Brief History of Paleoseismology and Reminder of Hazard Posed by Great Earthquakes along the Himalyan Arc

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Abstract

The career of K. S. Valdiya was marked by persistent calls to public agencies to organize and develop approaches to mitigating hazards posed by geologic processes. Prominent among them was the hazard posed by earthquakes. The observations brought forth with the development of paleoseismology over the past ~30 years have served well to quantify the size, location, and timing of great earthquakes that may be expected along the Himalayan arc in the future. The brief synopsis of the history of paleoseismology and the findings attendant to its application serve here to reiterate K. S. Valdiya's calls for public agencies to address the hazard posed by great earthquakes along the Himalayan arc.

Introduction

In the tradition of D. N. Wadia and A. Gansser, K. S. Valdiya brought forth contributions fundamental to understanding the stratigraphy and structural evolution of the Himalaya (Gansser, 1964; Thakur, 2003; Valdiya, 1980, 1984; Wadia, 1919). Equally significant were his unremitting efforts to distill scientific understanding of geologic processes attendant to the growth of the Himalaya in calls to public agencies to organize and develop approaches to mitigating the hazards posed by those processes (e.g., Valdiya, 1992, 1993, 2001, 2005, 2014, 2015). Among the most prominent of these remains that posed by earthquakes. I here provide a brief history of geologic studies that have advanced understanding of the expected location, size, recurrence rate of future large earthquakes along the Himalaya. The synopsis serves as a reminder and call to public and private agencies in India that, while the occurrence of great earthquakes cannot be prevented, society would be best served by organized approaches to mitigate the human and financial losses that will surely accompany the events.

The Beginning

Paleoseismology embodies the interpretation of the geologic record to assess the timing of past earthquakes. The discipline has its roots in efforts to recognize, understand and assess the rate and timing of development of geologic landforms produced by tectonic disturbance. The beginnings of such study along the Himalayan front are unambiguously traced back to the pioneering effort of the Japanese geographer Takashi Nakata. T. Nakata traveled to Calcutta, India and embarked upon a Ph.D thesis study that led to the seminal work entitled

Geomorphology of the Foot-Hills of the Himalayas (Nakata, 1972). Conducted at a time well before the conveniences of satellite imagery and general availability of topographic maps, the sketches and drawings at sites reached by the author largely on foot and public bus along ~2000 km of the Himalayan front clearly identify, describe, interpret, and attribute the occurrence of landforms produced by repeated earthquake displacements along the Himalaya Front Tectonic Line, a feature now more commonly referred to as the Himalayan Frontal Thrust (HFT). More specifically, he recognized along virtually the entire the length of the Himalayan Frontal Thrust the tectonic genesis of the numerous Dun valleys, youthful scarps in young sediments, and uplifted and back-tilted fluvial terraces that now serve to mark the trace of the HFT

Plate Tectonics and Blind Earthquakes

K. S. Valdiya and his predecessors early recognized that uplift of the Himalaya has resulted from displacement on major thrust faults that strike along the abrupt southern margin of the mountain range. Three major of these thrust systems strike the length of the Himalayan arc and from north to south include the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Himalayan Frontal Thrust (HFT) (**Figure 1**). All have been traced along the 2000 km length of the Himalayan Front. The development of plate tectonic theory in the late 1960s led to the generally accepted interpretation that the thrusting accommodates northward collision of the Indian subcontinent into Eurasia which commenced ~40 m.y. ago (Isacks et al., 1968; Molnar and Tapponnier, 1975, 1977). Seeber and Armbruster (1981) soon thereafter noted the tectonic similarity of the Himalayan arc with oceanic subduction zones and that major shaking during great historical earthquakes is confined largely to areas north of the HFT. From this they explained the occurrence of great earthquakes along the front to be the result of slip on a shallow decollement inclined northward at low-angle up to ~100 km and into which sole each the MCT, MBT and HFT (**Figure 1b**). The model and explanation is generally accepted today. The absence of observed surface rupture along any of the major thrusts during great historical earthquakes brought forth the idea that great Himalayan earthquakes were *blind*, such that the causative faults did not reach the surface to produce fault scarps but rather expressed only as warping or folding above the leading edge of the fault (Stein and Yeats, 1989). While the confinement of large earthquake ruptures to portions of the decollement may be expected and folding is observed along the front of the Himalaya, the early observations of Nakata (1972, 1989) had already provided clear indication that the largest displacements on the decollement consistently reach the surface to produce scarps and truncated terraces along the Himalayan frontal thrust.

Rates of Landform Development and Fault Displacement

Estimates of the ongoing rate of convergence across the Himalayan Front initially arose from plate tectonic and geodetic studies (Bilham et al., 1998; Molnar and Tapponnier, 1977). Such analyses today show ~40 mm/yr of northward convergence of India into Eurasia broadly distributed over a region extending ~1000 km northward into Tibet from the Himalayan front (Molnar and Stock, 2009), with 15 ± 2 mm/yr of the displacement today localized along the Himalayan front (e.g., Lindsey et al., 2018). The plate tectonic and geodetic analyses provide points of reference and comparison to geologic efforts to assess the slip rates of the major Himalayan thrust faults though the resolution of each method is insufficient to resolve rate of slip on the individual thrusts that strike the length of the Himalayan Front.

Efforts to geologically define rates of thrusting along the Himalayan front have largely been along the HFT. The focus arises chiefly in response to Nakata's early observations that repeated displacements is evident in Quaternary landforms along the HFT, whereas similar activity is not apparent along the MCT, and offsets of Quaternary landforms locally evident along the MBT show strike-slip displacements rather than w thrusting. Geologic estimates of the HFT slip rate have come largely from radiocarbon dating of detrital charcoal in fluvial terrace deposits uplifted and abandoned as a result of displacement on the HFT. The first of these efforts may be traced back to the studies of Wesnousky et al. (1999) and Lave and Avouac (2000) in India and Nepal, respectively. The India collaboration developed in response to Dr. V.C. Thakur's kind invitation to host this author at the Wadia Institute of Himalayan Geology as a visiting Fulbright Scholar. In these and similar studies to follow, division of the measured uplift of the stream terraces above modern stream grade by age of the uplifted deposit containing the detrital charcoal provide the measure of uplift rate due to offset along the HFT. Fault displacement rate is then assessed with assumption of the fault dip, which the few available direct measures place in the range of 30±10° (e.g., see Wesnousky, 2020). There now number about estimates of the rate of uplift at ~8 sites spaced along the HFT resulting from the collaborative efforts of Indian, Bhutanese, Japanese, French, and USA colleagues. The individual values of uplift rate determined from geology in this manner generally overlap with and thus agree with the 15 ± 2 mm/yr rate of convergence measured by modern GPS analyses (e.g., Wesnousky, 2020). Critically important to assessing seismic hazard along the Himalayan Front, the rate provides a measure of strain that is being accumulated each year along the decollement (MHT) that is ultimately released suddenly in earthquakes, the largest of which produce scarps along the HFT.

Timing and Size of Past and Future Surface Rupture Earthquakes: Paleoseismology

The collection of geological observations to assess the timing and size of past and prehistoric offsets on active faults is the substance of *Paleoseismology*. Along the Himalayan front and elsewhere around the globe the approach most often entails the application of structural, stratigraphic, soil, and radiocarbon analysis to young sediments deformed by fault displacement exposed in trenches excavated across active fault scarps. The earliest documented study using the approach dates to study of the 1968 Borrego Mountain earthquake (Clark, 1972) and subsequent excavations by Sieh (1978) across the San Andreas at Pallet Creek in California The first application of the approach along the HFT was led by Takashi Nakata in the 1990s (Nakata et al., 1998; Upreti et al., 2000). The brief abstract and conference proceedings that describe the work interpret the HFT to have produced surface rupture of 4 to 8 meters around 1200 AD. There now exist near 30 similar study sites the HFT as it strikes through India, Nepal, and Bhutan (**Figure 2**). The resulting observations provide measures of surface rupture displacements, the times of the displacements, and the potential length of HFT ruptures during these earthquakes. Taken together with measures of the HFT fault slip rate, the observations provide insight to the size of earthquakes that can be expected in the future and when they may occur.

Drawing upon the recent summary and analysis of Wesnousky (2020), the vertical displacement producing scarps along the HFT during the most recent geologically recorded events commonly range between 5 and 10 meters. Given that available direct observations place the dip of the underlying fault at an average of 30°, the displacement required to produce scarps of this magnitude are calculated to be twice the vertical separation: 10 m to 20 m (**Figure 3**). Average displacements of 5 to 10 m are commensurate with earthquakes that extend several hundred kilometers and more along the Himalayan arc (**Figure 4**), with magnitudes greater than Mw~8.5

(Leonard, 2010). The estimated values of rupture length are yet much greater if the scarps are the result of displacements between 10 m and 20 m. Strong support for these large rupture lengths and magnitudes (Mw>8.5) is also found in estimates of the timing of earthquake displacements interpreted from trench exposures. The bracket of time between the youngest sample from deposits deformed by fault displacements and the oldest from unbroken deposits in a trench is the *event horizon*: the range of ages bracketis when the displacement producing the deformation occurred. The similar and overlapping *event horizon* ages at adjacent sites along the arc is consistent with ruptures reaching ~500 km and plausibly ~800 km, the same as suggested by the vertical separation observed across numerous HFT fault scarps (**Figure 5**).

Modern GPS measurements tell us that slip is accruing on the Main Himalayan Thrust (MHT) at a rate of 15±2 mm/yr. The amount of slip accumulated and waiting to be released in an earthquake may be estimated by multiplying the rate times the period of time slip has been accumulating, which is marked by the event horizons shown for each site in **Figure 5**. It is found in this manner along the length of the Himalayan arc that the amount of slip stored and awaiting release is now equal to or approaching the amount of slip that occurred in the most recent earthquakes (**Figure 6**). The event horizon times viewed in this context tell us that the occurrence of similarly great earthquakes in the not-so-distant future cannot be viewed as a surprise: accrued slip since the times of last rupture is equal or approaching equal to the slip that occurred during the last earthquake.

Further reasoning that many of the scarps along the HFT are due to earthquakes of at least Mw~8.5 and very possibly reaching Mw~9 can be drawn from the historical record of past earthquakes. Several great earthquakes have been recorded historically along the HFT: the Mw>~8.6 ±.3 earthquake of 1505, the Mw 8.4 Bihar earthquake of 1934, and the Mw>~8.6 ±.3 Great Assam earthquake (e.g., Bilham, 2018). Each has been attributed to have produced hundreds of kilometers of rupture along the HFT. Yet, to the authors reviews, there remains no clear or definitive evidence that any of the events produced rupture of sufficient extent to reach the surface and produce scarps along the HFT or elsewhere (Wesnousky, 2021; Wesnousky et al., 2018a).It follows that earthquakes that have produced large scarps along the HFT are the result of events even larger than the great 1505, 1934, and 1950 earthquakes.

Today

Nakata's geomorphic study is that on which subsequent study of active faulting along the HFT has developed. The development of paleoseismologic methods later provided the means to recognize the occurrence and size of discrete earthquake displacements responsible for forming fault scarps. The ability to commonly assess the timing of the recognized displacements came with the concurrent development and application of Accelerator Mass Spectrometry in radiocarbon dating of very small pieces of charcoal and organic matter preserved in displaced deposits. The observations resulting from steady application of these approaches along the HFT over the last ~30 years are sufficient to confidently assert to the public that earthquakes in the past have produced surface ruptures reaching 10 – 20 m displacement along 300-500 km lengths of the HFT in earthquakes of magnitude certainly equal to at least Mw 8.5 and even approaching Mw 9. The physical and human devastation along the Himalayan front stands to be unmatched in recorded history when another of these events occur in the future. More sobering is that the observations inform us that the occurrence of another such earthquake along the HFT in the near future, be it next year or the next hundred, cannot be viewed as a surprise. Science and in significant part *Paleoseismology* have served well to define the real hazard embodied in the future occurrence of great earthquakes along the HFT.

May this note serve as a reminder of K.S. Valdiya's call to public agencies to not ignore but rather ultimately organize and develop approaches to mitigating this very real earthquake hazard.

Acknowledgements

Center for Neotectonic Studies Contribution #.

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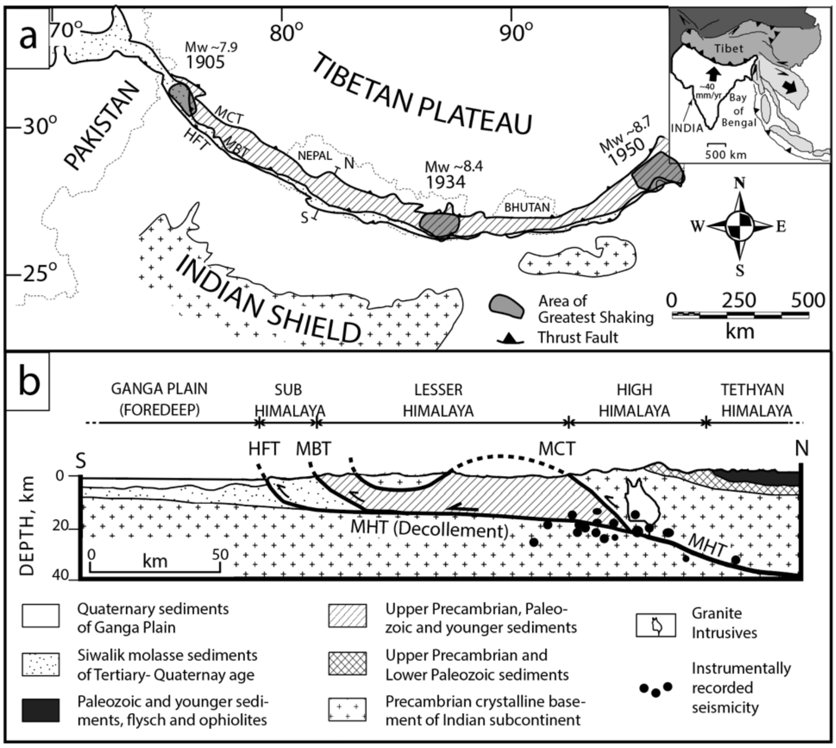

Figure 1. (a) Among the major structural elements of the Himalaya are the three major thrust faults that are largely continuous along the ~2500km long Himalayan arc: the Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT). Areas of greatest shaking during great earthquakes of 20th century are shaded and labeled with year. Inset illustrates on-going convergence between the Indian and Eurasia is ~40 mm/year. (b) Simplified cross section showing the Himalayan frontal thrust (HFT), the Main boundary thrust (MBT), and the Main Central Thrust (MCT) each soles into the shallow dipping Main Himalayan Thrust (MHT) decollement. Great earthquakes along the Himalaya are considered to be the result of displacement on the MHT. Figures adapted from Seeber and Armbruster (1981) and Kumar et al. (2006)

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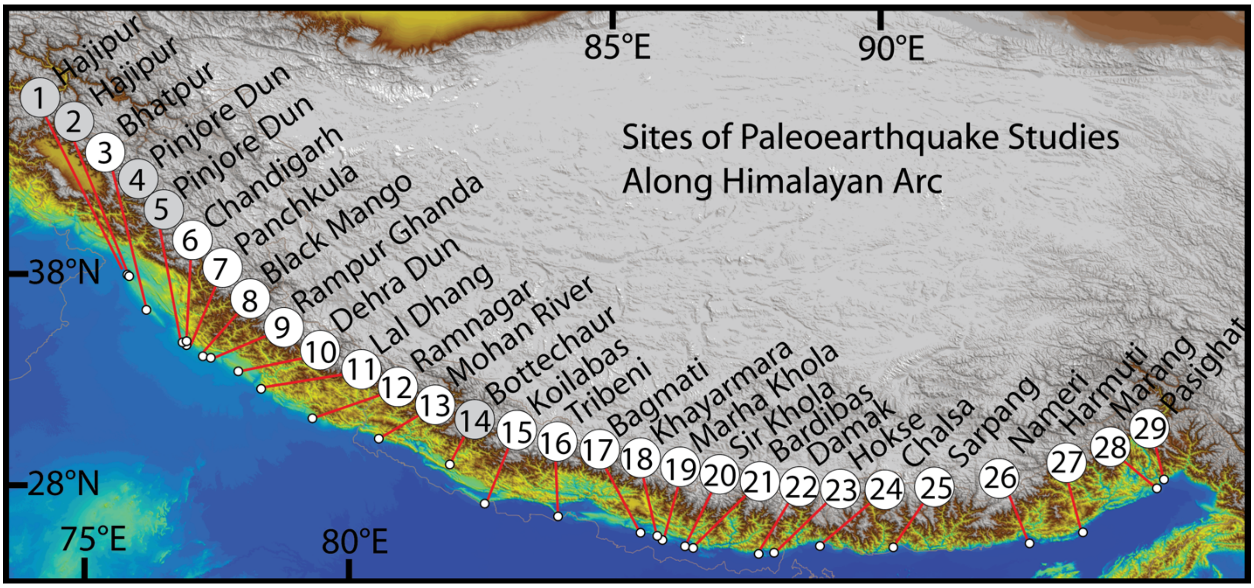

Figure 2. There now exist ~30 sites along the Himalayan Front where an international community of scientists have employed geologic principles to estimate the timing and size of past surface ruptures and the average rate of slip along the Himalayan Frontal thrust. (Citations of each study recorded in Wesnousky (2020).

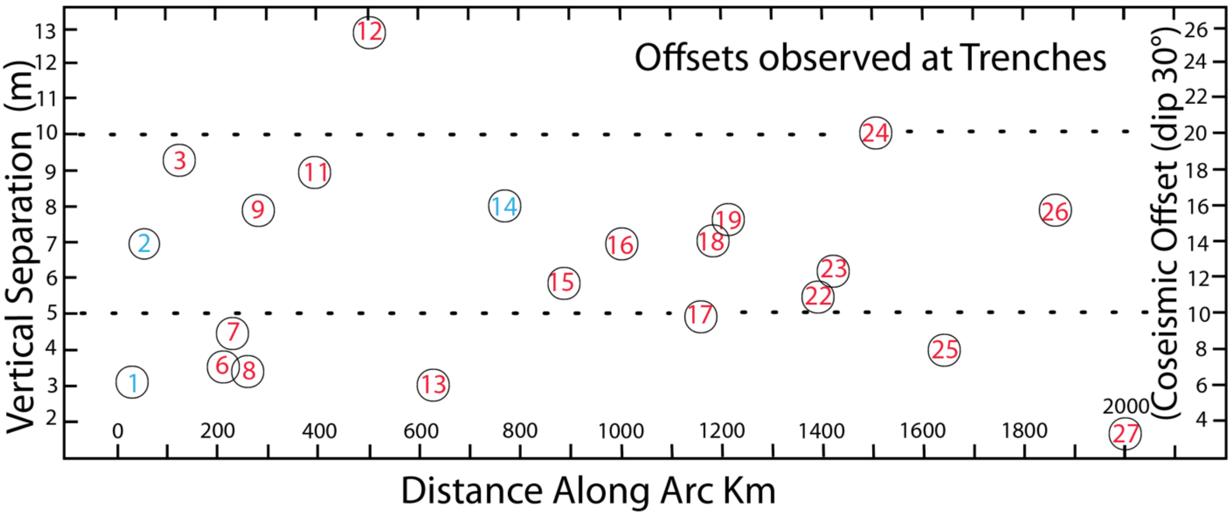

Figure 3. The vertical separation reported across fault scarps produced by the most recent displacement on the Himalayan Frontal Thrust (HFT) are commonly between 5 m and 10 m. The amount of slip on the HFT to create the vertical separation may actually be twice that (10 m to 20 m) when considering the dip of the HFT may be as low as 30° beneath the studied scarps.

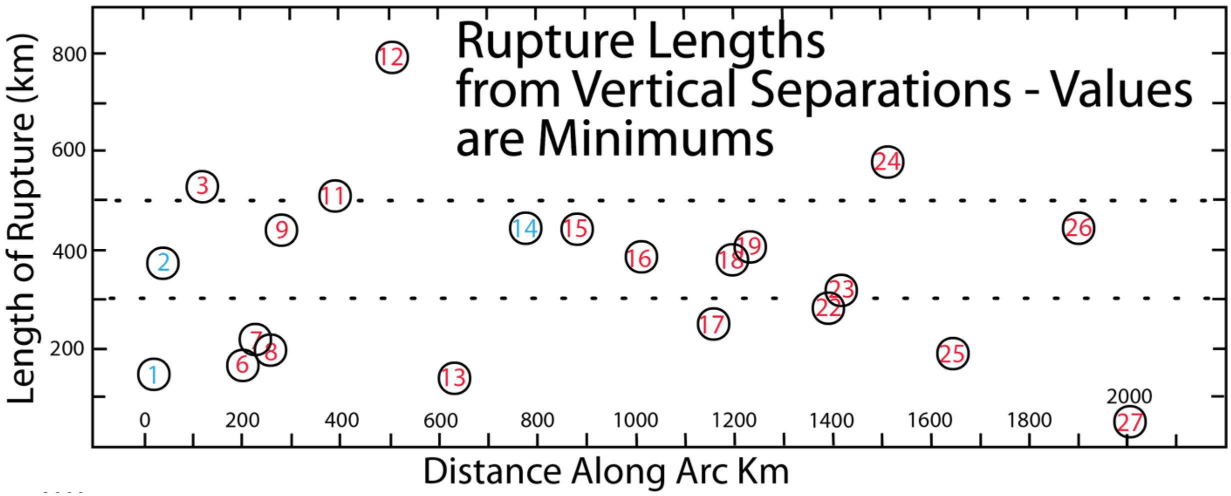

Figure 4. The rupture lengths of earthquakes that would on average be expected to produce the vertical separations observed across scarps at sites along the HFT are commonly between 300 km and 500 km, and significantly greater if the displacement producing the scarps is result of slip on a thrust that dips 30°.

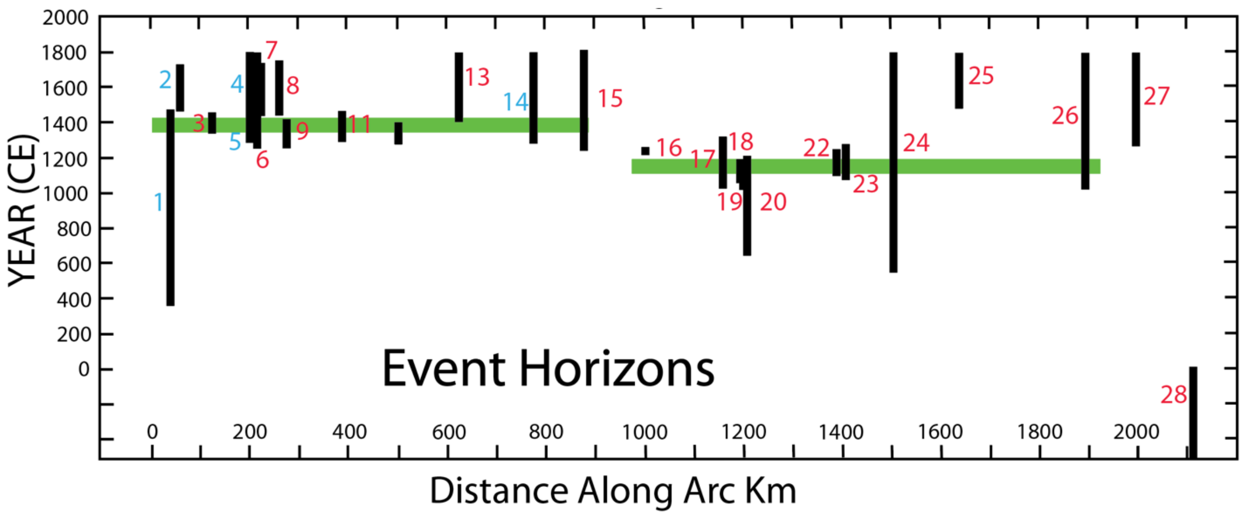

Figure 5. Paleoearthquake studies place limits on the timing of the most recent surface rupture earthquakes along the HFT. The overlapping event horizon ages determined at adjacent sites are plausibly due to the same earthquake with rupture lengths of 500 to 800 km (green bars).

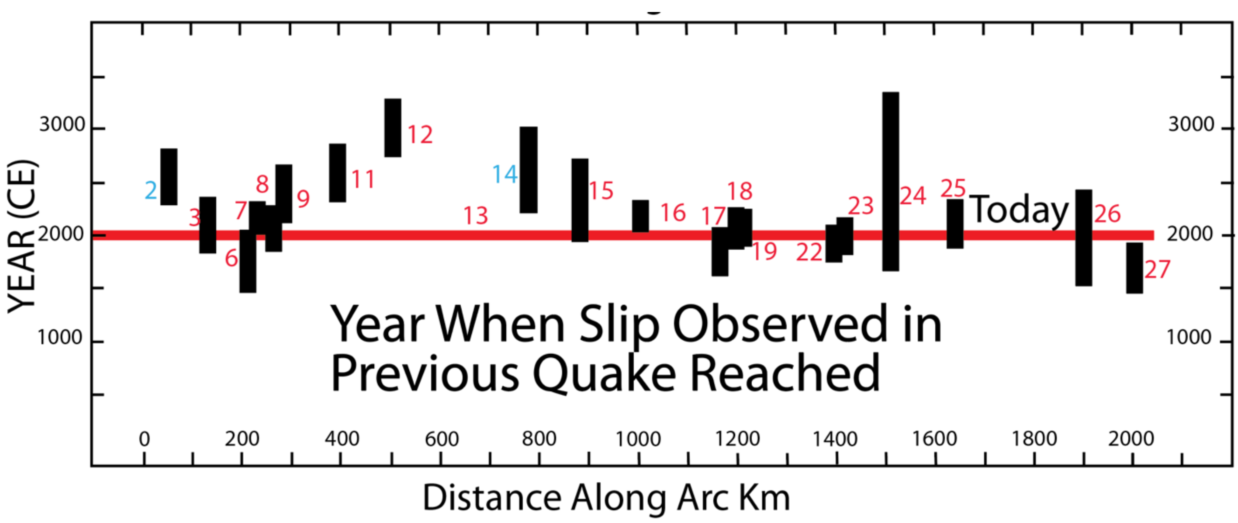

Figure 6. The amount of slip accrued since the time of displacement is now approaching or equal to the amount of slip registered in the last earthquake at sites studied along the HFT. The repeat of similar large earthquake displacements at any time in the future should be anticipated and if possible planned for.