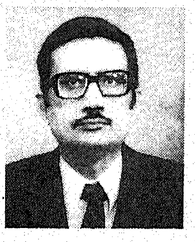
The Antiquity of Earthquakes

Ramesh Chander and Priyamvada Singh



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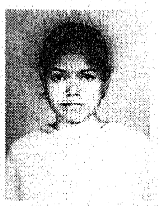

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If we adopt the definition that an earthquake is shaking of the earth due to natural causes, then we may argue that earthquakes have been occurring since the very beginning of the earth about 4.5 billion years ago.

Introduction

Earthquake catalogues provide chronological information about dates, source locations, magnitudes and other parameters of past earthquakes of specific regions and of the whole earth. The catalogues are useful for many scientific and societal concerns of seismology such as quantification of seismicity, assessment of seismic hazard, design of earthquake resistant structures and the cherished but elusive capability for earthquake prediction (see *Box* 1 for two anecdotes). The earliest earthquake, when identified will appear at the very top of the global catalogue. As yet, there are few estimates about this earthquake as it probably occurred in that early period of the earth's history about which astronomers, physicists, chemists and earth scientists are still sorting out their ideas. Yet, the notion of the earliest earthquake excites interest. We explore this theme here partly also because we are able to expose many basic facts and views about earthquakes in simple terms.

What Exactly is an Earthquake?

We seek clues about the date of the earliest earthquake from the very definition of the term. According to Webster's Seventh Collegiate Dictionary, an earthquake is a shaking of the earth that is volcanic or tectonic in origin. We may illustrate this terse statement as follows. On 29 March, 1999, shortly after 0030 IST, when people all over North India exclaimed 'earthquake!', they were experiencing ground shaking due to seismic waves that had arrived through the earth after having been excited beneath the

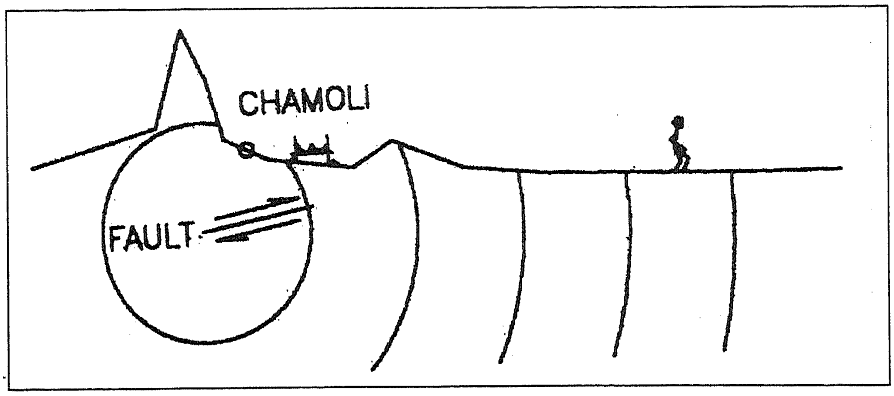

Figure 1.

Chamoli region of the Garhwal Himalaya by the tectonic process of shear failure (*Figure* 1) in rocks. The damage to houses and other man-made structures in the Garhwal and Kumaon Hills during this earthquake was due to severe ground shaking close to the source.

An earthquake is a complex natural phenomenon. The shaking of the ground that is 'earthquake!' for a layman is an ephemeral effect of a chain of events, most of which occur in a limited rock volume constituting the earthquake source. Seismic waves pro

Box 1

Nuclear waste disposal is a challenging technological and scientific problem for mankind. If a waste may emit harmful radiation for about 10000 years, then its repository should be safe against natural hazards, such as earthquakes, for at least that length of time. A catalogue of large earthquakes of the past 10000 years at the site could serve as a possible model for the anticipated seismicity over the next 10000 years. An earthquake catalogue spanning this length of time has not yet been prepared.

The 1966 Parkfield earthquake of California was investigated in detail. Historical research showed that similar earthquakes had been occurring in the locality at intervals of about 22 years since the nineteenth century at least. Thus, it was predicted in the early 1980's that the next similarly significant earthquake at Parkfield would occur between 1 January 1988 and 1 January 1993. The region was heavily instrumented and numerous earth science investigations were carried out prior to the opening of the prediction time window. The window closed six years ago. But, as of this writing, the anticipated earthquake has not occurred. Funding agencies have been very cross with seismologists. This does not mean that earthquake catalogues should not be used for earthquake prediction or that work on earthquake prediction should cease. Rather, the example serves notice once again that earthquake processes are complex and will have to be investigated further for routine earthquake prediction to be a reality.

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vide the necessary link between the culmination of the events at the source and the observers and seismographs located at different points of the earth's surface. Therefore, we explain here not only 'tectonic and volcanic origin' and 'shaking of the earth', but also 'seismic waves' which are not explicitly mentioned in the above definition.

Tectonic Origin: Tectonic earthquakes are by far the most common today and each of them is caused by a shear failure at its source. Volumes of intact rock or rock without macroscopic discontinuities may exist in the source regions of a few rare tectonic earthquakes today. Shear failure produces in such a rock volume, a discontinuity called a fault or shear fracture with the attribute that the rock fragments on either side move in opposite directions parallel to the discontinuity surface.

However, a discontinuity surface with rocks on its two sides pressing against each other, already exists at the source of each of the vast majority of tectonic earthquakes today. Due to shear failure, these rocks move relatively in opposite directions parallel to the discontinuity surface. This discontinuity may be (i) the surface of a previous fault or shear fracture, (ii) the surface of a previous tensile fracture that formed when intact rock was pulled apart by a strong tensile stress, or (iii) the surface of juxtaposition between disparate rock pieces. A discontinuity surface of either of the latter two types acquires after shear failure the above attribute of a fault. In this way, every tectonic earthquake is associated with movement on a fault at its source.

Plate tectonic processes are responsible ultimately for all tectonic earthquakes today. In each case, rock(s) at the source acquire strain and develop stresses due to these processes. Shear failure occurs in intact rock when the shear stress in the plane of the incipient fault exceeds the shear strength of the rock. Shear failure occurs along an existing discontinuity surface when the shear stress developed across it exceeds its shear strength. Cohesion and internal friction contribute to the shear strength of intact rock. The shear strength of a discontinuity surface comes mainly from friction between rocks on its two sides. The phrase 'frictional failure' is then a synonym for shear failure . As shear stress increases across an existing discontinuity surface, matching frictional stress also develops , but only up to a limit set by the friction coefficient for the discontinuity and the compressive normal stress exerted on it by the rocks pressing against each other.

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The movement of rocks during shear failure at the source of a tectonic earthquake sets up seismic waves and releases stored elastic strain energy. A significant part of the energy is radiated, while most of the rest appears as heat along the discontinuity surface.

Volcanic Origin: Only a few percent of the earthquakes today are attributable to volcanic activity. This activity may manifest itself through movements of magma and gases in the earth's crust or eruption of lava and escape of gases from the volcanic vents. Magma and lava are both molten rock but the former exists under and the latter above ground. Seismic waves are excited when magma and gases move in crustal rocks beneath a volcanic region. A part of the kinetic energy associated with these volcanic fluid movements is radiated as seismic wave energy.

Seismic Waves: R D Oldham worked with the Geological Survey of India for many years around the turn of the nineteenth century. He demonstrated in 1899 that seismic waves are elastic disturbances in the earth. He could do so by explaining the observed patterns on seismograms of the great Indian earthquake of 1897 using several theoretical results about elastic waves obtained by Poisson and Cauchy in the 1820s. Oldham argued that ground shaking due to both longitudinal and transverse seismic waves had been recorded on the seismograms. The waves had travelled from the earthquake source to the seismograph stations along paths through the interior of the earth. Similarly, Oldham used theoretical results obtained by Rayleigh in 1885 to argue that seismic surface waves too had been excited. As the name implies, they had travelled along the surface of the

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earth to reach the stations. Only longitudinal seismic waves travel through liquid portions of the earth, e.g., the oceans and the outer core. At least some of the seismic waves excited during an earthquake will reach every point on and in the earth.

Shaking: Two features of a mechanical wave may be recalled. Firstly, a mechanical wave is a disturbance travelling through a medium. Secondly, particles of the medium move locally in response to the disturbance. Seismic waves are mechanical waves for which the earth is the medium. They cause local movement or shaking of the particles of solids or fluids along their paths through the earth. The shaking of ground particles may be detected with seismographs and sometimes felt by human beings. Seismic surface waves produce the strongest ground shaking during an earthquake. Severe ground shaking causes damage and destruction of man-made structures. The region of damage is near the earthquake source because the intensity of shaking depends interalia on distance from the source. Thus, a large earthquake is often referred to by the geographic region where it produced maximum damage, e.g., the Uttarkashi earthquake of 1991. But, in principle, every earthquake however small produces shaking, however feeble, throughout the earth.

Some References to Earthquakes of the Past 5000 Years

In our attempt to estimate the date of the earliest earthquake, let us first see what observational evidence has been collected so far.

First Instrumentally Located Earthquake: Analyses of seismograms provide the most reliable data for earthquake catalogues. The seismograph was invented in Japan ca 1880 AD. The first earthquake would have been recorded with it soon afterwards. But to estimate the source location and the time of occurrence of an earthquake, we need records from at least five, but preferably many more seismographs at different locations. Initially, the number of seismographs grew slowly.

The first comprehensive worldwide catalogue of instrumentally located earthquakes was published by Gutenberg and Richter in

1954 in *The Seismicity of the Earth.* The earthquake of January 20, 1904 in Central America is the first in this catalogue. Gutenberg provided in 1956 instrumental locations of a few of the largest earthquakes of the 1896-1903 period also. The great Kangra earthquake of April 4 1905 is the first instrumentally located earthquake of the Indian region in Gutenberg and Richter's catalogue. The great Indian earthquake of 1897 appears in Gutenberg's supplementary catalogue.

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Historical References to Earthquakes: Since the 13th century BC, Chinese court historians have chronicled not only political affairs but also sundry notable events, including apparitions of comets and occurrences of earthquakes, epidemics, famines, and floods. The Chinese catalogue based on historical records begins with the earthquake of 1177 BC. However, Chinese legends mention other earthquakes dating back to ca 2221 BC. The earthquake of 416 AD is the most ancient earthquake identified from the historical records of Japan. Similarly, a destructive earthquake of 4th century BC is the first to be mentioned in the historical records of Iran.

Ari Ben-Menahem is a versatile Israeli seismologist. He suggests that catastrophic earthquakes between 2100 BC and 300 BC in Egypt, Israel, Jordan, Lebanon and Syria should have echoes in the Bible, especially the Old Testament. He attributes the destruction of the biblical cities of Sodom and Gomorrah to an earthquake south of the Dead Sea around 2100 BC.

Bapat, Kulkarni and Guha's catalogue of Indian earthquakes also goes back to the 3rd millennium BC, but its information is sparse for the period prior to 1800 AD. R N Iyengar, an earthquake engineer has been helping the cause of the Indian catalogue through examination of extant historical materials. He has drawn attention to Kalhan's *Rajtarangini*, the history of Kashmir from 2448 BC to 1150 AD, which mentions earthquakes in the valley between 1121 and 1125 AD.

Archeological Evidence for Past Earthquakes: Archeologists consider structural cracks, dislodged masonry and collapsed

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walls in ruins and offsets in archeological strata as evidence for past earthquakes. But caution and objectivity are needed. Settlements have existed near Jericho, north of the Dead Sea, almost continuously since about 9000 BC. Archeologists infer that the city was destroyed 17 times between 3100 BC and 2100 BC. Ben-Menahem argues that, if there is equal chance that destruction in each of these cases was due to erosion, flood, earthquake or war, then there should have been at least four earthquakes near Jericho in those 1000 years. He correlates archeological evidence to suggest that the earthquake ca 1560 BC may have damaged Jericho and Tel-Dir-Ala, 45 km away.

Recent archeological work in Egypt indicates that the ancient city of Alexandria may have been submerged due to earthquakes and floods in the 4th century AD. Excavations in the graveyard and mound near Sagzabad, in the district of Buyin Zara in NW Iran show that an earthquake in the 3rd millenium BC may have devastated many settlements.

In India, studies at Kalibangan I mound indicate that the pre-Harappan (ca 2600-2350 BC) occupation of this site in north Rajasthan may have been brought to a close by an earthquake. Also, many of the buildings in the second stratum of ruins near Taxila may have been destroyed during an earthquake ca 30 AD.

Paleoseismological Data: Paleoseismologists examine rocks and soils for evidence of past earthquakes. Gilbert's work during the 1870s and 1880s in the Great Salt Lake region of Utah, USA was the first study of this type. Studies of the San Andreas Fault at Pallett Creek in California indicate ten large earthquakes between ca 700 AD and 1857 AD. C P Rajendran of the Centre for Earth Science Studies investigated the sites of the 1993 Latur earthquake and the 1819 Kachchh earthquake. He finds evidence that respectively similar earthquakes may have occurred in the past at each site. Mohindra and Thakur of the Wadia Institute of Himalayan Geology attribute sedimentary features in a stream bed near Dehra Dun to earthquakes of 1720 and 1830 AD.

The Earliest Tectonic and Volcanic Earthquakes

While seismographic observations, scrutiny of historical records, archeological and paleoseismological investigations and a few other methods yield information on earthquakes of the recent past, the sense from geology is that we have to go literally a million times farther back in time to look for the earliest earthquake.

Our arguments are based on three assumptions. Firstly, we adopt the geological principle of uniformity as the philosophical basis for our inquiry and assume that earthquake processes in the past were similar to those today. Secondly, we adopt the above dictionary definition of an earthquake. Thirdly, we adopt the current view that the earth originated ca 4.5 GA through an accretion of cold particles. Here GA is giga annum or billion (10^9) years ago. Two of the many events that may have unfolded rapidly around that time are pertinent here. First, a substantial outer shell, if not the entire earth, melted within some tens of millions of years after its formation. Second, within a few hundred million years, a solid crust appeared due to cooling of the molten material.

The Earliest Tectonic Earthquake: Since shear failure occurs only in solids, such as rocks, we have an important conceptual constraint on the date of the first tectonic earthquake. It should have occurred when, during the cooling of the earth's outer molten part, one or more crustal rock fragments first solidified. Since, according to recent estimates, the solid crust of the earth may have formed between 3.8 and 4.2 GA, we may take this time range as our estimate for the probable period in which the earliest tectonic earthquake may have occurred.

It is conjectural whether the associated shear failure occurred in one of the intact crustal rock fragments or along the discontinuity surface between two fragments. The cause of the strain leading to the first shear failure is also conjectural. It could even be a rudimentary version of present day plate tectonics.

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The Earliest Volcanic Earthquake: Since the presence of a solid crust is visualised for the occurrence of volcanic earthquakes also, the first such earthquake too may have occurred in the period from 3.8 to 4.2 GA.

'Earthquakes' Prior to Solidification of the Crust: Richter, of the widely referred Richter magnitude scale wrote a monumental textbook with the deceptive title of *Elementary Seismology*. He recognised that seismic waves and the attendant shaking of earth may also be excited by causes other than tectonic and volcanic activity. He classified collapses of caves, landslides and meteorite impacts as minor causes of earthquakes today. He, in effect, defined an earthquake as a shaking of the earth that is of natural origin.

Acoustic waves in a lake, an ocean or an underground pocket of magma are longitudinal seismic waves. Artificially created bubbles have been used for decades to excite these waves for under water exploration techniques such as echo sounding, sonar and marine seismic methods. Thus, each episode of shaking of the earth due to seismic waves excited by a naturally formed bubble should be an earthquake. The intensity of shaking produced would depend interalia on the size and distance of the bubble and would be feeble in most cases. But the number of 'bubble' earthquakes overall could be extremely high.

The Earliest Bubble Earthquake: Innumerable bubbles would have formed naturally in the earth when it melted shortly after its cold origin. Each one of them would have shaken the earth to a degree commensurate with the energy involved. The earliest of these bubble earthquakes should be conceptually our second candidate for the earliest ever earthquake. Its date would be only a few tens of millions of years short of 4.5 GA.

The Earliest Collision Earthquake: Finally, let us recall again that Richter considered shaking of the earth due to a meteorite impact also as an earthquake. Let us then focus on the gas and solid particles in the solar nebula at a notional time epoch ${}_{sun}t_{earth}$. Prior to this epoch, the accretion for the future earth would be occurring in a part of the nebula. After the epoch, the accreted earth would be a planet of the solar system. In this part of the nebula/solar system, there would have been collisions galore before and after the epoch. Each collision would have excited longitudinal seismic waves in the gaseous portions and longitudinal and transverse seismic waves in the colliding dust, pebble, boulder or planetesimal sized pieces of solid matter. The shakings and reverberations due to these collisions were *sun quakes* prior to the ${}_{sun}t_{earth}$ epoch and earthquakes thereafter. This epoch then is our final estimate for the time of the earliest earthquake. The figure of 4.5 GA is appropriately suggestive and satisfactory here.

Discussion

Two sets of comments appear relevant here. Firstly, it is tempting to compare seismologists' search for the earliest earthquake to biologists' search for the earliest mother, say. In each case, the respective notion excites spontaneous interest but the goal is elusive when examined in detail. In each case, the long time elapsed poses immense difficulties for specific identification. In each case, the identification depends on a definition. Shall we restrict the search for the earliest mother to *Homo sapiens* only or shall we, with suitable logic look also among females of species from which *Homo sapiens* may have descended?

Secondly, we have conducted our inquiry by the stated assumption that earthquake processes of the past were similar to those operating today. Admittedly, this is restrictive. But, while it is scientific to allow other possibilities for the cause of the earliest earthquake, certainly the date of no other earthquake could be earlier than the suggested ${}_{sun}t_{earth}$ epoch for the first collision earthquake.

Conclusion

If we adopt Richter's broad view of what an earthquake is, then this phenomenon may be of great antiquity and the earth may have been shaking due to earthquakes literally from the very moment of its formation.

Suggested Reading

[1] C F Richter, *Elementary Seismology*, W H Freeman and Company, San Francisco, 1958.

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