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Dimension Reduction Study of Microseismic Activity in the Earth’s Crust and Mantle in the Plate Boundary Region

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Abstract

Microseismic activity of the crust and mantle in the southwestern Japan was studied by means of dimension reduction method using principal component analysis. The microseismicity rates defined by the number of the microseismic events of M1-M2 were estimated in the volume of the Japanese crust and the subducting Philippine Sea Plate and of 1998-2008 from the JMA1 database. The spatial dimension of this region is 96 and total number of the microseismicity rate data reaches 120.

The data were projected effectively on hyper surface of 10 dimension, and the components of this reduced space are obtained as the eigenvectors of the cross correlation matrix of the total data. It shows that the linear combinations of the microseismicity rates can be divided mainly into three types of postseismic signals after large earthquakes, slowly changing components, and annually changing components. The last term is probably derived from solid tidal force, and the first term is responsible for the relaxation after large earthquake and the second term is due to long term strain change in the crust and subducting plate.

Key words: microseismicity, dimension reduction, deformation of the earth interior, principal component analysis

1, Introduction

Recent heavily disaster at 3.11 of 2011 in the northeastern Japan attacked severe damages to Japanese islands and aftershocks of seismic large events now continue to take place in the subducting Pacific plate and overriding crust and wedge mantle beneath Japanese islands. The seismic activity of the crust and mantle is basically governed by the mechanical states and properties of the rocks, because seismic events are thought to be the shear crack propagation. The magnitude of earthquakes can be represented by the logarithmic intensity of the product of rigidity of rocks, displacement of shear, and the area of the shear crack surface, and thus the wide variation of the earthquake magnitude is responsible for the wide range of shear crack surface area. The earthquakes of M9 reach about 500km x 200km, and those of M1 do about 1mx1m.

The earthquake events are similar to the spike signals in the time series of the mechanical states in the mantle and crust (Aoki and Scholz, 2003; Terakawa and Matsu’ura, 2010). The intensities of the spikes are represented by the logarithmic magnitude of moment generated by the single earthquake and the their time intervals between various spikes with different intensities are not always the values but not perfectly random. The spike signals show clearly the mechanical states over the critical condition where the rocks behave brittle manner of shear deformation, namely the rapid propagation of shear cracks. On the other hand, the micro-earthquake signals are generated in the condition under the large scale failure stress, and then they rise repeatedly in the same volume by the repeated stress operation.

In the experimental investigation, repeated nature of shear crack activation has been shown by many authors (Ohnaka and Mogi, 1981). Especially, the acoustic emissions in the deformation of rocks can be sharply observed as repeated signals from the micro cracks corresponding to the magnitude of strain. The rate of the generation of the signals clearly increases with increasing strain magnitude, suggesting that the rate of acoustic emission signals is potentially indicator of the local strain in the sample, and that the distribution pattern of the signal rates should display the localization of the large strain or the degree of the strain localization responsible for the large scale failure of the specimen.

The strain localization in the plate boundary and within the crust and mantle is most important problem to understand the fracture process in the earth interior (Ashby and Sammis, 1991). Considering that the fault propagation, that is the large shear crack, is not point-source process but the crack tip source process that represents peripheral region source of the shear cracks. Therefore, the coeval strain localization can reveal several long tubed regions along the large scale shear cracks in the earth interior. Thus, in order to study the mechanical coupling of the strain magnitude among the regions apart from each other, we require intensities of correlation functions of the time series of strain magnitude measured by rate of repeated micro earthquake signals among many localities in the earth interior and also we need the secure observations of many localities and narrow time intervals because of clarifying the short term strain localization.

The author intends to study the dimension reduction of the microseismicity rate defined by the micro earthquake numbers generated in the proper time intervals and volume in the earth interior to obtain the time trajectories of some combination of the microseismicity rates of many localities. Such linear combinations represent the new unit vectors in the reduced orthogonal coordinate system and they imply the intensities of mechanical coupling among all localities studied here.

2, Microseismicity rate as an indicator of the combination of strain, stress and fracture toughness

The seismic activity of the earth interior is sharply concentrated along the plate boundary zone although deep activity is restricted in the subduction zone. As stated in the earlier section, the intensity of the earthquake can be represented by logarithmic moment release generated from fault slip motion as the magnitude which ranges from 0 to 10. In the past the maximum magnitude of the plate boundary earthquake recorded reaches 9.5 at the 1960 Chile, but 3.11 Tohoku-Pacific earthquake was that of M9.0. After such giant earthquakes there are lots of showers of various magnitudes of earthquakes, and they are called as post seismic events having the intensities from M1 to M8.

Considering that the earthquake takes place by rapid slip motion of the large scale shear cracks in the earth interior, the elastic strains are to be concentrated at the crack tips around the area of that cracks. However, the displacements along on the shear crack surface are not the same distance, the shear crack propagation should make the local accumulation of strain and stress. Thus, near the large scale shear slip, coincident strain and stress localized regions must be associated with the large shear cracks.

Experimental investigations of yielding and successive fracturing of compressed rock specimens have revealed many signals of acoustic emission with very high frequencies which were generated randomly in the initial stage and in the later signals become concentrated along on the maximum shear planes post dated by conjugated faults. It seems that the change of the spatio-temporal pattern of the signal distribution in the deformed specimens should be apparently recognized before and after the large scale earthquake as an excess signal over the noisy background.

The detection of such signals must be surveyed by means of through searches of many time series of seismic activities of many neighboring volumes of the crust and mantle. Then, first, the author will intend to define the microseismicity rate as the spike density rate in the earth interior as follows.

In this paper, he introduced the microseismicity rate to be the total number of seismic spike signals between M1 to M2 per one month in the unit volume of 0.5^o x 0.5^o x thickness with 20km of the island arc crust of the Southwest Japan and subducted Philippine Sea Plate. In these regions the widths of longitude and latitude are about 50 km length, respectively. Time window of one month is selected because of available spike numbers to investigate the stochastic analyses during the high resolution periods from 1998 to 2008 for well-defined time series of seismicity over M1 have been continuously observed by means of dense observatories network by Japan Agency of Meteorogy was started at 1998.

Here, the author avoided the seismicity rates exceeding M2 because rather large earthquakes represent the large scale shear crack propagation and then those action must change irreversibly the mechanical nature but more small size shear cracks may be reversible signature of the mechanical state of the crust and mantle as seen in the experimental deformation of the rock samples before yielding (Atkinson, 1984).

The studied area is ranged from 32 to 36 ^{o} of the latitude and from 132.5 to 138.5 ^{o} of the longitude, involving the Southwest Japan Arc and trench segment from Nannkai - Tonankai - Tokai region as shown in figure 1. Therefore, 12x8 blocks of the SW Japan crust and and those of the Philippine Sea Plate are chosen for data analyses. The time interval is taken as one month from January of 1998 to 2008, and thus sample number attains 120 in the time series. Thus the total number of independent parameters is 140x12x8.

In this study, the seismicity rate is taken as the vector data in the 12x8 dimensional space and therefore samples of vector data count 120 in the studied case. Accordingly the following data sets can be assembled to infer the trajectory of the mechanical states of the crust and subducting mantle in the SW Japan as shown in figure 2;

Xj (n(1j), n(2j), n(3j), ...n(kj)) for j=1 to 140

where n and X are microseismicity rates and their vector, respectively, and k is 96.

Expermenntal results of acoustic emmision in the deformation of rocks indicate clear relations between strain and number of acoustic signals. The time study of the numbers of signals also indicated repeated generation of micro shear cracks and show the scarce hysteresis between the strain and number of acoustic emission (Ohnaka and Mogi, 1981). It leads that the shear cracks under the size of critical Griffith crack must be reversible for instantaneous slip motion: the micro shear crack may retreat the undeformed state by elastic stresses induced by the foward slip. The critical size of the shear crack is estimated about 10 m in diameter in the earth interior. Consequently the shear cracks of M1-2 are less than the critical Griffith cracks.

In the case of water-filled shear crack the surface tension should decrease because of hydration reaction between mineral surface and water. According to critical size proportional to surface tension, the critical Griffith crack size becomes small. On the other hand, higher temperature condition yield enhancement of ductile behavior, suggesting an increase of fracture toughness.

Therefore, the shear cracks can be divided into two types by the length: the crack under the critical size is reversible type and that over the critical size is to be irreversible one. The shear cracks of M1-2 may be the reversible type. In this paper, the author intends to reveal the mechanical coupling among every reference volumes in the studied region with special reference to microseismicity rate time series as previously shown in figure 2.

2, Dimension reduction of microseismicity rate

The microseismicity rate vectors have apparently dependent parameters n(i,j) of given j and also, the time series of every n(i,j) of given i shows the tranjectories of local microseismicity rate. As shown in figure 3, the trajectories of the microseismicity rates are considered to be the unique attractor in the space of n(i) for i=1 to 96, because every components of Xj for j=1 to 140 are mutually as a function of them and the time. In other words, we can consider the following dynamical differential equations of n(i),

$$d\, n(i)/dt = f_i(n(j))$$

Thus, if we think of the strong dependency as exemplified by the perfectly continuous elastic mass applied by the external force through the boundary, every n(i) are approximatedly the same and the its trajectory in the high dimension space is uniquely governed by the external force change. On the other hand, the slider block system in which every blocks are connected by spring and frictional stresses operate between the block and the basement floor have strongly random slip motions of each block. In this system, the available linear comibinations of positions of every blocks display the clear attractor in the new low dimensional space. This space must be constructed by the dimension reduction method by using the principal component anaysis concerning the displacements of every blocks and their time series as shown in the plate boundary along the Japan trench by Toriumi (2009).

The actual dimension of the hyper space made by n(i) is to be determined by the hyper surface which contains almost always the trajectories of X as shown in figure 3 and then it is obtained by the transformed coordinates by made by rotation matrix W as follows;

$$Z = W X + g$$

in which g is the Gaussian noise term derived from projection onto the hyper surface.

In order to determine the unique rotation matrix W, the optimization of the distance from the newly obtained Cartesian coordinates Z with smaller dimension should be performed, leading to obtain the eigenvector of the cross correlation matrix composed with large number of time collection samples (Jollife, 2002). Consequently, we estimate the principal component vectors Z1, Z2, Z3, …and Zl (l is less than 96 in this study) in the decreasing order of the eigen value. Following the normal principal component analysis method, we choose the number of available number of new dimensions as the dispersion of the samples data becomes 90%. Actually, the dispersion curve against the number of new dimensions displays rapid decrease and then changes to be flat near the 90% of the value, suggesting the minimum Akaike information criterion at that point.

In this study, we use the projected hyper surface of 10 dimension for the necessary of the redundant number of dimensions. Later, it shows that the projected hyper surface changes during the time because of successive change of mechanical coupling modes among the studied blocks of the crust and mantle as sharply shown by localization of large earthquake and its following post seismic activity.

3, Results

The microseismicity rates are estimated from JMA1 database in the ERI of university of Tokyo. The time range studied here are from 1998 Jan.31 to 2008 Jan.31. The microseismicity rate of the earthquakes with magnitude ranging from 1 to 2 is to be number of event in the one month within the volume of 0.5^o x 0.5^o of latitude and longitude and depth range of 20km in the crust and of 50km in the Philippine Sea Plate.

Total number of micro earthquake events reaches about 60,000. The data processing has been carried out using the R-language open source. The visualization of the eigenvectors of the cross correlation matrix was performed by pseudo coloring in the map as shown in figures 4 and 5.

First, we intend to show the case of the Philippine Sea Plate which is subducting under the SW Japan arc reaching to the mantle under the front of the Japan Sea from the Nankai trough. As seen in figure 6, the first principal component Z1 indicates sharply the microseismic activities just after the large earthquake, judging from the localization of the intensity of Z1 just at the location of the large earthquake. The decay pattern of the seismicity rate after the large earthquake is similar to the power law type one, indicating the postseismic activity shown by Ishimori-Iida relation.

The second and subsidiary components of the microseismicity rates of the subducted oceanic plate can be classified into three types: one shows the time series having slow change, the second is the time series having annual and sub annual change as shown in figure 6. The third type shows the random variation in the time series as shown in figure 6. The geometrical patterns of slowly changing components display clearly the mechanical coupling among the regions of central area beside the Nankai trough and the areas of Kii and eastern Shikoku and Kinki regions. The time series of these components appear several to several ten years periodic changes with slightly correlation to the large earthquakes. Further, their time changes contain slight fluctuation.

The most striking temporal changes of the higher components are annual to sub annual periodic patterns as shown in figure 7. The periodicity of these patterns can be also suggested by the foulier spectra of the time series of the annual changes as shown in figure 8, showing that there are several periodicities having 1 and half years, three years and more long periodicities. The geometrical patterns of the annual periodicity of the higher components are identified to the mechanical correlations among the regions of near Nankai trough and Kii and Hamanako regions.

4, Discussions and conclusions

The dimension reduction method using the principal component analysis can be available for investigation of the strength of mechanical coupling within the island arc crust and subducting oceanic plate in the southwestern Japan region. The geometrical patterns obtained by the intensity distribution of the correlation matrix of the projected hyper surface, that is the eigenvectors, show sharply the several characteristic features and time series. Firstly, it should be said that the microseismicity rates of the crust and oceanic plate can be decomposed to principal components in terms both of geometrical patterns and temporal changes. The first component is identified to the localized microseismic activity just after the large earthquakes, that is the post seismic activity. The second type is the slowly changing microseismicity rates and it contains several to several ten years periodicities and small fluctuations. In addition, the third type is revealed to show the annual periodic change, suggesting that the microseismic activity of the small scale shear cracks is strongly responsible for the solid tidal deformation of the earth interior.

The first component of the reduced dimensional space has relaxation of the Poisson type just having logarithmic decrease with time, suggesting the diffusive relaxation of elastic strain energy around the center of the earthquake. In other words, the time change of the combination microseismicity rates have the following relation with time,

$$dZ1/dt = -kZ1$$

where k is the time decay constant of the postseimicity.

The behavior of the slow processes of the higher principal components displays long-term variation of the mechanical coupling among the plate boundary regions and the oceanic plate interior, and the mechanical relationships between the large earthquake event and the slow processes can be investigated by correlation diagram between the intensity of the first component Z1 and that of the higher components. In figure 9, the correlation diagrams between Z1 and Z2, and Z6 and Z7 are shown, suggesting that the peaks of slowly changing higher components are correlated with the time of large earthquake.

On the other hand, the annual changing components are suggested to be responsible for the change of tidal strain in the earth interior, judging from the peaks of the principal components showing the combination of the microseismicity rates occur near the equinox times in the year. Considering that the the microseismic signals are generated by the rapid slip of small shear cracks and that micro shear cracks should have the peculiar orientations related with the plate motion, the critical resolved shear stress acted on the micro shear crack surfaces becomes the peak magnitude at the maximum tidal periods as suggested by Nakata et al. (2008). Thus the maximum activity of the microshear cracks should take place annually or subannually as being revealed in this study.

The dimension reduction study of the microseismicity rates in the island arc crust and the subducting oceanic plate reveals that the microseismic activity can be divided into several types of the eigenvector space of the cross correlation matrix of the time series data. One is the post seismic activity after large earthquake, the second is the slow process involving the large earthquake effect, and the third is the tidal strain – inducing microseismic activity. These components show the strong mechanical coupling in the map displaying the intensity distribution of their components.

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References

Atkinson, B. K., Subcritical crack growth in geological materials. J.Geophys.Res., 89,4077-4114.1984.

Aoki, Y., and C.H. Scholz, Vertical deformation of the Japanese islands, 1996-1999. Jour. Gophys.Res., 108, 2257, doi:10.1029/2002JB002129, 2003.

Ashby, M.F., and C.G.Sammis, Damage mechanism of the solids in compression, Pure and Applied Geophysics, 133, 3, 489-521, 1991

Jollife, I.T., Principal Component Analysis, 530pp, Springer, 2002

Nakata, R., N.Suda, and H.Tsuruoka, Non-volcanic tremor resulting from the combined effect of earth tides and slow slip events. Nature geoscience, vol.1, Oct. 676-678, 2008.

Ohnaka, M., and K.Mogi, Frequency dependence of acoustic emission activity in rocks under incremental, uniaxial compression. Bull. Earthquake Res.Inst., 56, 67-89, 1981.

Terakawa, T., and M.Matsu’ura, The 3-D tectonic stress fields in and around Japan inverted from centroid moment tensor data of seismic events, Tectonics, 29, TC6008, doi:10.1029/2009TC002626, 2010.

Toriumi, M., Principal Component Analyses of Seismic Activity in the Plate Boundary Zone of Northeastern Japan Arc. Jour. Disaster Res., 4,2, 209-213, 2009.

Figure 1, The studied areas of dimension reduction of microseismicity rates of the Philippine Sea Plate (A) and island arc crust (B), showing the microseismic locations of M1 to M2 from 1998-2010.

Figure 2, Microseismicity rates and the microseismicity vector showing the number of micro earthquake events of the divided blocks in the oceanic plate. See text.

Figure 3, Trajectory of the microseismicity rate vector in the original space and reduced hyper surface. See text.

Figure 4, Spatial patterns of the principal components in the reduced hyper surface of the subducting Philippine Sea Plate, showing the color index of intensity of the components . Red color is positive and blue color is negative intensity, but the color contrast should be noticed.

Figure 5, Spatial patterns of principal components in the reduced hyper surface showing the strength of mechanical coupling in the island arc crust of SW Japan. The explanations are the same in the previous figure.

Figure 6, Time series of the principal components in the reduced hyper surface of the Philippine Sea Plate. See text.

Figure 7, Time series and the spatial patterns of the annually changing components of the reduced hyper surface of data from Philippine Sea Plate.

Figure 8, Fourier spectra of the annually changing principal components of the microseismicity rate vectors in the southwestern Japan crust and Philippine Sea Plate(upper).

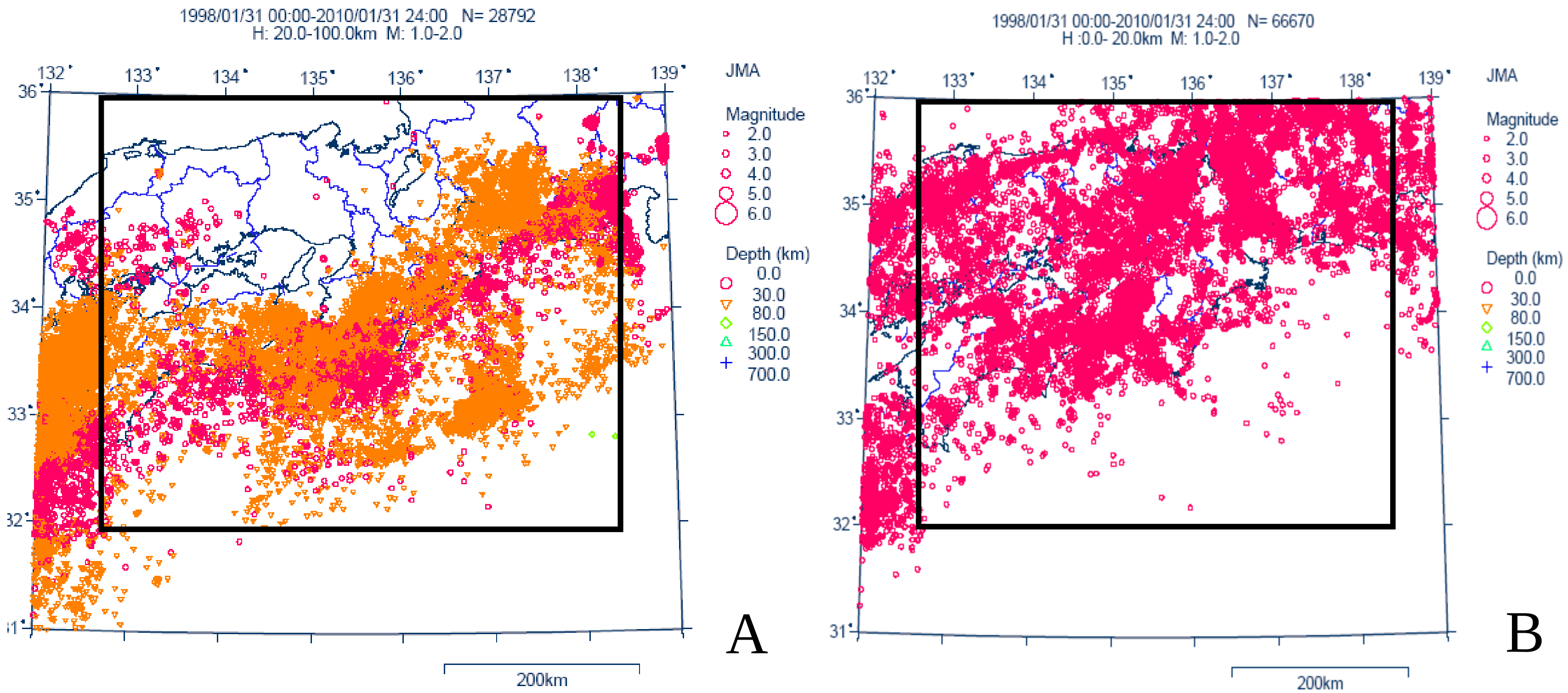
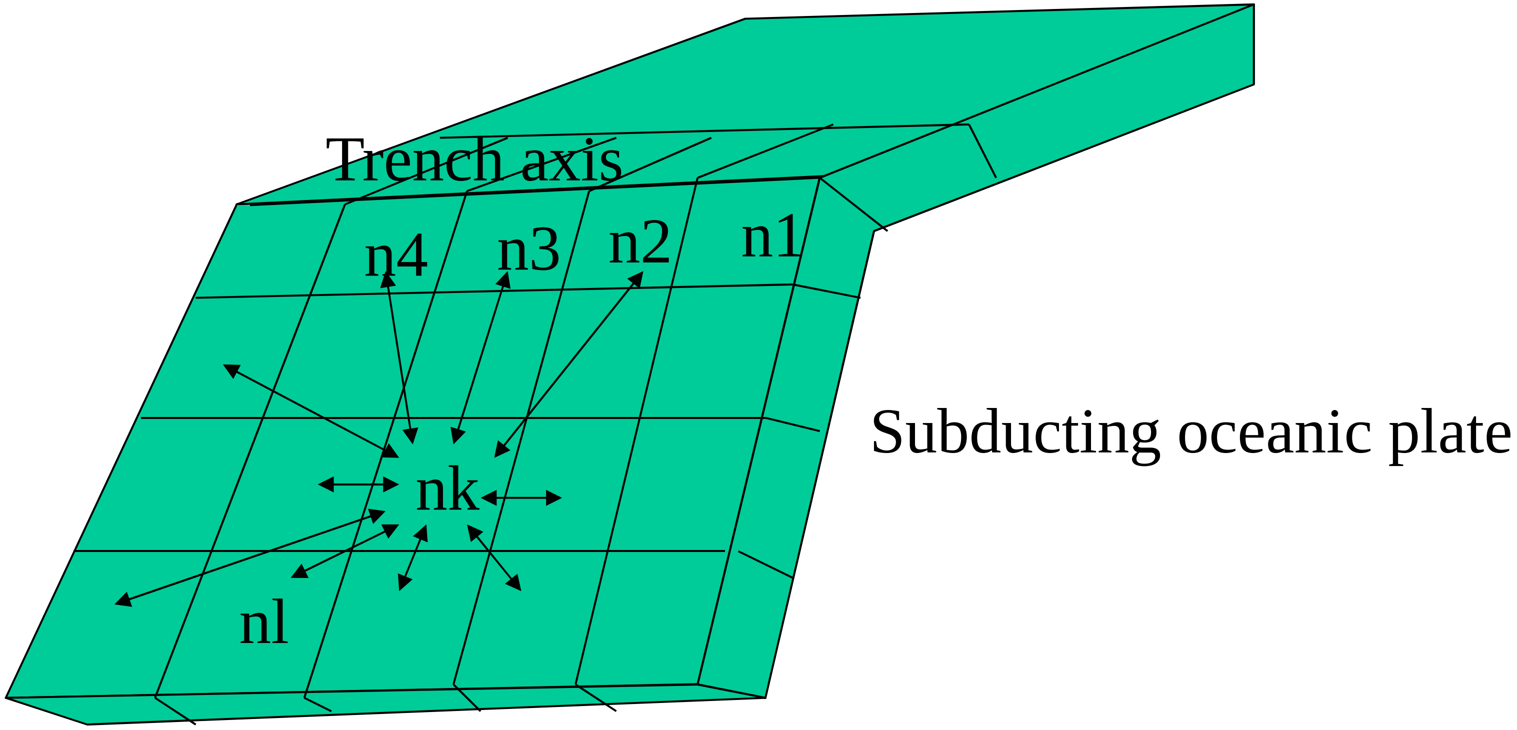


Figure 1, The studied areas of dimension reduction of microseismicity rates of the Philippine Sea Plate (A) and island arc crust (B), showing the microseismic locations of M1 to M2 from 1998-2010.

$\mathbf{X}(t) = (n1(t), n2(t), n3(t), , , nk(t))$; k - dimension



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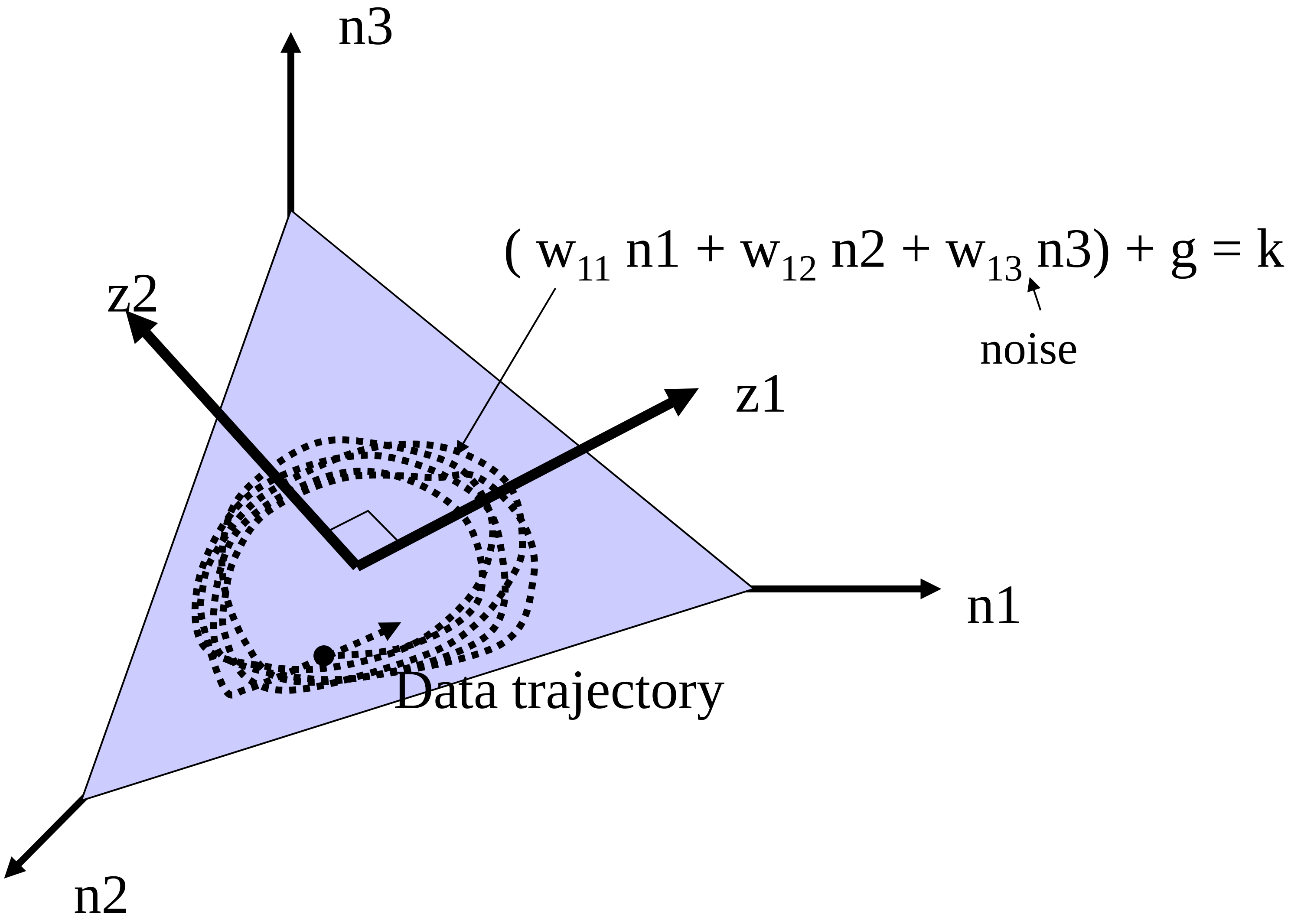
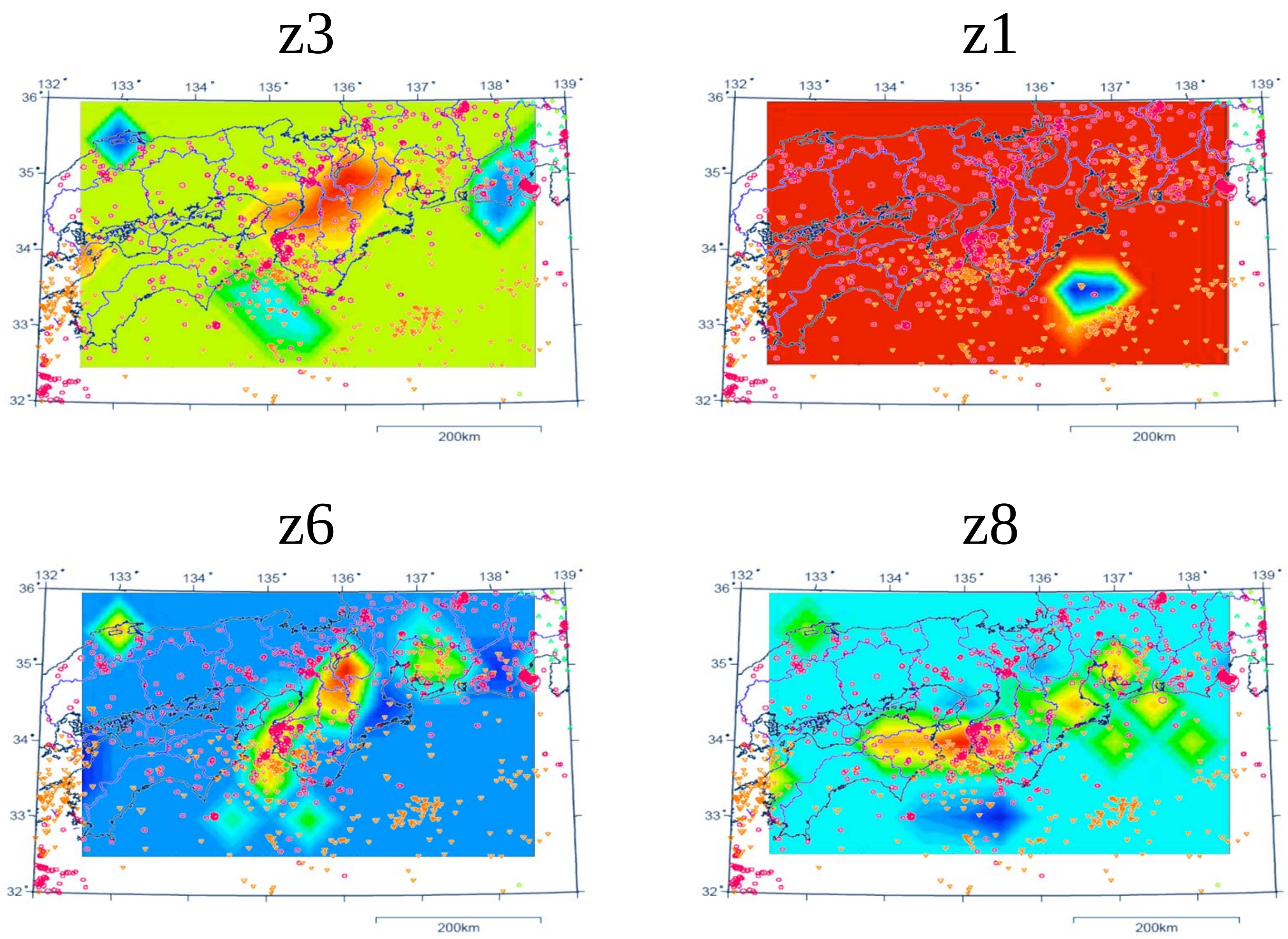


Figure 3, Trajectory of the microseismicity rate vector in the original space and reduced hyper surface. See text.

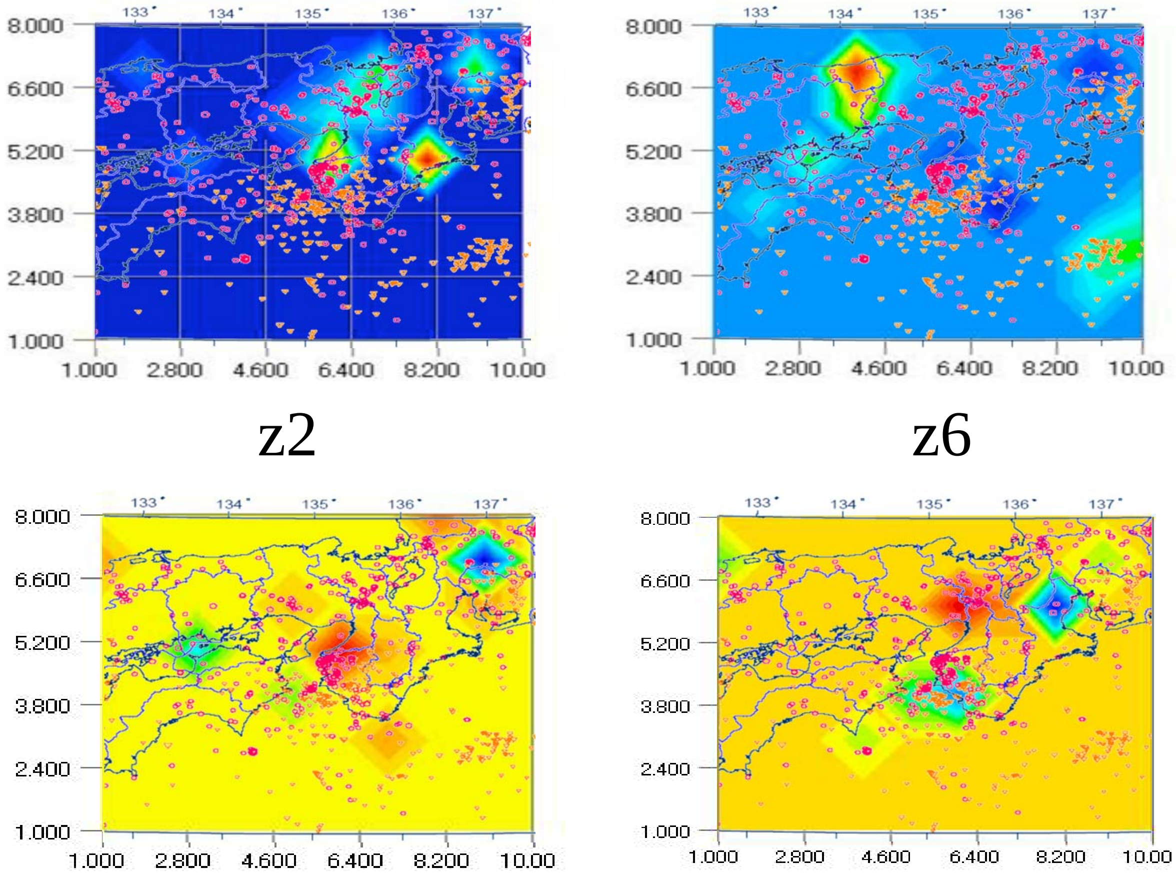

z3

z1

z6

z8

Figure 4, Spatial patterns of the principal components in the reduced hyper surface of the subducting Philippine Sea Plate, showing the color index of intensity of the components . Red color is positive and blue color is negative intensity, but the color contrast should be noticed.



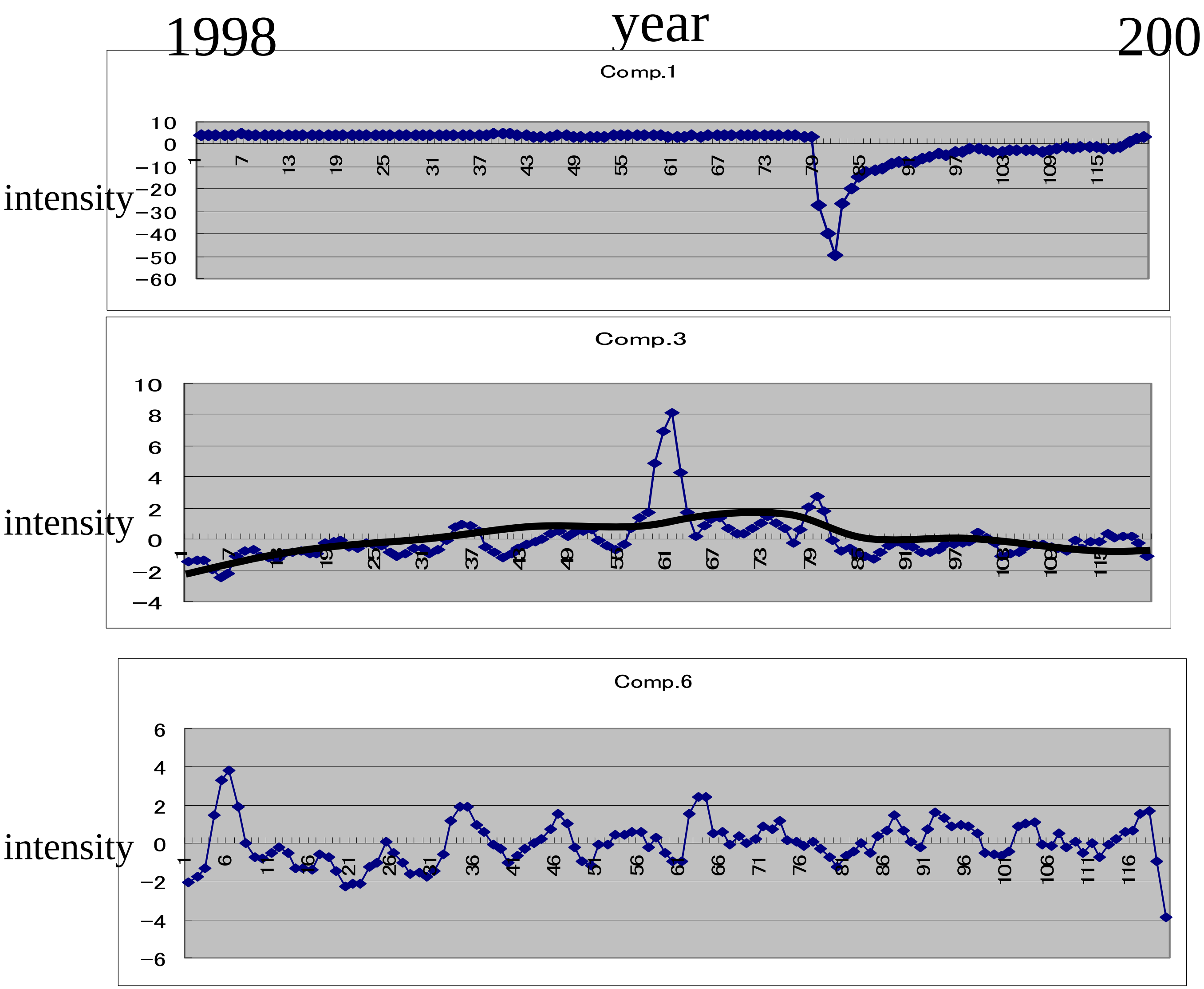
z2

z6

z4

z10

Figure 5, Spatial patterns of principal components in the reduced hyper surface showing the strength of mechanical coupling in the island arc crust of SW Japan. The explanations are the same in the previous figure.



Z1
relaxation process
after large eqs.

Z3

Slow process

Z6
Annual process

Figure 6, Time series of the principal components in the reduced hyper surface of the Philippine Sea Plate. See text.

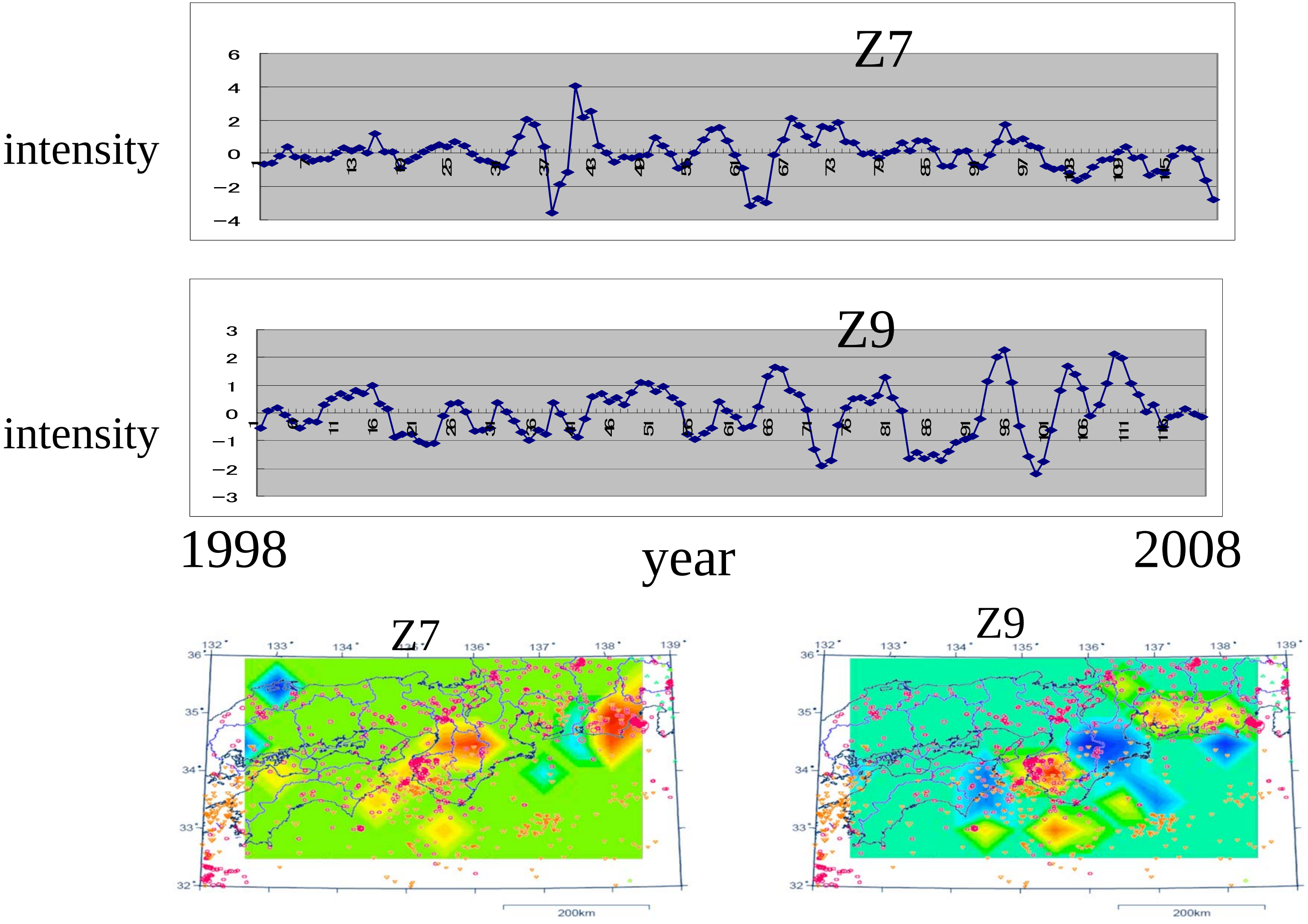


Figure 7, Time series and the spatial patterns of the annually changing components of the reduced hyper surface of data from Philippine Sea Plate.

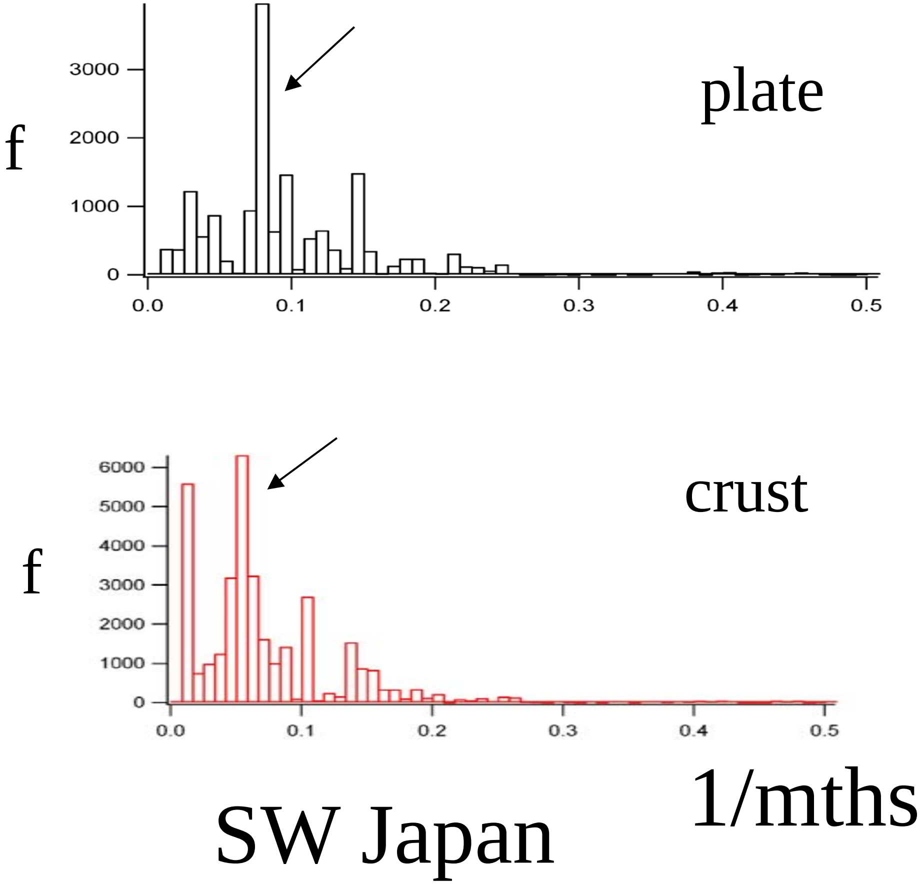


Figure 8, Fourier spectra of the annually changing principal components of the microseismicity rate vectors in the southwestern Japan crust and Philippine Sea Plate(upper).