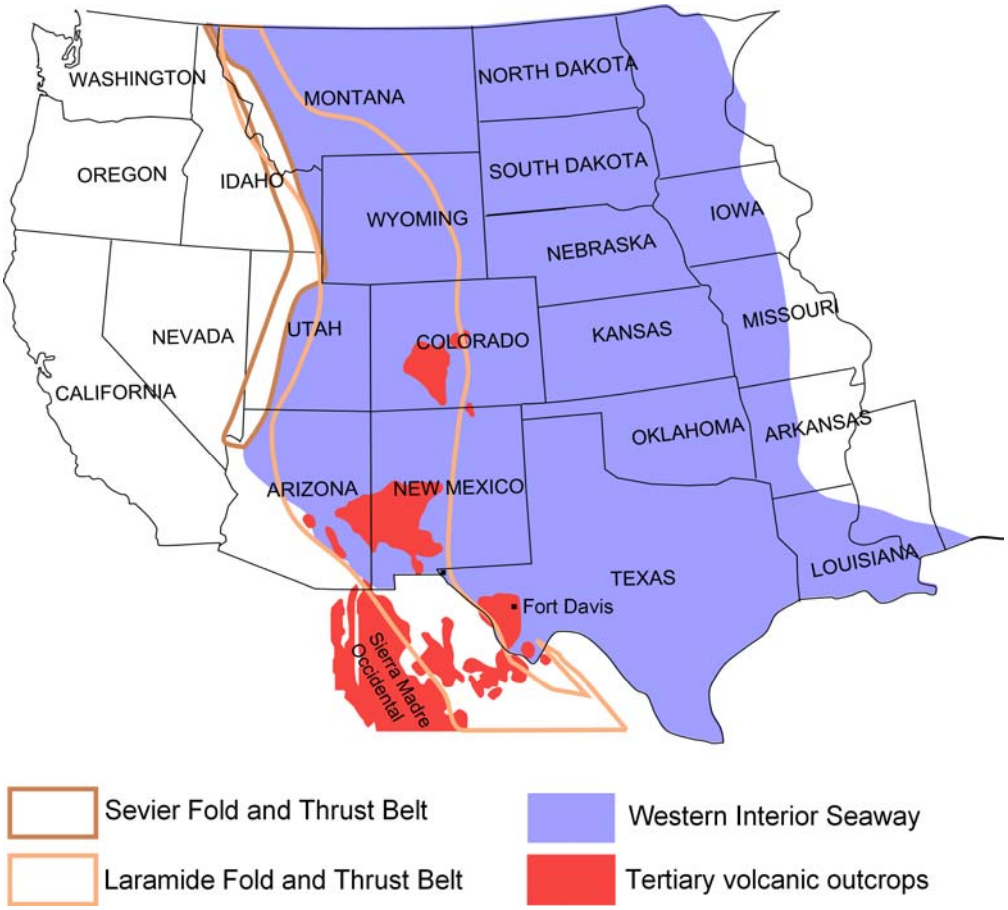

Fig. 4: The Sevier Orogeny and its continuation the Laramide Orogeny were mountain-building periods that lasted from about 140 Ma to 40 Ma. As the earth's crust was dragged down in front of these orogenies by suction from the subducting Farallon plate, the sea rushed in to create the Western Interior Seaway, which stretched from the Gulf of Mexico to Alaska. It covered all Texas by 100 Ma and retreated west to east across the Big Bend at 78 Ma. Tertiary volcanic activity broke out around 35 Ma and continued until about 20 Ma.

Midway through this orogenic episode, the earth's surface in front of the mountains sunk and the sea swept in from the Gulf of Mexico to create the Western Interior Seaway stretching from the gulf to Alaska. The earth's surface rebounded and the ocean retreated after about 50 million years, but not before a carpet of limestone was laid down on its floor. Finally, at about 35 million years ago, explosive volcanic eruptions broke out in Colorado, New Mexico, Texas and Mexico. By far the greatest activity was along what is now the Sierra Madre Occidental, where at least 7,000 feet of volcanic ash covered the landscape from the U.S. border down almost to Guadalajara.

The mechanisms involved in these tectonic events have been a matter of intense speculation and the subject of many hundred research papers. Most, however, have dealt with particular aspects of the subject. That is the way academic research works; there are few kudos to be gained from broad discussion. In 2003, however, an eminent group, the lead author of which was the geophysicist Gene Humphreys of the University of Oregon, published a comprehensive paper that attempted to integrate these events into a coherent theory. The paper proposed a variation on an old theory, the so-called flat-slab theory, first published in 1977, as illustrated by the diagrams below, and summarized as follows:

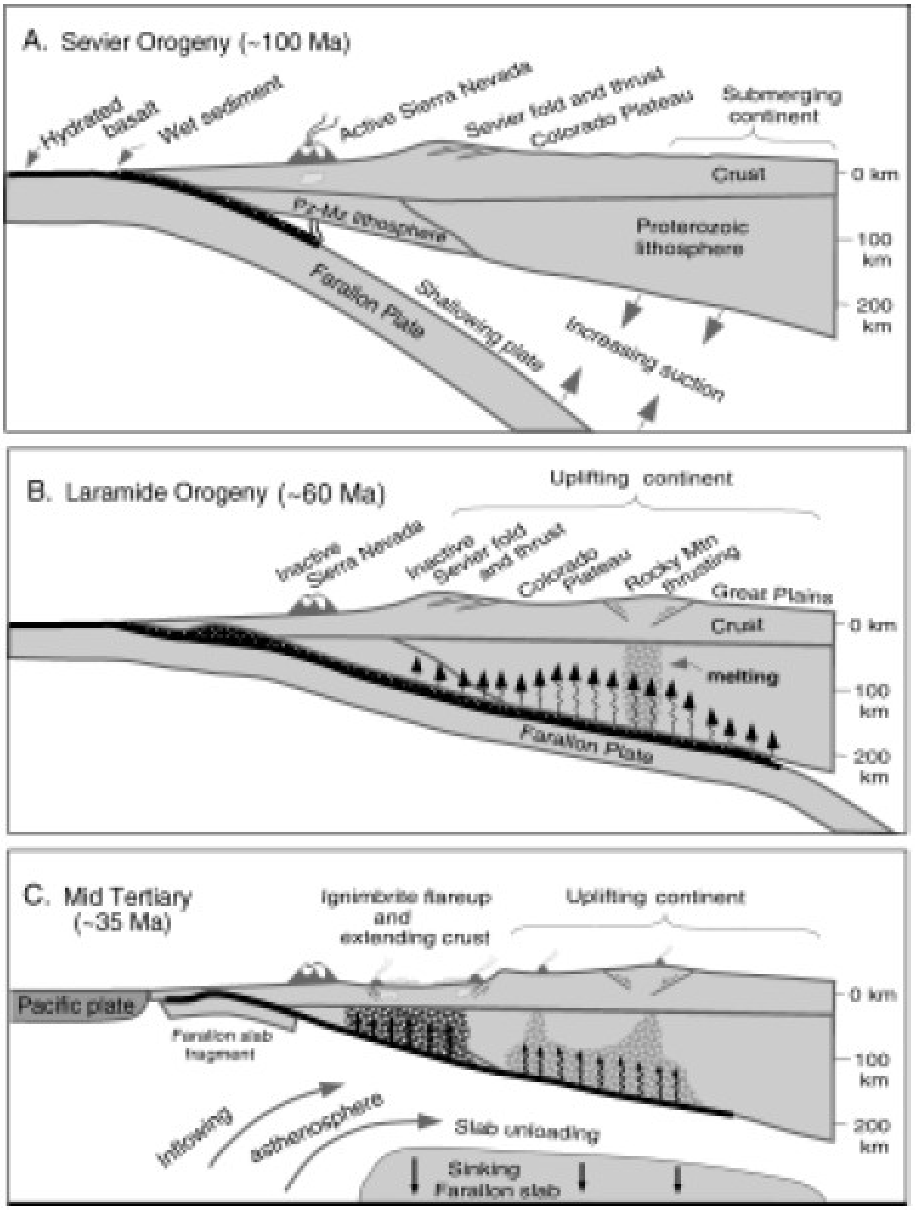

Fig. 5: The three phases of western tectonic activity as envisioned by Humphreys et al (2003)

A. <u>Sevier Orogeny:</u> During the Sevier Orogeny, the Farallon plate descended into the asthenosphere at a normal angle, 40° or so, dragging with it wet sediment from the ocean floor plus hydrated basalt from the upper ocean crust. Here, as is normal under subduction zones, the water helped melt the asthenosphere in contact with the upper part of the plate, generating molten rock or magma, at about 100 miles inland from the subduction trench. The magma rose to the earth's surface as volcanic rock in the Sierra Nevada of California. A fold and thrust belt formed further east as a result of basal traction inland from the subduction trench. The continental interior was dragged down by suction east of the fold and thrust belt, and the ocean rushed in from the Gulf of Mexico, creating the Western Interior Seaway. The thickness of the lithosphere in the continental interior is about 200 km (120 miles) as shown by the analysis of seismic shock waves.

Fig. 8: A shaded relief map of the United States (from Gail Thelin and Richard Pike, 1991)

B. Laramide Orogeny: By the time of the Laramide Orogeny at 60 Ma, the overriding of the continent had speeded up, either because the North American continent moved west faster or the Farallon plate moved east faster, so that the subsiding plate lay closer to the continent at a lower angle than usual. This brought the plate up into contact with, and began to cool, the base of the North America lithosphere. Thus, thrusting and volcanism took place much further inland than normal. A similar situation exists today to the south where part of the Nazca Plate is subsiding at a low angle under South America.

Water, brought into contact with the base by the combination of hydrated basalt from the ocean floor and wet sediments, weakened the lithosphere under the Rocky Mountains. The weakened lithosphere allowed mantle shortening which led to crustal thrusting, and generated magmatic activity under the Rocky Mountains.

C. Middle Tertiary: By the middle of the Tertiary period, 35 Ma, the Farallon Plate had broken up and began descending into the lower mantle. Very hot material from the asthenosphere flowed up towards the hydrated (water-containing) base of the lithosphere behind it, increasing its temperature and uplifting it. The water in the base of the lithosphere reduced its melting point and generated magma. The resulting magma on reaching the surface exploded violently, creating vast amounts of volcanic ash from the Davis Mountains south into Mexico, in New Mexico and especially in the Sierra Madre Occidental in Mexico (see Fig. 4). Explosive volcanism comes from having volatile matter, especially water, in the magma (it is labeled ignimbrite flareup in the diagram; ignimbrite is a word some geologists use to describe the products of explosive volcanic activity).

The physical results of all this tectonic activity over more than 100 million years is illustrated by Figure 8, a map of the United States in which elevations have been shaded by computer. The broad central part of the continent shows virtually no relief except in the Ouachita Mountains in Arkansas.

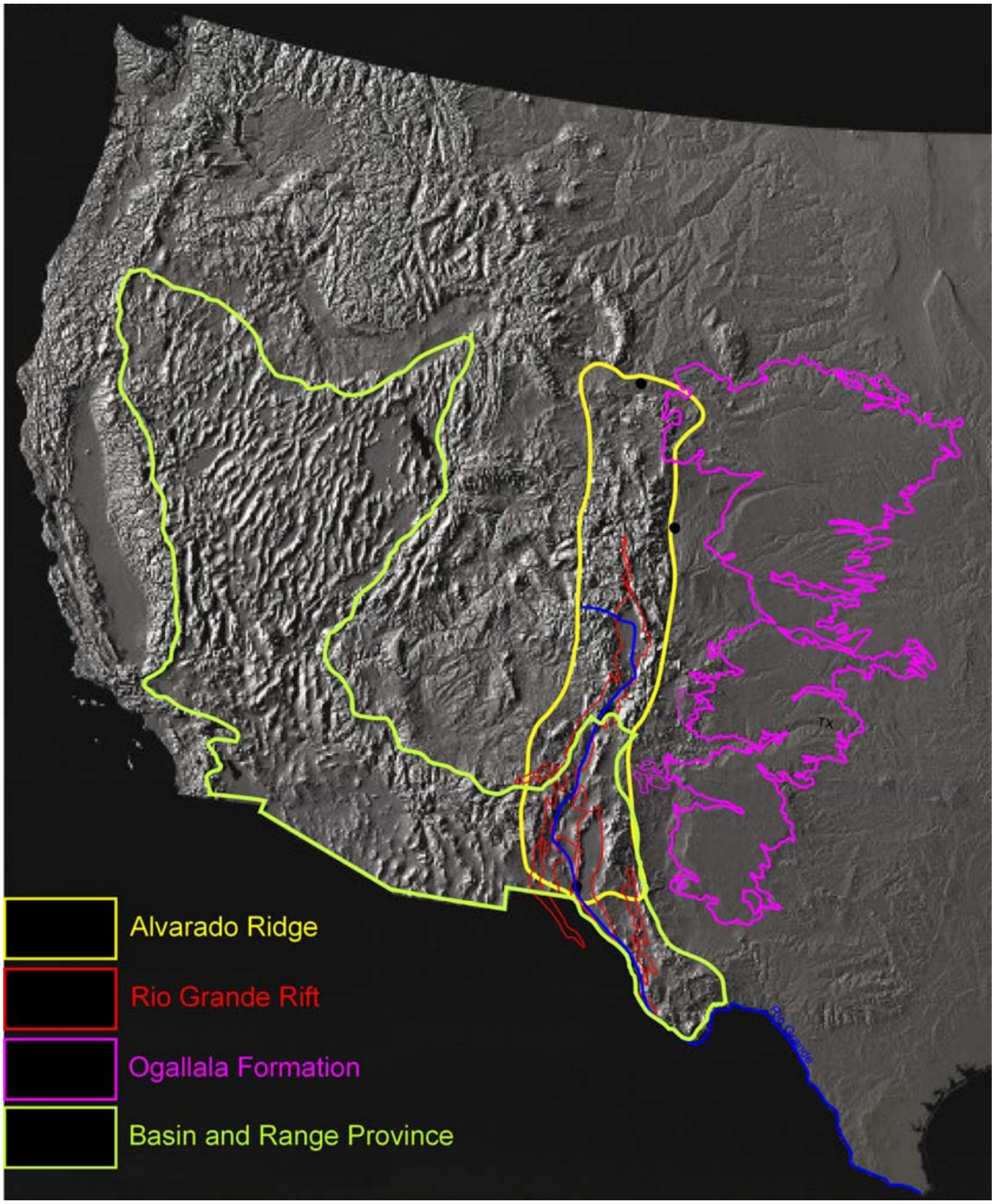

Fig. 9: The topography of the western United States (from Gail Thelin and Richard Pike, 1991) with the Alvarado Ridge, basins of the Rio Grande Rift, Ogallala Formation and the Basin and Range physiographic province superimposed. The Rio Grande River, shown in blue, runs up the center of the ridge as far as central Colorado.

The Appalachian mountain range in the east is the result of tectonic activity quite separate from that in the west. The overall trend of mountains in the west is north-north-west except for the most easterly mountains, the Sangre de Christo Range in New Mexico and the Front Range in Colorado. North of Colorado, the front veers north-north-west, parallel to the limit of Laramide deformation as shown in Figure 1. The Black Hills of South Dakota stand out alone to the east of the front.

After the end of Farallon plate subduction at about 29 Ma, compressive pressure on the crust was relieved and the western North American plate, after being under such pressure for a very long time, was released from it and began to extend. As it extended, faults developed to accommodate the extension, breaking the crust into fault blocks, some of which rose, some of which subsided. This created the Basin and Range topographical province where long mountain ranges running nearly north-south 15 to 20 miles apart are interspersed with basins 6 to 12 miles wide. According to Scott Baldridge, whose *Geology of the American Southwest* is indispensable to those studying the American West, the crust expanded across the Basin and Range province by 150-180 miles in a direction 73° west of north, mostly in the last 16 million years. The province runs down as far as the Big Bend, as shown in Figure 9, and continues into Mexico.

When were the Great Plains Uplifted

How does the tilting of the Great Plains fit into this picture? As Figure 1 shows, tilting took place along the Laramide front, i.e. the eastern limit of the Laramide fold and thrust belt, from Texas up into Canada. It happened after the Western Interior Seaway disappeared, when the ocean withdrew from continental North America during the Laramide Orogeny, about 78 million years ago in the Big Bend area. No ocean sediments have been created in the North American interior since then, so it has proved difficult to determine when the uplift occurred.

For a number of years, the accepted view was that the Rockies, first created by compression of the earth’s crust during the Laramide orogeny, which ended about 40 million years ago, were subsequently worn down by erosion until the end of the Miocene (6 Ma), overlapped by regional uplift which began around 17 Ma culminating in the late Miocene and early Pliocene (7-4 Ma).

In the early 1990s, a conflicting view was put forward by paleobotanists, scientists who study plant fossils. They argued, based on the evidence of fossil leaves, that the Rockies at the end of the Laramide orogeny were as high if not higher than today, have not changed much in the last 35 million years, and that the canyons seen along the fringes of the mountains were caused by a change to a wetter climate, not uplift (for example, see Wolfe, Forest and Molnar). Any uplift that occurred was due to isostatic not tectonic forces. (Isostasy is the condition of equilibrium in which the denser and cooler lithosphere or outer layer of the earth's surface floats on the warmer and less dense asthenosphere or upper mantle. When the lithosphere is thinned by erosion, the tendency is for the earth's surface is to rise). Admittedly, paleobotanical methods have their limitations. For example, you have to know climatic conditions to be able to extrapolate elevations from fossil plant remains. Wolfe, Forest and Molnar give the error estimation as +/- 2,900 feet.

In 2002, Beth McMillan, Charles Angevine and Paul Heller at the University of Wyoming attempted to time the uplift by examining evidence from the terrestrial sedimentary rocks of the Ogallala Formation. Best known in Texas as the main water source for the High Plains, the Ogallala is largely intact and forms one of the most widespread alluvial bodies on earth, created by a blanket of mud, sand and gravel eroded off the Rocky Mountains by rivers flowing east. Figure 9 shows the enormous extent of its present-day outcrop area, 800 miles from north to south and 400 miles across at its widest in Wyoming and Nebraska. In areas where it fills pre-existing valleys it is as much as 800 feet thick. In Paolo Duro State Park, it is up to 90 feet thick. Its base in Texas is about 12 million years old, in Wyoming about 17 million years old and it continued being created until about 5 million years ago.

McMillan, Angevine and Heller calculated the slope of the Ogallala Formation when it was first deposited using a method published by Chris Paola and David Mohrig of the University of Minnesota in 1996. This method involves determining the average grain size and the depth of flow at sample points and calculating the slope at the time of deposition as follows:

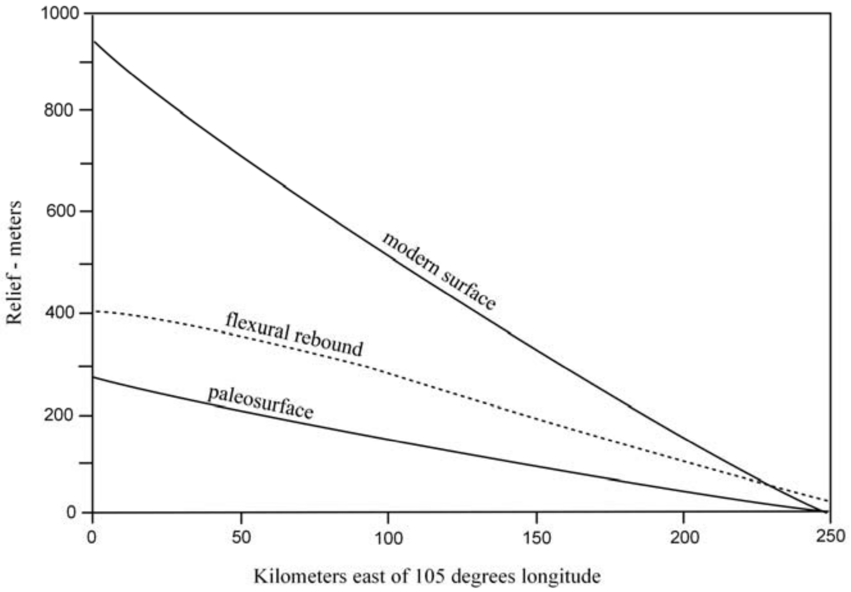

Fig. 10: Ogallala paleosurface compared to today's surface

*depositional slope = 0.094*median grain size/flow depth*

They measured the current slope of the formation by taking the elevation of its base along a 155-mile transect at latitude 41.15°N, just north of the Colorado border with Wyoming and Nebraska, along a section of the outcrop called the Cheyenne Tablelands where the formation has been preserved on high ground between the North and South Platte Rivers. They then measured flow depth and median grain size at 10 sites along the transect and calculated the paleoslopes.

The results are shown in Figure 10. Both slopes steepen from east to west, the modern surface less than the original or paleosurface. The researchers made allowance for the isostatic uplift that would have occurred as the Rockies and the western Great Plains were eroded by the Platte River and its tributaries, the dashed line in the diagram. After making this allowance, the Cheyenne Tablelands have been tilted at least 540 m (1,770 feet) up to the west after the deposition of the Ogallala Formation i.e. in the last 5 million years, most likely by uplift to the west of the Cheyenne Tablelands.

In the most recent paper in this series, to be published in the March/April 2006 GSA Bulletin, Beth McMillan, now at the University of Arkansas Little Rock, Paul Heller and Scott Wing, a paleobotanist at the Smithsonian National Museum of Natural History, take their analysis a step further. They reconstructed the topography of the basin fill that developed across the Rockies after the end of the Laramide Orogeny and its thickness. They then measured the depth of its subsequent erosion, and calculated when this erosion began across the region.

They found that the fill was nearly continuous across the western Great Plains and throughout most of Wyoming and Montana, but more limited in western Colorado and New Mexico, Arizona and Utah. The reconstructed surface forms a broad dome-shaped upland along the spine of the modern Rockies that decays gradually to the east and north across the western Great Plains. The thickness of the fill ranged from less than 300 feet to as much as 5,000 feet in the central Rockies with a broad swathe 1,000 to 3,000 feet thick being found across central and northern Wyoming into western Nebraska and down into northern Colorado. In Colorado and New Mexico, the thickest deposits were in grabens in the Rio Grande Rift with only a thin veneer over the Great

Plains. The gradient of the surface on the western Great Plains increases from 5 to 10 feet per mile at the eastern edge of basin fill to more than 50 feet per mile near the Rocky Mountain front.

The maximum incision into the basin fill is in major drainages such as those of the Colorado, Green and San Juan rivers and the major basins along the Rockies front, the Wind River, Powder River and Bighorn basins. Along the front, steep narrow canyons occur in the Precambrian crystalline rocks with broader but still deep valleys in Great Plains sediments. Depth of incision increases to the north from 4,000 feet in the Arkansas River to 2,300 feet in the South Platte and 1,000 feet in the North Platte Rivers. In the southwestern Great Plains incision began after 8 and before 3 million years ago. In other areas it began as early as 11million years ago and ended as little as 1.2 million years ago.

McMillan, Heller and Wink found that the fill was emplaced by through-flowing rivers, not by being trapped in structural basins, and conclude that it must therefore have been laid down on a slowly subsiding landscape. If not, to maintain a constant gradient, the fill would have had to spread out much further on to the Great Plains than it does. For example, the river gradients during deposition were up to 5 feet per mile on the western Great Plains of Nebraska. Without subsidence, the 2,800 feet of basin fill in central Wyoming would have had to spread 600 miles out into the plains to maintain that gradient. However, basin fill, 1,300 feet thick in the Nebraska panhandle, thins to less than 320 feet within 120 miles.

They estimate that the total subsidence was about 2,800 feet and took place from the end of the Laramide orogeny until about 6-8 Ma in the center of the Rockies and 3-4 Ma along the fringes of the region. If you assume that the recent uplift was of the same magnitude as the deepest incision, 5,250 feet, the net vertical uplift in the Rockies since Laramide times has been 2,480 feet. This is well within the error estimate on paleobotany, which Wolfe, Forest and Molnar give as +/-2,900 feet.

These results seem to reconcile all available evidence, paleobotanical and sedimentary. To summarize, the mountains created by the Laramide Orogeny were eroded after the end of the orogeny as the front subsided. The lithosphere then began rebounding and today’s southern Rockies and Great Plains, although showing some uplift prior to deposition of the Ogallala Formation, have been mostly uplifted in the last 5 million years.

Why did Uplift Occur?

To explain why the uplift of the Great Plains occurred, we must revisit the Farallon Plate and its legacy. Typically, the earth’s surface reacts to tectonic activity such as plate collisions. The Himalayas are the result of India ramming into Asia; the Andes come from the Pacific Ocean floor being subducted under South America. Similarly, the Sevier and Laramide orogenies created mountains in western North America.

However, the Great Plains have been uplifted although there has been no tectonic activity under them for a billion years or so. Similar uplands are found in other parts of the world. For example, the southern African plateau, 1,000 miles across and 6,000 feet high, is in an area where the last plate collision took place 400 million years ago.

The answer appears to come from analysis of seismic waves. In a process akin to the MRI scans that construct images of internal organs by analyzing the speed at which sound waves pass through a body, so can computers construct images of the Earth’s internal structure by analyzing the speed at which shock waves from earthquakes pass through the earth, in a process called tomographic reconstruction. Waves pass through dense material quicker than less dense material and through cold material quicker than hot material.

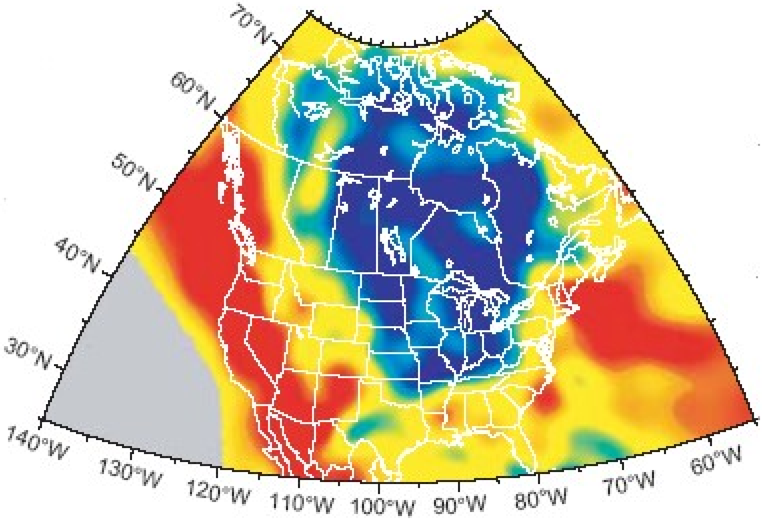

Fig. 11: North America at 85 miles below the surface. The blue center is cold and old. It has no tectonic activity for more than a billion years. The red part of the west is some 500°C warmer. The diagram is from a paper by Suzan van der Lee published in 2001.

This method has been widely applied for the last 20 years and as techniques improve and computer power increases, better and better images are constructed, revealing some unexpected enormous formations in the deep mantle. The largest single structure underlies southern Africa, an enormous plume of hot material which props up the plateau overhead.

A similar condition exists in the American west as illustrated by the 2001 geophysical map by Suzan van der Lee (Figure 11). The blue and red shades are proxies for the stiffness of mantle rocks at a depth of 85 miles; blue represents the stiffest or coldest material, red the least stiff or warm material. The map is based on the analysis of over 1200 seismograms from different seismographic networks in North America. The large blue region centered on Hudson Bay represents roughly the part of North America that has not had any tectonic activity for 1,000 million years. Geologists call it Laurentia. It comes south as far as Oklahoma. The western continent is underlain by hot material with a branch of warmer mantle through New Mexico and southern California.

In another paper, Suzan van der Lee and Saskia Goes created a topographical model of the United States based on the mantle thermal structure, i.e. the heat patterns in the mantle, down to 150 miles, calculating what the topography ought to be based on the temperature of the interior of the earth. Part of their model is shown on the right in Figure 12, reproduced in the McMillan, Heller and Wing paper. According to Goes and van der Lee, temperatures in the 30-60 mile depth are on average 500°C cooler in Laurentia than they are in the west. The adiabatic temperature, the point where the lithosphere switches from conductive to convective transfer of heat, is found at about 30 miles under the Nevada compared to 120-150 miles in the mid-West near the Canadian border.

In Figure 12, the Goes and van der Lee model is juxtaposed against, on the left, a map developed by McMillan, Heller and Wing. The latter is of reconstructed basin fill surface relative to today’s topography. The black squares give the upper and lower limits of the age of turnaround from aggregation to incision of the basin fill. Colors show the elevation in meters. For example, the boundary between light blue and dark blue is at 900 meters (about 3,000 feet).

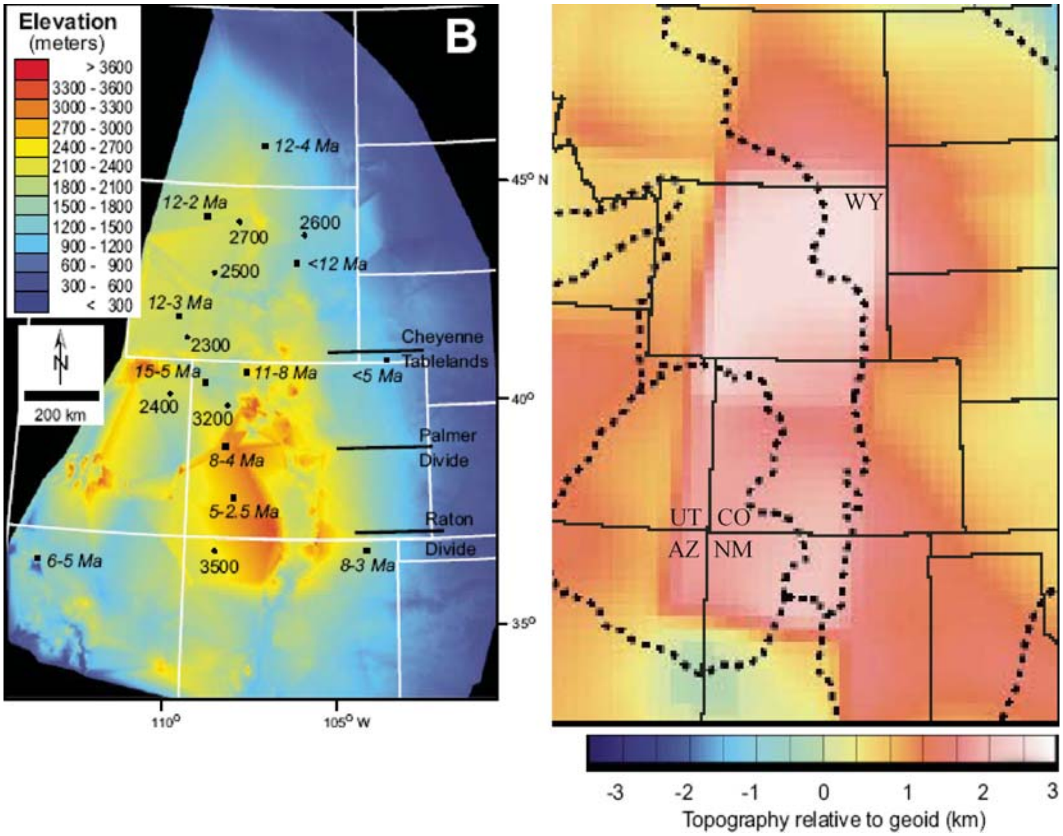

Fig. 12: On the map of western North America (from McMillan, Heller and Wing, adapted from the original in Goes and van der Lee), the topography relative to the geoid (the earth's surface at sea level) is calculated from the heat structure of the continent down to 150 miles.

The model matches the actual topography very well in the southern Rockies from Wyoming through Colorado to New Mexico. They attribute the erroneous high ground across the Texas Panhandle to incorrect mantle density in the model - the area actually coincides with a pronounced high gravity zone. The conclusion that McMillan, Heller and Wing draw from this comparison is that uplift in the west is substantially due to the elevated temperatures in the lithosphere and upper asthenosphere.

The Rio Grande Rift

As seen in Figures 9, the Rio Grande Rift runs up the crest of the Alvarado Ridge. A rift, in geological parlance, is a long, narrow trough where the entire lithosphere has been deformed while being extended or stretched. Sometimes a rift is a precursor to a continent splitting in two. The Rio Grande Rift developed quite slowly; by 25 Ma, shallow basins had developed along its length in which volcanic ash accumulated. For the next 10 million years it remained broad and shallow until 15 Ma when uplifting and block faulting began to produce the rift as it appears today. It now consists of 4 major linked basins up to 26,000 feet deep, filled with lake and river sediments and is more or less dormant.

Extension across the rift, i.e. the amount by which the Earth's crust was stretched, varies from about 10 per cent in Colorado to 28 per cent at Albuquerque and as much as 50 per cent near the

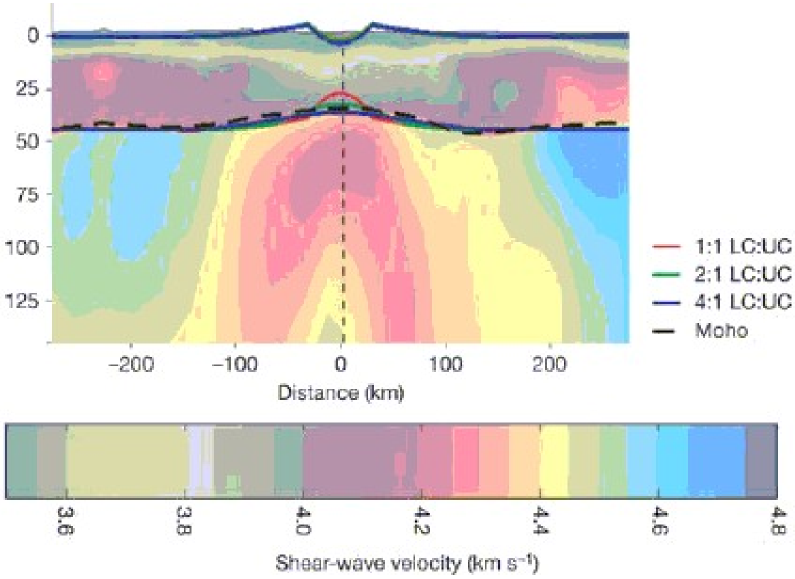

Fig. 13: This diagram is a good example of recent geophysical modeling along the La Ristra transect across the Rio Grande Rift (from Wilson et al, 2005).

Mexican border where the rift branches into multiple basins and uplifted blocks. The southern boundary of the rift is uncertain. It turns abruptly to the southeast at El Paso and may continue as far as the deep basin at Presidio.

A recently-completed seismic geophysical investigation called La Ristra provided new data about mantle conditions under the Rift. In the investigation, a series of seismic sensors were laid across the rift in 1999 from Pecos in Texas to Lake Powell in Utah and left for about 18 months. During this period, the instruments recorded shock waves from earthquakes of greater than 5.6 magnitude on the Richter scale that occurred anywhere on Earth, 29 in all. Figure 13 shows a section across the rift down to 150 km (90 miles), as determined by tomographic analysis of the seismic waves captured along the La Ristra line.

In it, the crust thins across the rift (the dashed line) to about 22 miles from about 28 miles to the east and west. The diagram attempts to fit observed data to various ratios of lower crust (LC) to upper crust (UC) extensions. The best fit is for a ratio of 2:1, i.e. where the lower crust has been stretched twice as much as the upper crust. The Moho dashed black line shown on the diagram is at the base of the crust. A quite narrow ridge of upwelling hot material appears to be responsible for development of the rift. Such currents send heat and mass up, creating magma chambers in the upper asthenosphere. This causes the lithosphere to uplift and form broad arches in which the crust is thinned. Faulting then occurs along the uplifted crest in to which magma oozes, leading to further uplift as the temperature increases. Finally, you have deep rifts composed of a series of grabens whose bottoms are moving down compared to the arches but moving up relative to the convecting magmas below.

The narrow upwelling current responsible for the rift therefore appears to be a localized feature of the broad currents responsible for the 1,600-mile wide overall uplift. The timing matches quite well – a limited uplift about 25 Ma creating shallow basins along the rift and producing some uplift in the pre-Ogallala landscape as suggested by Figure 10, followed by quiescence until 15 Ma, when uplifting and rifting began more strongly. Both the uplift and the rift appear to have been produced by similar processes - upwelling currents in the asthenosphere, currents that developed in the slipstream of the Farallon Plate as it roiled up the mantle.

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