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On the Migration of Precursors of Strong Earthquakes

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On the migration of precursors of strong earthquakes

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ABSTRACT

It is found that perturbations presumedly associated with swarms, the B patterns and the BG pattern precursors of strong earthquakes in New Zealand, California and Apennines, propagate in the crust of the Earth with a velocity of the order of $cm s^{-1}$. The hypothesis that a single travelling elastic perturbation causes a set of precursors of the same strong earthquake is discussed and it is concluded that each precursor is associated with a different perturbation.

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INTRODUCTION

In many studies of earthquake prediction swarms (Caputo *et al.*, 1977), B patterns (Keilis Borok *et al.*, 1980a; Keilis Borok *et al.*, 1980b) and BG patterns (Caputo *et al.*, 1983) are proved to be intermediate precursors of strong earthquakes (SE).

The rigorous definitions of these precursors, as well as a complete list of these studies, is found in the papers of Keilis Borok *et al.* (1980a,b).

The use of these precursors for long- to intermediate-term prediction has proved successful in several instances, however, improvements relative to the size of the area where the strong earthquake is expected are obviously desirable.

This paper is intended as a contribution to the solution of this problem with the estimate of the velocity of propagation of the presumed elastic perturbations associated with these precursors from the area, where the precursor has been found, to the epicentre of the expected strong earthquake (*VPSE*) or to the following precursor of the region (*VPSS*).

In a preliminary note only the VPSE were reported (Caputo, 1992). In the hypothesis of a single elastic perturbation moving with constant velocity and direction, however, the VPSE and VPSS of the same strong earthquake would obviously not be independent.

A reasonable hypothesis is that there are migrating elastic perturbations which manifest themselves with swarms, patterns B and patterns BG of earthquakes or a strong earthquake where they meet regions whose elastic conditions are of nearly unstable equilibrium and where a small perturbation may cause the release of the stored elastic energy.

In the computations and the discussion of the results it is assumed that the perturbation is moving in a straight line with constant velocity; however, due to the chaotic condition of the crust, this hypothesis is probably an oversimplification. For the same reason it would also be an oversimplification to assume a radially symmetric propagation. In their propagation the perturbations probably favour directions of weakness in geological structures.

One must also bear in mind that, in the hypothesis of an elastic perturbation plane wavefront moving with constant velocity and direction, the velocities, computed dividing the distance between the points where the supposed perturbation has arrived, by the difference of the arrival times, would give only a phase velocity which in turn would only be an upper limit to the actual velocity of propagation of the wavefront of the perturbation.

In the case where several successive precursors approaching the same strong earthquake, are caused by the same elastic perturbation, the smallest velocity computed would be the closest one to the actual velocity of the perturbation.

In appendix A we estimate the direction of propagation of the perturbation that is valid in the case when the strong earthquake is preceded by at least two precursors presumedly caused by the same perturbation. When the precursors are three then the method would allow us to estimate the direction of the perturbation with one constraint and to check the result. However, such favourable circumstances seldom arise. The case of 3 precursors preceding the same strong earthquake occurred once in New Zealand and California with the B precursors and once with the swarms and with the BG precursors in the Apennines.

If the VPSE and VPSS were independent of time and functions of the paths (hopefully only of the region) between the precursor and the expected strong earthquake, when calling the alarm it would be possible to reduce to a ring around the precursor the area where the strong earthquake is expected. The radius of the ring will increase with time depending on the local values of VPSE, on the VPSS and on the safety criteria.

In this paper we will report the VPSE and the VPSS in New Zealand, California and the Apennines and tentatively discuss the determination of the actual velocity of propagation of the perturbations and the possibility that the precursors of the same strong earthquake be caused by one or more perturbations. The possibility of reducing the size of the 'alarm region' and the geological implication of the motion of the perturbation may be discussed in subsequent studies.

THE VPSE AND VPSS IN CALIFORNIA

The computation of the VPSE and VPSS in California is based on the data of

Keilis Borok *et al.* (1980a) concerning the B precursors. The strong earthquakes preceded by the B precursor's patterns are 7 and have a total of 10 precursors. The results of the computations are presented in the columns of the VPSE and VPSS of Table 1. The coordinates of the precursors are those of the baricentre of the epicentres of the B pattern. The time is that of the B pattern.

THE VPSE AND VPSS IN NEW ZEALAND

The computation of VPSE and VPSS in New Zealand is also based on the data of Keilis Borok *et al.* (1980a) who used the B patterns. There are 5 strong earthquakes preceded by B patterns with a total of 11 precursors. The results of the computations are presented in the columns of the VPSE and VPSS of Table 2.

THE VPSE AND VPSS IN THE APENNINES

The computation of the VPSE and VPSS of the Apennines are based on the data of Caputo *et al.* (1977) for the swarms and on the data of Caputo *et al.* (1983) for the BG patterns.

The results of the computations are presented in Table 3 for the swarms with 13 strong earthquakes preceded by 20 precursors and in Table 4 for the BG patterns with 6 strong earthquakes preceded by 10 precursors.

Concerning the swarm precursors Caputo *et al.* (1977) report only the year of the swarm since this is defined by the number of earthquakes in a model area of given geometry per calendar year. Since three different earthquake catalogues were used for this work and two of them are no longer available it is simply assumed here that the time of the swarm is half of the calendar year when it occurred. The timing of the BG pattern is considered to be that of the earthquake which allowed an alarm to be called.

The VPSE computed in Caputo (1991, in press) for the swarms in the Apennines assume as time of the swarm the end of the calendar year when it occurred, giving somewhat larger values for the VPSE.

Table 1. Strong earthquakes in California with their magnitude M, B precursor patterns (as defined in Keilis Borok *et al.*, 1980a), velocity VPSE of propagation from the precursor to the strong earthquake and velocity VPSS of propagation between precursors. λ is longitude and φ is latitude. The numbers in the first column refer to the geographic position of the precursor in Fig. 1.

Reference to the position of the epicentre in Fig. 1	Date	φ(°N)	λ(°W)	*M*	VPSE ($cm\,s^{-1}$)	VPSS ($cm\,s^{-1}$)
	11 3 1933	33.6	118.0		0.59	
	31 12 1934	32.0	114.8	7.1		
	1 7 1941	34.4	119.6		0.95	
	21 10 1942	33.0	116.0	6.5		
(4.1)	15 3 1946	35.7	118.1		0.30	0.41
(4.2)	10 4 1947	35.0	116.6		0.24	1.02
(4.3)	24 7 1947	34.0	116.5		0.034	
(4)	4 12 1948	33.9	116.4	6.5		
	28 7 1950	33.1	115.6		0.61	0.80
	21 7 1952	35.0	119.0	7.7		
(6.1)	19 3 1954	33.3	116.2		0.28	
(6.2)	12 11 1954	31.5	116.0		0.088	
(6)	9 2 1956	31.8	115.9	6.8		
	1 12 1958	32.3	115.8		0.041	
	9 4 1968	33.2	116.1	6.4		
	21 3 1969	31.2	114.2		0.89	
	9 2 1971	34.4	118.4	6.4		

Table 2. Strong earthquakes in New Zealand and their B precursor patterns, as in Table 1. The numbers in the first column refer to the geographic position of the precursor in Fig. 2.

Reference to the position of the epicentre in Fig. 1	Date	φ(°S)	λ(°E)	*M*	VPSE ($cm\,s^{-1}$)	VPSS ($cm\,s^{-1}$)
	26 6 1946	43.2	171.5		2.02	
	27 8 1947	39.7	179.2	6.7		
(2.1)	22 5 1948	42.5	172.9		0.75	0.05
(2.2)	10 1 1951	42.8	173.2		7.91	
(2)	23 4 1951	37.8	178.2	6.7		
(3.1)	28 8 1952	39.9	176.9		0.37	0.25
(3.2)	14 3 1956	36.7	177.7		1.18	
(3)	24 5 1960	44.2	167.7	7.0		
(4.1)	10 5 1962	41.7	171.3		0.031	0.56
(4.2)	4 3 1966	38.8	178.2		0.89	
(4)	23 5 1968	41.8	172.0	7.1		
(5.1)	28 2 1974	36.6	177.0		1.76	6.39
(5.2)	20 9 1974	44.4	168.0		0.10	17.85
(5.3)	5 11 1974	39.5	173.5		1.61	0.80
(5.4)	20 3 1976	39.3	177.5		26.2	
(5)	4 5 1976	44.7	167.5	7.0		

THE VELOCITY OF PROPAGATION OF THE PERTURBATION

As we mentioned, there are cases in which a strong earthquake is preceded by more than one precursor; in Tables 1–4 it can be seen that there are 2 in California and 4 in New Zealand preceded by more than one B pattern and in the Apennines there are 8 strong

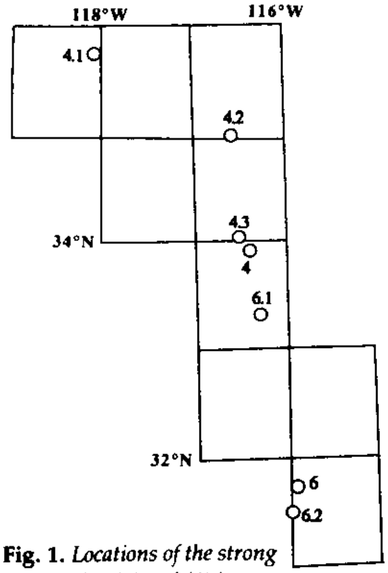

Fig. 1. *Locations of the strong earthquakes (6) and (4) in California and their precursors. The points with one reference number indicate the strong earthquake, those with two reference numbers indicate the precursors; the second number indicates the sequence of the precursors and is increasing with time. See also Table 1.*

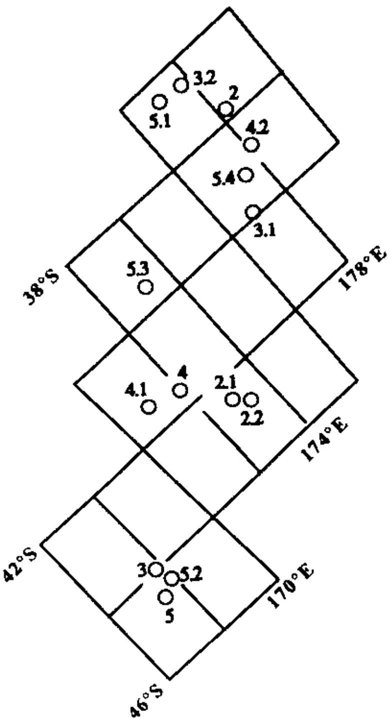

Fig. 2. *As in Fig. 1 for New Zealand. See also Table 2.*

Table 3. Strong earthquakes in the Apennines and their swarm precursors, as in Table 1. The numbers in the first column refer to the geographic position of the precursor in Fig. 4.

Reference to the position of the epicentre in Fig. 4	Date			φ(°N)	λ(°E)	M	VPSE ($cm\,s^{-1}$)	VPSS ($cm\,s^{-1}$)
(1.1)			1906	37.50	15.20		0.10	
(1.2)			1907	37.50	15.20		0.17	
(1)	28	12	1908	38.17	15.58	7.0		
(2.1)			1905	41.10	14.80		0.15	0.19
(2.2)			1907	41.90	14.00		0.34	
(2)	1	8	1910	39.00	15.00	6.8		
			1910	42.70	12.80		0.72	
	13	1	1915	41.98	13.60	6.8		
(3.1)			1917	43.50	13.60		0.28	
(3.2)			1918	43.50	13.60		0.55	
(3)	29	6	1919	43.90	11.50	6.2		
			1923	37.70	15.20		0.077	
	7	3	1928	38.60	15.80	6.6		
			1922	45.30	12.80		0.068	
	27	3	1928	46.40	13.00	5.8		
(4.1)			1924	42.50	12.80		0.14	
(4.2)			1927	41.30	14.40		0.093	
(4)	23	7	1930	41.05	15.42	6.5		
(5.1)			1924	43.70	13.20		0.0055	0.32
(5.2)			1927	44.50	9.60		0.30	
(5.3)			1928	44.50	9.60		0.42	0.40
(5.4)			1929	44.50	11.20		0.48	
(5)	30	10	1930	43.73	13.33	5.9		
			1935	37.70	15.20		0.20	
	13	4	1938	39.30	15.20	7.1		
			1947	38.70	16.80		0.12	
	26	12	1952	39.40	14.50	6.2		
			1955	39.50	16.40		0.46	
	1	2	1956	39.07	15.58	6.1		
			1961	42.30	13.20		0.57	
	21	8	1962	41.10	15.10	6.1		
			1960	46.30	12.80		0.16	
	19	5	1963	46.00	14.60	6.0		

earthquakes preceded by more than one swarm or BG pattern.

In these cases one may wonder whether the precursors have been caused by the same moving perturbation. It will be seen that the analysis of the data will give contradicting results. In fact, in California it is possible to model a single travelling plane wave which triggers the precursors and the strong earthquake as one may note in Fig. 1. However, concerning the strong earthquake of 1956, the position of the last precursor is past the epicentre of the strong earthquake; this could indicate that, if the B pattern and the strong earthquake are caused by the same perturbation, in some cases the strong earthquake requires more time to be triggered than the B patterns, which in turn would imply that the computed velocity of the perturbation to a following precursor should give a greater result than that to the strong earthquake.

In New Zealand there are 3 strong earthquakes preceded by 2 precursors and 1 preceded by 4 precursors as one may see in Fig. 2. However, only in the case of the strong earthquake of 1960 it is possible that a single perturbation

Table 5. Average values of VPSE and VPSS. The values in brackets are obtained neglecting the largest value: for the VPSS they are 11 cm s^{-1} in the Apennines and 17.9 cm s^{-1} in New Zealand, for the VPSE it is 26.2 cm s^{-1} in New Zealand associated with a swarm at more than 1000 km distance from the associated strong earthquake.

	California	Apennines	New Zealand
VPSE B Pattern	0.40		3.89 (1.66)
VPSE BG Pattern		0.42	
VPSE Swarm		0.23	
VPSS B Pattern	0.74		4.32 (1.61)
VPSS BG Pattern		3.76 (1.34)	
VPSS Swarm		0.30	

the set of the three regions, as shown in Table 5 and in Fig. 5. The VPSE and VPSS are consistent also with the average velocity of migration of earthquake foci (e.g. Bella *et al.*, 1990).

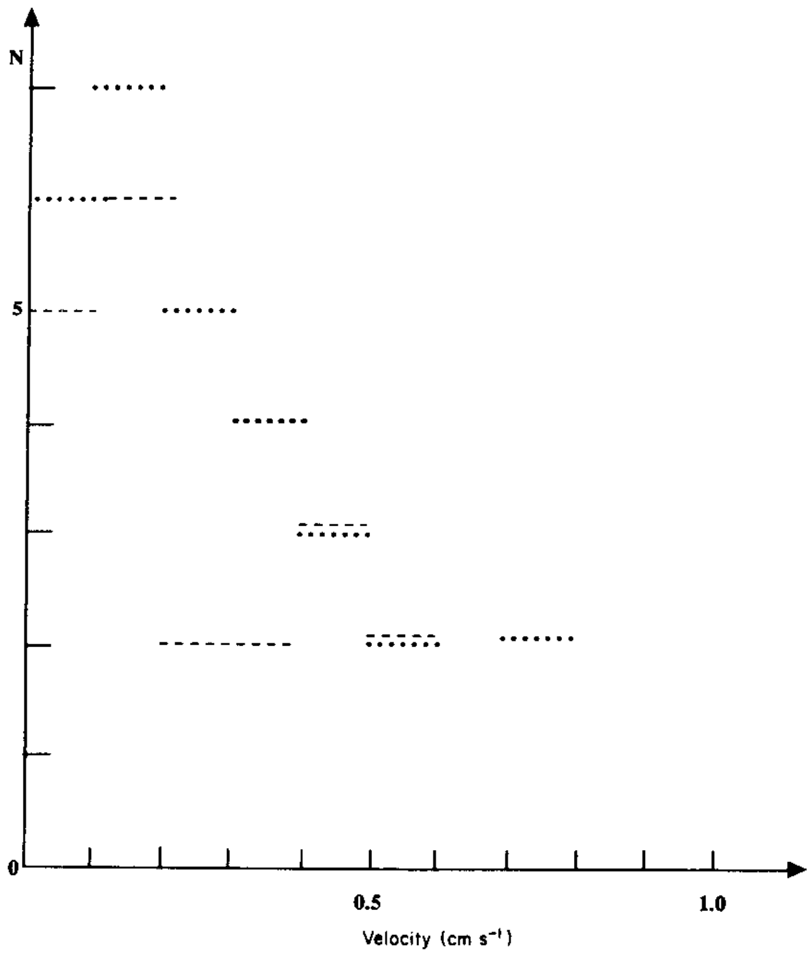

Fig. 5. *Distribution of VPSE of swarms (dotted line) and of BG patterns (dashed line) in the Apennines. The abscissa is cm s^{-1} and the ordinate is number of events.*

In this preliminary report the VPSE have been computed ignoring the fact that the pattern of earthquakes terminates in an epicentre different from the baricentre of the pattern. The corrections needed to take this into account may change the VPSE slightly; however, the tests made indicate that the changes would not be relevant to the results of this note.

It may seem that the limited size of the region considered and the limited time window between the swarms, B and BG patterns and the strong earthquakes they precede constitute a limit to the range of velocities VPSE.

The time window between the B and BG patterns and the strong earthquakes which they precede has a zero lower bound. This zero lower bound would theoretically allow a very large VPSE which we do not find. The VPSE are instead in a limited range in all cases considered.

The VPSE of California, New Zealand and the Apennines are remarkably consistent. But the difference between the set of VPSE and that of VPSS is relevant and, with the caution suggested by the limited number of VPSS, the data could indicate that the mechanisms involved in triggering the strong earthquake and of the successive swarm, or B, or BG pattern require different durations.

It is possible to compare the VPSE of the Apennines, California and New Zealand with the VPSE of three large earthquakes that occurred in the Iran–Afghan region preceded by BG precursors (Akasheh and Kossobokov, 1989). We find that the VPSE of these earthquakes are 2.2 cm s^{-1} for the earthquake of 1962 ($M = 7.3$), 2.5 cm s^{-1} for the earthquake of 1968 ($M = 7.3$ and 1.5 cm s^{-1} for the earthquake of 1978 ($M = 7.4$). These velocities are slightly larger than those observed in California and the Apennines but fall in the range of those observed in New Zealand.

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APPENDIX A

The direction of propagation of the perturbation

When two or more precursors precede the same strong earthquake, with the hypothesis that they are all caused by the same moving perturbation modelled as a plane wave, it is possible to retrieve the actual velocity of propagation of the perturbation v.

Let us call P_i the successive positions of the precursors of the same strong earthquake (including the strong earthquake) and $d_i = P_{i+1} - P_i$ ($i = 1, 2 \ldots n$) the distances of the successive precursors (Fig. 6).

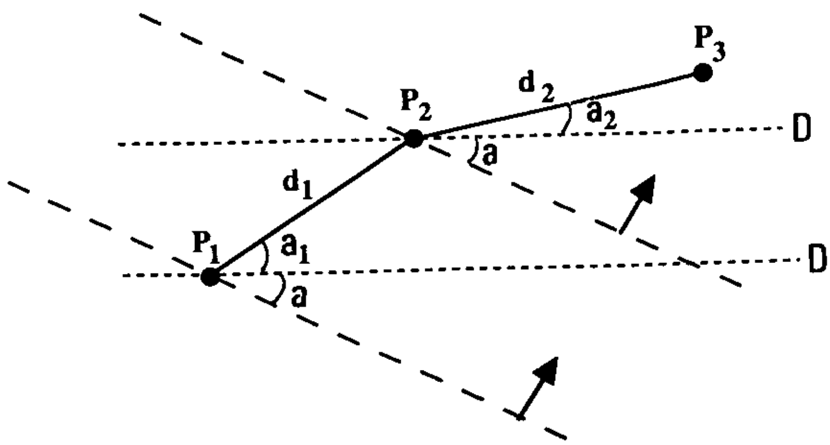

Fig. 6. *The points P_i are locations of the successive precursors of the same strong earthquake, d_i are the distances of the successive precursors. The dashed line represents the wavefront of the supposed travelling perturbation; the dotted line is an auxiliary direction for the computations.*

Preselecting an arbitrary direction D to represent the direction of propagation of the supposed single perturbation travelling from one precursor to the next and eventually to the strong earthquake, measuring the angles a_i of the segments d_i with D and adding to each of them the angle a, which D forms with the actual unknown direction of propagation of the perturbation, one may write for two successive segments d_i and d_{i+1}:

$$v = d_i(\sin(a_i + a))/t_i = d_{i+1}(\sin(a_{i+1} + a))/t_{i+1} \quad \text{(A1)}$$

where t_i are the times to travel from P_i to P_{i+1}.

The equation (A1) in the unknown a gives:

$$\tan a = (t_i d_{i+1} \sin a_{i+1} - d_i t_{i+1} \sin a_i)/(d_i t_{i+1} \cos a_i - d_{i+1} t_i \cos a_{i+1})$$

Substituting a in (A1) gives v.

When m successive segments are available one may write $m-1$ equations (A1) and take the average value of v. The method was applied to several sets of d_i, t_i. However, the significant cases are those which have more than 2 successive d_i, which are decreasing functions of time, because they allow one to check the stability of the velocity of the supposed single perturbation travelling from one precursor to the next and to the strong earthquake.

This case in California is associated with the strong earthquake of 1948 which has 3 precursors. The first three precursors give for the perturbation a velocity of 0.41 cm s^{-1} and a direction of propagation of 78° with that of the first two precursors; however the set formed by the second and third precursor together with the strong earthquake, give a direction of propagation of 56° and a velocity of 0.019 cm s^{-1} which are quite different.

This result, considered with the cases in which the distances between the precursors of the same strong earthquake and the strong earthquake are increasing functions of time, contradicts strongly the hypothesis that there is a single travelling perturbation between the precursors of the strong earthquake and the strong earthquake and we must assume that, in general, each precursor generates a perturbation which may trigger another perturbation, or the strong earthquake, where the conditions of instability of the crust are favourable for the event.