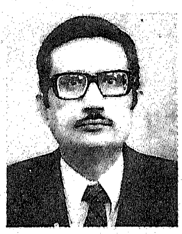
And Still They Moved

An Important Statement about some Rock Masses

Ramesh Chander



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Geologists find that many large masses of rock have been displaced great distances over surfaces of discontinuity called overthrusts. But how is the anticipated large force of friction along an overthrust overcome?

Introduction

Younger rocks normally lie above older rocks. This basic principle of stratigraphy, a branch of geology, is frequently belied in geologic structures called thrust faults and overthrusts. A thrust fault is a surface of discontinuity, with a dip or slope of less than 45°, along which relatively older rocks have moved up with respect to younger rocks below the fault. A thrust fault with a dip of 10° or less along with a large mass of rock having horizontal dimensions of the order of a hundred kilometres or more, when displaced over a distance measurable in tens of kilometres is called an overthrust or simply a thrust (as in the Jutogh thrust of the Himalaya). The displaced rock mass is called a *nappe* or a *thrust sheet*.

The phenomenon of overthrusting was recognised first in 1826 near Dresden, Germany. Thereafter slowly but steadily overthrusts were mapped in various mountain ranges around the world. Their existence was widely accepted by the geologists at around the beginning of the twentieth century. But then someone asked innocuously as to how such large rock masses could have moved over such long distances. Thus arose the mechanical paradox of large overthrusts. I elaborate here in simple terms some facets of this paradox.

Overthrusts in the Himalaya

An excursion through the Himalaya with a geologist is an

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enlightening exercise. One realises how the mostly grey and monotonous looking rocks could be clues for reconstructing the saga of the birth and subsequent vicissitudes in the life of the Himalaya. It transpires thus that some of the Himalayan rocks formed tens of kilometres beneath the earth's surface through slow cooling of magma, the molten rock material. Others formed in the depths of the Tethys, a former Mediterranean – like ocean whose waters have since moved into other existing oceans partly because of the sedimentation and partly because the adjoining land masses were brought together due to convergence of the Indian and Eurasian plates. Many rocks of both types show signs of subsequent metamorphism or alterations under elevated temperatures and or pressures. Since they now lie above sea level, all rocks exposed in the Himalaya have experienced uplift. Since thrust faults are very common in the Himalaya, most, if not all, rocks have also experienced sub-horizontal displacements.

Relatively older rocks appear above younger rocks in many ridges in the Himalaya as illustrated schematically in *Figure 1*. This is initial evidence for postulating at least a local thrust fault on every ridge. If the same older and younger rocks appear similarly in well-separated ridges, then, on the principle of economy of hypotheses, a basis arises to suggest that the different local thrust faults may be segments of the same overthrust in the region. The overlying older rocks may be regarded as parts of the associated thrust sheet, most of which may have disappeared

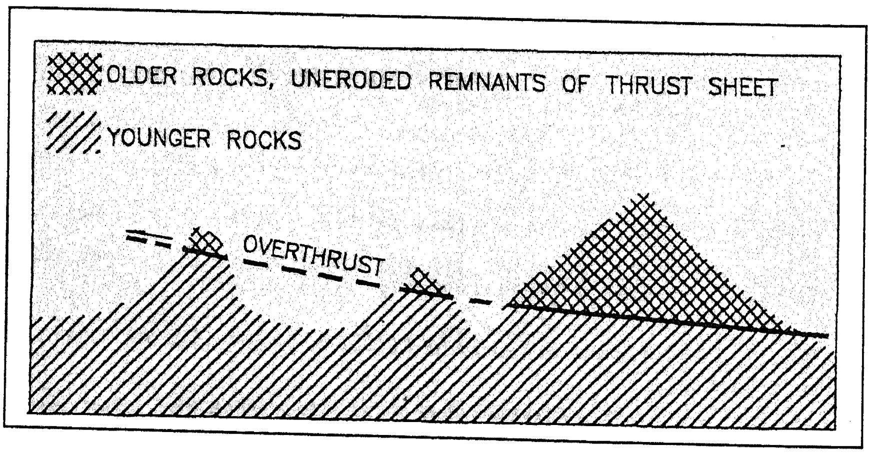

Figure 1. Illustrating the concept of overthrusts.

due to weathering and erosion. Thus precise estimation of the full areal extent of an initial thrust sheet and the magnitude of the displacement along the overthrust is difficult. This holds for even the most well-known thrusts around the world. Still, figures of thousands of square kilometres for area and tens of kilometres for displacement are reasonable in most cases.

Historically, R D Oldham was apparently the first to identify the phenomenon of overthrusting in the Himalaya in the later part of the nineteenth century. His initial observations were extended by Pilgrim, West, Auden and the Swiss team of Heim and Gansser in the first half of this century. They estimated horizontal translations of 30 to 80 km along some of the overthrusts. Valdiya's 1980 monograph on the Geology of Kumaun Lesser Himalaya presents inter alia post-independence work on overthrusts by Indian geologists.

Jutogh and Chail thrusts are the two major overthrusts of the NW Himalaya. They are named after the localities in the Simla Hills where they were observed first.

Other Examples

Some of the better known overthrusts in other parts of the world are the Glarus thrust in the Alps, the Moine thrust in the Scottish Highlands, the Taconic thrust in the Appalachian mountains of New York state, and the Lewis thrust in the Rocky, mountains on both sides of the Canadian–American border. Estimates of displacements along these overthrusts vary between 20 and 80 km.

A Serious Difficulty

T M Reade wrote in 1908 a single paragraph under the title 'The mechanics of overthrusts'. It reads in parts, "...some of the overthrusts postulated are approaching 100 miles... no force applied in any of the mechanical ways known to us in Nature would move such a mass, be it ever so adjusted in thickness to the thrust plane...." In other words, Reade surmised that the

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force of friction along the base of a large thrust sheet could be very strong and the push applied to overcome it could cause disintegration of the sheet.

Smoluchowski presented in 1910 an approximate but quantitative estimate of the frictional force involved. It may be deduced from his analysis that even if the rocks in the thrust sheet have the strength of granite and the coefficient of friction along the overthrust is as for iron on iron, the linear dimension of the sheet in the direction of movement should not exceed 20 km. Otherwise the sheet would break under the applied push.

The Argument by Hubbert and Rubey

Many articles were written in response to Reade's challenge. But the most notable of all is a two-part work by Hubbert and Rubey in 1959 under the title 'Role of fluid pressure in mechanics of overthrust faults'. Briefly, they suggested that friction at the base of a thrust sheet could be reduced, or even eliminated completely, if fluids at suitably high pressure exist along the overthrust, because then the vertically upward traction due to fluid pressure would counteract the contribution of the weight of the thrust sheet to the normal reaction across the overthrust (*Figure 2*). Hubbert and Rubey pointed out that fluids at sufficiently high pressures have been encountered in several oil wells that have been drilled through a few buried overthrusts.

Hubbert and Rubey's article is comprehensive. They tried to make their idea plausible with some experiments (see *Box 1*) and many examples. Among the latter, they consider the mechanism that facilitates rotation of the 508 cm, 200 inch, Mount Palomar telescope. The 4,500,000 Newton weight of the telescope and its supporting frame is virtually neutralised as far as friction is concerned by pumping oil around the bearings at a pressure

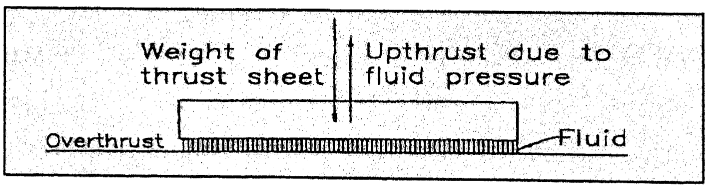

Figure 2. Interaction of the weight of the thrust sheet and upthrust due to fluid pressure according to Hubbert and Rubey (schematic).

Box 1. The Beer Can Experiment

The section on the so-called beer can experiment is the most widely quoted part of Hubbert and Rubey's article. Create a smooth planar surface with a gentle slope of about 1° using a large, clean, glass plate wetted with water. Remove the lid of an empty beer can ensuring that the cut edge is smooth and even. Chill it in a freezer, and place it, open end down, at the top of the slope. Pressure of the air trapped in the can increases with the rise in temperature. This leads to a reduction in the normal reaction and hence the frictional resistance between the can and the glass plate. The can slides down the slope. It comes to halt as soon as a part of its rim crosses the lower edge of the glass plate as that causes equalisation of air pressure and increase in the frictional force.

The beer can experiment reminds one of the air track experiments in the physics laboratory. Even more prosaically, I place an empty teacup on the gently sloping, wet slab in the kitchen. The cup slides as soon as I pour hot tea in it. I know what Hubbert and Rubey would have said about this phenomenon. Still, it gives me an eerie feeling every time.

sufficient to prevent metal to metal contact. The effective coefficient of friction is reduced to 2.6×10^{-6} at the rotating speed of the telescope, and a 62 Watts, 1/12 horsepower, motor is adequate as a source of power.

Hubbert and Rubey's article was hailed widely. It inspired several extensions as also substantial criticism. But Price made the most serious attack some thirty years later.

The Argument by Price

Price wrote an article entitled 'The mechanical paradox of large overthrusts' in 1988 on the occasion of the centennial of the Geological Society of America. The article begins with a quote attributed to John Tukey that bears repetition:

> *Far better an approximate answer to the right question, which is often vague, than an exact answer to the wrong question, which can always be made precise.*

Price's motive for recalling this quotation in the present context is to suggest that the question by Reade and the analyses of Smoluchowski as well as Hubbert and Rubey, although very precise as far as they go, address a fictitious problem. They

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assumed that the entire thrust sheet moves the full observed distance in one go, while actually different small parts of the sheet may move, in a staggered manner, small distances repeatedly over a period of time to attain their present positions.

Price recalls that a correct view on the paradox had been taken by R D Oldham in 1921 during a talk entitled 'Know your faults'. Oldham suggested that "...(Reade's) hypothesis needs correction, not the facts of observation (about overthrusts)... the thrust (sheets) did not move simultaneously over the whole of their extent, but partially, first in one part then in another, each separate movement involving an area limited by the strength of the rocks and their power to transmit or resist the effects of pressure... the movement would not be like that of a sledge, pushed bodily forward over the ground, but more akin to the crawl of a caterpillar which advances one part of its body at a time, and all parts in succession...."

Price cites field observations from the Canadian part of the Lewis thrust (see above) that appear to support this view. He backs it up by recalling the current seismological view on tectonic earthquakes because each one of them involves relative movement of rocks across a fault in its source region within the earth. I shall describe it in the context of a great earthquake, i.e., an earthquake of magnitude greater than 8, in the Himalaya. Examples of such earthquakes include the Kangra earthquake of 1905 and the Bihar–Nepal earthquake of 1934. The plate tectonic view is that such an earthquake occurs in the boundary surface between Himalayan rocks above and Indian shield rocks below. This boundary behaves as a mega thrust fault that lies under the entire 2400 km length of the Himalaya, and that, of late, has been referred to as a *late boundary fault*. A great Himalayan earthquake ruptures approximately 300 km × 100 km area of the plate boundary fault. Relative slip between rocks across the fault during the earthquake is of the order of 5 to 10 metres and it may vary from point to point over the ruptured area. Rather, it begins at a point called the focus or hypocentre of the earthquake and spreads from there to all parts of the rupture at a finite speed

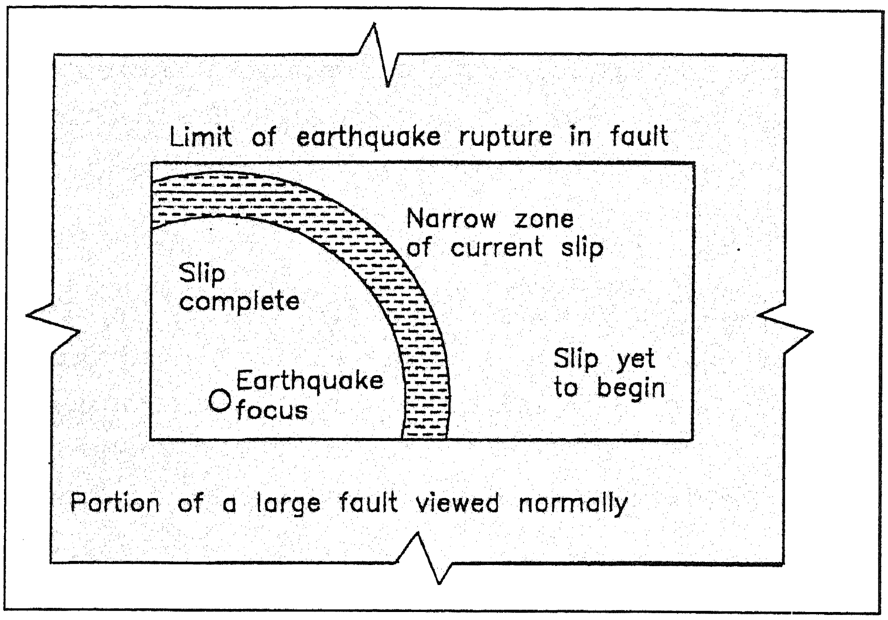

Figure 3. Only a limited part of the earthquake fault rupture slips at a given time instant.

of about 3 km s^{-1}. At any given time, only that much rock mass slips as is capable of moving as a coherent unit (*Figure 3*). Even the few metres of displacement of each particle at or near the fault occurs at a finite speed that has to be less than the speed of sound waves in the rock concerned. This speed is of the order of 6 km s^{-1} in upper crustal rocks. Finally, I recall also that each earthquake is preceded necessarily by an extended period of strain accumulation.

It is estimated that the area of rupture and the amount of slip during the magnitude 7 Uttarkashi earthquake of 1991 were respectively about a 100 times and about 10 times smaller than the area and slip mentioned above for a great Himalayan earthquake. But the ideas about slippage sequence, speed of rupture propagation and the speed of particle motion hold.

In short, in the view of Oldham and Price, the full displacement observed along an overthrust might be achieved through several thousand great earthquakes, occurring one at a time, over a fairly long period of time. Even in a given seismic episode, at a given instant of time, only a small portion of the thrust sheet would move over a short distance. Thus, the paradox of large overthrusts would appear to be illusory.

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I have not seen any written comments on the article by Price. It may mean either that the earth scientists accept it or, as appears more likely, they have become indifferent to this challenging problem.

Other Ideas

The paradox of large overthrusts excited many minds. They proposed a host of other explanations. Plastic and viscous behaviour of rocks in the nether parts of overthrusts have attracted attention most frequently. But, by and large, the view expressed by Hubbert and Rubey still holds sway.

A Philosophical Note

The paradox under discussion here is a celebration of the scientific paradigm at many levels. I mention here two of them. Firstly, the paradigm thrives on unfettered debate. The debate regarding overthrusts has been remarkable particularly as it has been joined by practitioners of two major branches of science, geology and physics. Secondly, the scientific paradigm holds observations supreme. The paradox of large overthrusts continues to defy resolution because the observations have yet to be explained to the satisfaction of all.

Concluding Remarks

Galileo appeared before the Inquisition to recant his views on planetary motion. But at the end of his ordeal, he is supposed to have whispered "...and still they move". Although the mechanism is yet to be sorted out, the fact of large-scale rock displacements along overthrusts is indubitable. Thus it seems appropriate to end this article by whispering "And still they moved".

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Suggested Reading

[1] **M King Hubbert and William W Rubey.** *Bulletin of the Geological Society of America.* 70, 115–166, 1959.

[2] **Raymond A Price.** *Bulletin of the Geological Society of America.* **100,** 1898–1908, 1988.