GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 11, PAGES 1157-1160, JUNE 2, 1992

SPATIAL AND TEMPORAL SEISMIC ENERGY RELEASE IN THE EFATE REGION (CENTRAL NEW HEBRIDES ISLAND ARC) : EVIDENCE FOR BUCKLING ?

Jean - Luc Chatelain [1] and Jean - Robert Grasso

Laboratoire de Géophysique Interne et Tectonophysique, Grenoble, France.

Abstract. A study of the spatial and temporal distributions of the seismicity in the central New Hebrides island arc shows that the Efate region (including the interplate boundary and the upper plate) can be considered as a single block under stress. Repeated activation of very specific zones within this block as indicated by seismic clusters is temporally correlated with larger than average energy release rates. These relative high rates are associated with main shocks with magnitude (Ms, mb) > 5.0 in the upper part of the interplate boundary and indicate that slip at the plate boundary is not steady. No correlation is found with main shocks located in the lower part of the interplate boundary, where slip occurs more freely. We propose that these observations are consistent with a buckling process with a wavelength of about 170 km within the overriding plate. Buckling or bending of the upper plate may be due to the impingement of a seamount on the subduction system, elevating the stress level of the Efate region, which behaves like a single mechanical entity.

Introduction

Numerous investigations of the connection between major interplate earthquakes and outer rise events show that the connections are time delayed (5 to 40 years) and suggest that visco-elastic processes may be involved [e.g. Li and Kisslinger, 1985 ; Rydelek and Sacks, 1990]. Corresponding models predict that occurrence of outer rise events varies both spatially and temporally. In a few cases (Kuriles, New Hebrides), a change in state of stress in the outer rise from extension to compression is temporally observed [Christensen and Ruff 1988], and some authors have proposed using this pattern for moderate term earthquake prediction [e.g. Dwomska and Lovison, 1988]. While the effect of coupling on the regional stress field is also evident in the overriding plate and in the subducting plate below the interplate coupled zone, its study requires preliminary identification of the processes involved as well as accurate hypocenter locations [e.g. Astiz and Kamamori, 1986; Dewey and Spence, 1979; Dwomska and Lovison, 1988, Dwomska et al., 1988; Lay et al., 1988; McNally et al., 1986; Seno, 1979; Spence, 1977, 1986, 1987]. In this study we focus on a possible connection between interplate events and events in the overriding plate using data from a local network located in the central part of the New Hebrides island arc. The events within the overriding plate are clusters of events occurring few months before or after the main energy release in the coupled part of the interplate boundary.

The central New Hebrides island arc can be divided into at least four segments (northern Santo, southern Santo-northern Malekula, southern Malekula, Efate) [Taylor et al., 1980]. A network of 19 seismograph stations was established in 1978-1979 in this part of the arc as a joint project between ORSTOM and Cornell University. As the focus of this paper is the seismicity of the Efate segment, the zone covered by the network has been divided in 3 regions, which for convenience we call the Efate region, the northern region, and the southern region without further distinction of blocks north or south of the Efate region (Figure 1). The edges of the Efate region are marked by two barriers limiting the development of aftershock zones, designated as boundary 1 and boundary 3 (boundary 2 located in the northern region is not considered in this study) [Chatelain et al. 1986]. These are roughly located at 17.2°s and 18.1°S respectively (Figure 1).

On a large scale, the Efate region is a transition zone between subduction to the south and a portion of the plate boundary that might be locked to the North [Chatelain et al., 1986] . At a smaller scale, the Efate region shows an interruption of the deepest part of the trench coinciding with the arrival of the ORSTOM seamount in the subduction system (Figure 1). These features together with the difference in seismicity regimes up-dip and down-dip are in favour of a stick-slip motion in the up-dip part of the interplate boundary, while the down-dip part slips more freely.

Using data collected by the local ORSTOM/Cornell network (detecting events with magnitude > 1.9) from

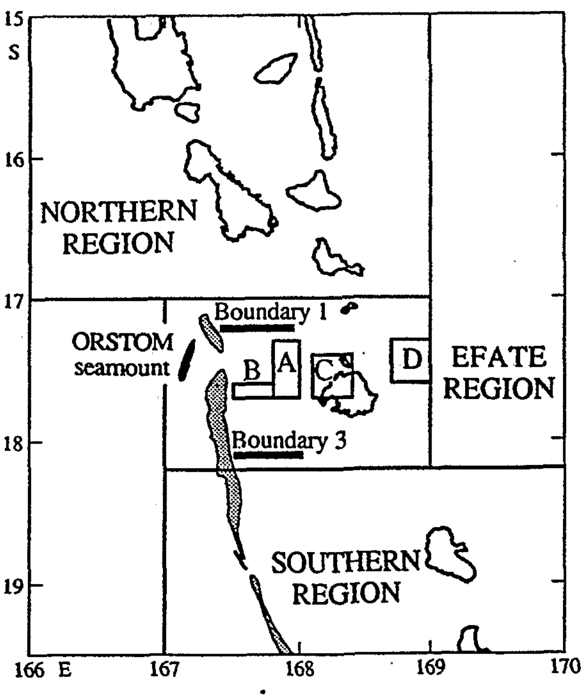

Fig. 1. Map of the central New Hebrides island arc, showing the northern, Efate and southern regions, as defined in this study. The black area represents the 4000 meter contour of the ORSTOM seamount. The grey area represents the 6000 meter contour of the trench. The two thick black lines represent boundaries 1 and 3, and the boxes represent the four zones (A, B, C, D) repeatedly activated by clusters of earthquakes, from Chatelain et al. [1986].

[1]Also at ORSTOM, Noumea, New Caledonia.

Paper number 92GL00975
0094-8534/92/92GL-00975$03.00

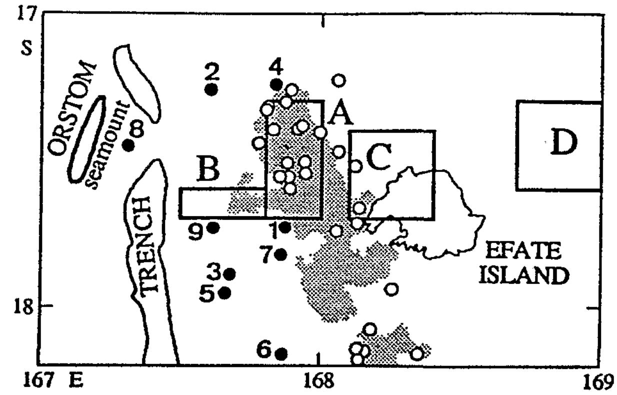

Fig. 2. Map of the Efate region, as defined in this study. The shaded area represents the down-dip zone with high background seismicity level. Boxes represent the four cluster zones from Chatelain et al. [1986]. ORSTOM seamount and trench contours as in Figure 1. The magnitude (M_S, mb) > 5.0 main shocks that occurred during the period 1978-1990 are shown by open circles in the down-dip zone, and by solid circles numbered by chronological order in the up-dip zone. Magnitudes of up-dip main shocks: 6.2 (1); 7.1 (2); 5.1 (3); 6.7 (4); 5.6 (5); 6.3 (6); 5.1 (7); 5.1 (8); 6.2 (9).

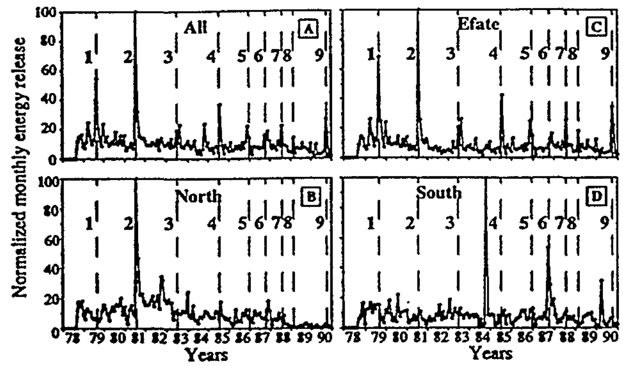

Fig. 3. Monthly energy release in the regions delimited in Figure 1: (A) entire region, (B) northern region, (C) Efate region, and (D) southern region. Occurrences of up-dip magnitude (M_S, mb) > 5.0 main shocks are shown by dotted numbered lines. Numbering for main shocks as in Figure 2. Energy has been calculated with the formula Log(E) = 11.4 + 1.5*M. For each month the summation of Log(E) is represented rather than summation of E, in order to avoid squeezing of the scale by the highest peaks. For each region, the energy release has been normalized to the highest peak of the given region. Energy values for the highest peaks are (in ergs) : 1.20 10 **22, 5.64 10**21, 1.17 10**22 and 8.00 10**21 for the entire, northern, Efate and southern regions respectively.

October 1978 to 1984, Chatelain et al. [1986] have shown that most of the seismicity is concentrated in the Efate region and that two regimes of seismicity characterize the Efate region. Next to the trench (termed the up-dip part of the contact zone), the background seismicity level is low, and main shocks (magnitude Ms, mb > 5.0) are followed by large aftershock zones. Nearer to the island arc (termed the down-dip part of the contact zone), the background level is very high, and main shocks are followed by small aftershock zones or no aftershocks at all. Most clusters of seismicity are located in the Efate region and are not randomly distributed. Instead, they occur in four distinct well determined zones: one is located up-dip (Zone B), one down-dip (Zone A), and two in the upper plate (Zones C and D) (Figure 2). These observations, revealed by the study of the seismicity from 1978 to 1984 are still observed through 1990. From 1978 to 1990, the station distribution in the Efate region remained the same, there is thus no variation of network sensitivity with time.

In this paper we investigate the temporal and spatial relationship between peaks of energy release in the up-dip part of the contact zone and occurrence of clusters in the Efate region, indicating that (1) this region behaves like a single mechanical entity and (2) the distribution of clusters in the upper plate can be explained by buckling process.

Data Analysis

From October 1978 (when the network started operating) to December 1990, 36 earthquakes with magnitude (Ms, mb) > 5.0 occurred in the Efate region (for seismicity crisis, only events with the largest magnitude were considered). Nine of these earthquakes occurred in the up-dip part, while the others occurred in the down-dip part (Figure 2). The nine up-dip main shocks can be correlated to the major seismic episodes in the larger region comprised between 15°S and 19.5°S, as well as in the Efate region, while activity North of the Efate region can be connected only to event 2 and activity South of the Efate region to event 6 (Figure 3). These observations attest that the main energy release in this time period is located in the Efate region.

We calculated the seismic energy released in the Efate region by earthquakes shallower than 80 kilometers in six distinct zones : up-dip, down-dip, and zones A,B,C,D. Whereas zones A and B overlap the up-dip and down-dip zones, zones C and D are totally separate (Figure 2). Peaks in energy release in these 6 zones are closely related within a few month time lag. Moreover, energy release in the different zones are correlated in time with magnitude (Ms, mb) > 5.0

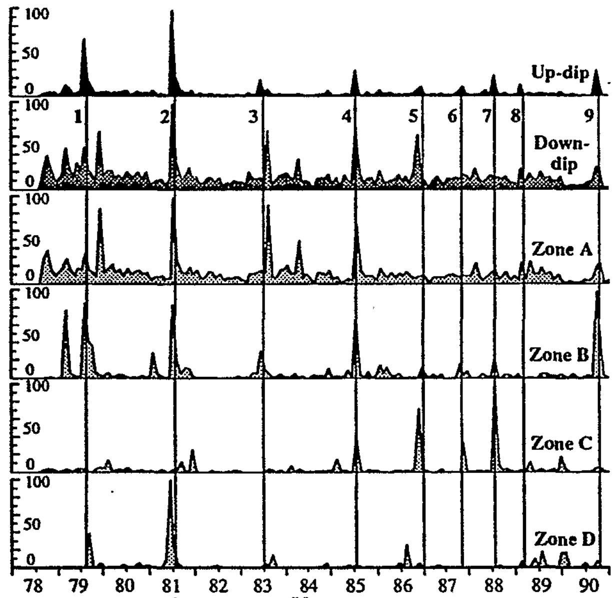

Fig. 4. Monthly energy release in the up-dip, down-dip and cluster zones A, B, C, D of the Efate region. For each zone the energy release has been normalized to the highest peak of the given zone. Numbered lines show the occurrences of magnitude > 5.0 up-dip main shocks in the Efate region. Numbering as in Figure 2. Maximum energy release are (in ergs) : 1.15 10**22, 2.81 10**21, 1.85 10**20, 5.37 10**20, 4.45 10**19, 2.87 10**19 for the up-dip, down-dip, A, B, C, and D zones respectively.

events located in the up-dip zone (Figure 4), but no correlation is apparent with the magnitude (Ms, mb) > 5.0 events that occur in the down-dip zone. No consistent cycle appears in the spatial distribution of energy release. The delay between energy release in the different zones is also variable from almost instantaneously to few months before and/or after the up-dip main shock occurrences (Figure 4). Thus, the activity in none of the 6 zones appears to control the triggering of seismic activity in the others, and no reproducible seismic migration can be observed. Rather, the Efate region (comprising the contact zone between the two plates and the upper plate east to zone D) behaves like a single entity under stress.

Discussion and Conclusion

Kanamori [1971] suggested that the great and apparently systematic variations in the size of large interplate earthquakes from one subduction zone to another correlates with the degree of compression across the plate boundary. Different idealized subduction types have been proposed according to their seismic coupling efficiency as estimated by the maximum earthquake size [Ruff and Kanamori, 1980] or by summing seismic moments [Petterson and Seno, 1984]. Thus, variations in seismic coupling along arcs can be related to variations in the mean normal stress that act across the subduction zone plate interfaces. At a smaller scale, in comparing arcs with different seismic coupling, Lay and Kanamori [1981] assumed that stresses are inhomogeneously distributed on the interface and that the areas of concentrated moment release are the most highly stressed regions and probably the most strongly coupled zones. In absolute value the New Hebrides subduction zone is of type 3, following Kanamori's classification, i.e. moderate coupling. In this study, at distances of the order of 100 km we work with, the Efate region is the highest coupled region of this part of the New Hebrides arc. Assuming the asperity model, we expect that this region undergoes the highest regional stress. This description points out the importance of the scale factor in investigating the mechanics of a tectonic area. This scale factor is fundamental to determine what are the driving forces of the object (Efate region) we study in this paper.

To explain the observations presented in the previous section, it is necessary to focus on the interface between the two plates. Sykes and Quittmeyer [1981] propose possible down-dip variations of seismic coupling in individual subduction zones. Our up-dip and down-dip seismicity zones correspond, respectively, with areas of strong and weak coupling. The correlation between energy release in the strongly coupled zone (up-dip events) and swarm activity eastward of this zone in the upper plate are indicative of high stress in the whole area. Earthquake clusters occur selectively in comparatively weak zones within the crust and sensitively reflect the state of crustal stress. Locations of such weak zones at different scales have been reported [e.g., Xu and Shen 1981]. The clusters located within the overriding plate occur in time intervals spanning a few months before and after the main energy release in the coupled part of the interplate boundary (up-dip zone). The correlation between the up-dip events and the clusters is neither the result of a propagation process nor the effect of faults as found in other regions [e.g., Li and Kisslinger, 1985 ; Mogi, 1981 ; Tsukuda, 1988]. Rather, this correlation is interpreted as the result of forces applied simultaneously to the whole Efate region, with small temporal separation (from almost instantaneously to 1-3 months; see Figure 4) being only a manifestation of differences in rheological responses.

The seismicity defines the Efate region as a block of homogeneous behavior. The east-west extent of the block (about 200 km) is bounded by the development of clusters of seismicity. The north-south extent of the block (about 150 km) is bounded by major events locations, background seismicity level, and aftershocks migration.

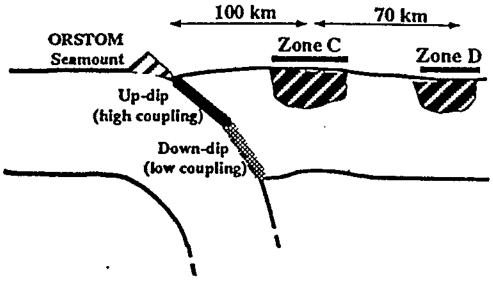

Fig. 5. Schematic cross section of the Efate block. In the up-dip part of the interplate boundary the subduction process is perturbated by the arrival of the ORSTOM seamount. As a consequence, the Efate region behaves like a single mechanical entity, leading to buckling process in the upper plate with repeated activation of weak zones in the upper plate linked to episodes of main energy release along the up-dip part of the interplate boundary.

The localization of the clustered activity in front of the most strongly coupled area (Figure 5), is induced by high stress in this zone, despite the fact that it is usually assumed that in subduction zones, earthquakes are result of slip instabilities that depend on the contrasting stiffnesses of the fault and the coupled plate system [e.g. Stuart and Mavko, 1979; Li and Rice, 1983a,b]. To solve this apparent paradox we need to describe the local source of stress, which is able to perturb the transient subduction slip. The geometry of the sea floor exhibits (1) an interruption of the trench in front of the Efate zone and (2) the ORSTOM seamount located westward of this interruption (Figure 2). These two features may explain the local high coupling between the two plates and the collision-like behavior of the overriding plate. Note also that these two features and the cluster zones are aligned in the direction of plate convergence (Figure 2).

We propose that a buckling process within the overriding plate explains the spacing between the cluster zones. This process is observed in different tectonic setting using either seismic activity or deep seismic imaging or geodesy [Sacks et al. 1978 ; Xu and Shen 1981 ; Awata and Kakimi 1985, Bull 1990]. The proposed models investigate different rheologies of the lithosphere to fit the available observations, i.e. plastic rheology or recoverable elastic properties [e.g., Turcotte and Schubert, 1982 ; Martinod and Davy, 1992]. The model of Martinod and Davy [1992] can be used to estimate the wavelength of oceanic buckling as a function of the lithosphere age in the New-Hebrides area. Unfortunately no estimate of the age of the upper plate in the Efate region is available. However, the spacing of weak areas deduced either from cluster activity ($D=l/2\approx70$ km), or from the distance to the trench of the first cluster $l/2\approx100$ km), imply a wave length, l, of about 170 km (Figure 5). Such a wavelength dimension is in agreement with a 35 Myr old plate, which is within the range of estimates of the age of the plate in the northern region [Recy et al., 1990].

Such correlation distances are observed with other tools (e.g. water level change). As with our observations, changes are not always coseismic (either few months before or after major events) and poroelastic effects fail to explain long distance correlation [e.g. Sadovsky et al., 1984; Roeloffs, 1988]. Thus, the model proposed here may have a general meaning and can apply in other settings.

Acknowledgements. We thank all the people involved in the data collection and analysis operations. We thank two anonymous reviewers and P. Molnar for their constructive criticisms and help in improving the manuscript. This work was supported by ORSTOM and Université Joseph Fourier.

References

Astiz,L., and H. Kanamori, Interplate Coupling and Temporal Variation of Mechanisms of intermediate-depth earthquakes in Chile, *Bull. Soc. Am.*, 76, 1614-1622, 1986.

Awata Y. and T. Kakimi, Quaternary tectonics and damaging earthquakes in northeast Honshu, Japan, *Earthq. Predict. Res.*, 3, 231-251, 1985.

Bull J.M., Structural style of intraplate deformation, Central Indian Ocean basin: evidence for the role of fracture zones, *Tectonophysics*, 184, 213-228, 1990.

Chatelain J.-L., B.L. Isacks, R.K. Cardwell, R. Prévot, M. Bevis, Patterns of Seismicity Associated with Asperities in the Central New Hebrides Island Arc, *J. Geophys. Res.*, 91, 12,497 - 12,519, 1986.

Christensen D.H., and L.J. Ruff, Seismic Coupling and Outer Rise Earthquakes,*J. Geophys. Res.*, 91, 13,421 - 13,444, 1988.

Dewey, J.W. and W. Spence, Seismic gap and sources zones of recent large earthquakes in coastal Peru, *Pure and Appl. Geophys.*, 117,1148-1171, 1979.

Dwomska, R. and L.C. Lovison, Intermediate term seismic precursors for some coupled subduction zones,*Pure and Appl. Geophys.*, 126, 643-664, 1988.

Dwomska, R., J.R. Rice, L.C. Lovison and D. Josell, Stress transfer and seismic phenomena in coupled subduction zones during the earthquake cycle, *J. Geophys. Res.*, 93,7869-7884, 1988.

Kanamori, H., Great earthquakes at island arcs and the lithosphere, *Tectonophysics*, 12, 187-198, 1971.

Lay, T. and H. Kanamori, The asperity model of earthquake sources and its implications for triggering and seismic gap discrimination, *in Earthquake Prediction, Maurice Ewing Series*, 4, D. Simpson and P. Richards, Eds., American Geophysical Union, Washington D.C., 579-592, 1981.

Lay T., L. Astiz, H. Kanamori, and D. Christensen, Temporal variation of large intraplate earthquakes in coupled subduction zones, *Phys. Earth Planet. Inter.*, 112-132,1988.

Li V.C. and C. Kisslinger, Stress transfer and nonlinear stress accumulation at subduction-type plate boundaries-application to the Aleutians, *Pure and Appl. Geophys.*, 122, 812-830, 1985.

Li V.C. and J.R. Rice, Preseismic rupture progression and great earthquake instabilities at plate boundaries, *J. Geophys. Res.*, 88, 4231-4246, 1983a.

Li V.C. and J.R. Rice, Precursory surface deformation in great plate boundary earthquake sequences, *Bull. Seism. Soc. Am.*,73, 1415-1434, 1983b.

Mc Nally K.C., J.R. Gonzales-Ruiz and C. Stolte, Seismogenesis of the 1985 great (Mw=8.1) Michoacan, Mexico earthquake, *Gephys. Res. Lett.*, 13, 585-588, 1986.

Martinod J. and P. Davy, Periodic instabilities during compression or extension of the lithosphere: 1. deformation modes from an analytical calculation method, *J. Geophys. Res.*, 97, 1999-2014, 1992.

Mogi K., Earthquake prediction program in Japan, *in Earthquake Prediction, Maurice Ewing Series*, 4, D. Simpson and P. Richards, Eds., American Geophysical Union, Washington D.C., 635-666a, 1981.

Peterson E.T. and T.Seno, Factors affecting seismic moment release rates in subduction zones, *J. Geophys. Res.*, 89,10,233-10,248, 1984.

Recy J., B. Pelletier, P. Charvis, M. Gerard, M.C. Monjaret and P. Maillet, Structure, age et origine des fossés arriére-arc des Nouvelles-Hébrides, *Oceanologica Acta*, 10, 165-182,1990.

Roeloffs, E. , Hydrological precursors to earthquakes: A review.*Pure and Appl. Geophys.*, 126,177-209, 1988.

Ruff L. and H. Kanamori, Seismicity and the subduction process, *Phys. Earth Planet. Inter.*, 23, 240-252,1980.

Rydelek P.A., and I.S. Sacks, Asthenospheric viscosity and stress diffusion: a mechanism to explain correlated earthquakes and surface deformations in the N. E. Japan, *Geophys. J. Int.* 100, 39-58, 1990.

Sacks I.S., A.T. Linde, B.A. Rodriguez and J.A. Snoke, Shallow seismicity in subduction zones, *Geophys. Res. Lett.*,5, 901-903, 1978.

Sadovsky, M.A., Monakov, F.Γ., Kissin, I.G., Shirokov, B.D., Short term hydrogeodynamic precursors of earthquakes, *in Earthquake prediction*, Terrapub Unesco, Paris, pp 233-243, 1984.

Seno T., Pattern of intraplate seismicity in south-western Japan before and after great interplate earthquakes, *Tectonophysics*, 57, 267-283, 1979.

Spence W., The Aleutian arc: Tectonic blocks, episodic subduction, strain diffusion and magma generation, *J. Geophys. Res.*, 82, 213-230, 1977.

Spence W., The 1977 Sumba earthquake series: Evidence for slab pull force acting at a subduction zone, *J. Geophys. Res.*, 91, 7225-7239, 1986.

Spence W., Slab pull and the seismotectonics of subducting lithosphere, *Rev. Geophys.*, 25, 55-69, 1987.

Stuart W.D. and G.M. Mavko, Earthquake instability on a strike slip fault,*J. Geophys. Res.*, 84, 2153-2160, 1979.

Sykes L.R. and R.C. Quittmeyer, Repeat times of great earthquakes along simple plate boundaries, *in Earthquake Prediction, Maurice Ewing Series*, 4, D. Simpson and P. Richards, Eds., American Geophysical Union, Washington D.C., 217-247, 1981.

Taylor F.W., B. L. Isacks, C. Jouannic, A. L. Bloom, J. Dubois, Coseismic and Quaternary vertical tectonic movements, Santo and Malekula islands, New Hebrides island arc, *J. Geophys. Res.*, 85, 5367-5381, 1980.

Tsukuda T., Linked activities at the adjacent seismic spots, *Seis. Res. Lett.*, 59, 6, 1988.

Turcotte D.L. and G. Schubert, *Geodynamics Applications of continuum Physics to Geological Problems*, John Wiley and Sons Eds, New-York, 1982.

Xu S. and P. Shen, Seismicity patterns in China, *in Earthquake Prediction, Maurice Ewing Series*, 4, D. Simpson and P. Richards, Eds., American Geophysical Union, Washington D.C., 117-125, 1981.

J.-L. Chatelain and J.-R. Grasso, IRIGM-LGIT, Domaine Universitaire, BP 53X, 38041 Grenoble CEDEX, France.

(Received November 25, 1991;
revised March 30, 1992;
accepted April 21, 1992.)