Thin-Skinned Crustal Extension Confirmed

Seismic reflection studies in the Basin and Range of Utah have detected extension along gently sloping faults that should not slip but do

Salt Lake City. The Basin and Range province, the high, corrugated land stretching for 750 kilometers to the west of here, has always seemed geologically odd. Such oddities as the thin crust beneath it and its abundant hot springs have been attributed to the stretching of the crust. Some extension is evident along the faults bounding the parallel mountain blocks that give the region its name, but how the crust far beneath the surface adjusts to extension has been the subject of wide-ranging speculation. Elsewhere, less extension has ruptured the crust and formed new ocean basins.

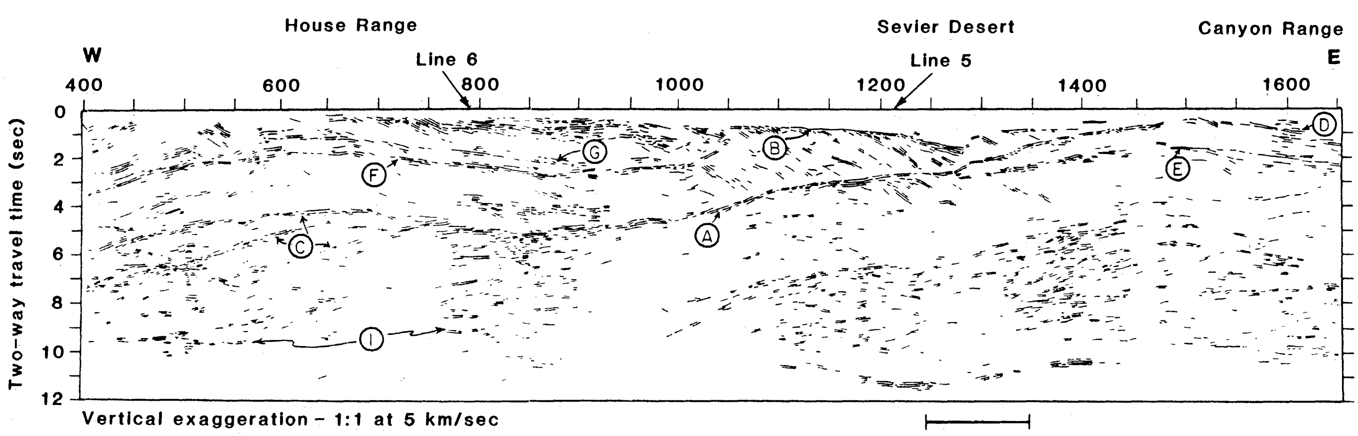
Recent probings of the deep crust carried out with the oil exploration technique of seismic reflection profiling have revealed several gently sloping faults, called detachments. The most extensive detachment slices at least halfway through the crust, allowing a 70-kilometer-wide sliver of rock to slide over the block below as the crust extends. Similarly thin sheets of rock have been thrust across the southern Appalachians, but conventional rock mechanics theory does not allow thin-skinned extension, only compression. Geologists now agree that theory will simply have to adjust.

The most recent and most convincing evidence of thin-skinned extension was presented here* by Richard Allmendinger and his colleagues at Cornell University. Within the program of the Consortium for Continental Reflection Profiling or COCORP (*Science*, 10 February 1978, p. 672), they studied a section of crust beneath the Sevier Desert in west-central Utah, near the eastern edge of the Basin and Range. As in oil exploration, truck-mounted vibrators generated pulses of acoustic waves that were reflected from surfaces at which rock properties change abruptly and were recorded by sensors at the surface. A major variation in the method when applied to crustal studies is a longer time spent listening for reflected signals, which helps extend the limits of seismic reflection profiling to as much as 50 kilometers beneath the surface.

COCORP's profile across the Sevier Desert confirmed the existence of a low-angle fault penetrating at least 12 to 15 kilometers beneath the surface and underlying perhaps 10,000 square kilometers of the Basin and Range. In a line drawing of the original reflection data, the fault appears as a continuous band of parallel reflections (labeled A) descending from the surface at an angle of about 12°. High-angle faults, inclined at an angle of about 60°, extend down to the detachment but do not cut it. In one of the classic theories of basin and range extension, these high-angle faults would extend about 15 kilometers through the crust until they intersect each other, allowing thick crustal blocks to drop between the faults in order to accommodate extension. Apparently, this block faulting and the resulting basin and range topography are relatively superficial expressions of limited, geologically recent extension.

There has been recent movement on the detachment, but how much is not certain. The truncated faults pierced a 4-million-year-old basalt formation, Allmendinger notes, so the upper sheet has slipped down to the west at least as recently as that. Shallow, high-resolution reflection profiling has allowed Samuel Harding and his colleagues at the U.S. Geological Survey (USGS) in Denver to trace a younger high-angle fault into the detachment, suggesting movement on the detachment within the past million years. Allmendinger believes that reasonable reconnections of rock strata and faults parted by the detachment require a minimum of 30 kilometers of slip

*At the annual meetings of the Rocky Mountain and Cordilleran sections of the Geological Society of America, 2–4 May.

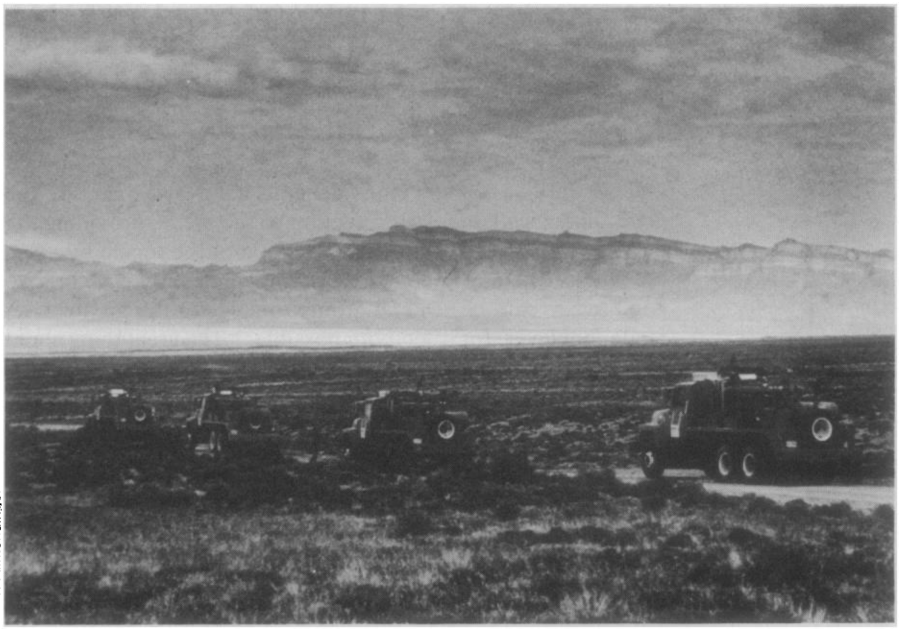


Thin-skinned extension beneath the Sevier Desert, Utah

In this line drawing abstracted from the original COCORP seismic reflection profile, feature A is the Sevier Desert detachment fault, along which the crustal sliver above it has slipped to the west. Contrary to some theories, this low-angle fault is not cut by high-angle faults, such as those at vibration points 1230 and 1285 (upper scale), nor does it merge with a nearly horizontal detachment. Feature B is a reflection from a basalt formation, C are splays from the detachment, D is related to the Pavant Range thrust, E is a possible thrust, F was most recently a detachment with slip to the west, and G is a bedding plane, a thrust, or both. [*Source:* Geology-*Allmendinger* et al., *COCORP*] on the detachment and perhaps 50 to 60 kilometers. Extension in the Basin and Range has varied greatly from place to place, but it is now generally assumed that the crust has been stretched to about double its original area, adding perhaps 300 kilometers to the breadth of the region. If the higher estimate of slip on the detachment is accurate, it could have contributed approximately 20 percent of that extension in the middle and upper crust.

The COCORP data, acquired last year, were not the first sign of detachments underlying parts of the Basin and Range. The oil companies knew years ago. In 1976 Robert McDonald, then at Wolf Energy, Denver, pointed out the Sevier Desert detachment in several short, relatively shallow reflection profiles that he published in a Rocky Mountain Association of Geologists symposium volume. The paper drew little attention at the time. Robert Smith of the University of Utah has had access to oil company seismic profiles, including one along the same line as COCORP's, but until now he has been restrained by his understanding with the firm from publishing any of them. And Mary Lou Zoback of the USGS in Menlo Park recently bought an oil company profile in the Sevier Desert, can talk about it, but cannot show the profile itself. Field geologists in academia were also finding some signs of major extension along low-angle faults. The particular attraction of the COCORP data is that they are public† and that they trace a detachment to the greatest depth yet.

The existence of the detachment may now be clear, but why it works the way it does remains a mystery. A low-angle fault slips readily enough when horizontal forces compress the crust nearly parallel to the fault and thrust the upper slab over the lower one. Compression created such thrust faults in the Sevier Desert more than 65 million years ago. But, under the extensional stresses of the past 30 million years or so, created by still obscure forces, the maximum compressive stress would be vertical. That would force opposite sides of a low-angle fault together, increase the frictional resistance to slippage, and lock the fault. Or so the theory goes. Even if the detachment is an old thrust fault reactivated by the recent extension, friction on the fault should be too high to let the upper slab reverse direction and slip downward. One solution would be to find a process that lubricates the fault to allow it to slip.


R. W. Allmendinger

Seismic reflection profiling in the Basin and Range province

The mountain range in the distance and the sediment-filled basin in front of it have been created by movement along a high-angle fault at the base of the range. This COCORP seismic reflection profiling crew is on the east side of the Confusion Range at the extreme left-hand edge of the seismic profile on the preceding page. The House Range is in the distance to the east. A shallow detachment underlies the House Range, and the splayed end of the Sevier Desert detachment is about 12 kilometers below the surface. In front of the rear wheels of the nearest truck is one of the vibrating pads that generate the seismic waves.

The new view of the middle crust of the Basin and Range creates problems for geologists too because it does not match exactly any of the proposed models of crustal extension. In central Utah at least, the high-angle faults do not extend to any great depth. They do not bend and become low-angle faults, nor do they merge into a single, horizontal detachment. Even the Sevier Desert detachment does not seem to level off. It does bear a resemblance, at least above 15 kilometers, to a radical model presented by Brian Wernicke, who will soon leave Syracuse University to take a position at Harvard University. He believes that a fault like the Sevier Desert detachment could not only pierce the 30-kilometer-thick crust, which forms the lighter, chemically distinct outer layer of the earth, but also the 65-kilometer-thick lithosphere, which forms the rigid continental plate.

Wernicke's idea is radical because it runs counter to the idea that rock properties change dramatically with the higher temperatures and pressures encountered at greater depths. As the rock becomes less brittle and more plastic, the crust should tend to deform or flow as a whole rather than break along a single fault, according to conventional thinking. In fact, at the lower end of the observable detachment, the fault splays into several downward curving reflectors (labeled C). These may outline lens-shaped lumps of brittle crust around which ductile flow has accommodated extension, as proposed by Warren Hamilton of the USGS in Denver. Below these lenses, the whole crust would stretch like a piece of rubber, according to this model. Smith did argue that rock temperature and composition would first favor some ductile flow at about the depth of the splays from the detachment. In this case, at least, reflection profiling does not provide unambiguous evidence as to how this deeper crust behaves.

With a sharper view of the deep crust, geophysicists have shown that the most dramatic geological clue at the surface, the Basin and Range topography itself, probably does not hold the key to deep crustal extension. The more subtle geological evidence must now be combined with geophysical data to determine how much extension of the upper and middle crust might have occurred along mid-crustal detachments and to identify the mechanism of extension in the lower crust. In a related task, seismologists may encounter even greater problems than in the past identifying which faults can generate major earthquakes in the area, now that some of the suspect high-angle faults are seen to be too shallow to generate large shocks.

—Richard A. Kerr

†The group from Cornell and Smith have a paper in press in *Geology* that includes the profile, and the COCORP data will be available within a few months.