Space-Time distribution of asperities as a possible clue to the seismicity role in tectonics

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Abstract

Statistical regularities of seismic process observed at Garm seismological polygon in Tadjikistan and Parkfield segment of San Andreas fault suggest that seismic process could be interpreted by assuming a number of fixed in space, self restoring asperities each responsible for earthquakes of a certain magnitude. Any process of asperity restoration under high confining pressure would result in pre-stressed state of the asperity material, which could explain its higher strength compared to surrounding media as well as high stress drop while asperity breaks. It is proposed that the latter is owed to the volume failure typical in a case of pre-stressed material. The above scheme shed a new light on the possible role of the asperities, i.e. earthquakes in tectonic flow, supplementing stick and slip view of seismogenesis by that involving an energy transfer from short scales (collapsing asperities) to long ones (tectonic flow), as it is the case in numerous ‘negative viscosity’ systems typified by ‘inverse energy cascade’ in terminology of Victor Starr [Starr, 1968].

1. Introduction

After nearly 50 years of instrumental seismology the earthquakes are still considered to be a dissipative phenomenon, although the simple frictional models of the beginning have greatly changed especially in recent years.

The need for such changes was caused by many discrepancies between accumulated observational data and those frictional models of seismogenesis of the past. To mention but a few:

1. The inter-plate stresses are low compared to intra-plate ones, in contrast to seismicity which tends to concentrate in the inter-plate zones [Zobak, 1992; Rodkin, 2001; etc].
2. High local stress drops versus low average stress drops observed at teleseismic distances [Hanks, 1974; Madariaga, 1979; Hardebeck and Hanksson, 1997;

Anderson, 1997]. A true push in this direction was given by the works on the San Fernando earthquake [Trifunac, 1972]. For the first time a strong earthquake was recorded with accelerographs placed in the near field of the main shock. These accelerograms gave the unique possibility to determine earthquake parameters from almost within the focal zone itself. This determination showed that the main shock was restricted to a very small volume compared to the zone of subsequent rupture, not to speak of the aftershocks zone. The stress-drop for this volume in the San Fernando earthquake was 700 bars compared to the stress-drop of the total rupture of 70-100 bars, suggesting that the main shock locality had material properties different from those of the surrounding media.

Work on the San Fernando earthquake triggered a number of papers in which parameters of strong earthquakes were reexamined. As emerged from these studies, a strong earthquake consists of at least two sub-processes: the main shock and a subsequent rupture [Madariaga, 1979; Aki, 1984; Bouchon, 1997; Santini et al, 2003; etc].

3. Spectral analysis of seismic radiation revealed for majority of earthquakes two angular frequencies instead of one as it follows from the models of smooth slip along total focal zone. This led to the notion of small volume high frequency sources coexisting with the low frequency ones due to overall slip along the fault zone [Aki, 1984; Hanks, 1981; Rautian et al, 1980; Rautian, 1991; etc].

4. Smallness of the main shock locality shed a new light on the problem of strong earthquake prediction. This smallness was the likely explanation of no precursors ever reliably observed prior to strong earthquakes [Scholz, et al, 1973; Nersesov, Lukk et al, 1973; Savage, 1993; Geller et al, 1997; Wyss, 1997; Wyss and Dmowska, 1997].

   Experimental evidence of main shock, for earthquakes of M≈5-5.5 in the central part of Garm region ([Lukk et al., 1995]) showed (Table 1) that linear dimension of the seismic source for those earthquakes yielded a length scale shorter than the accuracy of the epicenter location (1-1.5 km), whereas the existing models predicted a scale no shorter than 3 km for earthquakes of such magnitude [Wells and Coppersmith, 1994; Nadeau and Johnson, 1998; etc].

To come to terms with this experimental evidence, rather sophisticated models of seismogenesis were introduced just to mention a few of them [Aki, 1984; Bakun and McEvilly, 1984; Rautian et al, 1980; Rautian, 1991; Anderson, 1997; Nadeau and Johnson, 1998; Rodkin, 2001].

However in all cases of these models a particular single earthquake is viewed as a two stage process, which starts with a high strength small volume asperity break, producing a high first shock stress drop, followed by a low stress drop rupture spreading along the fault zone [Aki, 1984; Sammis and Rice, 2001; Chen and Sammis, 2003; etc].

Table 1. *Average residuals of the travel times for 16 seismic stations from 9 strong ($M \approx 5$ or $K=13–14$) and 100 weak ($M \approx 2.5$ or $K=8–9$) earthquake in central part of Garm test site*

Seismic stations	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Δ_{aver}, km	30	29	18	13	19	30	33	25
res_K=13 , sec	–0.26	–0.17	+0.31	–0.03	+0.14	–0.11	–0.04	–0.18
res_K=8–9, sec	–0.29	–0.18	+0.32	–0.01	+0.07	–0.05	–0.12	–0.20
Seismic stations	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Δ_{aver}, km	39	32	26	37	43	10	43	64
res_K=13 , sec	+0.18	+0.14	–0.03	–0.35	+0.02	–0.37	–0.28	+0.18
res_K=8–9, sec	+0.15	+0.26	–0.02	–0.35	+0.09	–0.44	–0.17	+0.24

If to consider that the asperities are occupying less then 1% of contact zone (see, for example, [Nadeau and Jonson, 1998]) though their breakdown stress drop is orders of magnitude larger than the stress drop resulting in the subsequent rupture along the fault zone [Rautian, 1991; Anderson, 1997; Bouchon, 1997; Nadeau and Johnson, 1998; Sammis and Rice, 2001] and so its energy fraction constitutes nearly 80% of the total energy of the earthquake; one has to suggest that asperities might play much more important a role than just being a trigger of a dissipative process of fault fracturing in the course of an earthquake.

2. Space-time statistics of asperities

If such a small volume disturbances, not bigger then ~1 km^3 even for the strongest quakes [Wyss and Brune, 1967; Hanks, 1974; Bouchon, 1997; Nadeau and Johnson, 1998; Chen and Sammis, 2003], may yield most of the earthquake energy release, their space-time statistics becomes particularly important not only for estimating the seismic hazard along a seismoactive fault zone, but also, as a possible clue to the physics of asperity and seismicity as a whole.

Several questions are to be answered:

1. How many asperities are there in each seismoactive region, and how are they distributed?
2. Are asperities restored after each earthquake in the same place or do the new ones appear along the faulting zone; or, present initially, are they destroyed one by one, resulting in the seismicity dying out in the region.

To the best of our knowledge, neither paleo-seismo-dislocation analysis nor the available historical data show such a seismicity dying out for in at least 10^3-10^4 recent years, moreover, numerous seismic cycles have been recorded in a region comparable in size with the focal zone of a strong earthquake [Fedotov, 1966]. If local strong seismicity is not decaying for many periods of quake repetition at the same locality, the asperities responsible for the first shocks are to be somehow restored in the region. Thus, another question of central importance for seismic mapping as well as for a physics of asperity could be formulated as follows:

3. Are the relevant asperities localized and restored in the same locality or, rather, show up anew each time at a different location with an equal probability along a seismoactive faulting?

Even without being able to penetrate the tectonic interior we may try to answer these questions based on an accurate statistical analysis of the first shocks seismicity.

Unfortunately, no such instrumental data are available for strong earthquakes. The shortest recurrence time for strong quakes with $M \geq 7$ in the same region is in the range of 100-150 year that is larger than any period of available instrumental observations.

On the other hand, for ‘weak’ and ‘average’ earthquakes with magnitudes up to M~4-5 such observations do exist, for a number of seismoactive areas including the San Andreas fault zone in California, USA, Matzushiro region in Japan, and the Garm Seismological Polygone in Tadjikistan ([Lukk et al., 1995]). The data from the latter collected during 38 years of continuous observations on the same dense network of seismic stations equipped with identical instruments and earthquake’s parameters estimation, invariable through the entire period of observations seem to form quite suitable a base for such an accurate statistical analysis. Such an analysis carried out by one of the authors nearly 40 years ago [Tsvetkov, 1971] and confirmed by our recent analysis of the accumulated Garm data ([Lukk et al, 2009], in prepared) revealed a number of regularities in the spatiotemporal behavior of the first shocks and the asperities, or high strength small volume disturbances, related to these shocks. The main findings may be summarized as follows:

1. Low magnitude seismicity possesses a well defined fixed and self repeating spatial structure the more pronounced the higher is the shock energy [Tsvetkov, 1969, 1970, 1971].
2. Seismic epicenters of stronger shocks concentrate in regions whose area shrinks with the increase of the shock’s strength [Lukk, 1978; Tsvetkov, 1971], so that for the strongest earthquakes of the region we observe a small number of space-fixed localities, each producing a semi-regular sequence of seismic events (see Figure 1). Naturally, to identify these localities, the data are needed for a time period longer than the average time interval T_M between subsequent shocks with

magnitude M at the same focal zone that is the mean recurrence time of the shocks of a given magnitude in a single focal zone, that is, related to the same asperity.

3. The average recurrence time for a single focal zone, as well as the number of potential focal zones, varies with their related energy according to the following approximate empirical rule. Let us consider a sequence of energies $K_k = 4+1.8$ M (K_k – energy class in Rautian scale analogous to $M \approx m_b$ – magnitude earthquake in Richter scale) and their corresponding recurrence times T_k. Then, for the average recurrence time we have $T_k = \alpha\, T_{k-1}$ where $1.5 < \alpha < 1.7$, with the number of potential seismic sources in the observation region decreasing in approximately the same proportion (see Figure. 2 and Table 2).

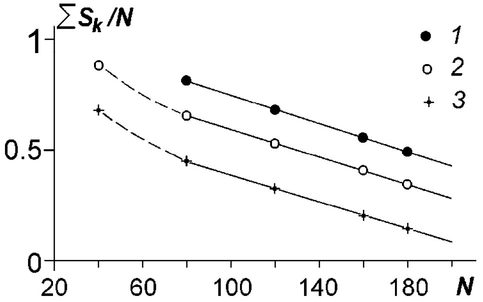

Figure 1. Specific area occupied by earthquakes epicenters: S_k – error of a single epicenter area determination, N – number of epicenters; only once intersecting epicenter's' areas were taken into account in sampling

1 – random case;

2 – shocks with K=7 (M=1.7);

3 – shocks with K=10 (M=3.3)

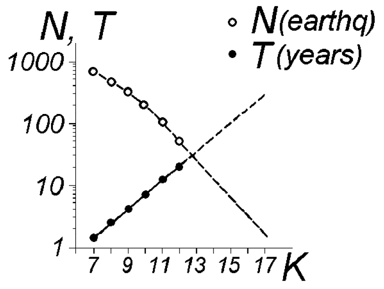

Figure 2. Number of earthquakes and the corresponding time of observation necessary to form a stable spatial distribution of first shocks asperities in the Garm Region

Table 2. *The number of years necessary to form a stable space distribution of earthquakes of different magnitudes obtained through extrapolation of one asperity period for K=10 to higher energies. Extrapolation step is 1.5 taken from Figure 3. Comparison with magnitude-frequency graph shows, that there is only one asperity corresponding to $K \approx 17$*

K (M)	10 (3.3)	11 (3.9)	12 (4.4)	13 (5)	14 (5.5)	15 (6.1)	16 (6.7)	17 (7.2)
T years	8-10	12-15	18-22	27-34	40-50	60-75	90-112	135-170

4. The time series of shocks for a single focal zone follow Poisson distribution with a 'dead' time no shorter than 3/4 the average recurrence time between successive earthquakes, (see Figure 3).
5. Correlation between the identified spatial distributions for different energies drops with the increase of energy increment [Tsvetkov, 1971].

The obtained results were interpreted through the following simple model picture of seismogenesis.

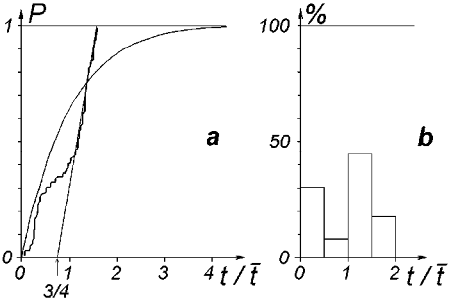

Figure 3. *Distribution of the intervals between successive shocks with K=10 (M=3.3) at the same asperity throughout the Garm Region (a) and the corresponding histogram (b). First maximum at the histogram may be interpreted as a noise due to shocks which occurred at the near-by asperities. Second maximum at the histogram corresponds to the average period of shock recurrence at the same asperity within a 3 km wide zone of standard error of epicenter location (*$t_{over} \approx 10$ *years). Straight line at the first graph of distribution function (a) corresponds to the truncated Poisson distribution with "dead" time no less than 3/4 of the average interval between shocks at the same asperity.*

In a given region, the seismic process is produced by a number of nonintersecting self restoring seismic sources fixed in space, each responsible for earthquakes of a certain magnitude. The number of these seismic sources, asperities, in a current terminology, depends on their related energy, as does the corresponding shocks recurrence time.

Extrapolated predictions of this model to higher energies were tested against independent observations and compared with each other. For example, according to this model, only a 1.5-1.7 longer time of registration is needed for K_{k+1} compared to K_k in order to reach the same level of space distribution stability in the earthquakes occurrence. However in terms of magnitude-frequency distribution this means that there should be 1.7-2 times fewer shocks with energy K_{k+1} compared with quakes K_k to have the same stable picture. Thus, for K=10 there should be approximately 5 to 8 times fewer shocks than for K=7 for the same stability of spatial seismic picture in accord with data in Figure 2.

According to this line of reasoning, one could estimate the number of asperities in a given region for different low magnitude earthquakes, with a subsequent extrapolation of the obtained figures to earthquakes of higher magnitude. Thus, for example, according to Figure 2, for $K=10$ the number of earthquakes in 10 years (average period of repetition at one asperity) should be expected to be around 200-250 shocks. For $K=13$, this figure stands already at about 25 shocks, that is 8-10 times fewer than for $K=10$. By assuming the same proportion for the $K=16$ earthquakes, we arrive at the estimate of one shock, that is, one asperity per entire region. This yields according to Table 2 the estimate of 135-170 years for the $K=17$ recurrence time, in accord with the estimate based upon the frequency-magnitude graph. As well as historic records of the strongest quake in the region [Lukk et al, 1995] Several successful tests of this kind suggested that seismic activity could be reasonably modeled as a self repeating process generated by spatially fixed sources.

Instrumental data analysis of microseismicity for Parkfield segment of San-Andreas fault seem to lead to similar a conclusion [Nadeau and Johnson, 1998]. It appeared that microearthquakes with seismic moments M_0 from 10^{15} to 10^{25} dyne·cm (magnitudes from –2 to +4) are produced by space fixed asperities which occupy less then 1% of total length of seismic zone. Each asperity generates a quasi-regular sequence of shocks with identical wave form of seismic graphs, which strongly supports the idea of shocks being to be produced by the same restored asperities [Nadeau and Johnson, 1998].

Another approach invoking the possibility to extrapolate the results obtained for low magnitude earthquakes to higher energies is that of fractal models of seismogenesis [Bak et al, 1988; Narkounskaia et al, 1992; Lukk et al, 1996; Sammis and Smith, 1999; Johnson and Nadeau, 2002; Chen and Sammis, 2003]. These models intrinsically assume self-similarity of the seismic process in the entire range of magnitudes and energies as a fundamental prerequisite of fractal presentation.

3. Restoration Cycle

According to the above general picture of seismic process, a finite number of high strength localities fixed in space (asperities) generate high stress drop first-shocks. These latter, followed by ruptures in the low stress drop fault zones, determine the seismic activity in the region. After each event of this kind, every asperity has to restore its strength in preparation for the next shock at the same focal locality.

This implies, in particular, that any admissible mechanism of restoration has to repeatedly provide a failed asperity with strength much higher than that of the surrounding, as a necessary prerequisite for storing an amount of potential energy sufficient for producing a subsequent shock with energy release no weaker than the previous one.

Comparison of the stress drops of the first-shock with those of the ruptures that follow, 1000-1500 bars versus ~50-100 bars, suggests that only a complete volume failure (crash) of the asperity may account for such an enormous difference. This also applies to the energy proportion of the first shock versus the total energy of the earthquake. Inspection of the values of destruction modules of various materials in Table 3 supports the notion that volume crash may provide sufficient energy difference compared with energy release due to rupture or slip as well as absolute values of the modules relate exactly to the corresponding stress drops.

Table 3. *Strength of mineral compounds [De Sitter, 1966]*

Compound	k_c, *kG/cm*^{2}	k_s, *kG/cm*^{2}	k_t, *kG/cm*^{2}
Granite	1350	102	48
Sandstone	530	46	27
Limestone	1360	104	64
Dolomite	1300	70	28

k_c – compression strength; k_s – sheer strength; k_t – stretching strength

Central for this argument is the view of asperity's restoration whatever is the consolidation process under a very high confining pressure exerted by the surrounding. Consolidation under a high confining pressure would result in the restored asperity being highly pre-stressed. The analogy here is with a pre-stressed glass or concrete, characterized by their high strength combined with brittleness. Such pre-stressed high strength materials are known to be subject to a total volume failure, an explosive 'crash'. Little energy is needed to trigger such an explosion; a slight local 'scratch' or any other defect, say, due to ageing of the surface of a pre-stressed glass, capable to withstand enormous macroscopic loads, may suffice for its complete collapse into dust.

Volume failure of this kind of an asperity could account for the high proportion of the first shock energy in the total energy released by an earthquake. In addition, such a 'crash' nature of failure might considerably contribute to rapidness of the subsequent asperity's consolidation. Indeed, the 'crash' may yield the appearance of a very porous volume, thus, providing the conditions for a rapid infiltration into it of a two-phase magmatic liquid, undergoing adiabatic cooling followed by a rapid crystallization under pressure. As a result, a pre-stressed asperity is restored, closing the cycle.

Curious an instance of a complete volume asperity 'crash' into powder was personally communicated to one of the authors (E.Tsvetkov) by I.L.Nersesov (1970), well known geophysicist and coordinator of experiments at the Garm test site. According to Nersesov, (on a unique occasion, after a coal mine shock, the miners were able to reach the very hypocenter of the shock (locality where the shock originated). This hypocenter turned out to be in spherical inclusion of powder, about 2 meters in diameter.

In any case, whatever the specific mechanism behind an asperity restoration cycle might be, the instrumental statistical data at our disposal support its very existence, and allow us to draw the following possible general picture of a seismic process as follows:

1. Asperities are self restored in a form of fixed distribution over tectonically active contact zone.
2. Brittle strength of each asperity higher than in the surroundings is due to its pre-stressed state caused by influence of high confining pressure, whatever is the process of this asperity restoration.
3. The next strong earthquake originates as a crash of a restored asperity due to a minor local perturbation such as any accidental deformations or erosion of the brittle pre-stressed volume.
4. Volume destruction of an asperity yield a high energy release registered as a high stress drop in the first-shock locality.
5. The high energy release due to volume destruction of asperity initiates spreading of a rupture in a low stress drop media in accordance with the Griffith's theory of simple crack propagation [Griffith, 1921].
6. Crack propagation results in a simultaneous 'slip' along the contact tectonic zone.

Thus, according to this phenomenological picture, the nature adopts the minimal energy waist strategy employing the interplay of the three material strength modules, those of bulk failure, rupture and slip. According to this picture, the high strength asperities might draw their potential energy from some phase change process rather than from the general tectonic flow. This amounts to supplementing the classical stick-and-slip view of seismo-genesis by that involving an energy transfer from the short scales (collapsing asperities) to the long ones (tectonic flow), as a 'negative viscosity' process typified by 'inverse energy cascade' [Starr, 1968]. In this framework the high strength brittle asperities perform an active triggering function producing 'slips', rather than being a passive slip preventing agent. In this respect, 'negative friction', due to the phase change may play an active role of initiating and organizing the tectonic movement.

4. Discussion

The idea of active role of strong earthquakes in the tectonic process was introduced nearly three decades ago by one of the authors [Tsvetkov, 1980].

By active role we mean the momentum and energy transfer from earthquakes to the mean tectonic flow. This situation is reminiscent of the relation between the large and small scale turbulent structures in hydrodynamics known as the inverse energy cascade [Levich and Tsvetkov, 1985], which may be related in terms of «negative viscosity» [Star, 1968]. The author of this term, Viktor Star, attributes to «negative viscosity» the role of basic instrument of organization and pattern formation in large complex systems with various mechanisms of energy transformation. Active tectonic systems may well fall into this category of self-organization, experiencing a similar inverse cascade from the small short-time seismic scales towards the large long-time scales of general tectonics. At the same time, energetically, it is more advantageous to crash a number of small volumes with in-thrust at the moment of rupture rather than in-thrust as a steady sliding. Thus, assuming the nature 'playing a minimum energy game', we parallel the in-thrust of tectonic plate to the in-thrust of a nail into a brick through light strokes, instead of applying a steady pressure which should be very high for this purpose.

The results of Garm polygone studies have not been yet applied directly to other locations of seismic activity either in the form of models or seismic risk estimates. On the other hand, it appears that based on them some new insight may be drawn both regarding the general approach to seismicity and practical risk assessment through a more detailed and objective seismic regionalization. Simultaneously, if indeed the first shocks repeatedly originate at the same fixed locations, the possibility of the anticipated strong earthquake forecast in a given region is greatly simplified. This view is supported by numerous paleo-dislocations studies which suggest that in the geological past major documented earthquakes indeed often reoccurred in practically the same locations [Dolan and Rockwell, 2001; Rogozhin et al., 1998; etc.]. As well as the recent terrible 2004 Indonesian earthquake (M_W=9.2) [Nelson et al, 2000]. In terms of our model, another earthquake of comparable strength should not be anticipated in Indonesia in the 100-150 years to come; whereas in San-Francisco, where another major earthquake occurred in the beginning of 20th century, an earthquake of comparable magnitude may occur at any moment with the same epicenter of the first shock.

Development of a high strength inclusion may only slightly affect the deformation processes in a region. Thus, such a development may manifest itself only short time prior to the collapse of asperity and only in its nearest vicinity. In practical terms, this means that for an efficient earthquake forecast, measurements should be carried out in the locations of previous strong-shock epicenters, and short term rather fluctuations of geophysical fields preceding the asperity collapse should be looked for [Deshcherevsky, Lukk, Sidorin, 2003].

The asperities active role concept may also help to resolve the following long standing ‘driving force’ problem [Andrews, 1972; Artyshkov, 1973; Richardson et al, 1979]. Estimates of the compressive stresses of the expansion centers indicate that absolute magnitudes of the deviatory stress components are only about a few hundred bars which is hardly sufficient to constitute a ‘driving force’ for interplate movement [Andrews, 1972; Artyushkov, 1973]. If, however, one accepts the active role of the first-shock disturbance these stresses prove sufficient to carry on the under-thrusting process.

5. Conclusion

The proposed mechanism of recurrent strong shocks, albeit speculative, originated from the analysis of instrumental data. This mechanism naturally leads one to considering the possibility of an active role played by strong earthquakes in tectonic movements.

It is probable that the low-magnitude shocks play more dissipative a role compared to the strongest shocks in a region. It is difficult to see the difference between the strongest inter- and intra-plate earthquakes, the latter possibly being decaying remnants of the former.

Of course, the most convincing proof of the proposed scheme would be recurrence of a strong earthquake at the very same location where it already occurred in the past and had been instrumentally recorded, but in practical terms, and perhaps fortunately for contemporaries, waiting for such a natural test, e.g., Pacific earthquakes to recur, may take too long.

Nevertheless, admitting the notion of earthquake acting as a mediating factor for plates under thrust could affect considerably our views on the subject of seismicity as well as the large scale tectonic movements. Strongest shocks serving as a momentum transfer mechanism from the smaller-scale disturbances to the mean tectonic flow would place the large-scale tectonic movements into the general category of ’negative viscosity‘ phenomena in self organized systems abundant in nature.

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