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Geodynamic evolution of the northeast Japan continental margins during Cenozoic times : new insights

by SERGE LALLEMAND *, JEAN-PAUL CADET ** and LAURENT JOLIVET *

Key words. — Geodynamic, Continental margins, Plates, Subduction, Obduction, Compressive stress regime, NE Japan.

Abstract. — We attempt to clarify and compare the tectonic behaviours of the NE Japan margins during Cenozoic, with special reference to the Amur - Okhotsk plate boundary.

According to the authors analysis and previous studies, we consider the following sketches between east and west margins of NE Japan. 1) The formation of the rifted eastern margin of Japan Sea occurred during Eocene-Oligocene along a N-S right-lateral shear zone which extended northward through the Tartary gulf. At that time, subduction of the paleo-Pacific plate was not very active or even ceased and the forearc uplifted giving rise to the Oyashio landmass. 2) The opening of the Japan Basin as a mega-pull-apart between two large N-S right-lateral shear zones occurred during late Oligocene-early Miocene owing to the motion of the North America plate relative to Eurasia. Thus, the tectogenesis of the eastern margin of the Japan Sea as a strike-slip margin with small en-echelon pull-aparts occurred from Eocene to early Miocene. Subduction started again on the western side of this new island arc from late Oligocene and the emerged forearc began to subside. The Japan trench axis was located at least 200 km eastward of its present position. 3) The Yamato and Tsushima basins as well as many smaller ones inside the Korean Plateau or the eastern margin of the Japan Sea opened during middle Miocene related to the subduction of the Pacific plate under NE Japan simultaneously with the erosion of the front of the forearc and westward retreat of the trench. 4) Since 2 Ma, the forearc shows an uplift well correlated with the closing initiation of the Japan Sea along its eastern margin due to the rejuvenation of the ancient normal faults into reverse ones (ESTASE I cruise results). Major shallow earthquakes occurring in the back-arc clearly determine a convergent zone running along the entire margin and it is likely that this deformation better represents the present plate boundary between the Amur and Okhotsk plates than the central Hokkaido tectonic belt. The gravity sliding which affects the frontal zone of at least the northern Japan trench (KAIKO cruise results), is induced by the motions of oceanic faults below the edge of the continental wedge and does not reflect the general tectonic regime of the arc. Most of the data are consistent with a major influence of the Pacific plate subduction on the NE Japan arc tectonic regime at present.

L'évolution géodynamique des marges continentales du Japon nord-oriental au cours du Cénozoïque : une nouvelle interprétation

Résumé. — Cette étude tente de clarifier et de comparer le comportement géodynamique des marges du Japon nord-oriental entre elles, du Cénozoïque à l'Actuel, à la lumière des nouveaux travaux issus entre autres des campagnes à la mer : KAIKO et ESTASE I.

Le calendrier tectonique concernant l'évolution de l'avant et de l'arrière-arc du Japon nord-oriental, que nous retenons, est le suivant. 1) La marge est de l'actuelle mer du Japon prit naissance à l'Éo-Oligocène le long d'une zone de cisaillement dextre méridienne se prolongeant vers le Nord à travers le détroit des Tartares. A cette époque, la subduction de la paléo-plaque Pacifique n'était pas aussi active qu'actuellement à en juger par l'absence de volcanisme du Paléocène à l'Oligocène inférieur. L'avant-arc se souleva jusqu'à l'émersion d'une île, à présent enfouie sous 3 000 m d'eau et de sédiments, baptisée Oyashio. 2) L'ouverture du bassin du Japon (bassin principal de la mer du Japon) en méga-pull-apart entre deux grandes zones de cisaillement dextres sub-méridiennes eut lieu à l'Oligocène supérieur-Miocène inférieur comme la conséquence du mouvement relatif entre les plaques Amérique du nord et Eurasie. Autrement dit, la tectogenèse de la marge est de la mer du Japon en marge décrochante flanquée de petits pull-aparts en-échelon dura de l'Éocène au Miocène inférieur. La subduction reprit sous la marge opposée de ce nouvel arc insulaire et la paléo-île d'Oyashio commença à subsider. A cette époque, l'axe de la fosse du Japon se trouvait 200 km plus à l'Est qu'actuellement. 3) Les bassins secondaires de Yamato, Tsushima ainsi que de nombreux autres plus réduits dans le plateau coréen ou la marge orientale de la mer du Japon s'ouvrirent au Miocène moyen. Il s'agit cette fois-ci d'ouvertures arrière-arc liées à la subduction de la plaque Pacifique sous le Japon nord-oriental. Le rebord de l'avant-arc se consuma en réponse au retrait vers le continent de la fosse du Japon d'au moins 200 km. 4) Depuis 2 Ma, l'avant-arc se soulève en même temps que la mer du Japon commence à se fermer le long de sa bordure orientale grâce notamment au rejeu inverse des anciennes failles normales orientées sensiblement N-S (résultat de la campagne ESTASE I). Les principaux séismes superficiels arrière-arc déterminent clairement une zone convergente le long de la marge orientale de la mer du Japon. Cette marge intensément déformée correspond vraisemblablement à la frontière actuelle entre les plaques Amur et Okhotsk, plutôt que le long de la chaîne centrale d'Hokkaido. Notons que les glissements en masse se produisant au front de la zone de subduction, au moins dans la partie nord de la fosse du Japon (résultat des campagnes KAIKO) ne reflètent en rien le régime tectonique général de l'arc ; ils sont simplement dus au jeu des failles océaniques sous le mur interne de la fosse. La plupart des données semblent indiquer une influence majeure de la subduction de la plaque Pacifique sur le régime de contraintes actuel dans l'arc, au sens large, du Japon nord-oriental.

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I. — INTRODUCTION.

The aim of this study is to compare the geodynamic evolution of the NE Japan continental margins during Cenozoic times in order to clarify what is related to the subduction of the Pacific plate and what can be attributed to the relative motion of the other surrounding plates.

The island arc of Japan is located : — at the junction of at least four plates (fig. 1) ; — above two contorted subducting slabs and — at the edge of the Asian mainland.

The problem is to estimate the role of each factor in the tectonics of the arc. The influence of the subducting Pacific plate, for example, is a function of the subduction rate, the dip of the slab, the convergent angle between the plates [i.e. Takeuchi, 1983] and the shape of the slab especially at trench corners. Forearc tectonics are obviously mostly related to subduction, to what extent this applies to back-arc basin is difficult to ascertain. In the same way, strike-slip tectonics are likely at the border of continents as was the case in East Asia during Cretaceous times, with the activity of major left-lateral faults like the central Sikhote-Alin fault or the Tanakura fault (fig. 1) [Otsuki and Ehiro, 1978].

New data obtained during the Leg 3 of the french-japanese KAIKO cruise [Cadet *et al.*, 1985, 1987] and during the ESTASE 1 cruise [Lallemand *et al.*, 1985] in 1984 onboard R/V Jean Charcot on one hand and recent field survey in Hokkaido on the other allow us to propose new ideas on recent tectonics, especially for the eastern margin of the Japan Sea and for the base of the northern Japan trench lower slope. Taking, also, into account previous studies, a comparative tectonic evolution scheme of both margins is proposed.

II. — STRUCTURAL EVOLUTION OF THE NE JAPAN AND ITS MARGINS SINCE CRETACEOUS.

During the Upper Cretaceous, the Japanese islands were still part of the Asian continent and belonged to the Okhotsk-Chukotka volcanic belt [Takahashi, 1983]. This active margin underwent a strong shearing along NE-SW left-lateral strike-slip faults [Otsuki and Ehiro, 1978].

1) Pull-apart opening of the Japan Sea in Oligo-Miocene times.

We proposed recently [Lallemand and Jolivet, 1986] that the opening of the Japan Basin was induced by the right-lateral motion of the paleo North-America plate (East of the Hidaka shear zone, fig. 1) relative to the paleo Eurasia plate (west of the Hidaka shear zone, fig. 1) during Paleogene and Lower Miocene. Then, the opening of the Yamato and Tsushima basins occurred as back-arc spreading related to the subduction of the Pacific and Kula (PAC) or proto-Philippine Sea plates (PH.S).

Figure 2 illustrates the two main stages of opening. After an Eo-Oligocene rifting of a pull-apart basin accommodated along two large right-lateral shear zones as defined by Lallemand and Jolivet [1986], one east of Korea and the other west of NE Japan and Sakhalin (fig. 2-1), the main opening of the Japan Basin began during late Oligocene-

FIG. 1. — Structural context and physiography around the Japanese islands. Thick lines represent the assumed plate boundaries.

OKH : Okhotsk plate ; PH.S : Philippine Sea plate ; PAC : Pacific plate ; ISTL : Itoigawa-Shizuoka tectonic line ; HSZ : Hidaka shear zone ; CSAF : Central Sikhote Alin fault ; YF : Yangsan fault ; Ts. F : Tsushima fault ; T.F : Tanakura fault ; Y. Rd : Yamato ridge ; K. Pl : Korean Plateau ; G. Tr : Genzan Trough ; O. Tr : Oki Trough.

FIG. 1. — Grandes lignes tectoniques et physiographie de la région des îles japonaises. Les traits gras représentent les frontières de plaques présumées.

OKH : plaque Okhotsk ; PH. S : plaque de la mer des Philippines ; PAC : plaque Pacifique ; ISTL : ligne tectonique d'Itoigawa-Shizuoka ; HSZ : zone de cisaillement d'Hidaka ; CSAF : faille centrale de Sikhote Alin ; YF : faille de Yangsan ; Ts. F : faille de Tsushima ; T. F : faille de Tanakura ; Y. Rd : ride de Yamato ; O. Rd : ride d'Oki ; K. Pl : plateau coréen ; G. Tr : dépression de Genzan ; O. Tr : dépression d'Oki.

early Miocene (fig. 2-2). Then, the Yamato, Tsushima and other smaller basins on the Korean and Japanese margins (such as the Genzan trough and Oki trough in figure 1) opened at the end of Lower Miocene and during Middle Miocene [Lallemand and Jolivet, 1986] (fig. 2-3). This model is in good agreement with the compiled and newly obtained palaeomagnetic data obtained by Lee *et al.* [1987].

FIG. 2. — Reconstruction of the circum Japan Sea region from Eocene to Present according to Lallemand and Jolivet [1986].

FIG. 2. — Différentes étapes de l'ouverture de la mer du Japon de l'Eocène jusqu'à l'Actuel d'après Lallemand et Jolivet [1986].

FIG. 3. — Interpretation of seismic profiles P 1 (see location on fig. 1).

FIG. 3. — Interprétation des profils sismiques P 1 (voir localisation fig. 1).

2) Quaternary compressive tectonics along the eastern margin of the Japan Sea.

This margin underwent strong E-W compressive deformations since 1 or 2 Ma (fig. 2-4) [Fukao and Furumoto, 1975 ; Nakamura and Uyeda, 1980]. According to Nakamura [1983, 1984] and other authors [Kobayashi, 1984 ; Seno, 1983], it could correspond to a new convergent plate boundary between the North America and Eurasia plates (the Okhotsk and Amurian plates on figure 1). Their evidence (earthquakes, seismic profiles, discontinuity in P waves velocities) favours a nascent trench at the base of the margin where the Japan Basin begins to subduct eastward under the margin. Five seismic profiles were recorded during the ESTASE 1 cruise (chief scientist : L. Labeyrie), crossing the assumed nascent trench in order to test this hypothesis [Lallemand *et al.*, 1985]. No conclusive evidence was found to support the nascent trench hypothesis, however many features indicated E-W compression along this margin, the compression accommodated on east and west dipping N-S reverse faults [Tamaki and Honza, 1985]. Figure 3 shows an example of eastward thrusting (deduced from regional considerations) of the Japan Basin on the fringing ridges of the continental margin [Lallemand *et al.*, 1985 ; Okada *et al.*, 1985].

Active faults exist also on land and follow approximately the same strike as on the eastern margin of Japan Sea. Most of them are reverse-type [Research Group for Active Faults, 1980] and seem to be rejuvenated pre-existing faults [Otsuki *et al.*, 1979]. Fault analysis in the southeastern part of NE Japan [Otsuki *et al.*, 1979] and focal mechanisms of shallow earthquakes [i.e. Hasegawa *et al.*, 1983] permit the determination of the Quaternary tectonic stress field in NE Japan. It is characterized by an horizontal maximum principal stress axis with a N125E strike parallel to the direction of convergence between the Pacific plate and the Japanese continental margin.

3) Tectonic relations with the Japan trench forearc.

An E-W cross-section of NE Japan [Ishiwada *et al.*, 1977] (fig. 4) shows clearly the contrast between the east and west Japanese margins.

Based on the results of DSDP Legs 56 and 57 (see the locations of holes on figure 5) [Von Huene *et al.*, 1982], we can summarize as follows the Cenozoic history of the northern Japan trench forearc. Subduction off NE Japan occurred during Cretaceous to early Paleogene and might have been responsible for perhaps through repartition in an accretionary complex the great thickness (± 45 km !) of the landward dipping Cretaceous sequence. Late Paleogene time was characterized by subaerial erosion of the Oyashio landmass caused by the emergence of the « accretionary complex ». The absence of Eocene to early Oligocene volcanism seems to show that no subduction occurred during this period. At the end of the Paleogene, this paleo-landmass began to subside simultaneously with the reactivation of subduction and associated volcanism. Neogene sedimentary cover overlies unconformably the previous complex and records, through the benthic foraminiferal assemblages, the subsidence. This last period of convergence does not show obvious accretion but, instead, it is marked by erosion at the front of the margin and the retreat of the overriding plate by at least 200 km.

Figure 4 gives an idea of the change of the basement depth from Miocene across the island arc [Sugi *et al.*, 1983] deduced from palaeontologic and lithologic characteristics. It appears that the opening of the Japan Sea from late Oligocene to middle Miocene can be correlated with the subsidence of the forearc and the Quaternary compressive regime well expressed along the eastern margin of the Japan Sea coincides with the recent uplift of the forearc. It seems, therefore, that the tectonic regime across the island arc is governed by the same phenomenon, i.e. the coincidence of crustal movements on each side of the arc, but the effect

FIG. 4. — East-West cross-section of northeast Japan along latitude $39^{\circ}30'N$ adapted from Ishiwada *et al.* [1977] and the change of the basement depth determined by Sugi *et al.* [1983] on land and at the forearc region (DSDP, sites 438/439, see fig. 5).

N-Q : Neogene-Quaternary sediments ; PG : Paleogene ; K1 : Upper Cretaceous system ; K2 : Lower Cretaceous system ; B : basement rocks : pre-Cretaceous and granitic rocks.

FIG. 4. — Coupe Est-Ouest du Japon NE suivant la latitude de $39^{\circ}30'N$ d'après Ishiwada *et al.* [1977] et les variations de profondeur du socle déterminées par Sugi *et al.* [1983] à terre et sur l'avant-arc (DSDP, sites 438/439).

N-Q : sédiments néogènes et quaternaires ; PG : Paléogène ; K1 : ensemble crétacé supérieur ; K2 : ensemble crétacé inférieur ; B : socle : roches granitiques et anté-Crétacé.

is amplified in the back-arc basin or at the boundary between the back-arc and the arc causing intense Plio-Quaternary folding and the reactivation of Miocene normal faults into reverse ones [Lallemand *et al.*, 1985]. In contrast, the Neogene-Quaternary sedimentary cover of the forearc is only slightly folded. According to Takeuchi [1983] and others, variations of the different parameters of the Pacific plate subduction, like the angle of convergence between both plates and the inclination of the downgoing slab, are the only factors which are responsible for the tectonic stresses within the island arc system including the Japan Sea margin. Alternatively, it may be due to the occurrence of a zone of weakness inside the margin created at the time of the opening of the Japan Basin.

FIG. 5. — Location of the Kaiko survey (leg 3, box 1) off northeast Japan in addition to the previous multichannel seismic lines. DSDP sites (legs 56-57 and 87) were also plotted on this map. Isobaths are derived from the bathymetric chart of the adjacent seas of Nippon n° 6301 [Hydrographic Department, Maritime Safety Agency, Japan, 1966].

FIG. 5. — Localisation de la zone étudiée pendant la campagne Kaiko (leg 3, boîte 1) au large du Japon NE ainsi que des lignes sismiques multitraces réalisées auparavant. Les sites de forage DSDP (legs 56-57 et 87) sont figurés. Les isobathes ont été dessinées à partir de la carte bathymétrique des « Mers environnant le Japon » n° 6301 [Hydrographic Department, Maritime Safety Agency, Japon, 1966].

FIG. 6. — Reprocessed seismic record section ORI 78-4 after Von Huene [1986]. Location on figure 5.
 FIG. 6. — Section du profil sismique retraité ORI 78-4 d'après Von Huene [1986]. Localisation sur la figure 5.

III. — NEW INSIGHTS ABOUT TECTONIC EROSION AT THE FRONT OF THE NORTHERN JAPAN TRENCH LANDWARD SLOPE INFERRED FROM KAIKO RESULTS.

An excellent seismic profile crossing the northern Japan trench (ORI 78-4, see figure 6 for location) and reprocessed by Von Huene (fig. 6) [Von Huene, 1986] indicates that the oceanic sedimentary cover descends, without obvious accretion, down the subduction zone probably with additional sediments supplied from the inner wall. It is also possible to follow the horst and graben oceanic structure below the edge of the margin. The front of the margin is composed of a thick sequence of, probably Cretaceous or Paleogene strata of which reflectors are cut at the contact with the oceanic plate. It indicates that abrasion by the oceanic subducting crust occurs below the margin. A Neogene sedimentary cover unconformably overlies the older consolidated sediments which outcrops at a huge slump scar. The toe, located between this scarp and the trench axis, is mostly composed of slump debris supplied by the inner wall in association with listric faults [Lehner *et al.*, 1983]. The absence of thick trench fill sedi-

ments seems to indicate that slump debris are subducted rapidly. This is probably a second erosional factor responsible for the progressive retreat of the margin. A simple calculation shows that a 400 m thick trench fill, continuously subducted at a constant rate of 8 cm/year, is sufficient to explain the 200 km retreat of the Japan trench since early Miocene. This distance is deduced from the occurrence of dacite boulders at site 439, dated radiometrically 23.4 ± 5.5 Ma by Moore and Fujioka [1980]. The problem then, is to know which mechanism induced the gravity slidings down to the trench axis. This area was surveyed in detail during the french-japanese KAIKO cruise (see figure 5 for location), which provided accurate seabed maps, closely spaced single channel seismic profiles, gravity and magnetic maps [Cadet *et al.*, 1985, 1987]. These data combined with focal mechanisms of earthquakes occurring either in the subducting or the overriding plate lead us to say that the intermittent fault motion of the N65°E (parallel to the magnetic lineations) and N-S (parallel to the trench axis) oceanic faults continues under the continental margin and induces, from time to time, major block movements of the front of the margin [Lallemand *et al.*, 1986].

FIG. 7. — Focal mechanisms of some earthquakes which occurred inside the upper plate from 1932 to 1983.
See table I for more details.

FIG. 7. — Mécanismes au foyer de quelques séismes ayant eu lieu au sein de la plaque supérieure de 1932 à 1983.
Voir tableau I pour plus de détails.

IV. — PRESENT TECTONIC STRESS IN NE JAPAN AND THE PROBLEM OF THE AMUR-OKHOTSK PLATE BOUNDARY.

Based on a study of dike swarms, faults and earthquakes data, the trajectories of the maximum horizontal tectonic stress have been compiled by Nakamura and Uyeda [1980] especially in the NE Japan. They found WNW-ESE extension from 21 to 7 Ma BP (27 to 7 Ma for Takeuchi [1983]) and WNW-ESE compression since 6 Ma. The analysis of seismic profiles recorded across the eastern margin of the Japan Sea indicates that the thrust activity began only 1 or 2 Ma ago [Lallemand *et al.*, 1985 ; Tamaki and Honza, 1985]. DSDP results in the forearc area also indicate a

major change from subsidence to uplift since 1 or 2 Ma [Von Huene *et al.*, 1982].

Major earthquakes which occurred inside the upper plate in NE Japan during this century together with their focal mechanisms are shown in figure 7 and listed on table I. Interpretations in terms of fault planes are represented in figure 8. The reverse faults along the eastern margin of the Japan Sea deduced by seismic profiles analyses and earthquakes analyses [see references on table I] determine an active convergent zone with a WNW-ESE direction of some tens of kilometers wide. It could be a nascent plate boundary between the Amurian plate and the Okhotsk plate [i.e. Nakamura, 1983 ; Seno, 1985] rather than that

proposed along the Hokkaido central tectonic belt extending southeastward to the Japan and Kuril trench junction [Chapman and Solomon, 1976]. There are several reasons to support this : it appears that the eastern margin of the Japan Sea is characterized by intense N-S axes folding [Mizoue *et al.*, 1982 ; Mogi, 1981] and active faults [The Research Group for Active Faults of Japan, 1980]. Focal mechanisms of earthquakes all along this margin are also quite consistent with a WNW-ESE compression. Further, only the Pliocene sediments lying west of the central tectonic belt record compressive stress, whereas Quaternary sediments are not affected [Mitani, 1978]. And major earthquakes occurring inside the upper plate are distributed in a small zone south and southwest of the central tectonic belt. The possible plate boundary on the Japan Sea side can conveniently be extended southward in a strike-slip boundary along the Itoigawa-Shizuoka tectonic line [Nakamura, 1983 ; Seno, 1985]. Another contradiction at the central Hokkaido plate boundary is the great variety of earthquake focal mechanisms ; these are sometimes consistent with a NE-SW compression along NW-SE reverse faults (earthquake n° 5 and 6 on figure 7 and 8) and sometimes with a ENE-WSW extension along NNW-SSE normal faults

(earthquakes n° 7 and 8 on figure 7 and 8). Most of them correspond to left-lateral strike-slip faulting [Takanami, 1976], compatible with an E-W to ENE-WSW compression along the southwestern coast of Hokkaido and presumably also near Kushiro. This complexity may be due to the contortion of the subducting Pacific plate at the « Hokkaido corner » [Stauder and Mualchin, 1976].

The earthquakes occurring inside the upper plate along the frontal zone of the forearc probably denote the effect of the active oceanic faults passing below the margin.

V. — DISCUSSION AND CONCLUSION.

We can observe that the tectonic regime of the arc is roughly the same from the back-arc to the forearc at least since Middle Miocene.

It has been demonstrated that the eastern margin of the Japan Sea was a right-lateral strike-slip margin from Eocene to Lower Miocene [Lallemand and Jolivet, 1986] (fig. 2) with simultaneous right-lateral relative motion between North-American and Eurasian plates along the Hidaka shear zone [Jolivet and Miyashita, 1985]. The small basins on the Japan Sea margin were initiated at this time as subordinate pull-aparts along a zone of weakness. Subsequently, a second opening phase took place and these subordinate pull-aparts opened like graben-basins controlled by N-S normal faults during Middle Miocene. This period coincided with the WNW-ESE extension in the arc described by Nakamura and Uyeda [1980] and also with the subsidence of the forearc [Von Huene *et al.*, 1982]. Finally, the N-S ancient normal faults of the Japan Sea margin were rejuvenated during the last 1 or 2 Ma BP into reverse faults which sometimes evolved into thrusts [Lallemand *et al.*, 1985] and simultaneously with this occurred the recent uplift of the forearc region.

What is at the origin of the present tectonic regime all over the arc ? As we indicated in the introduction, there is three possibilities each depending on relative motions and mechanical interactions between plates.

1) The location of the Japanese archipelago at the edge of the Asian mainland favours intracontinental extensional or strike-slip tectonics because of the relative free oceanic side (see the propagating extrusion tectonics in Asia [Tapponnier *et al.*, 1982]). It was the case during Cretaceous and Paleogene times, but now the tectonic regime is clearly compressional in an E-W direction.

2) The Japanese islands are located at the junction of two continental and two oceanic plates. If we consider that the boundary between the Amurian and the Okhotsk plates runs along the eastern margin of the Japan Sea and extends southward along the Itoigawa-Shizuoka tectonic line, we have some difficulties to explain first the tectonic regime of the forearc because of the Okhotsk plate configuration ; and second, according to Zonenshain and Savostin [1981], the counter-clockwise rotation of the Amurian plate relative to the Eurasian plate around a pole located on the northern Amur-Eurasia boundary is incompatible with an eastward movement of the Amurian plate relative to the Okhotsk plate as Tamaki and Honza [1985] emphasized.

N°	Date-Time	M.	Latitude	Longitude	Depth	F-Strike	F-Lg	F-Wd	F-Dip	F-D-Sl	Faulting-type	References
1	26 nov. 1932	7	42°24' N	142°24' E	40	NW-SE					Left-lateral strike-slip	ICHIKAWA, 1971 TAKANAMI, 1976
2	19 oct. 1955	5.7	40°18' N	140°12' E	0.2*	N-S	15	4	64°	20.5	Reverse	MIZOUE <i>et al.</i> , 1982
3	7 may 1964 (7h 58')	6.9	40°39' N	139°05' E	22	NNE-SSW	50	20	45°	120	Reverse	FUKAO and FURUMOTO, 1975
4	16 Jun. 1964	7.5	38°25' N	139°15' E	1*	N 9°	80	30	(34°E)	330	Reverse (main fault) Reverse (subsidiary fault)	ABE, 1975 SATAKE and ABE, 1983
5	20 Jan. 1970 (17h 33')	7	42°29' N	143°02' E	25	N 300°			24° NE		Reverse with left-lateral strike-slip comp.	MORIYA, 1972 CHAPMAN and SOLOMON, 1976
6	21 Jan. 1970	6.7	42°23' N	143°08' E	50	N-S			80° W		Reverse	MORIYA, 1972 TAKANAMI <i>et al.</i> , 1978
7	31 oct. 1976 (23h 30')	5.0	42°22' N	142°57' E	54	NW-SE			80° E		Normal	TAKANAMI <i>et al.</i> , 1978
8	1 nov. 1976 (13h 06')	4.7	42°20' N	142°56' E	53	NW-SE			55° E		Normal	TAKANAMI <i>et al.</i> , 1978
9	13 Jan. 1979 (1h 37')	4.2	42°31' N	141°52' E	21	N 311°			50° E		Left-lateral strike-slip	TAKANAMI, 1980
10	6 apr. 1979 (23h 30')	3.3	36°44' N	137°49' E	15						Strike-slip	FUKAO and YAMAOKA, 1983
11	19 apr. 1979 (5h 25')	2.6	36°31' N	137°32' E	1.3						Strike-slip	FUKAO and YAMAOKA, 1983
12	16 nov. 1979 (0h 57')	4.3	37°14' N	138°03' E	20	N-S					Reverse with strike-slip component	FUKAO and YAMAOKA, 1983
13	20 dec. 1979 (7h 12')	2.6	36°44' N	138°08' E	5.5						Strike-slip	FUKAO and YAMAOKA, 1983
14	20 feb. 1980 (9h 13')	3.3	36°50' N	137°30' E	7.3						Strike-slip	FUKAO and YAMAOKA, 1983
15	9 Jul. 1981 (10h 19')	3.9	39°44' N	143°49' E	10	ENE-WSW					Reverse	DBS Division Earthquake Research Inst., 1983
16	9 Jul. 1981 (10h 28')	4.3	39°49' N	143°43' E	10	NE-SW					Reverse	DBS Division Earthquake Research Inst., 1983
17	10 Jan. 1982 (0h 22')	4.1	37°18' N	138°43' E	1*	N 4°	10	4	85°W	25	Reverse	MIZOUE <i>et al.</i> , 1982
18	26 May 1983 (12h 00')	7.7	40°24' N	139°06' E	14	N-S	40 60	30 30	40°E 25°E	760 308 54	Double reverse ←southern fault ←northern fault left-lateral comp.	AIDA, 1984 HATORI, 1984 ISHIKAWA <i>et al.</i> , 1984

TABLE I. — List of crustal earthquakes located on figure 8 with their parameters.

M : magnitude ; Depth : in km ; F-Strike : strike of the fault plane ; F-Lg : length of the fault plane in km ; F-Wd : width of the fault plane in km ; F-Dip : dip of the fault ; F-D-Sl : dip-slip of the fault in cm.

TABL. I. — Liste des séismes crustaux représentés sur la figure 8 avec leurs différents paramètres.

M : magnitude ; Depth : profondeur en km ; F-Strike : orientation du plan de faille ; F-Lg : longueur du plan de faille en km ; F-Wd : largeur du plan de faille en km ; F-Dip : pendage de la faille ; F-D-Sl : projection du rejet net de la faille en cm.

FIG. 8. — Interpretation, in terms of faulting type and maximum horizontal stress field, of earthquakes in addition to some faults recognized by Tamaki and Honza [1985], Lallemand *et al.* [1985] or the Research Group for Active Faults [1980]. Circles outline the Quaternary volcanic front. The main tectonic lines are represented in dotted lines. Thick numbers refer to the earthquakes listed in table I, whereas thin numbers correspond to earthquakes from 1973 to 1981, deduced from the Japan Meteorological Agency Reports, which date of occurrence follows : 1- 14.06.78 [JMA, 1982] ; 2- 14.07.80 [JMA, 1984] ; 3- 15.03.76 [JMA, 1980] ; 4- 18.02.77 [JMA, 1981] ; 5- 24.03.81 (M = 4.9) [JMA, 1985] ; 6- 18.06.74 [JMA, 1978] ; 7- 14.08.74 [JMA, 1978] ; 8- 12 and 15.10.74 [JMA, 1978] ; 9- 20.02.79 [JMA, 1983] ; 10- 10.09.75 [JMA, 1979] ; 11- 10.03 (M = 5.0), 14.04 (M = 5.1) and 15.10.81 (M = 6.0) [JMA, 1985] ; 12- 04.09.74 [JMA, 1978] ; 13- 06.07.73, 25.04.77 and 17.03.80 [JMA, 1977, 1981 and 1984] ; 14- 10.09.73 [JMA, 1977] ; 15- 16.08.79 and 19.01.81 (M = 7.0) [JMA, 1983 and 1985] ; 16- 06.06.73 [JMA, 1977] ; 17- 23.01.81 (M = 6.6) [JMA, 1985] ; 18- 04.06.76 [JMA, 1980] ; 19- 12.06.78 [JMA, 1982] ; 20- 08.11.76 [JMA, 1980] ; 21- 05.05.74 [JMA, 1978] ; 22- 08.04 and 13.04.75 [JMA, 1979] ; 23- 07.08.76 [JMA, 1980] ; 24- 24.08.73 and 04.05.75 [JMA, 1977 and 1979] ; 25- 21.03.74 [JMA, 1978] ; 26- 17.08.79 [JMA, 1983] ; 27- 06.02.81 (M = 4.4) [JMA, 1985].

FIG. 8. — Interprétation, en terme de fracturation et de contrainte horizontale maximum, des séismes ainsi que quelques failles reconnues par Tamaki et Honza [1985], Lallemand *et al.* [1985] ou The Research Group for Active Faults [1980]. Les cercles délimitent le front du volcanisme quaternaire. Les lignes tectoniques principales sont représentées en pointillés. Les chiffres en traits gras correspondent aux séismes listés dans le tableau I, tandis que ceux en traits fins correspondent aux séismes de 1973 à 1981 déduits des rapports du Japan Meteorological Agency.

An alternative explanation may be the continuation of the westward movement of the Okhotsk plate relative to the Amurian plate, but there is not sufficient data, at present, to support this hypothesis, except the focal mechanism of the Sept. 5, 1971 earthquake which occurred in the south-western part of Sakhalin Island ($M = 7.3$) showing WSW-ENE compression [Savostin *et al.*, 1983].

3) Considering the high subduction rate of the Pacific plate under the NE Japan (10 cm/year), the low dip of the slab and the curvature between the Japan and Kuril trenches, it is possible to relate the tectonic regime all over the arc since the Middle Miocene to the subduction process. One possible interpretation of the particular eastern margin of Japan Sea activity may be the past tectonic history with the creation of a zone of weakness where the continental lithosphere preferentially accomodates the deformation.

Finally, from Eocene to Lower Miocene, the right-lateral movement between the North-America and the Eurasia plates governed the tectonics, at least for the first stage of opening of the Japan Sea [Lallemand and Jolivet, 1986]. The reactivation of the Pacific plate subduction occurred sometime during Oligocene [von Huene *et al.*, 1982]. The tripling of the Pacific plate motion at 25 Ma [Van Andel, 1974] may be at the origin of the back-arc

spreading (second opening) in the Japan Sea associated with E-W extension, i.e. Mariana-type mode of subduction of Uyeda [1982]. This mode must have changed from Mariana-type to Chilean-type during Pliocene [Sugi *et al.*, 1983] for some reason. Was it due to a detachment of the Pacific slab [Kanamori, 1977 ; Niitsuma, 1978] as suggested by the seismic gap under the Japan Sea if we extrapolate the slab or to the change of the Pacific plate motion at 5 Ma as stated by Cox and Engebretson [1985] ?

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