MANABU HASHIMOTO

学 位 審 査 報 告

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（学位論文題目）

Three-Dimensional Stress Field in the Crust and Upper Mantle beneath the Southwestern Japan ---- with Special Reference to the Configuration of the Subducting Philippine Sea Plate ——

（西南日本の地殻及び上部マントル内の3次元応力分布

—— 沈み込むフィリピン海プレートの3次元形状に関連して ——）

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（論文内容の要旨）

本論文は，西南日本下へ沈み込むフィリピン海プレートに関連して，この地域の地殻及び上部マントル内で期待される３次元応力分布を計算し，観測から推定される複雑な応力状態の原因を解明し，あわせてその応力の大きさを推定することを目的としたものである。この地域の現在の応力状態は，地震の震源の深さ分布と発震機構の研究（例えば Shiono，1977）から次のように考えられている。(1)南海トラフ内側の深さ20～30kmの浅い部分では南東－北西方向に圧縮力が働く。(2)内陸部の地殻内部ではほゞ東西ないし東南東－西北西方向の圧縮力が働いている。(3)中部地方南部から四国地方西部の深さ40～80kmの部分には，フィリピン海プレートの沈み込み先端にほゞ平行する張力が卓越する。(4)九州－琉球弧北部の深さ200km程度迄には，深発地震帯の傾斜に平行する張力が働いている。申請者はこのような応力分布が何故生じているかを明らかにするため，フィリピン海プレートの３次元的形状や，西南日本全域に加わる力を考慮して，次のような解析を行った。

主論文第１部においては，地殻下に発生する地震分布からフィリピン海プレートの形状を推定するとともに，上下２層より成るプレートの構造，プレートより上の大陸地殻の構造，プレートより下にある asthenosphere の構造，及びプレートと大陸地殻の間の薄い漸移層を考慮の上，媒質を弾性体として扱い，これらの構造をヤング率と密度の差で表現した。さらにこのモデルに加わる力として，沈み込むプレートと周囲の密度差によって生ずる負の浮力，太平洋プレートの西進による西向きの圧縮力，フィリピン海プレートの運動による北西方向の圧縮力を考え，３次元有限要素法を用いて，西南日本各地域の種々の深さにおける応力を計算し，先に述べた観測結果と詳細な比較検討を行った。この結果，四国地方西部の地殻下の応力分布を除いては，ほゞ観測された応力方向を説明出来ること，この地

域内に働く剪断応力の大きさが数百バールを超えないことなどの重要な結論を得ている。

主論文第2部においては，特に西南日本最西端の九州地域に着目し，特に最近測地測量から明らかにされた九州中部の地殻内に働く南北方向の張力分布のパターンと地殻変動速度，九州下へ沈み込むフィリピン海プレート内の張力分布及びプレートの沈み込みの角度の解明を目的としている。この論文においては第1部と異なり，長年月に亘る歪の変動速度や応力の変化をも問題とするため，媒質としては非圧縮性粘性流体を考え，3次元有限要素法による計算を行った。このモデルで採用した粘性は，地殻及びリソスフェアの部分で 4×10^{23} poise，asthenosphere 内で 4×10^{20} poise である。こゝで考えた力は，沈み込むプレートに働く負の浮力のほか，海洋プレートの生成に伴なう ridge push force，asthenosphere 中の流れによる圧縮力，密度の小さい島弧地殻に働く正の浮力，沖縄トラフの拡大に伴なう浮力，低密度の九州－Palau 海嶺に働く正の浮力などである。これから，これらの力の種々の組合せによってどのような応力や地殻変動を生ずるかを詳細に計算している。この結果，九州西部と瀬戸内海地域を含む中国西部に見られる地殻の最近の沈降や，重力の負の Bouguer anomoly を除いては，九州地域の応力分布とテクトニクスを説明することに成功し，種々の重要な結論を得ている。

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〔論文審査の結果の要旨〕

地殻及び上部マントル内部で応力がどのような状態で分布し，かつこの応力特に剪断応力がプレート境界や大陸リソスフェアの活断層周辺でどの程度の大きさを持つかは，地震発生のメカニズムを知る上で極めて重要な問題であり，また地震予知にとって１つの手掛りを与えるものと期待される。

地殻内部の応力を直接測定する試みは最近，応力解放法や水圧破壊法によって行われるようになったが，これは地殻の極めて浅い部分に限られる。また地震発生の際の地殻変動や地震波の観測データから応力降下量を求め，さらにある仮定を置いて初期応力を推定する方法は極めて間接的である。一方，地殻や上部マントル内部の応力の方向に関しては，地震メカニズムの解析から推定が可能であり，西南日本においても多数の地震の解析をもとに，複雑な方向分布が明らかにされて来た。しかしながら，このような応力の絶対値がどの程度であるのか，また複雑な応力分布を生ぜしめる原因が何処にあるかは，これ迄未解明の問題であった。

申請者が行った研究はこれらの点を明らかにすることを目的としたもので，西南日本下の地殻及び上部マントル内に応力を発生させる主たる原因と思われるフィリピン海プレートの沈み込み及び太平洋プレートの運動などを考慮して種々の解析を行っている。この研究では，震源分布から想定されるフィリピン海プレートの先端の形状が複雑であるため，このような問題としては始めて３次元有限要素法を適用した。

論文第１部においては，沈み込むフィリピン海プレートの先端に働く張力は，主としてプレートに働く負の浮力とプレート先端の複雑な形状によって生じていること，内陸部の地殻に働いている東西ないし東南東－西北西方向の圧縮力は，太平洋プレートによる力が大部分であること，フィリピン海プレートによる北西方向の圧縮力は約500 bars以内で太平洋プレー

トによる力に比べて半分以下と見積られることなどの重要な結果を得た。さらにまたこの地域に働く最大剪断応力の大きさは高々数百 bars 以内であるが，この応力の大きさはプレートの形状に依存し，地殻底地震の活動度や，南海トラフ沿いに起る巨大地震の破壊過程に顕著な影響を与えていること，沈み込むプレートの上に若し実際に薄い漸移層が存在すると，低角逆断層の地震のメカニズムに著しい効果を及ぼすことなど，注目すべき結果を得ている。

論文第2部の研究からは，九州中部に働くほゞ南北方向の張力場は，沈み込むプレートによる引張力，地殻に働く正の浮力及び asthenosphereの流れの相互作用によって説明され，沖縄トラフの拡大はあまり大きい影響を及ぼしていないこと，深発地震帯中の下向きの張力は主として slab pull で起ること，最上部マントル中で正断層を発生させる水平方向の張力場は asthenosphere 中の流れによって生じ，主として九州東方の海洋側で発生することなどを明らかにした。さらにまた応力の大きさに関しては，沈み込むプレートの傾斜角を説明するためには asthenosphere 中の流れによる圧縮力の大きさは100～250 bars程度，流れの大きさは地表面付近で1㎝/yr 程度，沈み込むプレート内部とその上の大陸地殻の中の最大剪断応力の大きさは500 bars程度と見積られることを示し，第1部で得た結果をさらに確める結論を得た。

以上に述べた申請者の研究は，西南日本全域にわたる地殻・上部マントル内の応力分布や地殻変動を生ずる原因を明らかにし，また応力の絶対値を見積ることを可能にしたものであり，この地域のテクトニクスと地震発生の研究に寄与する所が大きく，高く評価される。参考論文3篇は本論文に密接に関係したもので，申請者の学識を示すものである。よって本論文は理学博士の学位論文として価値あるものと認められる。

なお，主論文及び参考論文に報告されている研究業績を中心とし，これに関連した研究分野について試問した結果，合格と認めた。

論 文 目 録

学位授与申請者
橋本　学

主論文

1．題目

Three-Dimensional Stress Field in the Crust and Upper Mantle beneath the Southwestern Japan
– with Special Reference to the Configuration of the Subducting Philippine Sea plate –
（西南日本の地殻及び上部マントル内の３次元応力分布
–沈み込むフィリピン海プレートの３次元形状に関連して–）

2　公表の方法，時期

１部　Numerical modelling of the three-dimensional stress field in southwestern Japan.
（西南日本の３次元応力分布の数値モデル）
Tectonophysics, Vol.84, Nos.3-4, p 247-260
（1982年4 月刊行）掲載

２部　Finite element modeling of the three-dimensional tectonic flow and stress field beneath the Kyushu island, Japan.
（九州下のテクトニックな３次元流れ及び応力場の有限要素モデル）
Geophysical Journal of the Royal Astronomical Society に投稿中

3　冊数　　1冊

参考論文

1　題目
西南日本に沈み込むフィリピン海プレートの形状と三次元応力分布（序報）
地震　第２輯　第３３巻　第４号　465-478 頁

2　題目
西南日本ニ沈み込むフィリピン海プレートの形状と三次元応力分布（第２報）
地震　第２輯　第３４巻　第２号　197-212 頁

3　題目
Finite element modeling of deformations of the lithosphere at an arc-arc junction : the Hokkaido corner, Japan.
Journal of Physics of the Earth に投稿中

主論文オ一部

Tectonophysics, 84 (1982) 247–266
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NUMERICAL MODELLING OF THE THREE-DIMENSIONAL STRESS FIELD IN SOUTHWESTERN JAPAN

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ABSTRACT

Hashimoto, M., 1982. Numerical modelling of the three-dimensional stress field in southwestern Japan. *Tectonophysics*, 84: 247–266.

It has been inferred from the focal mechanism of earthquakes and their hypocenter distribution (Shiono, 1977) that the stress field in southwestern Japan indicates complicated features; a NW–SE compression at shallow depths along the Nankai trough, an E–W or ESE–WNW compression in the inland crust, an extension parallel to the leading edge of the Philippine Sea plate at subcrustal depths in the region from the southern Chubu to northwestern Shikoku, and a down-dip tension beneath the Kyushu island.

In order to investigate possible sources of these complex features of the stress state, a three-dimensional finite element method is employed to model the configuration of the subducting Philippine Sea plate, taking into consideration the following three possible types of forces:

(1) A negative buoyancy due to the density contrast between the subducting plate and the surrounding mantle.

(2) A northwestward compressive force generated by the movement of the Philippine Sea plate.

(3) A westward compressive force due to the movement of the Pacific plate.

For various combinations of different magnitudes of these forces, and of different elastic moduli, the stresses at a number of selected sites are calculated, and their directions are compared with those inferred from the focal mechanism and other geophysical information.

It is found that the observed extensional stresses parallel to the leading edge of the subducting Philippine Sea plate may be caused mainly by the negative buoyancy. The northwestward compressive force may not play an important role in generating the complex stress field in southwestern Japan. The observed E–W compressional stress field prevailing in the inland region appears to result mainly from the westward-moving Pacific plate. The present results suggest that if a thin low-velocity transitional layer exists just above the subducting Philippine Sea plate, it could give appreciable effects on the mechanism of low-angled thrust faulting off the Kii peninsula and the Shikoku island.

The magnitude of the shear stress in the continental crust and in the subducting plate is estimated to be of the order of several hundred bars, although the calculated shear stresses are considerably affected by the configuration of the subducting plate and also by the applied forces.

It is interesting that the stress distribution appears to have some relations to seismicity of subcrustal earthquakes, and to the rupture process of large thrust earthquakes along the plate boundary.

INTRODUCTION

Crustal and upper-mantle earthquakes taking place in southwestern Japan (Fig. 1) may be divided into three groups according to their locations of hypocenters and stress orientations (Shiono, 1977), (Fig. 2);

(1) Off-shore earthquakes located at the inner margin of the Nankai trough and in Hyuganada just east of the Kyushu island, which indicate low-angled thrust faulting, due to the subduction of the Philippine Sea plate (Fitch and Scholz, 1971; Kanamori, 1972; Ando, 1975), suggesting the existence of a northwestward compressive stress.

(2) Shallow inland earthquakes whose axes of greatest compressive stress (P-axes) lie in a nearly E–W or ESE–WNW direction (Ichikawa, 1971). These horizontal stress directions appear nearly consistent with those inferred from geodetic work (Nakane, 1973) and also from geological studies of distribution of active faults and volcanic dykes (Ando, 1979), (Fig. 3).

(3) Subcrustal earthquakes that occur over an extensive region from the southern Chubu district to Iyonada, northwestern Shikoku, which are characterized by systematic alignments of the minimum compressional axes (T-axes). The T-axes are

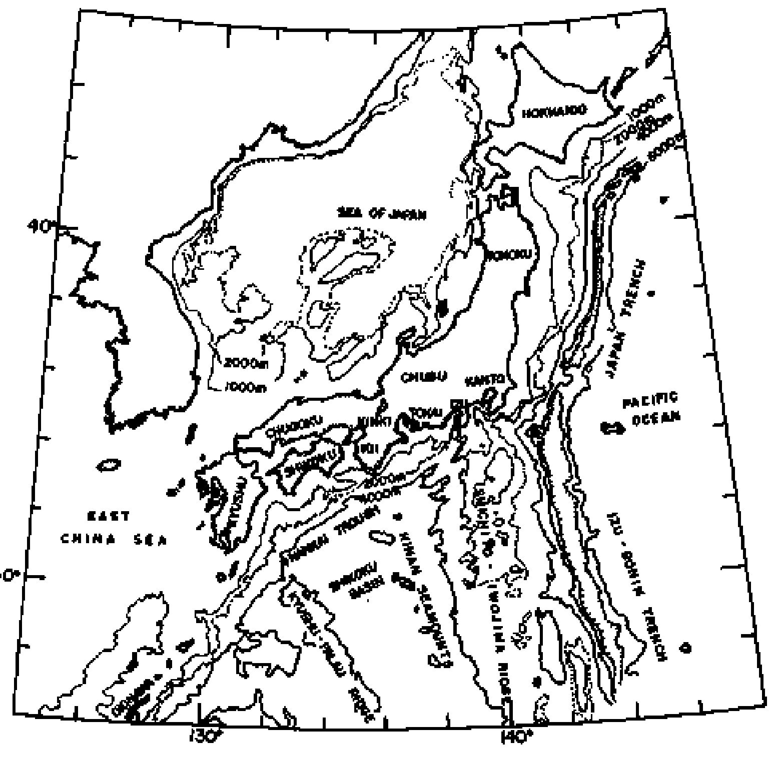


Fig. 1. Index map around the Japanese islands, which includes bathymetry (after Hirahara, 1981).

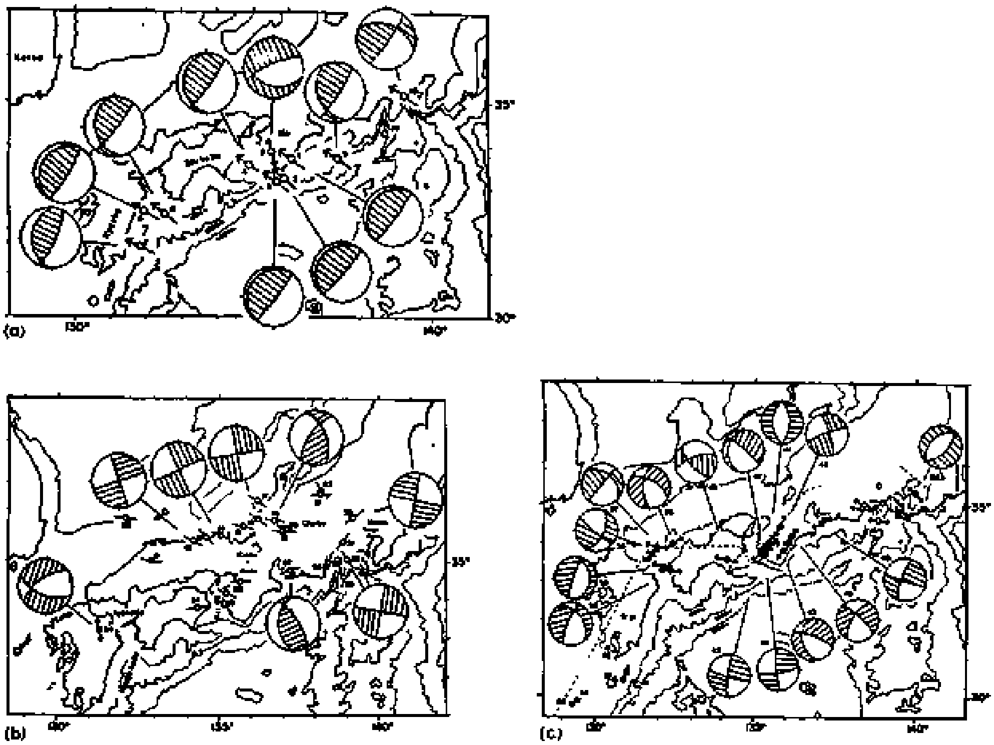


Fig. 2. Focal mechanisms in southwestern Japan projected onto the lower hemisphere of the Wulff's net (after Shiono, 1977). a. Slip direction (arrow) and mechanism diagrams of earthquakes along the Nankai trough and in Hyuganada. b. Distribution of the *P*-axes for crustal earthquakes and mechanism diagrams. c. Distribution of the *T*-axes for subcrustal earthquakes and mechanism diagrams. A dotted line gives the location of the presumed leading edge of the Philippine Sea plate.

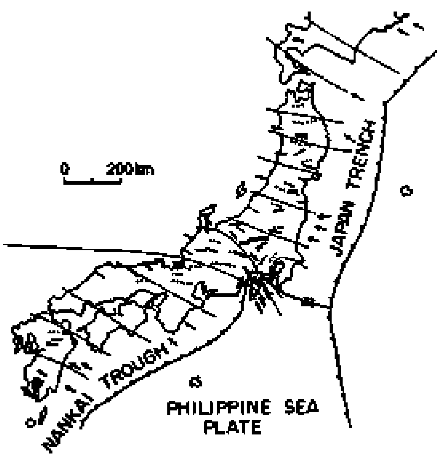


Fig. 3. Directions of the greatest horizontal compressive stresses ($\sigma_{H_{max}}$) obtained from mechanism solutions of earthquakes, strikes of active faults and volcanic dykes (after Ando, 1979).

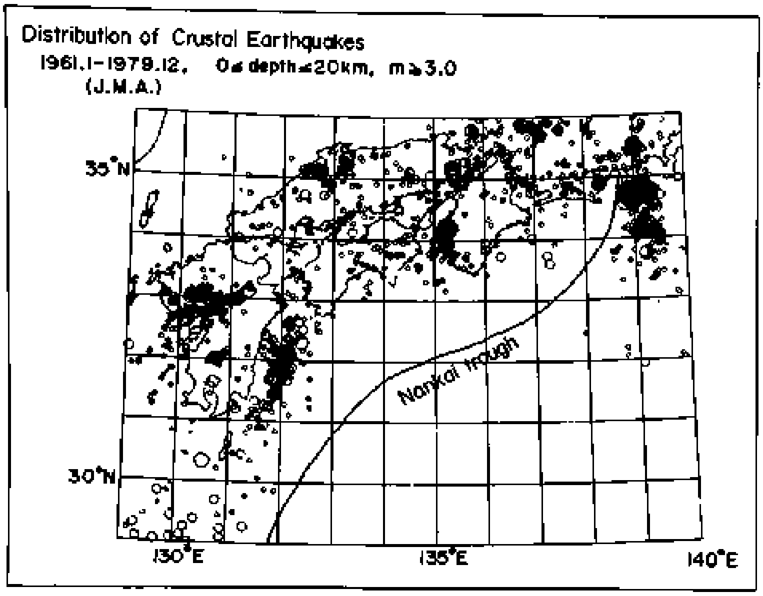
parallel to the leading edge of the subducting Philippine Sea plate (parallel extension). Under the Kyushu island and the northern Ryukyu arc, the *T*-axes dip westwards and are approximately parallel to the dip of the inclined seismic zone (Shiono et al., 1980).

Recently, however, Shiono (1973) and Okano et al. (1980) pointed out that the stress orientation changes abruptly at some depths beneath the western Kii peninsula and Shikoku regions. Thus, it may be inferred that the stress field in southwestern Japan has rather complicated features.

On the other hand, it has been revealed from the distribution of subcrustal earthquakes and the travel-time analysis that the configuration and the shape of the leading edge of the subducting Philippine Sea plate are also quite complex (Shiono, 1974; Mizoue, 1977), (Fig. 4). Recent studies by Hirahara (1981) using an inversion technique have revealed a more detailed three-dimensional structure of the subducting plate. It was found from these investigations that the plate appears remarkably distorted beneath the eastern Shikoku and the Iyonada regions. Hurukawa and Hirahara (1980) also suggested a possibility that there could be a low-velocity layer with a thickness of 4–8 km between the subducting and the overlying plates beneath the Kii peninsula.

Under these situations, it seems difficult to explain the observed stress state in this region in terms of such simple tectonic models for a typical subduction zone as in northeastern Japan (e.g., Utsu, 1971; Okada, 1979).

In the present paper, we attempt to model the observed complicated stress field in southwestern Japan by applying a three-dimensional finite element method (F.E.M.) to account for possible sources of these stresses. Several investigators have studied the tectonic stress field in some regions in the world by using a two-dimensional F.E.M. (e.g., Shimazaki, 1974; Yoshiwara, 1975; Richardson et al., 1979; Seno, 1979a,b; Bird and Piper, 1980). However, it is impossible to calculate the stresses at depths in the crust and upper mantle from a plane model (e.g., Richardson et al., 1979). On the other hand, we cannot evaluate the effects of lateral bending of a downgoing plate using a two-dimensional section model (e.g., Shimazaki, 1974). It is undoubtedly necessary to use a three-dimensional F.E.M. to solve these problems, and only a few studies along this line have been made (e.g., Kosloff, 1977; Minamino and Fujii, 1981). We calculate all stress components at a number of selected sites and depths in southwestern Japan within the scheme of a 3-D F.E.M., taking into consideration a three-dimensional configuration of the subducting Philippine Sea plate and several combinations of possible forces working in this region, and then compare them with the observed pattern of the stress field.



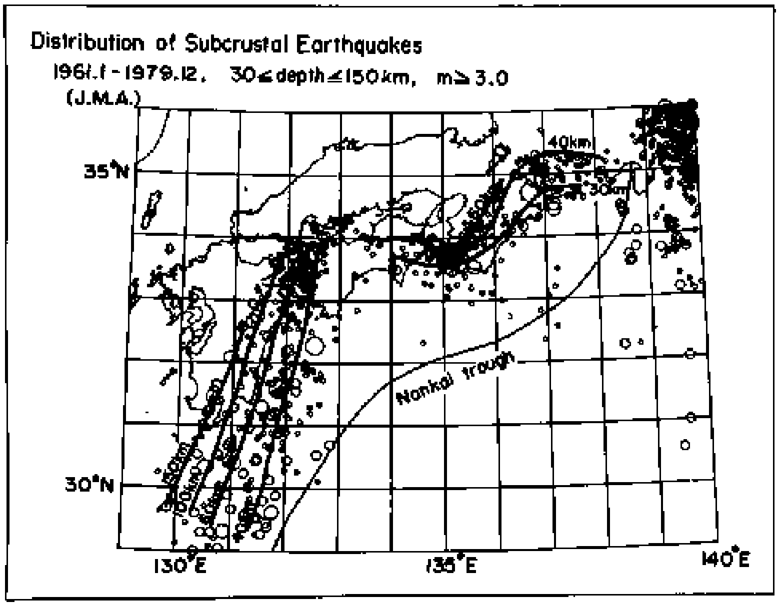


Fig. 4. Epicentral distributions of crustal (upper) and subcrustal (lower) earthquakes. Contours in the lower figure represent the average depths of hypocenters, modified from Mizoue (1977) and Shiono (1977).

THREE-DIMENSIONAL MODELLING

Finite element grids and elastic moduli

For a finite element, we use a hexahedron isoparametric element with eight nodes following Zienkiewicz and Cheung (1967). The horizontal projection of the finite element grids constructed here is shown in Fig. 5, and its vertical section is schematically illustrated in Fig. 6. The total numbers of nodes and elements assigned here are 810 and 585, respectively. Our model space is composed of five layers; the first layer (the uppermost layer) corresponds to the continental crust, and the second layer includes a transitional layer, which is assumed to exist just above the subducting plate, and a part of the asthenosphere. The third and fourth layers include the upper and lower portions of the subducting oceanic plate and partly the surrounding mantle, and the fifth layer (the lowest layer) coresponds to the asthenosphere. The depths to the upper surface of the subducting plate range from 30 to 150 km at the leading edge and from 10 to 15 km at the Nankai trough, respectively, modelling the configuration of the plate, which has been taken to include a seismic zone of shallow to subcrustal earthquakes, as estimated by Mizoue (1977), (Fig. 4). We assume here the thickness of the third and fourth layers as 30 km, respectively, and depths to bottom of the lowest layer as 250 km.

The thickness of the second layer (dotted part in Fig. 6) has been assumed as 5 km following Hurukawa and Hirahara's (1980) estimate for an intervening low-velocity layer beneath the Kii peninsula. We also assume that the Philippine Sea plate penetrates into the asthenosphere beneath the eastern Kyushu region (shaded

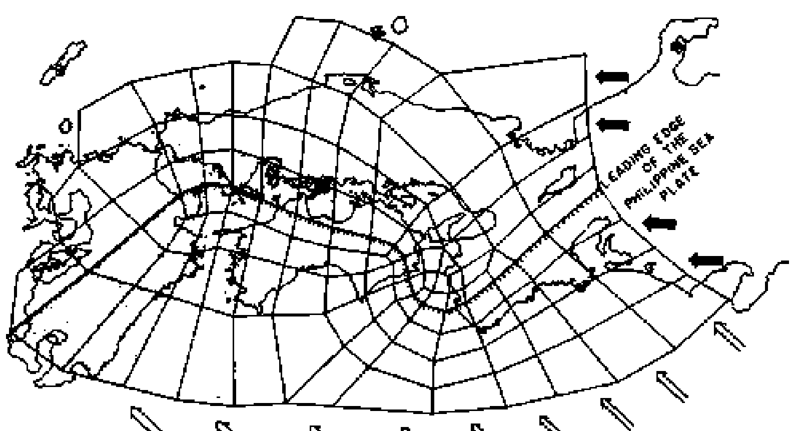


Fig. 5. Horizontal section of the present finite element grids. White and black arrows show the directions of *PN* and *PW*, respectively, which are compressive forces applied to the boundaries of the finite element grids.

portion in Fig. 5). We think that the degree of contact between the continental and oceanic plates may be varied by changing elastic moduli of this layer. Now we consider four different cases; elastic moduli assigned to each case are tabulated in

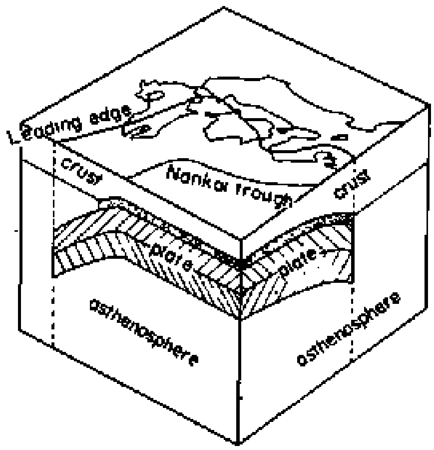


Fig. 6. Schematic representation of the present finite element modelling in three dimensions.

Table I. The first model, Model L, preserves a tight contact between the continental and subducting oceanic plates, while Model D has a weak transitional layer between them. Model M corresponds to an intermediate case between Models L and D. Model H has a harder asthenosphere than Model L with an elasticity just half of that in the lithosphere. These values have been chosen on the basis of the results of Smith and Toksöz (1972), Richardson et al. (1979) and Bullen's Model A (1965).

TABLE I

Young's moduli used in the present finite element model

Layer	Young's moduli ($\times 10^6$ bars) *			
	model L	model M	model D	model H
Continental crust	1.6	1.6	1.6	1.6
Transitional layer	*1.6*	*0.8*	*0.09*	*1.6*
Oceanic plate (upper)	1.8	1.8	1.8	1.8
Oceanic plate (lower)	*0.9*	*0.9*	*0.9*	*0.9*
Asthenosphere (upper)	0.09	0.09	0.09	*0.9*
Asthenosphere (lower)	0.45	0.45	0.45	*0.9*

* These values are modified from Smith and Toksöz (1972), except those in italics which are adopted in this paper. Poisson's ratio is assumed as 0.25.

External applied forces

We consider here that the following three different types of external forces are acting on the crust and upper mantle in southwestern Japan:

(1) A negative buoyancy due to the density contrast between the subducting plate and the surrounding mantle. We denote this force as *NB*. The density contrast used in the present calculation is taken as 0.171 g/cm^3, which corresponds to 5% of the average density at depths between 100 and 200 km in Bullen's model A. This force acts on the subducting plate.

(2) A northwestward horizontal compressive force generated by the underthrusting of the Philippine Sea plate. We denote this as *PN*. We assume that this force acts horizontally on the southern rim of the upper part of the subducting plate along the Nankai trough in the N50°W direction which is parallel to the movement of the Philippine Sea plate (Seno, 1977).

(3) A westward horizontal compressive force due to the subduction of the Pacific plate. We denote this as *PW* We assume that this force acts horizontally only on the continental crust at the eastern boundary of our model space.

The horizontal directions of these applied forces are depicted in Fig. 5 and their schematic diagram in a vertical section is indicated in Fig. 7.

Bischke (1974) indicated that vertical downward forces acting on or within the oceanic lithosphere are mainly responsible for preseismic and coseismic displacements that occurred on Shikoku island. Hashimoto (1980) has also suggested that the negative buoyancy is a predominant factor to produce tensile stress fields in or around the subducting plate. For these reasons, we consider here several models including a negative buoyancy.

Other possible forces such as mantle drag, trench suction, etc. (e.g., Forsyth and Uyeda 1975; Chapple and Tullis, 1977; Chase, 1978) are not considered here. This is because the mantle drag force under oceanic plates is much less than the negative buoyancy (Forsyth and Uyeda, 1975; Chapple and Tullis, 1977; Richardson et al., 1979), and also because the base of the Philippine Sea plate is not clearly defined (Hirahara, 1981). It may be difficult to consider that the trench suction force as postulated by Forsyth and Uyeda (1975) exerts along the Nankai trough, since the

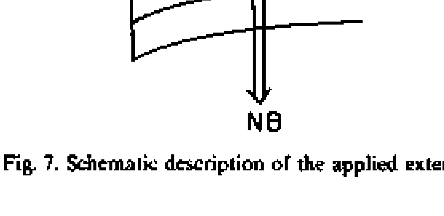


Fig. 7. Schematic description of the applied external forces.

subduction of the Philippine Sea plate is believed to begin at only 0.3–0.5 m.y. ago (Sugimura, 1972) or 2 m.y. ago (Kanamori, 1972).

We calculate the resultant stress field from linear combinations of the respective solutions, when more than two of the forces described above work together in the region now considered.

Boundary conditions

If we consider that the continental plate is fixed with respect to the oceanic lithosphere, we may assume the E–W and N–S components of the horizontal displacements at the western and northern edges of the model space as zero, respectively. We also take vertical displacements at the bottom of the model as zero, which implies that the resistance due to the mesosphere against the movement of the lithosphere is extremely large.

THREE-DIMENSIONAL STRESS DISTRIBUTION

All models studied here are listed in Table II. In order to compare the results derived from these models directly with the observed stress field mainly from focal mechanism solutions, the direction and magnitude of the calculated stresses are projected onto the lower hemisphere of the Wulff's net. These stresses mentioned here are deviatric stresses (i.e., $\sigma'_{ij} = \sigma_{ij} - \sigma_{kk}/3$). The patterns of stress distribution and the magnitude of the stresses are affected by the type and magnitude of the external forces working in this region, and also by elasticities of the crust, upper mantle, subducting plate and the asthenosphere. We investigate these effects. In this chapter, the results for some typical cases are summarized in some detail.

Effects of applied forces

Negative buoyancy

This is the case when only a negative buoyancy is acting on the subducting plate. In this case, we refer to Model L, which seems most appropriate to test this effect. The calculated results shown in Fig. 8 indicate that almost all sites and depths are subjected to tensile stresses, which yield normal faulting earthquakes. In the second and third layers beneath the region from the Kii peninsula to the Kii channel, except near the tip of the subducting plate, the tensional axes lie almost parallel to the leading edge of the subducting plate. Some of the *T*-axes perpendicular to the edge just along the tip may be caused by some interactions due to gravitational pull between the subducting and continental plates. Beneath the region from eastern Shikoku to eastern Kyushu, they appear parallel to the leading edge in the third layer, while perpendicular to it in the second layer. These results are partly consistent with the patterns inferred from focal mechanism solutions in the Kii peninsula.

TABLE II

External force models: fit of the predicted to observed stress directions

Model	Force parameters			Fit to observed stresses *					
	NB	*PN*	*PW*	*KP*	*ES*	*TF*	*WS*	*IZ*	Fig.
L-1	1	0	0	3	3	0	1	0	8
L-2	1	0.5	0	3	2	0	1	0	
L-3	1	1	0	3	2	0	0	0	
L-4	1	0	0.5	3	3	0	1	3	
L-5	1	0.5	0.5	3	2	0	1	2	
L-6	1	1	0.5	2	1	1	0	0	
L-7	1	0	1	3	3	0	1	3	
L-8	1	0.5	1	3	2	1	0	2	
L-9	1	1	1	2	1	1	0	2	
L-10	1	0.3	0.5	3	2	0	1	3	
M-1	1	0	0	3	3	0	1	0	
M-2	1	0.3	0.5	3	2	0	1	3	
M-3	1	0.5	0.5	3	2	0	1	2	
D-1	1	0	0	3	3	0	1	0	
D-2	1	0.5	0	3	2	1	1	0	
D-3	1	1	0	3	2	2	0	0	
D-4	1	0	0.5	3	3	0	1	3	
D-5	1	0.5	0.5	3	2	1	1	2	
D-6	1	1	0.5	2	1	3	0	0	10
D-7	1	0	1	3	3	0	1	3	
D-8	1	0.5	1	3	2	2	0	2	
D-9	1	1	1	2	1	3	0	2	
H-1	1	0	0	3	3	0	1	0	
H-2	1	0	0.5	3	3	0	1	3	
H-3	1	0.5	0.5	3	2	0	1	2	
H-4	1	0.3	0.5	3	2	0	1	3	9

Density contrast used in the present calculation of *NB* is taken as 0.171 g/cm^3. Units for *PN* and *PW* are 1 kbar.

* *KP* is the extensional stress field parallel to the leading edge of the subducting Philippine Sea plate (parallel extension) beneath the Kii peninsula; *ES*, the parallel extension beneath the eastern Shikoku; *TF*, thrust faulting off the Kii peninsula and the Shikoku island; *WS*, normal faulting beneath the western Shikoku; *IZ*, compressional stress field working in the E–W direction in the inland region.

Numeral 3 indicates a satisfactory good visual fit to general pattern of the observed stress directions; 2, reasonable fit to the orientations of *T* or *P* axes; 1, a reasonable fit to the type of the observed fault mechanism, if not in the exact orientation; 0, no fitness in both type of faulting and orientation of principal stresses.

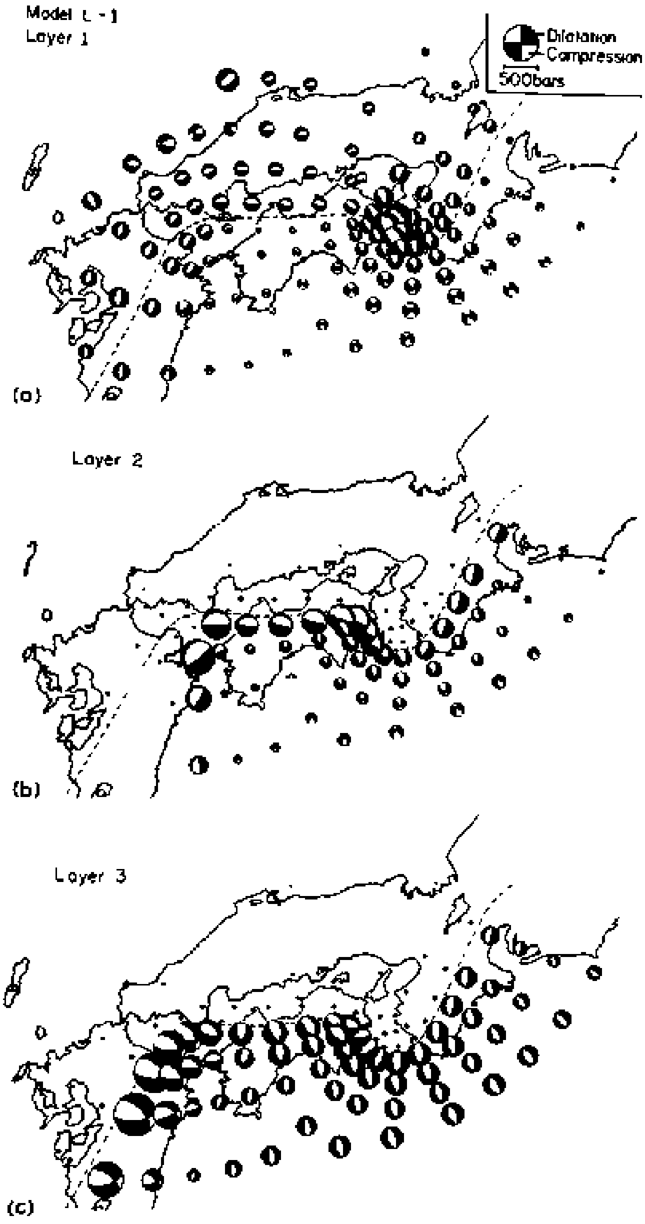


Fig. 8. Results for Model L-1 (only a negative buoyancy is applied to the Model L). The calculated stresses are represented by stereographic projection on the lower hemisphere of the Wulff's net. The dark and open quadrants indicate tensile and compressive stresses at source region, respectively, which yield pushing and pulling P-wave first motions, and open quadrants show dilatational and compressional ones, respectively. The radii of diagrams are proportional to maximum shear stress.

a. Layer 1 corresponds to the continental crust. Depths range from 10 km off the Kii peninsula to 20 km in the inland region.

b. Layer 2 includes a transitional layer and a part of asthenosphere. Depths range from 20 km off the Kii peninsula to 40 km in the inland region.

c. Layer 3 includes the subducting oceanic plate and the asthenosphere. Depths range from 30–50 km in the Kii peninsula and Shikoku region to 120 km beneath the Kyushu island. The same explanations apply to the following figures.

Combined forces

Next, we consider several cases when *NB*, *PN* and *PW* are working together at the same time. We have tested various combinations with different magnitudes of *PN* and *PW* ranging between 0–1000 bars, for all the four types of models described before. Figure 9 gives an example of the calculated stress field in Model H in the case when *PW* and *PN* are 500 and 300 bars, respectively. It can be seen in case (a) that a horizontal compressive stress field trending in a nearly E–W direction arises in layer 1 of the inland region, which leads to strike-slip faulting. This pattern could explain quite well the observed stress patterns in the inland crust. In the second layer on the oceanic plate side, the stress field corresponding to strike-slip arises off coast of the Kii peninsula and that to dip-slip type occurs to the east of Kyushu, as shown in Fig. 9b. These stress patterns do not appear consistent with the observed thrust type faulting. In this case, however, it may be more adequate to compare the stress directions with observations, rather than the type of faulting, since the present calculations are for static cases and not for coseismic ones. In this sense, the direction of the *P*-axes is consistent with that of the observations. The stress field in the third layer tends to be that of horizontal extension on the oceanic plate side except along the leading edge (Fig. 9c), which could yield normal faulting earthquakes. This pattern can explain the observed focal mechanism of subcrustal earthquakes beneath the Kii peninsula.

However, the *T*-axes in the second and third layers beneath the Shikoku region lie almost perpendicularly to the leading edge of the subducting plate, and could not give satisfactory explanations to the observed stress patterns there.

The next step is to estimate how these stress patterns will change if the magnitudes of the two compressive forces, *PN* and *PW* are raised. The calculated results for these cases are not shown here but described below. (1) If the northwestward force *PN* increases to greater than 500 bars, with a fixed value of 500 bars of *PW*, it is found that the stress field in the first layer, and in the second layer beneath the Kii peninsula and the Kyushu region, changes into that of thrust faulting, and that the field of parallel extension in the third layer turns out to be that of strike-slip faulting. These changes do not account for the observed stress patterns except in the second layer. From these results, it seems that the magnitude of *PN* would not exceed 500 bars if *PW* is of the order of 500 bars. (2) If, on the other hand, the westward compressive stress *PW* is considerably smaller than 500 bars and extremely small, the horizontal compressive stress field trending in the E–W direction in the inland crust turns to that in the N–S or NW–SE direction, and hence cannot account for the observed stress patterns. These results suggest that *PW* should have considerable magnitude. If *PW* takes large values up to 1 kbar, the calculated results are not significantly different from those for 500 bars. This situation implies that the upper boundary of *PW* cannot be exactly estimated in the present study.

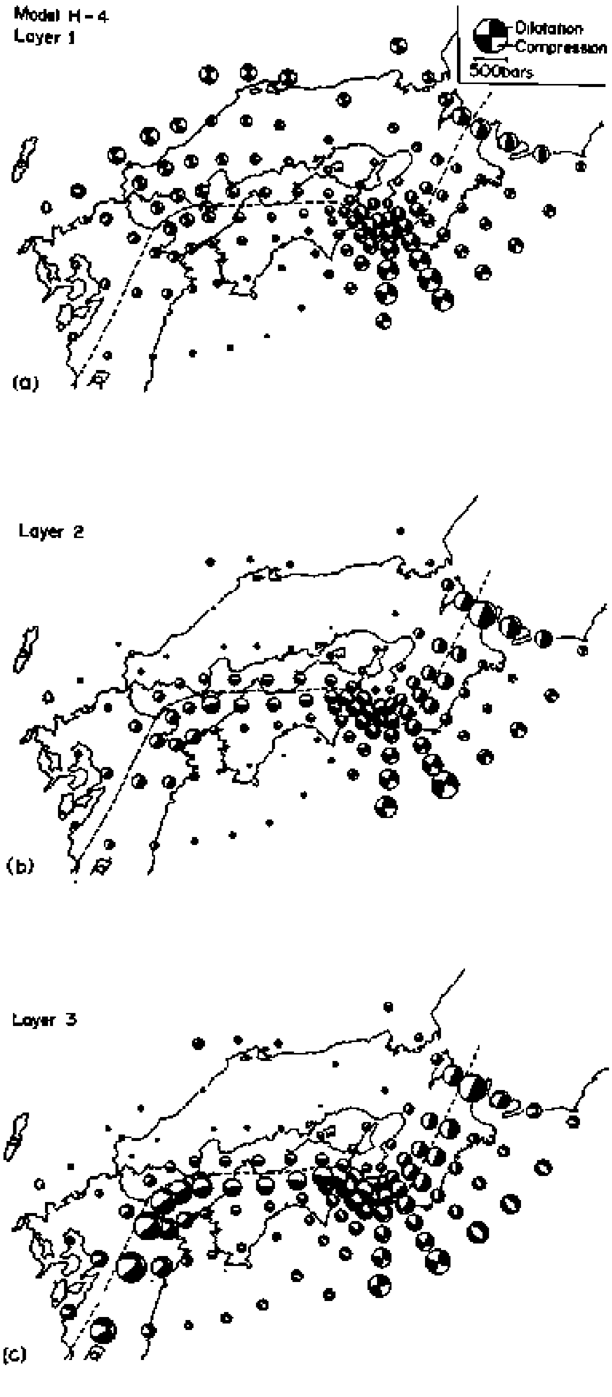


Fig. 9. Results for Model H-4.

Effects of elasticity

We next investigate the effects of differences in elasticities in each layer for the four different models mentioned before, Models L, M, D and H.

We compare Model H with Model L, to investigate how elasticity in the asthenosphere affects the whole stress field. Model H has a harder asthenosphere. The present calculations show that the stress patterns are not seriously affected even if the elasticity there takes larger values. In Model H, the magnitude of stresses in the oceanic and continental plates becomes slightly smaller, but that just around the tip of the subducting plate tends to be larger. However, the stress patterns there do not indicate the parallel extension field, and hence could not explain the observations.

In order to see the effects of the possible existence of a weak transitional layer between the subducting oceanic and overlying continental plates, we calculate the stress field for Models D and M and compare the results with those obtained from the foregoing models. In these cases we assume the Young's modulus in the transitional layer to be 1/2 for Model M and 1/20 for Model D, respectively, of that in the oceanic plate.

Calculations for Model M provide similar results to those obtained for Model L, which suggests that the difference of elastic moduli down to about 1/2 in the transitional layer does not give serious effects on the whole stress patterns.

Figure 10 shows the results for the case when *NB*, *PN* of 1 kbar and *PW* of 500 bars are applied to Model D. It is noticed that the apparent stress field leading to low-angled thrust faulting appears only in the transitional layer, and that the *P*-axes lie in a nearly NW–SE direction. This type of stress field only appears when *PN* is greater than 500 bars, as mentioned before. Moreover, it has been confirmed that even if the magnitude of *PW* raises to considerable extent, the stress patterns are not greatly affected.

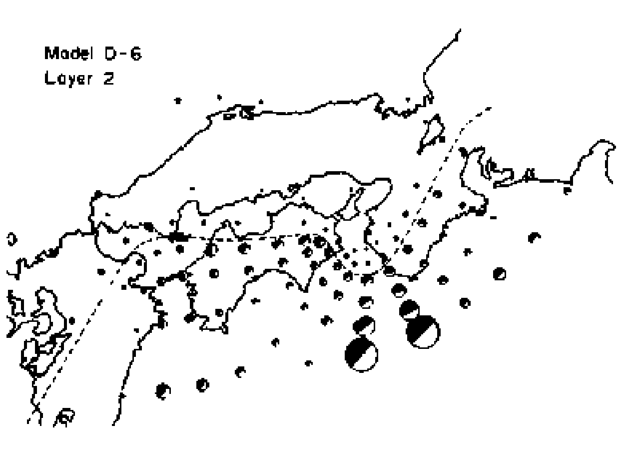


Fig. 10. Results for Model D-6. Only the second layer is given for this case.

POSSIBLE SOURCES OF THE COMPLEX STRESS FIELD IN SOUTHWESTERN JAPAN

In this section, we discuss possible sources of the complex stress field in southwestern Japan, by comparing the calculated results with the observed stress pattern from focal mechanism solutions. In Table II, the degree of fitness in the general stress pattern between the calculated and observed results for each model is listed with four grades.

Parallel extension

It is noticed that systematic alignments of *T*-axes along the leading edge of the subducting plate can be seen for all models at depths around 50 km beneath the Kii peninsula, while such stress patterns appear in the eastern Shikoku region only for models with small *PN* values. This fact seems to suggest that a concave shape of the leading edge of the subducting plate around the Kii channel may be responsible for stress field of parallel extension in the Kii peninsula and the Kii channel. In the eastern Shikoku region, on the other hand, the leading edge trends nearly parallel to the *PN* direction, and hence the parallel extension field tends to be overcome in this region if a large *PN* force is applied. From the present calculations, it may be reasonable to consider that *PN* does not exceed 500 bars. The parallel extension field does not appear in Iyonada, the western Shikoku region. It is difficult, however, to discuss the stress field in this region in more detail, since the finite element grids used there do not seem to be fine enough for this purpose.

To explain the stress field of parallel extension, Shiono (1977) has postulated a relation between the dip angle and the curvature of the subducting plate, an interaction between subducting and overlying plates and effects of thermal contraction. The present calculations imply, on the other hand, that strong compressive *PN* forces, which cause strong resistance by the continental plate, tend to yield a horizontal compressive stress field in the subducting plate, and that a negative buoyancy is a predominant factor in generating the extensional stress field. Wu (1972) suggested that the Philippine Sea plate sinks down into the upper mantle by its own weight. The present results appear consistent with his postulation and also with Bischke's (1974) results. Shiono (1977) postulated that the parallel extension field could arise in the continental plate under specific geometrical conditions together with thermal ones. Shiono and Mikumo (1975) show that the 1968 Bungo channel earthquake with normal faulting mechanism occurred in the continental plate. Hurukawa and Hirahara (1980) also suggested that a normal faulting earthquake beneath the Kii channel took place in the continental plate. As may be seen from Figs. 8 and 9, the present results show that this type of earthquakes could take place in and just above the oceanic plate.

Low-angled thrusts

The stress field corresponding to low-angled thrust faulting off the Kii peninsula and Shikoku appears only for Model D with large *PN* values. This implies that the existence of a weak transitional layer between the continental and subducting oceanic plates provides an apparent stress field corresponding to low-angled thrust faulting. However, the stress fields calculated here are static and hence interseismic ones. Since the observed low-angled thrust faulting is a coseismic event under a horizontal compressive stress, it is not appropriate to compare the calculated stress patterns directly with observations.

It has been stated (Fitch and Scholz, 1971) that compressive stresses give rise to low-angled thrust faulting in subduction zones. Under these situations, it may be more appropriate to compare the direction of *P*-axes rather than the type of faulting. From this point of view, it may be stated that calculated stress directions account for the observations quite well (e.g. Fig. 9).

E–W compressional stress field in the crust

It has been revealed from a number of focal mechanism studies that the shallow crust in the inland region of southwestern Japan is subjected to horizontal compressive stress in the E–W and ESE–WNW direction.

The present calculation indicates that several models with *PW* could provide the compressional stress field. However, if large *PN* is applied simultaneously, the stress field tends to be that leading to high-angled thrust faulting. Models for which *PN* is less than 300 bars provide the field which fits well to the observed focal mechanisms of strike slip type. This implies that *PW* is prevailing over the crust in this region, and that *PW* seems to be about twice as large as *PN*.

On the other hand, all models tested here could not give a satisfactory explanation to the observed change at depths in the stress direction, which has been suggested by Shiono (1973) and Okano et al. (1980). In order to explain these patterns, it would be necessary to calculate more local stress for models with finer structures.

MAGNITUDE OF THE PREDICTED STRESSES

In order to estimate the average stress level in the lithosphere and also the stress required to cause earthquake faulting, we calculate the magnitude of maximum shear stress, which is expressed by the radius of the stress diagrams in Figs. 8, 9 and 10. The magnitude of the maximum shear stress in the Model H-4 ranges from 70 to 400 bars in the crust, from 50 to 400 bars in the transitional layer, from 100 to 500 bars in the subducting plate and from 50 to 300 bars in the upper asthenosphere, respectively. These magnitudes in the crust and the subducting plate are of comparable order to the stress level estimated by Solomon et al. (1980) from F.E.M. modelling and the estimate of regional stresses. Although the above estimated values are dependent on the two applied forces as well as on the densities and rigidities assigned here, it is reasonable to consider that the stress in the lithosphere may be less than 1 kbar in the region under consideration.

There appear stress concentrations in all layers around the Kii channel and Iyonada. These concentrations may be probably attributed to the distortion effects of the leading edge of the subducting plate. It is interesting to note that the magnitude of the stress within the plate (layer 3) subducting beneath the eastern Kyushu region reaches the order of 500–600 bars (Fig. 9), and that these relatively high stresses have relation to intermediate-depth earthquakes there. It should be just mentioned that the magnitude of shear stress along the Japan Sea coast regions may be due to edge effects.

It is to be noticed that there is remarkable contrast in the estimated stress between the regions around the Kii channel and central Shikoku. Mizoue (1977) has noticed high activity of subcrustal earthquakes over regions extending from the Kii peninsula to the western Shikoku except in the central Shikoku region (Fig. 4). It appears that high shear stresses, particularly along the leading edge of the plate calculated from the present model, correspond quite well to high activity regions of subcrustal earthquakes. Ando (1975) showed, on the other hand, that the 1946 Nankaido earthquake had two different types of fault planes; a sudden breakage occurred first in a brittle fault area between the Shikoku island and the Kii peninsula and then the fracture propagated slowly westwards to a ductile fault area, causing extensive crustal deformations over the Shikoku region. It is interesting to note that the brittle area seems to correspond to the high stress region and the ductile area to the low stress region calculated for the present model, respectively. It is important that the configuration of the subducting plate could give appreciable effects not only to the activity of subcrustal earthquakes, but also on the process of great earthquakes.

ADDITIONAL REMARKS

In the present paper, we assume the thickness of both the upper and lower layers of the subducting plate to be 30 km. If the thickness is taken as 40 km (Hashimoto, 1980) instead of 30 km, the fit of the calculated stress directions with those of observations becomes worse. Hirahara (1981) estimated the thickness of a high-velocity layer corresponding to the Philippine Sea plate as about 30 km around the Izu peninsula and thicker beneath the Kyushu region, from the analysis of a three-dimensional velocity structure. Kanamori and Abe (1968) have also obtained a thickness of about 19 km for the Philippine Sea plate from surface wave analysis. These estimates are not inconsistent with the present results, if we regard the upper layer with higher elasticity in our model as the main part of the oceanic plate.

Hirahara (1981) indicated that there exist narrow low-velocity zones intervening within the Philippine Sea plate, where two aseismic ridges, the Kyushu–Palau and Shichito–Iwojima ridges (see Fig. 1), extend northwestwards, and the existence of these low-velocity zones seems to support the "buoyant subduction" hypothesis (Kelleher and McCann, 1976).

On the other hand, Nakanishi (1980) suggested that the Philippine Sea plate could extend further north of the leading edge now considered beneath the Chugoku region, and Hirahara (1981) also suggested the possibility that there could be a small high-velocity zone at depths between 100 km and 150 km beneath the Kinki region. It is not clear, however, whether these are the extended portions of the present subducting plate or the remnants of the past subducted plate. It would be necessary to take into account these evidences, in order to investigate more detailed stress distribution in southwestern Japan. It would also be important to introduce viscosity or visco-elasticity into our model when we discuss time-dependent behaviours of the stress field.

In the present study, only three types of forces have been considered. We might have to take into consideration other possible forces such as mantle drag, trench suction, slab resistance, colliding resistance, etc., in future investigations.

CONCLUSIONS

The main results we have obtained in the present study are summarized as follows:

(1) The extensional stress fields parallel to the leading edge of the subducting Philippine Sea plate are mainly caused by a negative buoyancy or gravitational pull working on the plate. The complex shape of the plate plays an important role in generating this type of stress.

(2) There is a possibility that a thin weak transitional layer might exist between the subducting and overlying continental plates.

(3) The compressive stress field in the E–W or ESE–WNW direction observed in the inland crust may be generated by a westward compressive force due to the subduction of the Pacific plate.

(4) The northwestward compressive force resulting from the subduction of the Philippine Sea plate may be smaller than 500 bars within the scope of the present calculation. This force may be less than half of the westward compressive force.

(5) The maximum shear stress in the lithospheric plates may be of the order of several hundred bars and may not exceed 1 kbar. The distribution of the stress magnitudes is closely associated with the configuration of the subducting plate, and appears to provide appreciable effects on the seismicity of subcrustal earthquakes and the rupture process of great earthquakes.

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主論文第二部

FINITE ELEMENT MODELING OF THE THREE-DIMENSIONAL TECTONIC FLOW AND STRESS FIELD BENEATH THE KYUSHU ISLAND, JAPAN

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Running title : Finite element model of Kyushu

Summary. Three-dimensional patterns of tectonic deformations and stresses are calculated to simulate the tectonics of Kyushu and its surrounding regions in southwestern Japan by using a finite element method. The configuration of the subducted Philippine Sea plate is modeled by means of three-dimensional finite elements. Viscosities in the crust and upper mantle assigned are taken from the data of postglacial or postseismic rebounds. Several possible loads are taken into consideration: a slab pull force arising from the density contrast between the subducted slab and the surrounding asthenosphere; a ridge push force due to an evolution of oceanic plates; a traction due to the flows in the asthenosphere; a crustal buoyancy acting on a low-density crust; a buoyant force in the back-arc region which may simulate the spreading of a back-arc basin; a positive buoyancy acting on the aseismic ridge; compressive forces in the E-W direction exerting on the crust and subducted slab.

The results suggest that the tensile stress field observed in the crust of Kyushu may be generated by the interaction between the slab pull force, crustal buoyancy and flows in the asthenosphere. It may also be concluded that the stress field of down-dip extension in the Wadati-Benioff zone can be raised mainly by the slab pull force. The asthenospheric flows might give a significant effect on the genesis of near-horizontal extension which yields normal faulting in the uppermost mantle, and such stresses would be more likely to appear on the oceanic side than on the continental side. In order to explain the dip angle of the subducted slab, if it is a manifestation of the flow pattern at a subduction zone, a traction due to asthenospheric flow of about 200 bars must be required in the asthenosphere. The predicted values of velocities of tectonic flows and of maximum shear

stresses are a few cm/yr and 500 bars at most in the crust and the subducted slab beneath Kyushu, though these are dependent on viscosity.

1. Introduction

The plate tectonic hypothesis has gained a success to explain a variety of geophysical and geological observations. Although the lithospheric deformations in subduction zones are well understood from the convergence of plates, the dynamic mechanisms for driving the converging plates are not. Several cross-sectional models have been presented to synthesize the tectonics of the island arc, and they yielded many insights on the stress distribution within the crust and the upper mantle in subduction zones(Smith & Toksöz,1972; Andrews & Sleep,1974; Shimazaki,1974; Bischke,1974; Kato,1979; Toksöz et al.,1973; Sleep,1975; Bird, 1978a,b). These models, however, are only two-dimensional and may not be applied directly to such regions with three-dimensional geometrical complexities as arc-arc junctions, with lateral bending of the subdubcted plate and so on. In these cases, it is essentially important to apply three-dimensional modeling, instead of two-dimensional one.

In this paper, we examine several possible sources for lithospheric deformations in subduction zones east of Kyushu with three-dimensional heterogeneities, and then determine their relative importance by a three-dimensional finite element technique. The finite element technique is one of the most powerful tool for the stress analysis in heterogeneous media. The present author has investigated the three-dimensional stress field in the Japan arc by using this technique (Hashimoto,1982,1984, hereafter referred as Papers I and II) In Paper I, the stresses in the crust and upper mantle beneath the southwestern Japan arc have been investigated on the assumption of a perfectly elastic medium. This purely-elastic analysis, however, could not well simulate time-dependent displacement and velocity fields. In Paper II, a viscoelastic rheology was incorporated to account for the anomalous stress patterns observed around the Hokkaido corner and also for temporal variations of the observed strains in the region with the order of 10^{-6} yr^{-1} The technique adopted in Paper II, however, is not necessarily suitable to calculate the displacements and stresses over an extremely long period after the initiation of loading, and the calculated results might be contaminated, to some extent, with transient responses. In order to overcome these problems and to improve the accuracy of our stress calculations, with an aim for better explaining the observations, we finally decided to adopt a viscous fluid model in this paper Viscous fluid model can synthesize time-dependent features of tectonic movements over a long time range such as the rate of increase in horizontal crustal strains or vertical crustal uplifts which are usually observed. Some authors have calculated flow and stress field in subduction zones (Sleep,1975; Bird,1978b) by two-dimensional analyses. On the other hand, Hager and O'Connell(1978,1979,1981) and Hager et al.(1984) calculated flow vectors on the whole earth model. The viscosity profiles assumed in their models, however, are radially symmetric, and the grid-spacing in their calculations are too coarse to discuss the flow field around subduction zones. The purpose of the present paper is to model the southwestern Japan and Kyushu-Ryukyu arcs as an example of subduction zones with three-dimensional geometrical complexities and calculate the flow vectors and stresses on the assumption of imcompressible viscous fluid to explain the observed crustal movements, focal mechanisms and some other data in these regions.

2. Tectonics around the Kyushu island

It is widely accepted that the Philippine Sea plate is now subducting beneath the southwestern Japan and Kyushu-Ryukyu arcs from the Nankai trough and the Ryukyu trench, respectively (Fig.1). and that this may be a controlling factor for the tectonics of these arcs. The stress field, however, is not uniform but differs considerably between the two arcs. It has been observed from geodetic triangulation surveys that an E-W to NW-SE horizontal compressional strain is prevailing in the Shikoku island and the Chugoku regions, while a tensile strain in the N-S direction dominates in the Kyushu island over the 90 years(G.S.I.,1983,1984) (Fig.2) It is considered (Tada,1983) on the basis of these observations that the spreading axis of the Okinawa trough, which is a back-arc basin of the Ryukyu trench, reaches the Kyushu island.

On the other hand, geodetic data from leveling surveys in western Japan clearly indicate that vertical ground uplift and subsidence have an unusual pattern as that in island arcs(Fig.3) (Dambara,1971). Tectonic subsidence may be noticed in the Seto inland sea and the northern Kyushu region, while tectonic uplift is predominant in the rest of other regions (Dambara,1971; Kato & Tsumura,1979) The ground subsidence in the northwestern Kyushu region might be related to the extension of the spreading center in the Okinawa trough.

Distribution of earthquakes with magnitudes greater than 3.0 and focal mechanisms of some typical large ones in and around the Kyushu region are shown in Figs.4 and 5, respectively Great interplate earthquakes with a low-angled thrust type mechanism such as the 1946 Nankaido earthquake often occur along the Nankai trough off the

Shikoku island (e.g. Ando,1975). This type of low-angled thrust earthquakes also takes place in the Hyuga-nada off the east coast of the Kyushu island, but these earthquakes are somewhat smaller and more frequent than those along the Nankai trough (Shiono,1977; Shiono et al.,1980) On the other hand, large intraplate earthquakes also occur in Kyushu. The 1975 Oita earthquake (focal depth : 15 km) may be considered to have a mechanism of normal faulting with an N-S tension (Yamashina & Murai,1975), which agrees with the pattern of the observed strain field, although Maki et al.(1984) recently proposed a strike-slip faulting mechanism for this earthquake.

A Wadati-Benioff zone with a shallow dip can be recognized only down to a depth of 80 km beneath the eastern Shikoku region and the Kii peninsula (Mizoue,1977; Shiono,1977) The typical focal mechanism of the earthquakes that occur in this zone is of normal or strike-slip faulting with its maximum tensional axis (T axis) being parallel to the leading edge of the subducted Philippine Sea slab (parallel extension) (Shiono,1977; Ukawa,1982). On the other hand, the Wadati-Benioff zone goes down to a depth of 70 km beneath the Suo-Nada but extends deeper as going to the south, and reaches about 200 km underneath the southern Kyushu region(Fig.4) This seismic zone, however, changes abruptly its dip around depths of about 60 to 100 km. It underthrusts with a dip of 10° to 20° at depths shallower than about 60 km and steepens up to 70° below this depth (Shiono et al.,1980) Besides these, their activities and focal mechanisms are also different from each other Normal faulting earthquakes with T axes in the E-W to NWN-ESE direction occur frequently at the shallower depths. On the other hand, there is a gap of seismicity around a depth of 100 km, and earthquakes with the mechanism of high-angled thrust with a down-dip extension axis(Imagawa et al.,1984) tend to cluster below this quiet zone (Shiono et al.,1980; Imagawa et al.,1984). There are only few earthquakes beneath the central part of Shikoku, which may result from the stress state due to a three-dimensional configuration of the subducted Philippine Sea plate (Hashimoto,1982).

There are many active volcanoes in the Kyushu island, and high heat flow anomalies are observed. Thus, the Kyushu-Ryukyu arc has many properties appropriate to typical island arcs. On the contrary, the southwestern Japan arc has no active volcanoes which could be related to the subduction of the Philippine Sea plate. This might suggest that the southwestern Japan arc is now in the incipient stage of subduction (Kanamori,1972; Sugimura,1972). Besides this, there is a zone of high heat flows in the Shikoku basin (Watanabe et al.,1977), which may be an evidence that the Shikoku basin is a back-arc basin that has just ceased to spread (Kobayashi & Nakada,1978). Hirahara(1981) found that the Philippine Sea plate in this region may be thinner than that in the western part.

Ocean-bottom topography and other geophysical data suggest that the Kyushu-Palau ridge collides with the Kyushu-Ryukyu arc at the junction of the Nankai trough and the Ryukyu trench, and that there is a zone with a negative Bouguer gravity anomaly which may be an evidence for the subduction of this buoyant ridge (Tomoda & Fujimoto,1981). Hirahara(1981) found that a low velocity zone is intervening between the high velocity zones which may correspond to the subducted Philippine Sea plate. Such a buoyant zone has some effects on the tectonics of the junction of island arcs.

Hashimoto(1984) showed that such an anomalous zone in the upper mantle might yield the rotation of P axes (maximum compressional axes), which are observed on the landward side of the Hokkaido corner We will also have to take into account the effects of such buoyant sea mounts on the stress field of island arc.

3. Finite element model

We model the Kyushu arc to the northern part of the Ryukyu arc, which are shown in Fig.6a, by using a hexahedron isoparametric finite element with 8 nodes (Zienkiewicz,1977), together with an infinite domain element with 4 nodes and 4 reference points (Beer & Meek,1981). Now, we apply a viscous imcompressible fluid with a high Reynolds number to the present finite element model. There are a variety of techniques to solve a steady state flow problem in this case. Among them, we use the penalty function approach (Zienkiewicz,1977), because a computer program for elastic stress analysis can readily be applied to the present case with minor modifications.

3.1 GEOMETRY OF THE KYUSHU MODEL

A cross-section of finite element meshes is shown in Fig.6b. The geometry of the meshes is constructed in such a way that we may synthesize three-dimensional configuration of the subducted Philippine Sea plate. The interface between the overlying and underthrusting plates inclines with a dip of about 10° at the northeastern section and steepens beyond 20° at the southwestern section of the model space. As stated above, the abrupt change in the dip angle of the subducted slab is incorporated in this model around a depth of 60 km, below which the dip is taken to be 60° The subducted slab penetrates down to deeper than 200 km near the southern rim of the model space, while the depth of its leading edge is about 60 km beneath the northeastern part. The horizontal projection of the leading edge is also shown in Fig.6a. The projection of the slab on a vertical cross section is shown in Fig.6c. The thicknesses of the continental and the oceanic crusts in this model are assumed to be 30 km and 10 km, respectively. We assume that the subducting plate is 20 km thick in the shaded region in Fig.6a and 40 km thick in the rest of the model space, on the basis of Hirahara's(1981) suggestion that the Philippine Sea plate beneath the Shikoku island may be thinner than its western part. We also assume that there exists a buoyant zone corresponding to the Kyushu-Palau ridge (the dotted part in the figure). After all, our model space occupies a region extending for about 650 km long, 600 km wide and 300 km deep. Besides this, infinite domain elements (Beer & Meek,1981) are added on the northwestern, southeastern and bottom boundaries of the model space, to avoid the boundary effects. The total numbers of nodes, elements and infinite elements are 3207, 2647 and 456, respectively.

3.2 VISCOSITY PROFILE

We divide the entire region into 11 subregions according to their medium properties (Fig.6c). In Fig.6c, subregions 1 to 9 are shown in a vertical section. Subregions 10 and 11 are the buoyant ridge and the assumed spreading zone, respectively, which are shown in Fig.7 as dotted and shaded portions, respectively Viscous properties assigned to each of the subregions are tabulated in Table 1. Linear viscosity is assumed here, although non-linearity might be appropriate to such a high stressed region as in a subduction zone or continental collision zone (Neugebauer & Breitmayer,1975; Sleep,1975;

Bird,1978; England & McKenzie,1983) We do not incorporate a temperature dependence of viscosity (Hsui & Toksöz,1979) in the present model.

The observed data of post-glacial crustal uplifts poses some bounds on the viscosities in the earth's mantle, and several models have been presented (e.g. Haskell,1935; Takeuchi & Hasegawa,1964; Walcott,1973; Cathles,1975; Peltier & Andrews,1976) These models give a similar viscosity of the order of 10^{22} poise to the upper mantle, and require a low viscosity channel of 10^{20} poise, which is about 100 km thick. On the other hand, Thatcher & Rundle(1979) and others showed that a low viscosity layer in the asthenosphere with a viscosity of about 10^{20} poise may be required to explain postseismic lithospheric deformations. Referring to these models, we assume an asthenosphere with a viscosity of 4×10^{20} poise.

The viscosity of the crust and lithosphere is assumed here to be 4×10^{23} poise. This parameter, however, might give sensitive effects for the absolute values of flow velocities. The strain rates and stresses so far obtained from various geophysical measurements are of the order of 10^{-15} sec^{-1} and 100 bars, respectively. Since these values predict a viscosity of the order of 10^{23} poise, our assumption for the modeled lithosphere may be reasonable.

For the wedge region (No.5), we tentatively assign a lower viscosity (4×10^{19} poise) than the surrounding asthenosphere. There are high heat flows and active volcanoes around the back arc region in normal island arcs. Many authors predict high temperatures to explain these high heat flows (e.g. Hasebe et al.,1970; Andrews & Sleep,1974; Toksöz et al.,1973; Hsui & Toksöz,1979; Bird,1978b)

This prediction would lead to a low viscosity in the wedge region.

We assign the same value as that in the lithosphere to the wedge zone on the seaward side of a aseismic front. Yoshii(1979) proposed a model with the wedge zone of high velocity for the northeastern Japan arc on the basis of seismicity. Umino et al.(1983) obtained a Q structure in northeastern Japan which has a relatively high Q value in the wedge zone. These results would lead to a high viscosity for the wedge zone. We assume a similar state for the Kyushu arc to the northeast Japan arc.

The viscosity assigned in the lower mantle is somewhat controversial. Cathles(1975). Peltier & Andrews(1976) and others predicted large values as those in the upper mantle, while Walcott(1973) evaluated much higher values for it. Hager and O'Connell(1978,1979) showed that the Cathles'(1975) model is more favourable for global mantle flow than any other models with a highly viscous lower mantle. Yuen et al.(1983) also suggested a uniform mantle with a thin low viscosity asthenosphere, from the analyses of the length of a day and the spectra of polar wandering. We adopted the uniform mantle model here. For the infinite elements attatched there, we assign the same viscosity as that of the bottom layer

3.3 BOUNDARY CONDITIONS AND APPILED LOADS

Free-slip conditions are posed on the earth's surface after Sleep(1975), and the traction conditions are also applied to the southeastern, northeastern and northwestern boundaries. On the southeastern boundary, a 100 bars traction is applied in the N50°W direction to the rims of the plate and asthenosphere, respectively (abbreviated as RP and AF in Fig.7). RP simulates a ridge push force produced by the evolution of an oceanic plate (Hager,1978) or the spreading of a ridge. AF would correspond to a part of mantle convection. The magnitude of these forces assumed here may be reasonable, since the estimated viscosities and observed strain rates give this order of magnitude. Sekiguchi(1984) also evaluated a similar magnitude for the collision forces on the basis of calculation for the relative importance of plate driving forces. An eastward traction is applied to the northwestern edge of the crust (abbreviated as EP). which may simulate a compressive stress transmitted from the Eurasia plate. We assume that a westward compressive force exerts on the northeastern rim of the crust (abbreviated as WP1). This force may result from the westward movement of the Pacific plate subducting at the Japan trench or the proposed collision of the north American plate with the Eurasia plate at the Fossa-magna (the Itoigawa-Shizuoka Tectonic Line) (Nakamura,1983) As stated in the previous section, a tensile stress parallel to the local trend of the leading edge of the subducted Philippine Sea slab is prevailing in this region (Shiono,1978; Ukawa,1983). We should take into account this tensile stress. To incorporate this effect, we consider a horizontal traction (WP2) on the northeastern boundary of the subducted slab in the same direction as WP1 (Fig.7) and assign a negative value when we assume a tensile stress (Table 2).

We consider several types of body forces caused by the density contrasts. The primary one is a negative buoyancy acting on the subducted slab which may be caused by the density contrast between the cold slab and the surrounding hot asthenosphere. We assume this value to be 0.0667 g/cm^3 (abbreviated as SP). The others are a positive buoyancy which may act on the crust in the island arc

(CB) (Sleep,1975), that predicted from the existence of buoyant sea mounts (BR) and that expected from a high temperature zone in the back arc (SC). We assume the density contrasts for these load to be 0.1 g/cm^3 Normal density contrast between the crust and upper mantle are estimated to be about 0.3 g/cm^3 However, this assigned value of density contrast for the island arc crust may not be unreasonable, since the positive buoyancy force may not act on the whole crust. We also perform the calculation for 0.3 g/cm^3 to assure this assumption. For BR and SC, the structure of the aseismic ridge and back-arc region is not clear We apply some weights to the calculated flow and stress field when superposing them.

4. Calculated flow and stress field

We calculate the patterns of the flows and stresses for each of the applied loads under consideration, superpose them with their weights and then compare the combined field with the observed one. The ratio of their weights and the degree of fitness to the observations in all the calculated models are given in Table 2. For some representative cases of all these models, we show the horizontal stresses in the crust, three-dimensional stresses in the subducted slab, vertical projections of the stresses, velocity vectors of tectonic flow in a vertical section and vertical stresses acting on the surface. The velocity vectors of tectonic flow is a manifestation of the direction of tectonic movements over a long time range, while vertical stresses should be related to vertical crustal movements or topography, respectively

4.1 SLAB PULL MODEL

As a first step, we discuss the flow and stress field due to a slab pull force or negative buoyancy which may arise from the density contrast between the subducted slab and the surrounding asthenosphere (Fig.8) This force is considered to be the primary driving force for plate motions (Forsyth & Uyeda,1975; Chapple & Tullis,1978; Sekiguchi,1984) In the preceding papers, it has been found that the negative buoyancy plays a significant role on the generation of characteristic features of the stress field in southwestern Japan and Hokkaido. For this reason, it is necesary to take into account the effect of this load.

In Fig.8, we immediately notice the following features; horizontal compressions are prevailing in the crust, lacking any tensile stresses. The trend of P axes is in the NW-SE to N-S direction in the Shikoku, NE-SW to N-S in Kyushu and E-W to NW-SE in Chugoku region, respectively High compressional stresses in the EW direction are concentrated along the east coast of Kyushu and somewhat lower stresses beneath Shikoku (Fig.8a). In the upper mantle, down-dip extension predominates in the downgoing slab below the bending point, which agrees well to the observations, while the present model gives horizontal compressional stresses in its shallow portions where normal faulting earthquakes have been observed (Fig.8b,c). It is found in this case (Fig.8d), however, that the velocity vectors of the calculated flow tend to be almost perpendicular to the slab, which appear to follow the hanging down of the slab. Some other sources must be required to maintain the observed dip angle of the sinking slab and also to explain the tesile stress field observed in the crust and the shallow part of the upper mantle. In this model, negative vertical stresses with considerable magnitudes appear along the east coast of Kyushu (Fig.8e). and their peak is not located around the trench axis, but is somewhat shifted landwards.

As stated above, it is clear that the observed tectonics in this region cannot be explained only by the slab pull force, although it has the greatest importance of the plate driving forces (Forsyth & Uyeda,1975; Chapple & Tullis,1978; Sekiguchi,1984) For this reason, we superpose the flows and stresses caused by other sources onto those by the slab pull force, and then compare them with the observations to evaluate the probable ranges of forces under the present model.

4.2 EFFECTS OF RIDGE PUSH AND ASTHENOSPHERIC FLOW

A ridge push force may have a great importance next to the slab pull force on the tectonics in island arc regions (Forsyth & Uyeda,1975; Sekiguchi,1984), while Davies(1978) suggested that the asthenosphere should drag the overlying plate. We examine the combined effects of these loads.

In the case when only a ridge push force is applied, horizontal compressive stresses are predominant in the crust and the subducted slab. The dip angle of the calculated flow vectors does not agree with the observed one. In the case when only a traction due to the flows in the asthenosphere is applied, on the other hand, horizontal compression also appears in the crust, while horizontal tension appears in the shallow portion of the slab. The dip of the flow vectors are nearly horizontal down to the bottom. Thus, either of the two forces alone cannot explain the observed stresses and deformations in the region under consideration (Table 2).

Next, we consider the combined effects of these forces and that for the slab pull. In Figs.9 and 10 are shown the calculated results in the cases when either of the ridge push (Model K-2) or a traction due to asthenospheric flow (Model K-4) with a magnitude of 250 bars are applied on the southeastern wedge, respectively, in addition to the slab pull. We have tentatively taken this magnitude, because the observed stresses and deformations could not be explained in the cases when these forces with a magnitude of 500 bars are applied (Table 2). It is found that either of the models cannot produce a tensile stress field in the crust, while horizontal compressive stresses are predominant (Figs.9a and 10a). In the shallow portion of the slab, horizontal compressive stress which leads to thrust faulting is also prevailing in the ridge push model (Figs.9b.c), while horizontal tension yielding normal faulting appears in the asthenospheric flow model (Figs.10b,c). The flow field in the latter model is more favorable than that in the former, in the view of the calculated dip angle of the descending slab (Figs.9d and 10d). A ridge push greater than 1 kbar would be required to reproduce the observed dip angle solely by means of this force. It seems, however, that this value may be too large, in the view of a recent estimate from global plate tectonics (e.g. Sekiguchi,1984).

On the other hand, the calculated dip angle of asthenospheric flow becomes smaller than the observed one in the case of a 250 bars traction, whereas a 100 bars traction in the asthenosphere(Model K-3) could not sustain the slab. Thus, a traction within the range from 100 to 250 bars in the asthenosphere might be a possible source that should account for the observed stress and flow field in the upper mantle. Positive vertical stress which could support topography appears in the central part of the Kyushu region in the two cases discussed here (Figs.9e and 10e), and we feel that Model K-4 is better than Model K-2 in view of their stress magnitudes. A significant stress off Shikoku might be due to the boundary effect.

It has been found here that a traction due to asthenospheric flow of 100 to 250 bars can explain several observations such as the dip angle of the subducted slab, and normal faulting in the shallow depths, and that a ridge push force might not be the source of these phenomena. We must, however, look for other possible sources to explain the observed tensile stresses in the crust of the central Kyushu region.

4.3 LOW-DENSITY CRUST IN ISLAND ARCS

Sleep(1975) suggested that the existence of a low-density crust may be required to produce the observed topography or gravity anomalies in the Aleutian Islands. For this reason, we take also the effect of crustal buoyancy due to the low density into consideration.

In Fig.11, we show the results for the model with a buoyant load due to a density contrast of 0.1 g/cm^3 in the crust superposed onto the field by the slab pull force and the traction due to asthenospheric flow of 250 bars (Model K-8). We see that horizontal tension in the NE-SW direction appears in the crust almost all over the region now in consideration but is accompanied also by a NW-SE compression, which leads to strike-slip faulting (Fig.11a). This type of the stress field could account for some of the observed earthquake mechanisms in this region (Eguchi,1984; Maki et al.,1984), but the trend of T axes in the central part of Kyushu shows a deviation of about 45° from the strain field obtained from triangulation data. The calculated stress and flow fields in the upper mantle are essentially similar to those by the slab pull force and the traction due to asthenospheric flow (Figs.11b-d).

The calculated vertical stress (Model K-8) in the central part of Kyushu is larger than that in the Model K-4. Besides this, large positive vertical stresses appear around the buoyant ridge which is assumed to be located east of Kyushu, and the large negative stresses in Model K-4 have been surpressed, which appeared around the trench southeast of Kyushu.

If we assume the density contrast to be 0.3 g/cm^3 (Model K-28 to K-33) instead of 0.1 g/cm^3 stated above, an isotropic tension dominates and the stress concentration in the coastal region east of Kyushu disappears. However, such a large density anomaly would not be realistic. Thus, the crustal buoyancy is a likely mechanism to give rise to a tensile stress field in the crust.

In this model, the maximum shear stresses are of the order of 200 bars in the crust, about 200 bars in the shallower portion of the slab and 500 bars in the deeper part of the slab, respectively These predicted values are similar to the previous estimate of stresses in the elastic model (Hashimoto,1982), and about the same order of magnitude as that expected from observed shear strain rates. Particle velocities on the surface are about 1 cm/yr, which is somewhat smaller than the observed relative plate velocity for the Philippine Sea plate. The calculated vertical stress in the crust are about 1 kbar, which may be large enough to support the topography of the central Kyushu region, although these values are dependent on the assumed viscosity of the crust.

4.4 BUOYANT FORCES ON LOW-DENSITIES OF BUOYANT RIDGE AND AN ASSUMED SPREADING CENTER AND E-W COMPRESSIVE FORCES

There are some geophysical evidences that the Kyushu-Palau ridge collides with the Eurasia plate at the junction of the Nankai trough and the Ryukyu trench. This ridge is considered to be a remnant island arc, which had been aparted from the Shichito-Iwojima ridge about 15-25 m.y ago. The subduction of such a buoyant ridge would give a significant effect on the tectonics of the Kyushu region.

It is now accepted that the Okinawa trough is an acitve back-arc spreading center (Uyeda,1977) and that northern the extension of this trough might reach the western part of the Kyushu island (Tada,1984). Therefore, a tectonic upstream flow might exist beneath the back-arc region, and this would cause a tensile stress field there.

We calculate the stresses and flows due to these buoyant forces (Model K-9. Fig.12). In this calculation, the ridge push forces and tractions due to the asthenospheric flow are not included. The results show that large tensile stresses appear in the back-arc west of Kyushu and around the Kyushu-Palau ridge (Fig.12a). A few earthquakes took place in the region west of Kyushu, but their focal mechanisms have been well determined only in limited cases. From these considerations, it has been found that buoyant forces due to such a large density contrast as 0.1 g/cm^3 do not provide the stress field consistent with observed focal mechanism, and hence may not be realistic. Besides them, large stresses of horizontal tension are concentrated in the deeper part of the slab (Fig.12b,c), but earthquakes with such a mechanism have not taken place there. The tectnic flow field obtained here cannot explain the dip angle of the slab (Fig.12d). Large vertical stresses appear along the assumed spreading center and around the buoyant ridge (Fig.12e). Thus, it has been shown that these models could not explain various observations to a sufficient degree, and that these two types of forces assumed here have only a secondary effect.

We also take into account compressive forces in the E-W direction exerting on the crust or the subducted slab (Fig.13). The calculated stress and flow fields are found to be very similar to those for Model K-8. Their effects may be less important than those from the slab pull, traction due to asthenospheric flow and crustal buoyancy.

5. Discussions

5.1 TENSION IN BACK-ARC AND COMPRESSION ALONG THE COAST IN SHALLOW DEPTHS

It has been suggested (Tada,1984) that the tensile stresses observed in northwestern Kyushu may be caused by possible extension of the spreading center in the Okinawa trough towards this region. Our present models, however, do not seem to favour the existence of the spreading center there. One of our models (Model K-9) with a buoyant force acting at the assumed spreading center gives an extensional field in the crust, but causes, at the same time, a significant upwarping of the ground in the central Kyushu region. This prediction does not agree with the observed topography and crustal uplifts. In this model, unusual horizontal tensile stresses with significant magnitudes which could yield normal faulting also appear in the deep portions of the subducted plate. This is not supported by observed earthquake mechanisms. These results appear to suggest that the existence of a positive buoyancy in the back-arc region may not be probable, although this conclusion is somewhat model-dependent.

Our favoured models which could explain the observed extensional field are those with a buoyant crust. This gives a quasi-isotropic horizontal extension in the central Kyushu. On the other hand, the ridge push force or traction due to the asthenospheric flow yields a stress field corresponding to a strike-slip type mechanism in the crust. By superposing all these effects, we would be able to obtain an NNE-SSW extension and WNW-ESE compression fields, which would cause a significant shear stress in the crust. The western extension of the Median Tectonic Line to the central Kyushu region might have been formed under such a stress field. Maki et al.(1984) proposed that the observed N-S tensile stresses there may be related to this shear zone. Although the predicted trend does not agree well with the observations, these types of models are more favourable because they could explain the other observations for the focal mechanisms and dip angle of the subducted slab.

A possible high stress concentration in the Hyuga-nada, which is supported by high seismicity there, would be explained by the slab pull force. This force yields horizontal compressive stresses in the wedge region outside of the aseismic front, which lead to thrust faulting. Yoshii's(1979) model for the northeastern Japan is very similar to our results.

5.2 STRESS FIELD IN THE UPPER MANTLE

Shiono & Mikumo(1975) suggested that the 1968 Bungo channel earthquake with a normal faulting mechanism took place above the interface between the subducting Philippine Sea plate and the continental plate. Hurukawa & Hirahara(1981) and Hurukawa(1982) also showed that subcrustal normal faulting earthquakes beneath the Kii peninsula should occur in the continental plate. On the other hand, there is a hypothesis that these earthquakes may take place in the subducted oceanic crust (Fukao et al.,1983). Yoshii(1979) presented a typical model of seismic structure in northeastern Japan, and showed that the wedge part in the uppermost mantle should have a capability to cause earthquakes, the mechanisms of which may be of thrust type. We calculated the stress field at these depths, and found that horizontal tensile stresses leading to normal faulting hardly appeared in the wedge zone. These types of stresses appear in the subducted plate in the case when asthenospheric flows with significant importance are included. On the other hand, the slab pull force should produce vertical extension in the wedge zone, but horizontal extension may not be generated there as long as the slab pull is assumed to have primary importance.

We suggested in Paper I that the horizontal extension parallel to the leading edge of the subducted Philippine Sea plate may be caused mainly by the negative buoyancy. around the Kii peninsula and Kii channel where the leading edge has a concave shape. However, the parallel extension field observed in the Iyonada and the western Shikoku region has not been well explained by this model. The present model incorporating asthenospheric flows provides a more favorable explanation particularly to the latter region. The asthenospheric flows will push the lower, steeply-dipping portion of the plate, and yield a down-dip tensile stress there when they are combined with the slab pull force. In the upper, gently-dipping portion of the plate, on the other hand, a nearly horizontal tensile stress would be generated in the direction parallel to that of the movement of the Philippine Sea plate, particularly beneath the eastern Kyushu region. This is consistent with the focal mechanism of a subcrustal earthquake there (Imagawa et al.,1984). Since the leading edge of the plate changes its direction eastwards in the western Shikoku region, the horizontal tensile stresses appear to act almost parallel to the leading edge there.

Shiono(1977) suggested also a thermal contraction model in order to explain this tensile stress. In Paper II, we estimated the importance of thermal load arising in the subducted plate, and found that this load might give significant effects on the stress field in island arcs, even if a small expansion of the order of 1 % would take place. We do not take into account this type of thermal load in the present paper, because the Philippine Sea plate subducting beneath the southwestern Japan is so young that significant thermal contraction may not be expected.

Earthquakes with the mechanism of down-dip tension type frequently occur in the subducted slab beneath the Kyushu region. This type of the stress field may be explained by the slab pull force. However, the calculated shear stresses are concentrated near the bending point of the slab and attenuated in the deeper part. This situation does not agree well with the observed seismicity, because many earthquakes do not occur around the bending point but tend to cluster below there (Shiono et al.,1980) This discrepancy is a problem to be solved after the source mechanisms of earthquakes occuring in the upper mantle in this region have been determined to a satisfactory degree.

5.3 FLOWS IN THE UPPER MANTLE

We have the standpoint that the configuration of the subducted slab may be a manifestation of the flow field in the upper mantle.

From this viewpoint, the predicted dip angle of flow vectors should explain the observed one. Since the negative buoyancy should pull the plate down, some moments are required which may balance against the negative buoyancy in order to hold the dip of flows. Some attempts have been made to explain the slab dip. Yokokura(1981) calculated the dip-angles of slabs in many subduction zones on the basis of torque balance between the negative buoyancy on the slab and flow pressures caused by plate motion, and intended to obtain a probable viscosity model. On the other hand, Hager & O'Connell(1978) showed that the dip angle of slabs can be explained by the flows caused by the suface velocities of plates, although their calculations are based only on kinematic flow fields. Recently, Hager et al.(1984) calculated the dip angles with models including the density contrast between the slab and the surrounding mantle, incorporating the surface velocities of plates as the boundary conditions and also the negative buoyancy on the slab. The surface velocities, however, may be the results which include the effects of the slab pull, ridge push, basal shear, and so on. Therefore, their calculated flow fields may have double effects of the slab pull. The models given by Sleep(1975) and Bird(1978a) might be in the same situation. On the other hand, our model takes no velocity boundary conditions into consideration and hence may be more realistic than theirs.

Although we calculated the flow field for several possible models along this line, only those with significant asthenospheric flows could explain the observations, which leads to the idea that the flows in the asthenosphere should drive the plate motion. On the other hand, many authors showed that basal shear stress may act as a resisting force (Forsyth & Uyeda,1975; Chapple & Tullis, 1978; Sekiguchi, 1984). Their models are kinematic ones on the assumption of rigid plates. Richardson et al.(1979) calculated the stresses in plates on the basis of global membrane finite element model and also showed that basal shear stresses are resistive to plate motion, but their models also lack the effects of the slab on the flow in the mantle. Hager & O'Connell(1981) estimated relative importances of plate driving forces and showed that a slab pull and a ridge push due to the density contrast between the lithosphere and asthenosphere may be primary sources of plate motion. However, their dynamic model also might have double effects of the slab pull and ridge push, because they introduced the plate velocities as boundary conditions and the density contrasts as body forces. In our model, the source of flows in the asthenosphere remains ambiguous. Since we have modeled the subduction zone only down to a depth of 300 km, local effects might be dominant. The present boundary conditions might not well simulate the global flow field in the mantle. Global dynamic flow models are expected in a near future to be able to give a solution to the above problem.

Our calculated flow velocities are somewhat slower than the observed plate veloctities. This may be dependent on the viscosity of the lithosphere. Viscous lithosphere slows down the flows around the slab (Hager et al.,1984) The viscosity assigned to the lithosphere in our model is 4×10^{23} poise, which is a little greater than that in Cathles'(1975) model. Surface velocities are about 1 cm/yr Thus, the viscosity of about 10^{23} poise may be probable to the lithosphere.

6. Conclusions

The following conclusions are derived from the present study.

(1) The horizontal extension in the N-S direction observed in northwestern Kyushu could be caused by the interaction of a slab pull force, crustal buoyancy and asthenospheric flows. The existence of a spreading center may not give strong effects to the observed stress field.

(2) The near-horizontal tensile stresses which yield normal faulting at subcrustal depths may be caused by flows in the asthenosphere and would be more likely to take place on the oceanic side in the Kyushu region.

(3) The stresses of down-dip tension in the deeper portion of the slab may be caused mainly by a slab pull force.

(4) The traction ranging between 100 and 250 bars due to flows in the asthenosphere may be required in order to explain the dip angle of the subducted slab.

(5) The maximum magnitude of tectonic flows is as large as 1.0 cm/yr on the ground surface, and that of the stresses is less than 500 bars in the slab and the crust, although they are somewhat dependent on the viscosity models.

Acknowlegements

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The calculations included were made at the Data Processing Center of Kyoto University. I used the hypocentral data of J.M.A. in the database "JISHIN" at the Data Processing Center of Kyoto University.

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Hill, Berkshire, 787pp.

Table 1 : Viscosity and density profile

No.	identification	viscosity	density contrast
1	crust	4000	-0.1
2	lid	1000	0.0
3	asthenosphere-1	4	0.0
4	asthenosphere-2	400	0.0
5	wedge mantle-1	0.4	0.0
6	oceanic crust	4000	0.0
7	wedge mantle-2	1000	0.0
8	oceanic plate-1	4000	0.0667
9	oceanic plate-2	1000	0.0667
10	buoyant ridge	4000	-0.1
11	spreading zone	4	-0.1

Units are as follows : 10^{20} poise for viscosity and g/cm^3 for density contrast

Table 2 : Weights for respective loads (abbreviations should be refered to text).

Model	CB	SP	BR	SC	RP	AF	EP	WP1	WP2	slab dip	stress C	stress S	stress I
S-P	0	1	0	0	0	0	0	0	0	no	T	T	T
R-P	0	0	0	0	1	0	0	0	0	no	T	T	T
A-F	0	0	0	0	0	1	0	0	0	no	T	N,S	T
K-1	0	1	0	0	1	0	0	0	0	no	T	T	T
K-2	0	1	0	0	2.5	0	0	0	0	no	T	T	T
K-3	0	1	0	0	0	1	0	0	0	poor	T	N	T
K-4	0	1	0	0	0	2.5	0	0	0	fair	T	N,S	T
K-5	1	1	0	0	1	0	0	0	0	no	N	T	T
K-6	1	1	0	0	0	1	0	0	0	poor	S	N	T
K-7	1	1	0	0	2.5	0	0	0	0	no	S	T	T
K-8	1	1	0	0	0	2.5	0	0	0	fair	S	N	T
K-9	1	1	1	1	0	0	0	0	0	no	N	N	N,T
K-10	1	1	0.5	0.5	0	0	0	0	0	no	N	N	N,T
K-11	1	1	1	0	5	5	0	5	5	no	S	N	T
K-12	1	1	1	0	5	5	0	5	-5	no	S	N	T
K-14	1	1	1	1	2.5	2.5	0	5	-5	fair	T	N	T
K-15	1	1	1	3	2.5	2.5	0	5	-5	fair	S,N	N	N,T
K-16	1	1	1	3	1	1	0	1	-1	poor	N	T	N,T
K-19	1	1	0	0.25	0	0	0	0	0	no	N	N	T
K-20	1	1	0	0	1	1	0	1	-1	poor	S	S	T
K-22	1	1	0	0	0	0	1	0	0	no	S	T	T
K-24	1	1	0	0	0	1	1	1	0	poor	S	T	T
K-25	1	1	0	0	1	2.5	1	1	-1	fair	S	N	T

K-26	1	1	0	0.25	1	2.5	1	1	-1	fair	S	N	T
K-27	1	1	0	0	1	2.5	2.5	2.5	-1	fair	S	N	T
K-28	3	1	0	0	0	0	0	0	0	no	N	N	T
K-29	3	1	0	0	1	0	0	0	0	no	N	N	T
K-30	3	1	0	0	0	1	0	0	0	poor	N	N	T
K-31	3	1	0	0	0	0	0	1	0	no	N	N	T
K-32	3	1	0	0	2.5	0	0	0	0	no	N	N	T
K-33	3	1	0	0	0	2.5	0	0	0	fair	S	N	T

The column for slab dip shows a degree of fitnesses of the dip-angles of calculated flow between the observed one: "fair" means fairly good fitness, "poor" means poor agreements, and "no" means no fitness. The column for stress shows a type of predicted faulting predominant in crust(C), subcrustal depths(S) and intermediate depths(I): T means thrust, N normal and S strike-slip faulting, respectively

Figure captions

Fig. 1 : Index map of southwestern Japan after Hirahara(1981)

Fig. 2 : Strain field in Kyushu, Shikoku and Chugoku, after Tada(1984).

Fig. 3 : Vertical land movements in southwestern Japan after Dambara(1971).

Fig. 4 : Distribution of earthquakes. All the data are published by J.M.A.

a) crustal earthquakes (H < 40 km).

b) subcrustal earthquakes (H >= 40 km).

c) a vertical cross-section from the viewpoint of ocean side.

d) a vertical cross-section normal to the trend of the arc.

Fig. 5 : Focal mechanisms of major earthquakes.

a) Mechanism diagrams of large earthquakes along the Nankai trough and the Ryukyu trench after Shiono(1977).

b) Mechanism diagrams of large earthquakes in the crust of southwestern Japan after Shiono(1977)

c) Mechanism diagrams of large subcrustal earthquakes after Imagawa et al.(1984).

Fig. 6 : Geometry of the present finite element model.

a) a horizontal projection. Dotted part shows the buoyant ridge which has a lower density than the surrounding region. The subducted plate in the shaded portion is thinner than that in the southwestern part. The horizontal projection of the leading edge of the subducted plate is shown by the broken line. The doubled line shows the assumed trench axis in the present model.

b) a typical vertical cross-section.

c) subdivisions according to material properties.

Fig. 7 : Boundary conditions and assumed loads.

Fig. 8 : Results in the case where only a slab pull or negative buoyancy on slab is assumed.

a) horizontal stresses in crust.

b) three-dimensional stresses in the subducted plate. (lower hemisphere projection)

c) stresses in a section of S-S' in Fig.6a. (front side hemisphere projections)

d) flow vectors on a vertical cross-section F-F' in Fig.6a.

e) vertical stresses in crust.

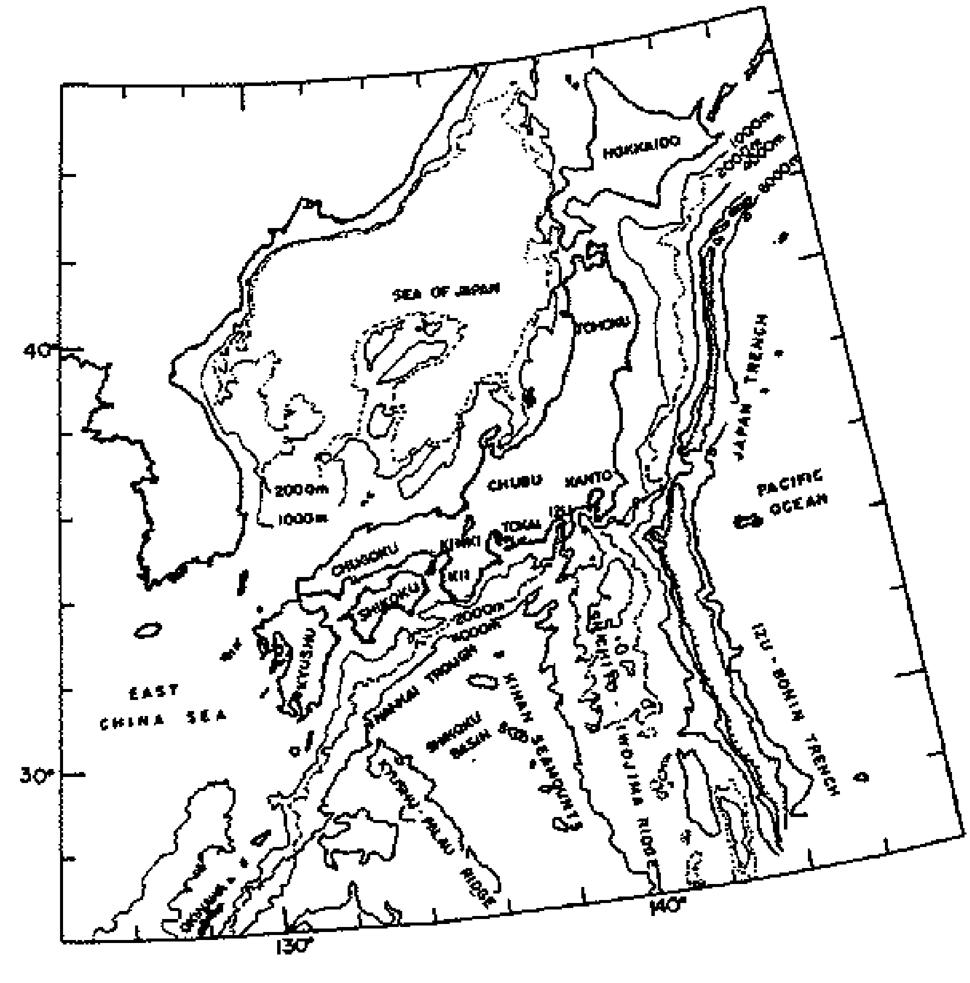
Fig. 9 : Results for the Model K-2. (See legend for Fig.8)

Fig.10 : Results for the Model K-4. (See legend for Fig.8)

Fig.11 : Results for the Model K-8. (See legend for Fig.8)

Fig.12 : Results for the Model K-9. (See legend for Fig.8)

Fig.13 : Results for the Model K-27 (See legend for Fig.8)



SEA OF JAPAN
HOKKAIDO
TOHOKU
CHUBU
KANTO
CHUGOKU
KINKI
TOKAI
IZU
KII
SHIKOKU
KYUSHU
EAST
CHINA SEA
PACIFIC
OCEAN
JAPAN TRENCH
IZU - BONIN TRENCH
NANKAI TROUGH
SHIKOKU
BASIN
KINAN SEAMOUNTS
IWOJIMA RIDGE
PALAU RIDGE
2000m
1000m
40°
30°
130°
140°

Fig. 1

Fig. 2

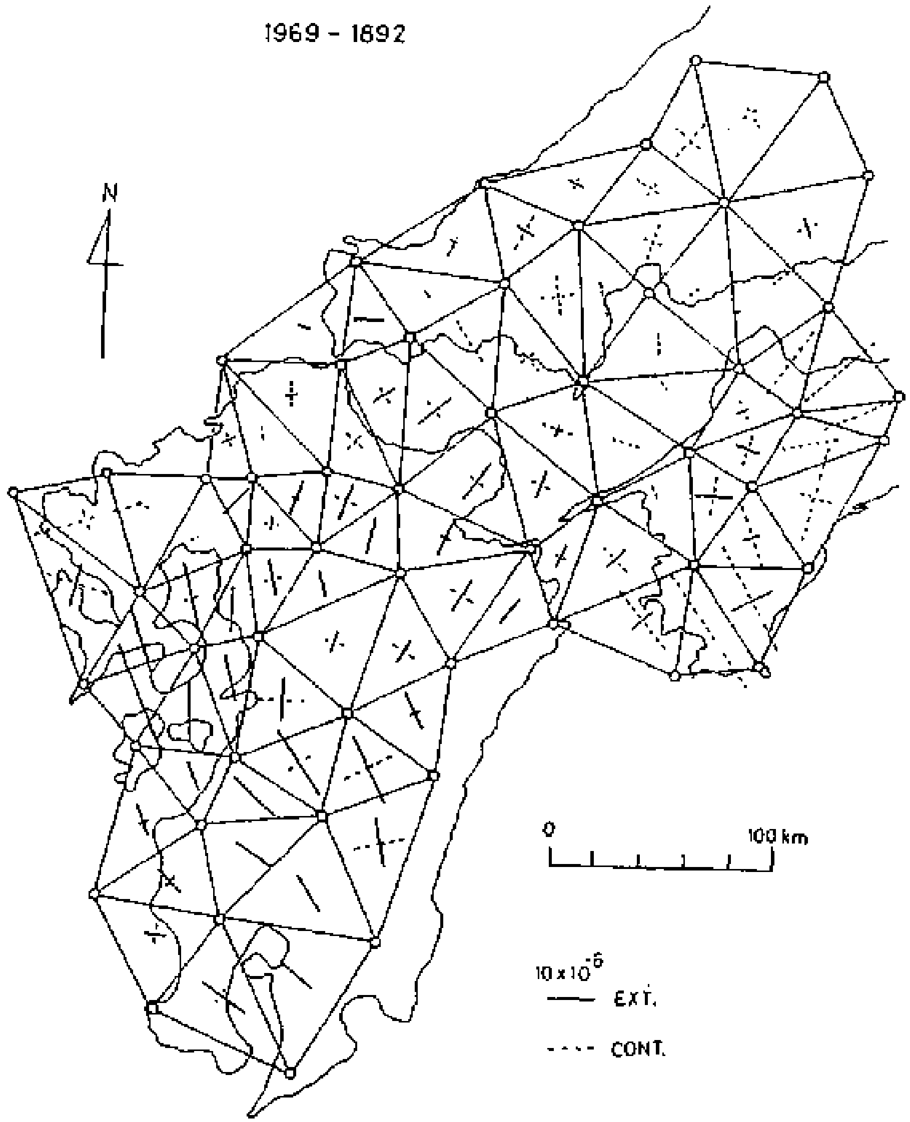

1969 - 1892
N
0
100 km
10 x 10^-6
EXT.
CONT.

Fig. 3

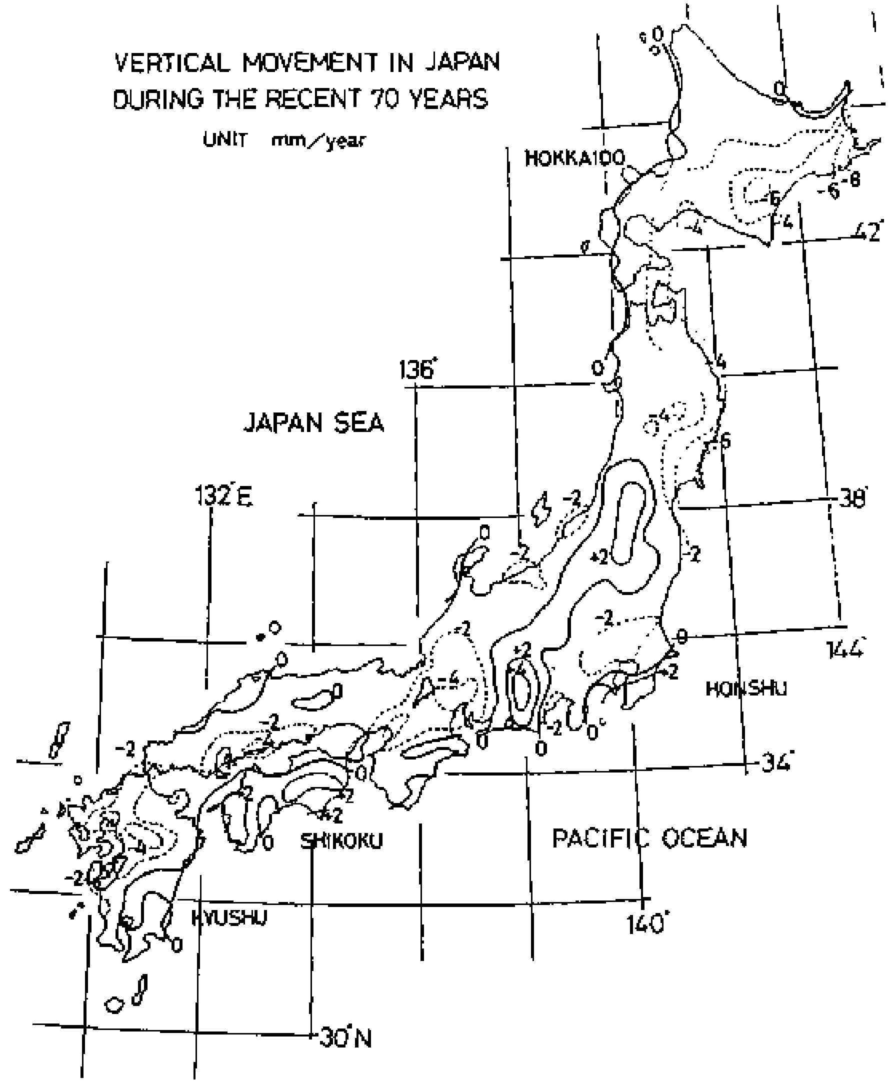

VERTICAL MOVEMENT IN JAPAN
DURING THE RECENT 70 YEARS
UNIT mm/year
HOKKAIDO
JAPAN SEA
136°
132°E
38°
42°
144°
34°
140°
30°N
HONSHU
SHIKOKU
KYUSHU
PACIFIC OCEAN

Fig. 4(a)

DISTRIBUTION OF EARTHQUAKES : 1961 JAN - 1983 JUN
DEPTH : 0 - 39 (KM) MAG : 4 0 - 9 0 (JMA)

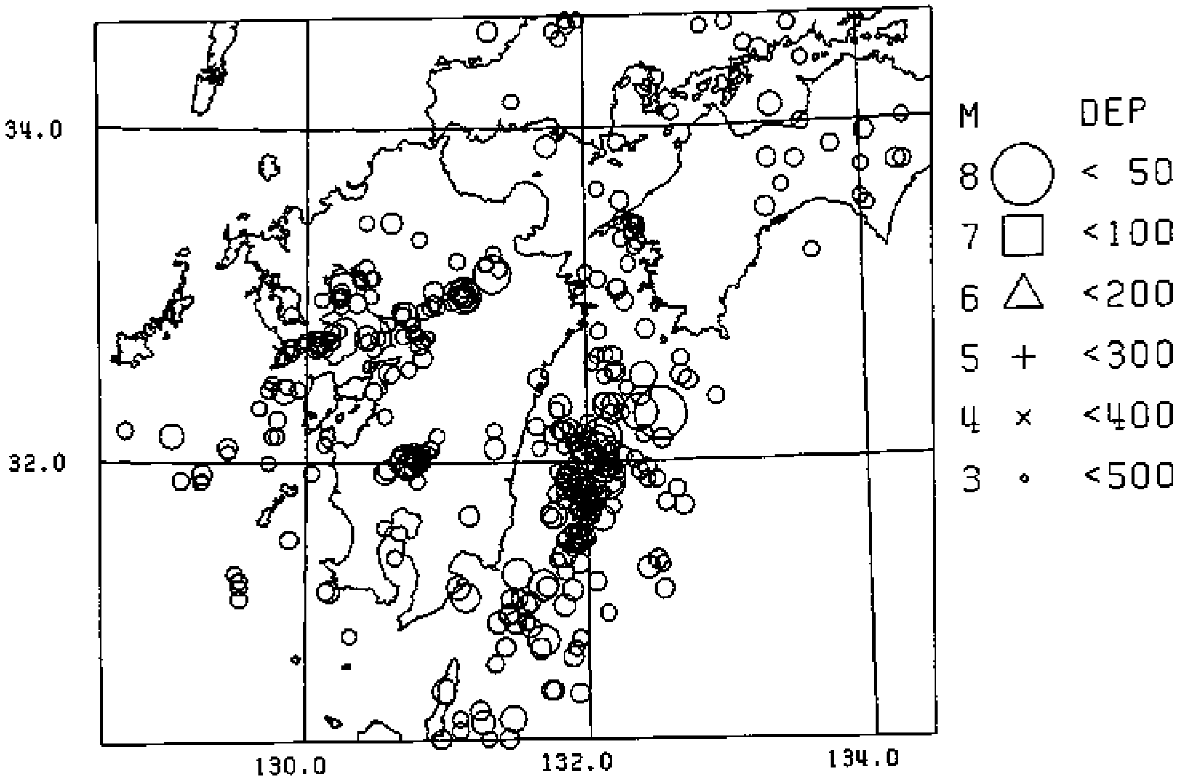


Fig. 4(b)

DISTRIBUTION OF EARTHQUAKES : 1961 JAN - 1983 JUN
DEPTH : 40 - 300 (KM) MAG : 4.0 - 9 0 (JMA)

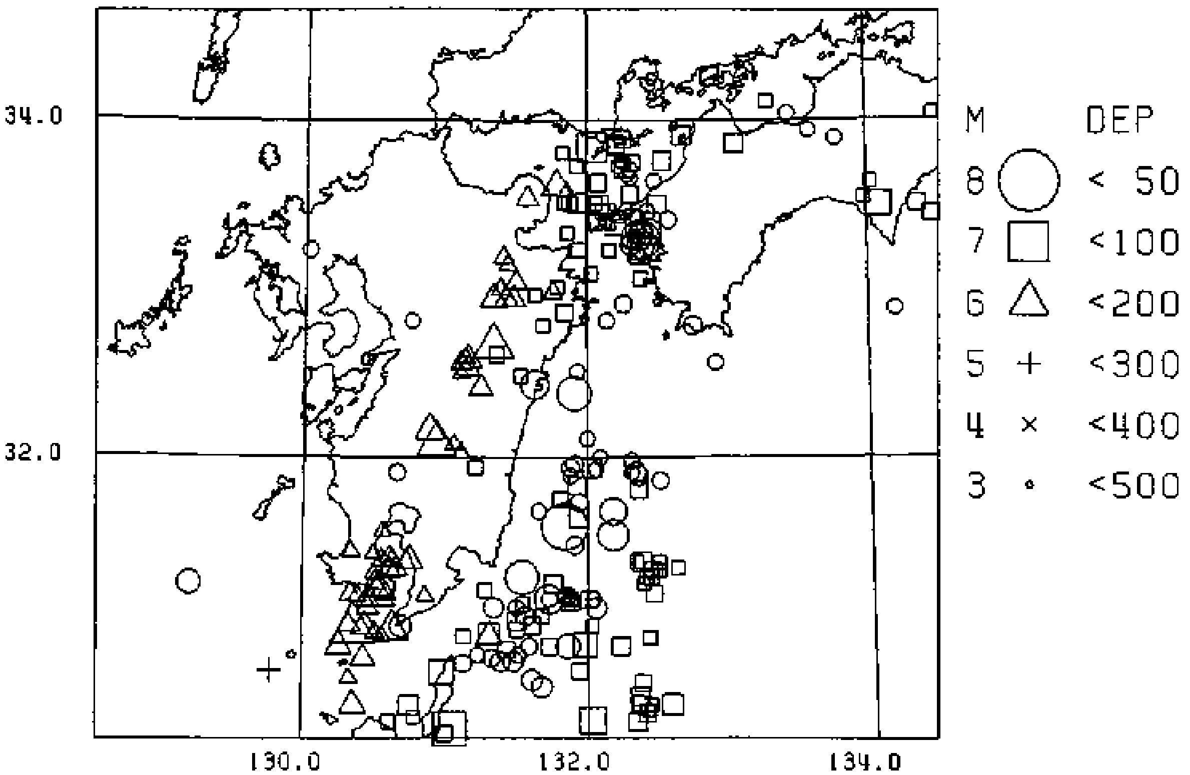


Fig. 4 (c)

VERTICAL CROSS SECTION : 1961 JAN - 1983 JUN
LAT : 29.0 - 35.0 LON : 129.0 - 134.0
DEP : 0 - 300 (KM) MAG : 4.0 9.0 (JMA)

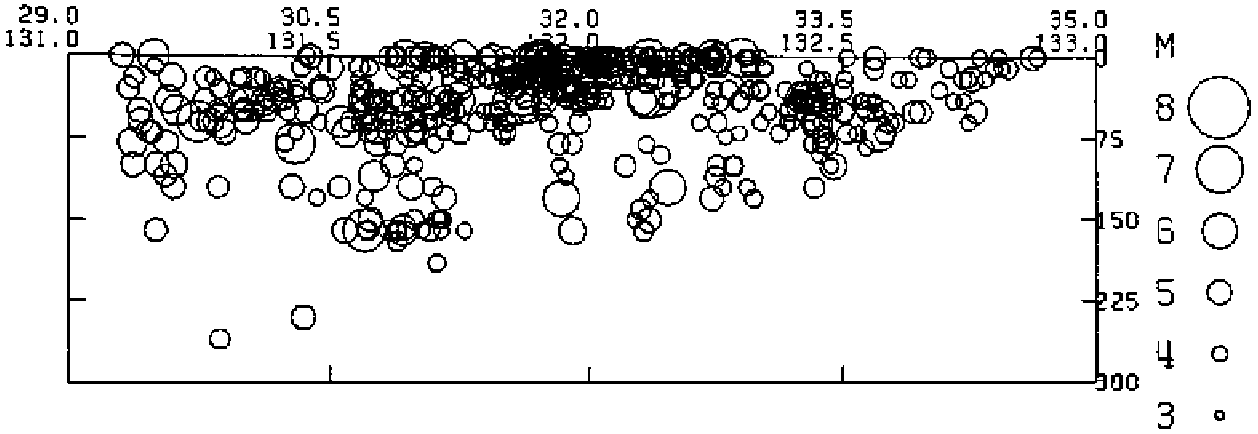


Fig. 4 (d)

VERTICAL CROSS SECTION : 1961 JAN - 1983 JUN
LAT : 30.5 - 33.0 LON : 129.0 - 133.0
DEP : 0 - 300 (KM) MAG : 4.0 - 9.0 (JMA)

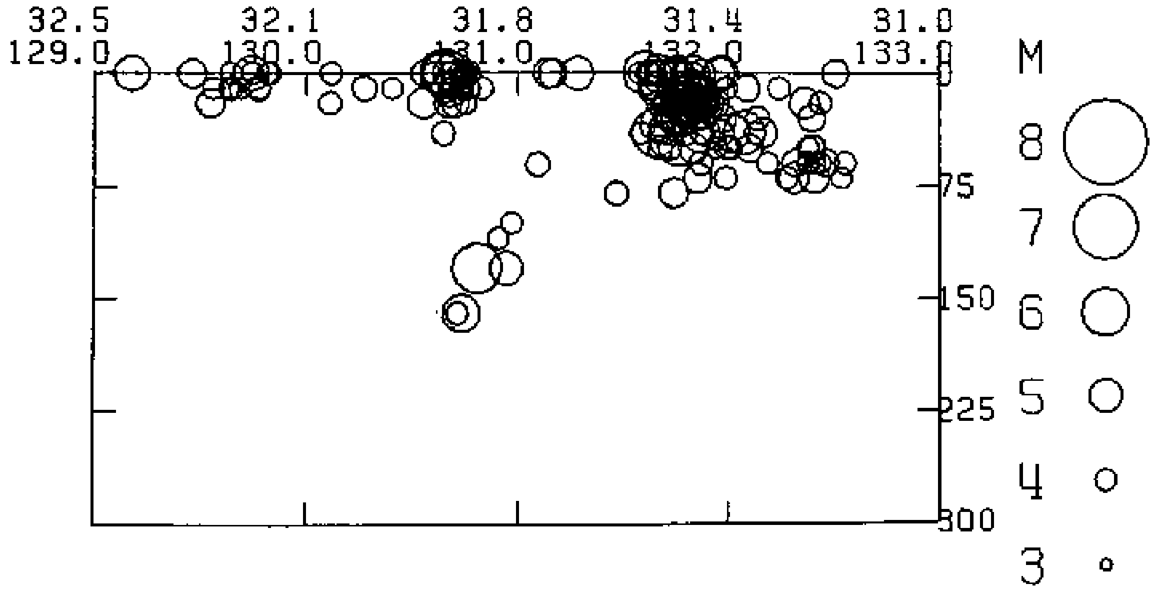


Fig. 5(a)

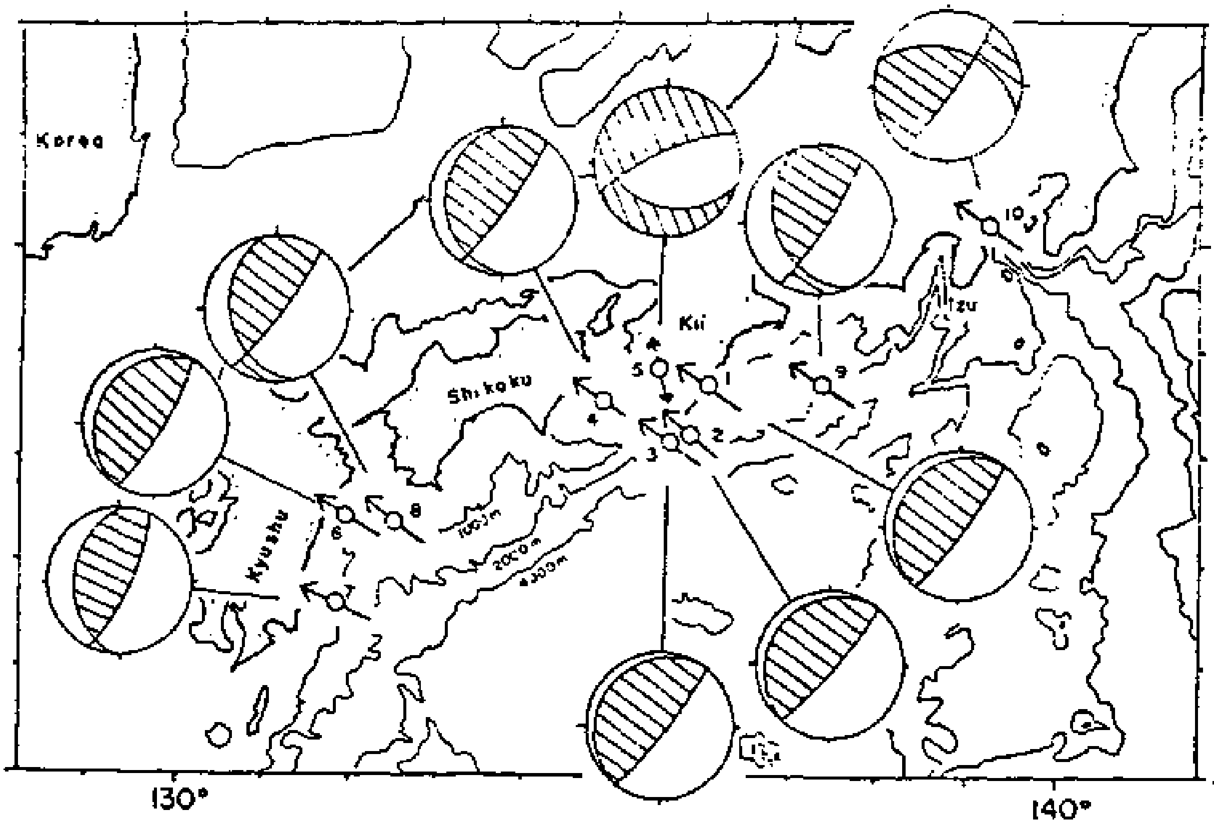
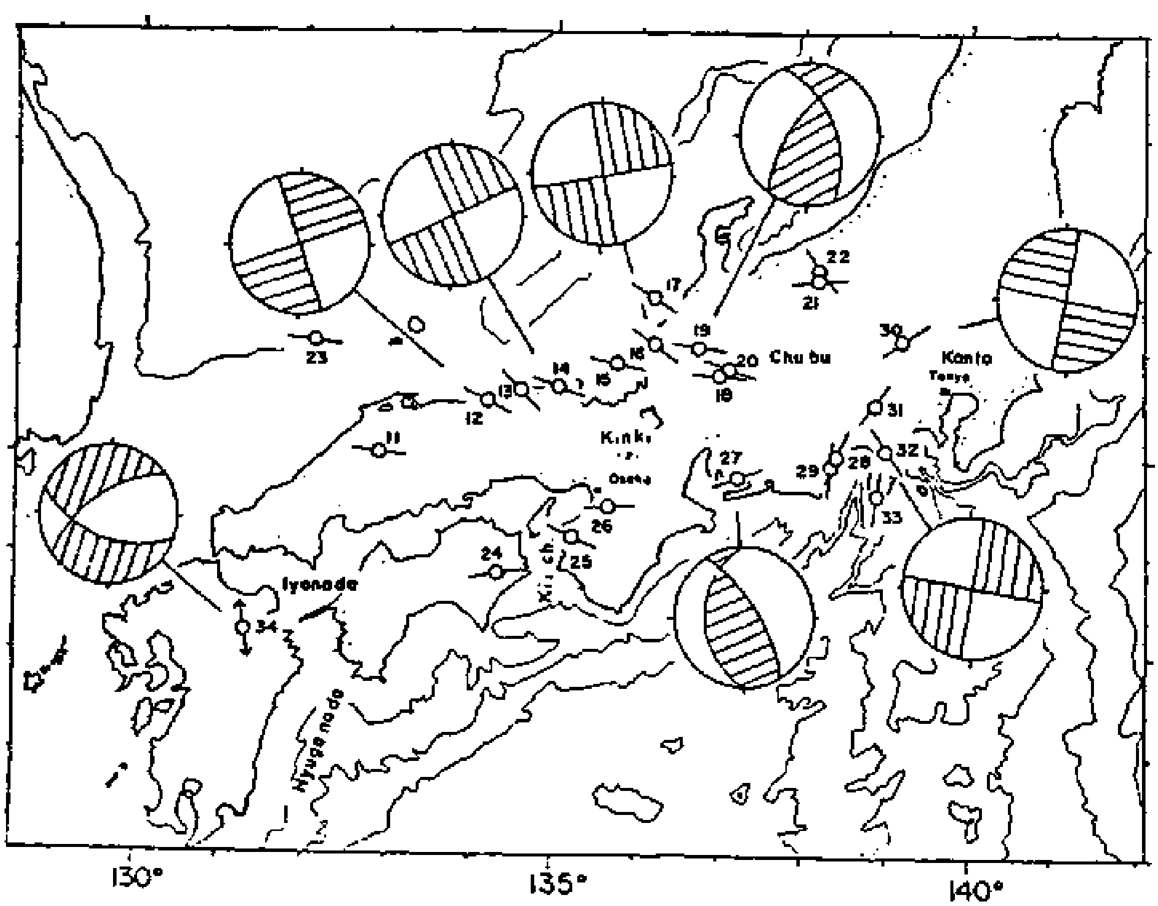

Korea
35°
30°
130°
140°
Kii
Izu
Shikoku
Kyushu
1
2
3
4
5
6
7
8
9
10

Fig. 5(b)


130°
135°
140°
35°
Chubu
Kanto
Kinki
Osaka
Iyonada
Hyuganada
11
12
13
14
15
16
17
18
19
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21
22
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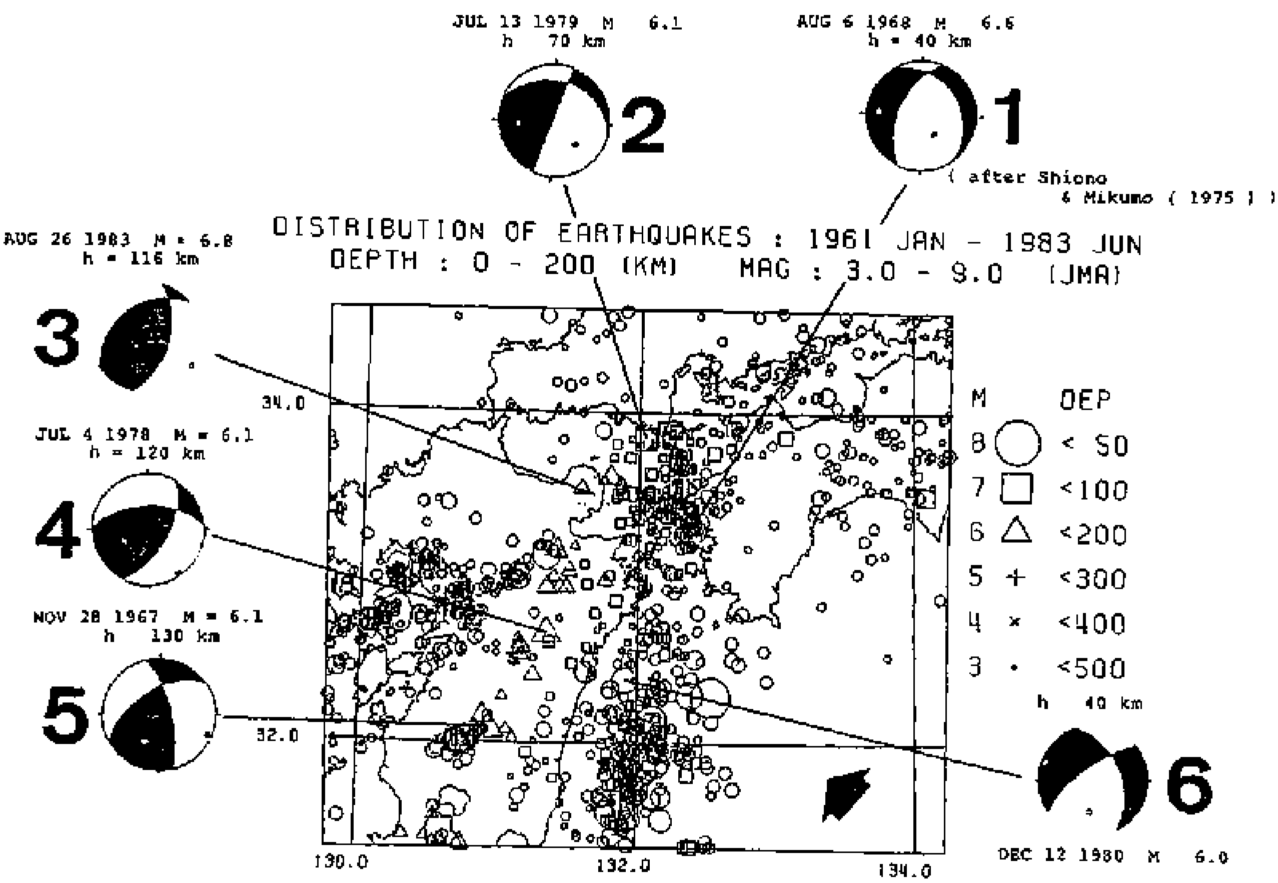
32
33
34

Fig 5(c)



JUL 13 1979 M 6.1
h 70 km
2
AUG 6 1968 M 6.6
h = 40 km
1
(after Shiono & Mikumo (1975))
DISTRIBUTION OF EARTHQUAKES : 1961 JAN - 1983 JUN
DEPTH : 0 - 200 (KM) MAG : 3.0 - 9.0 (JMA)
AUG 26 1983 M = 6.8
h = 116 km
3
JUL 4 1978 M = 6.1
h = 120 km
4
NOV 28 1967 M = 6.1
h 130 km
5
34.0
32.0
130.0
132.0
134.0
M DEP
8 < 50
7 <100
6 <200
5 <300
4 <400
3 <500
h 40 km
6
DEC 12 1980 M 6.0

Fig. 6(a)

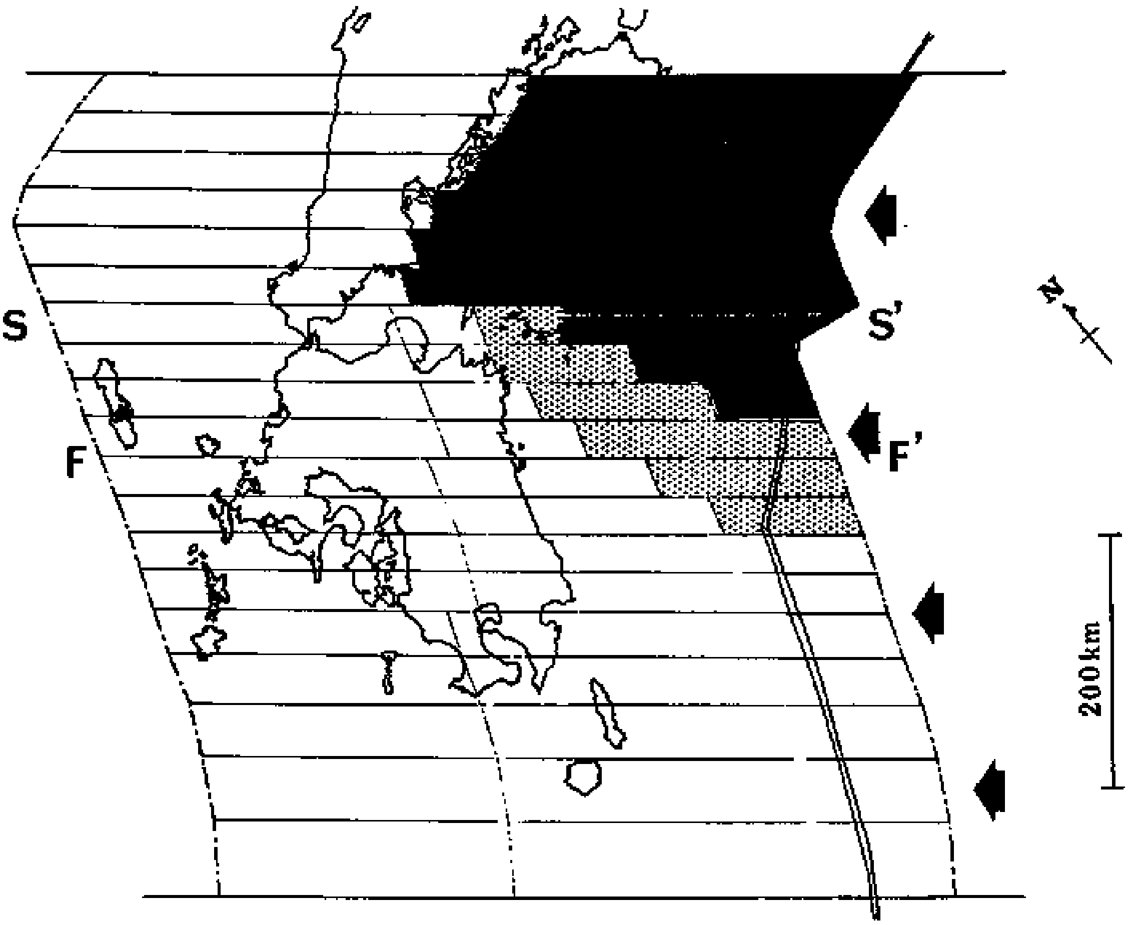


Fig. 6(b)

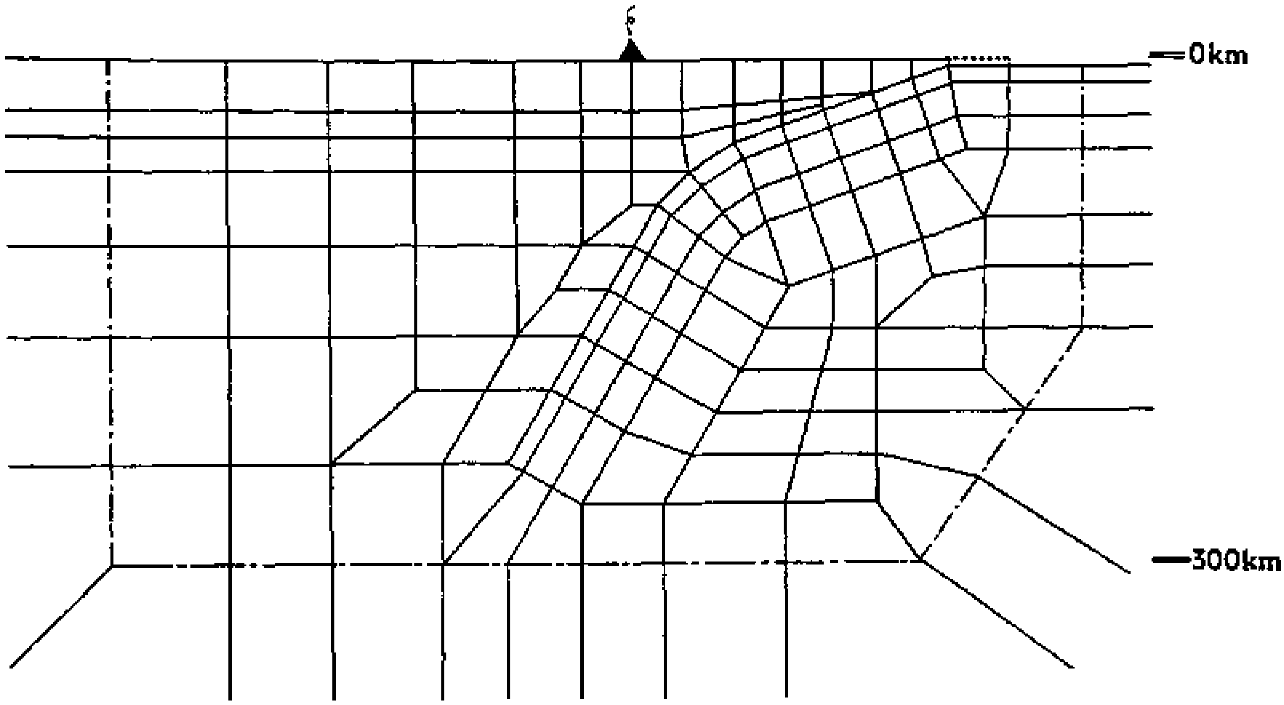
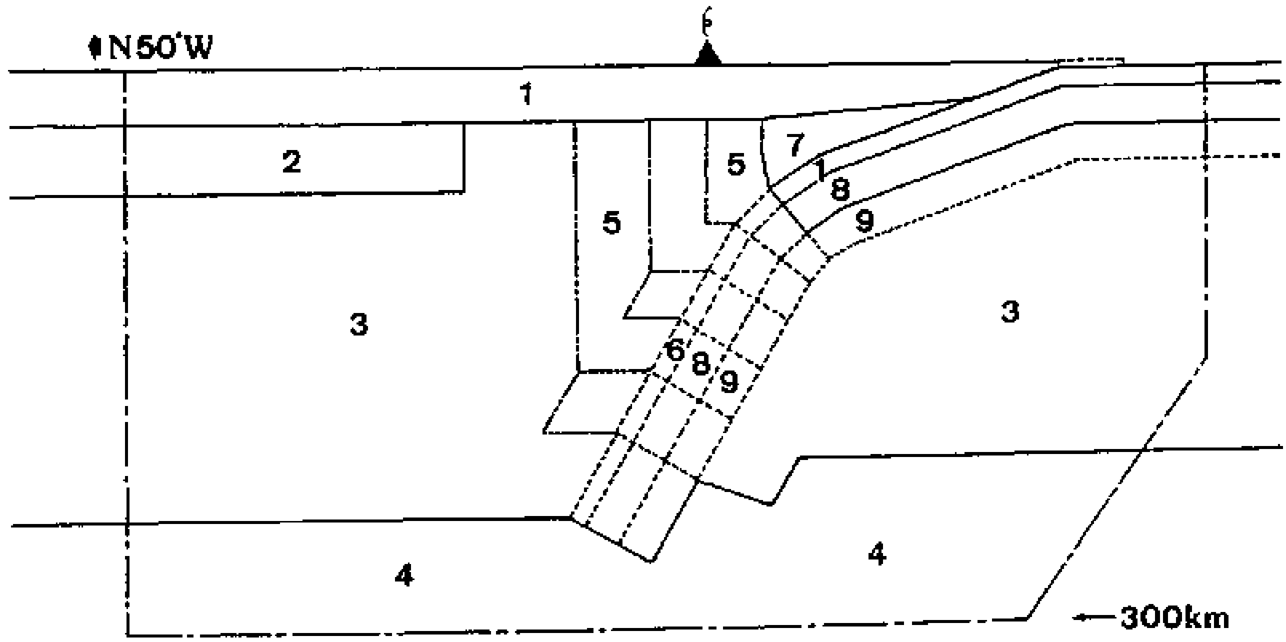


Fig. 6(c)



Infinite Element

Fig. 7

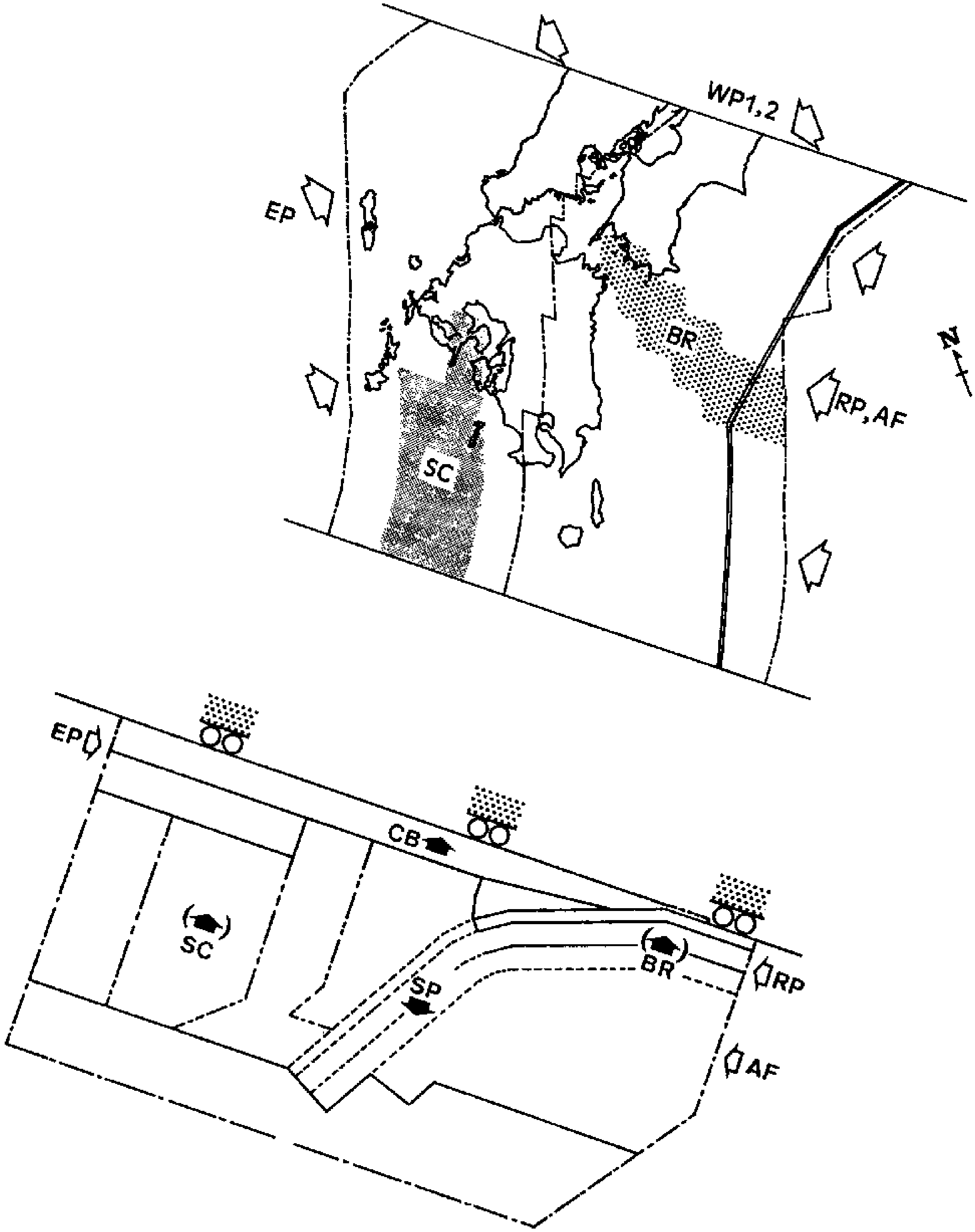


Fig 8(a)

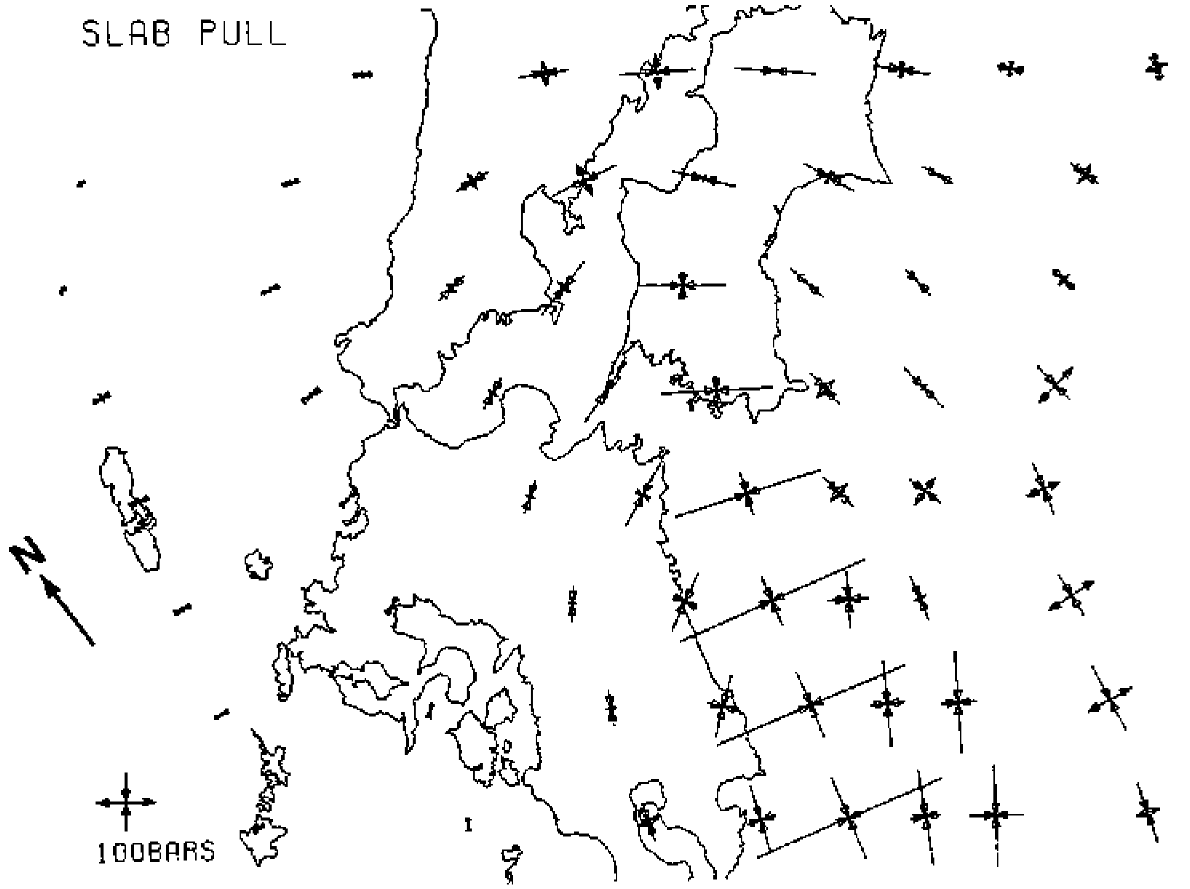


Fig. 8(b)

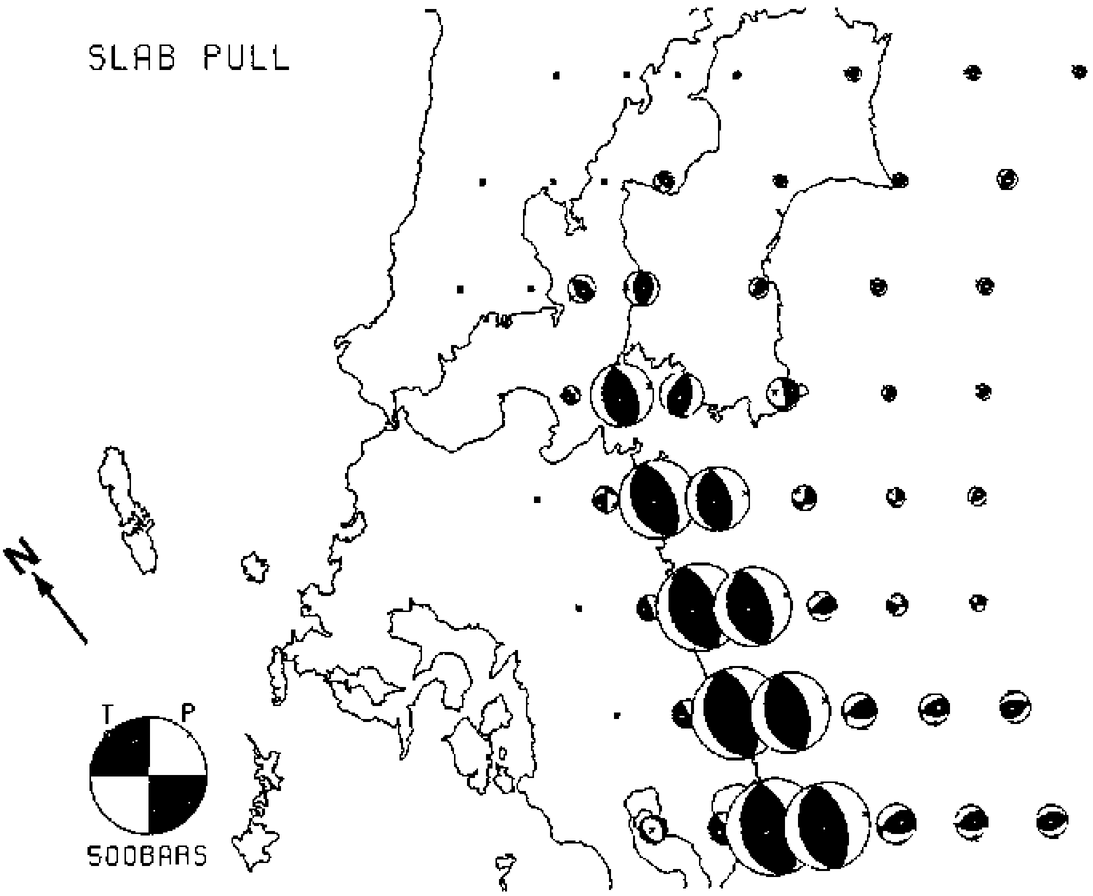


Fig. 8(c)

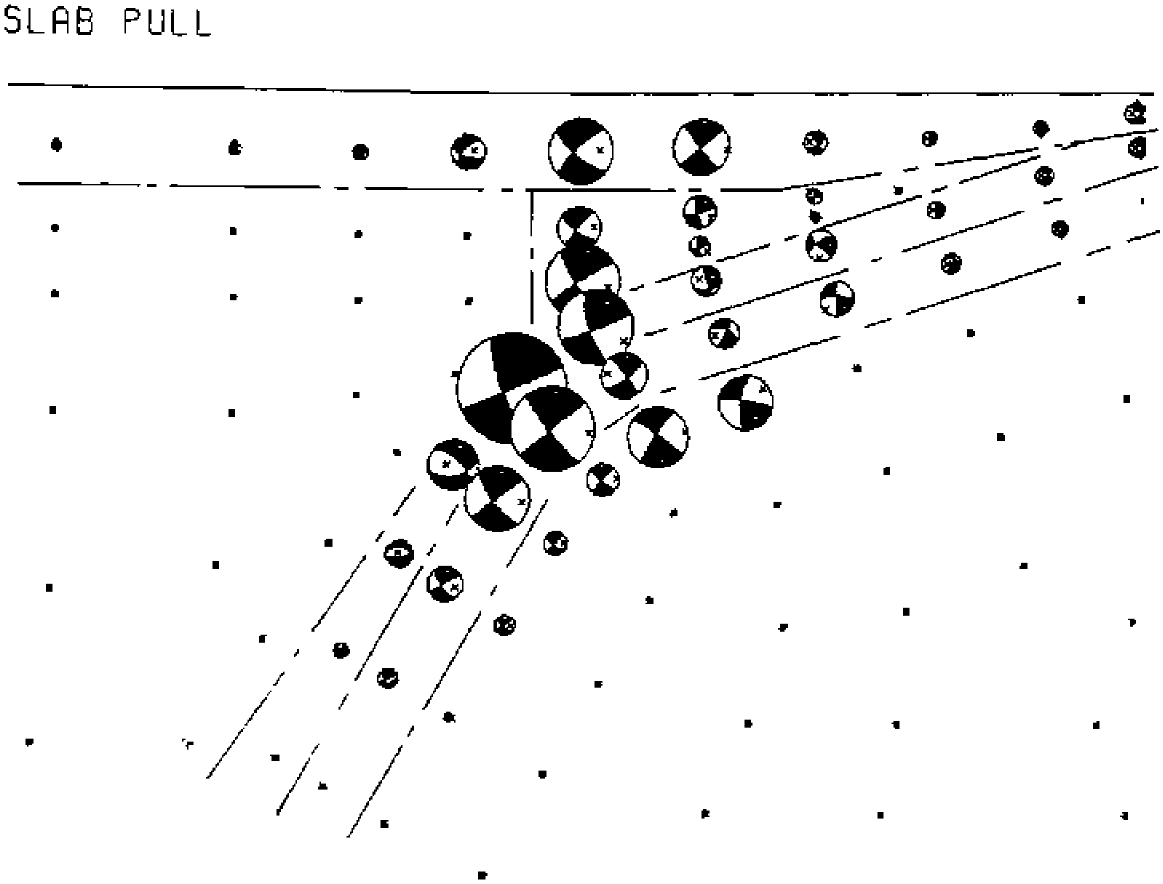


Fig. 8(d)

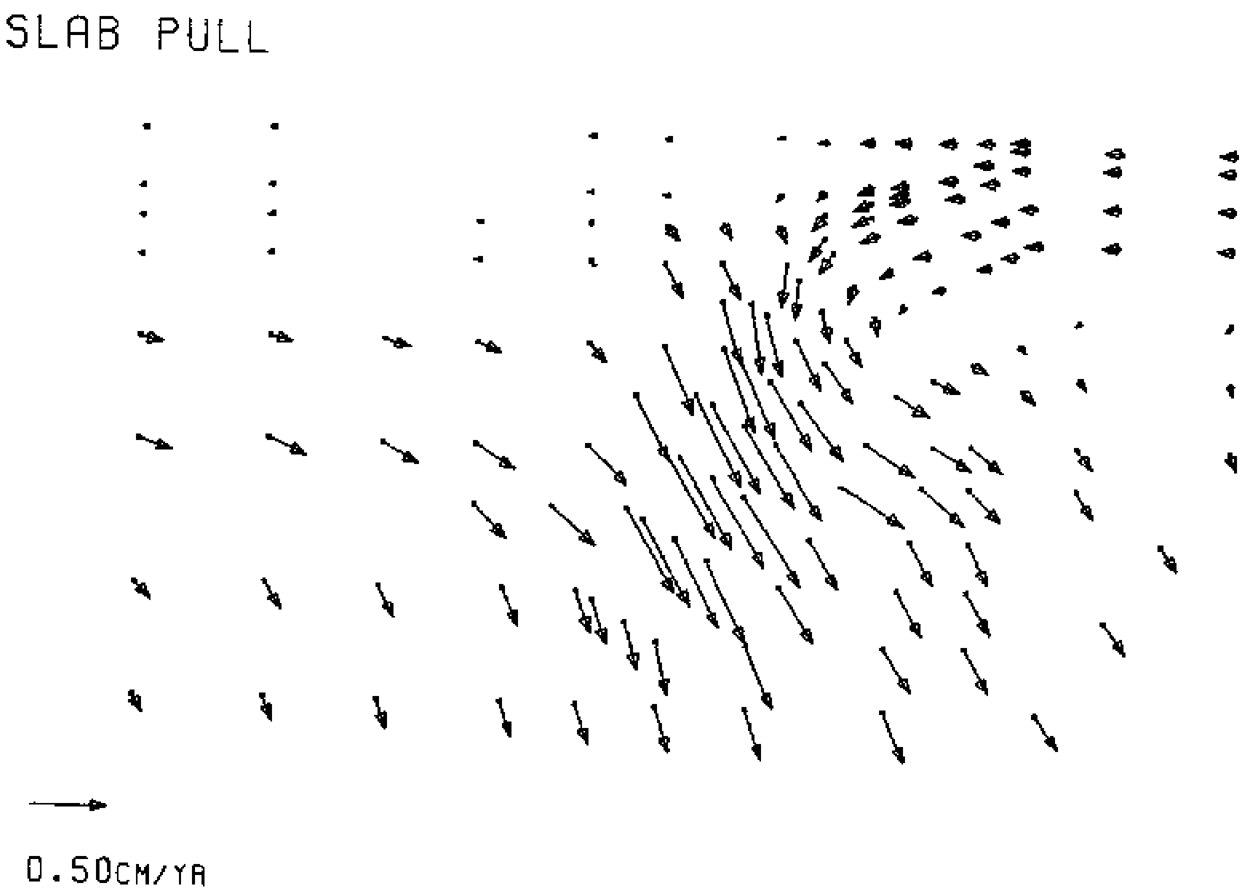


Fig 8(e)

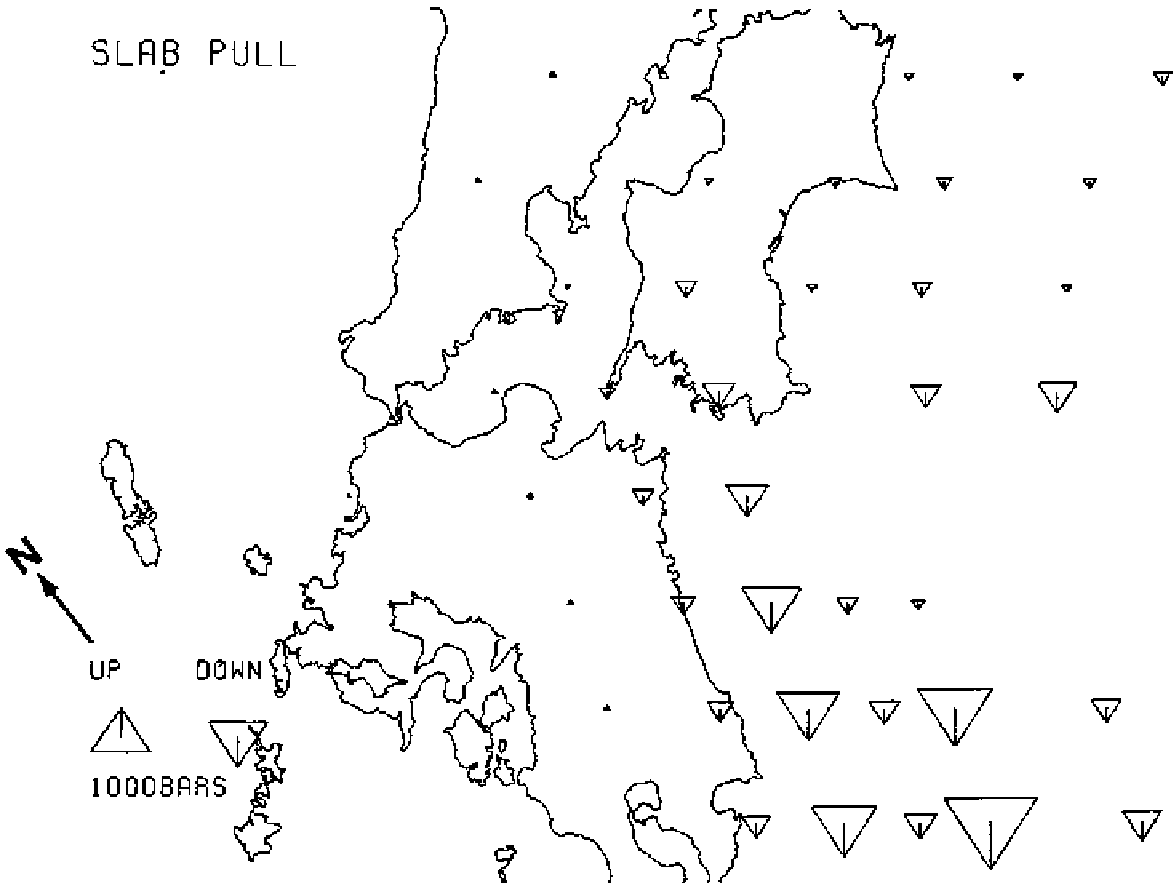


Fig. 9(a)

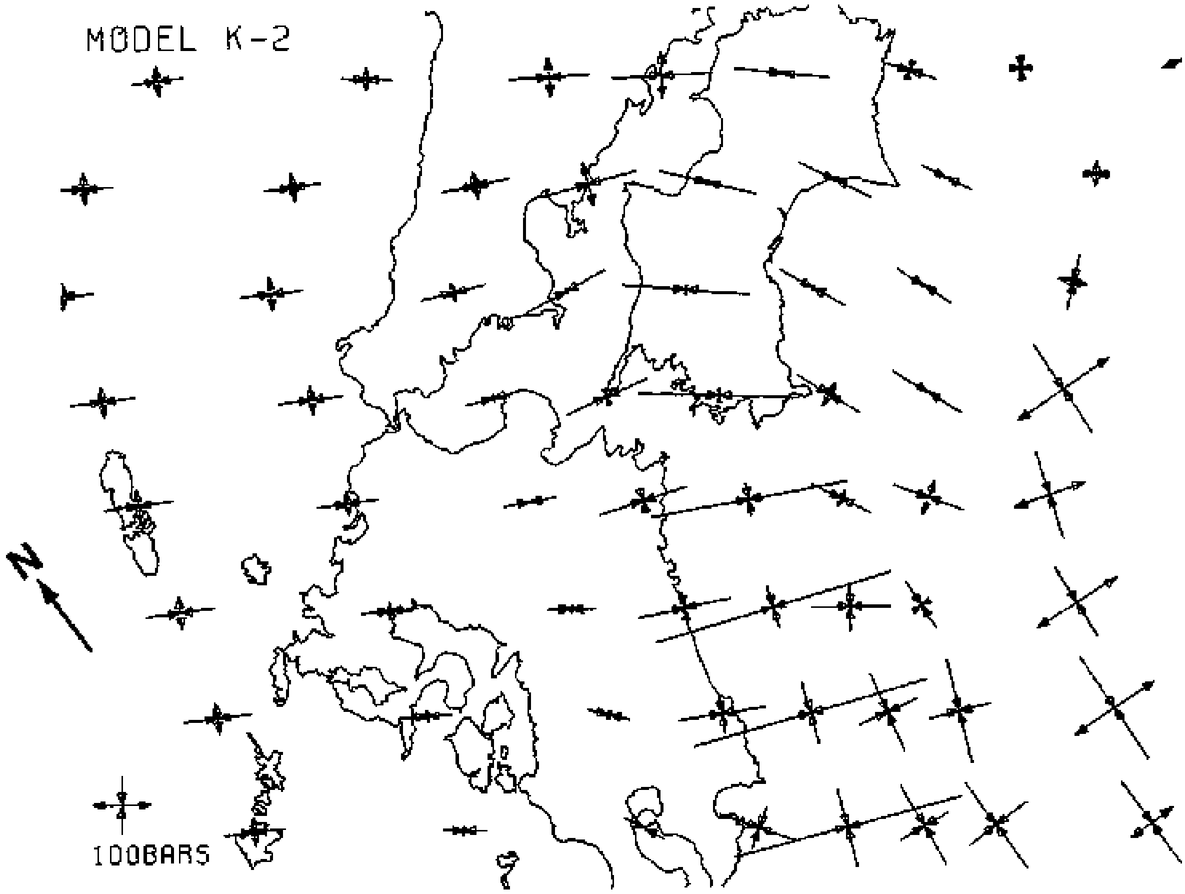


Fig. 9(b)

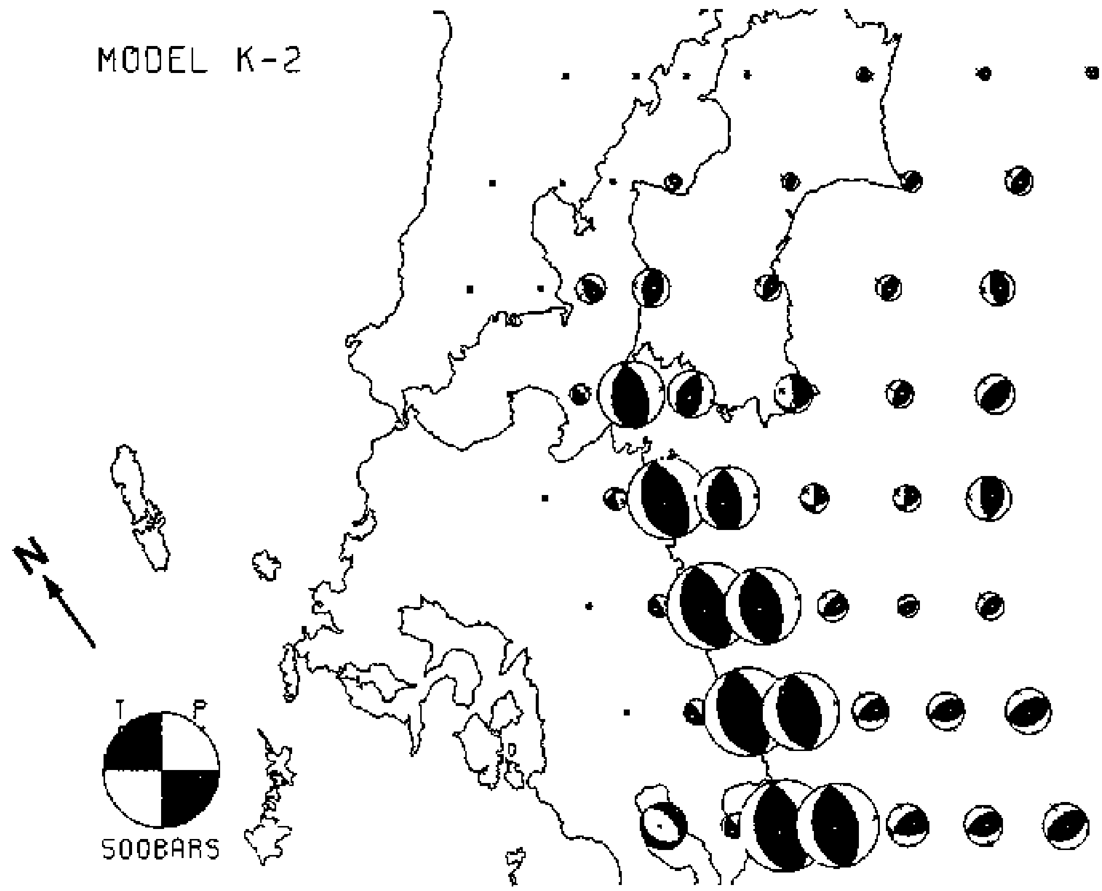


Fig. 9(c)

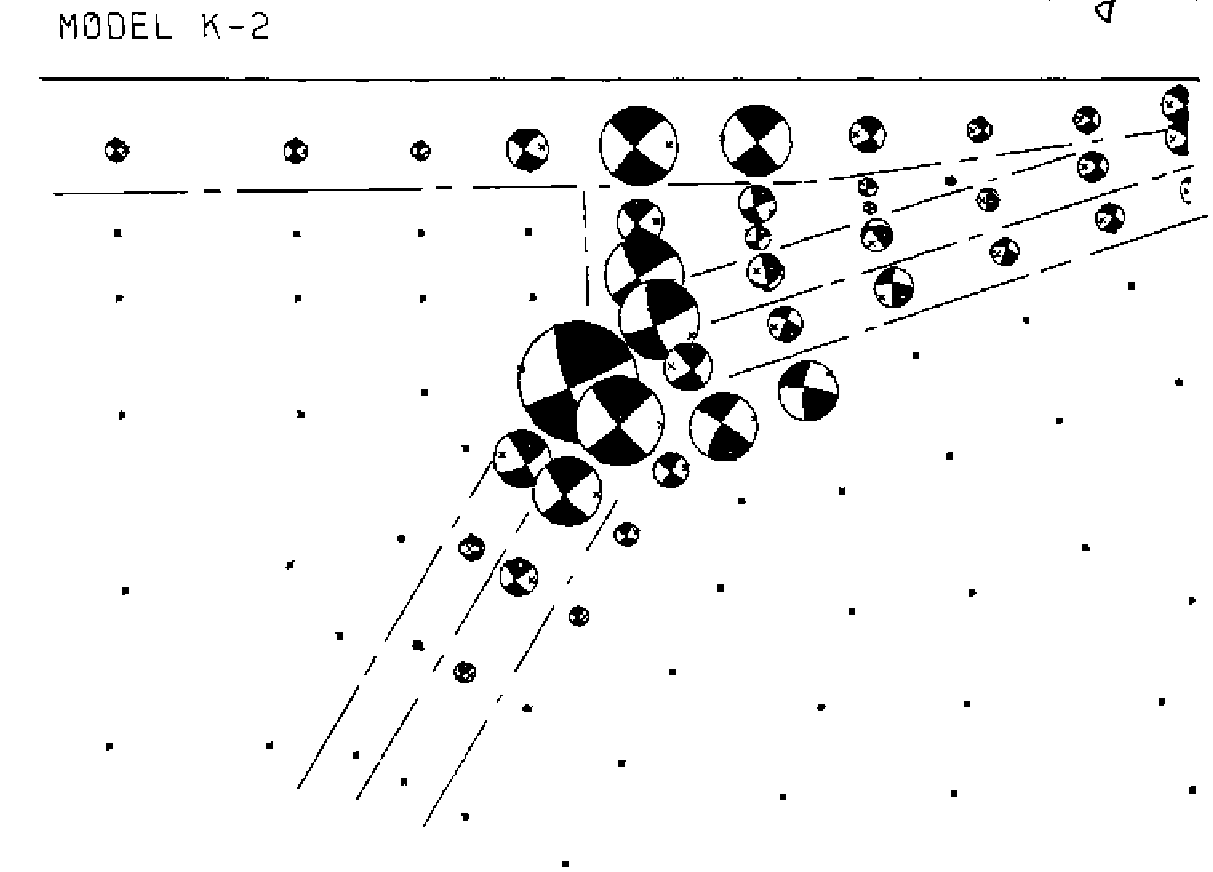


Fig 9(d)

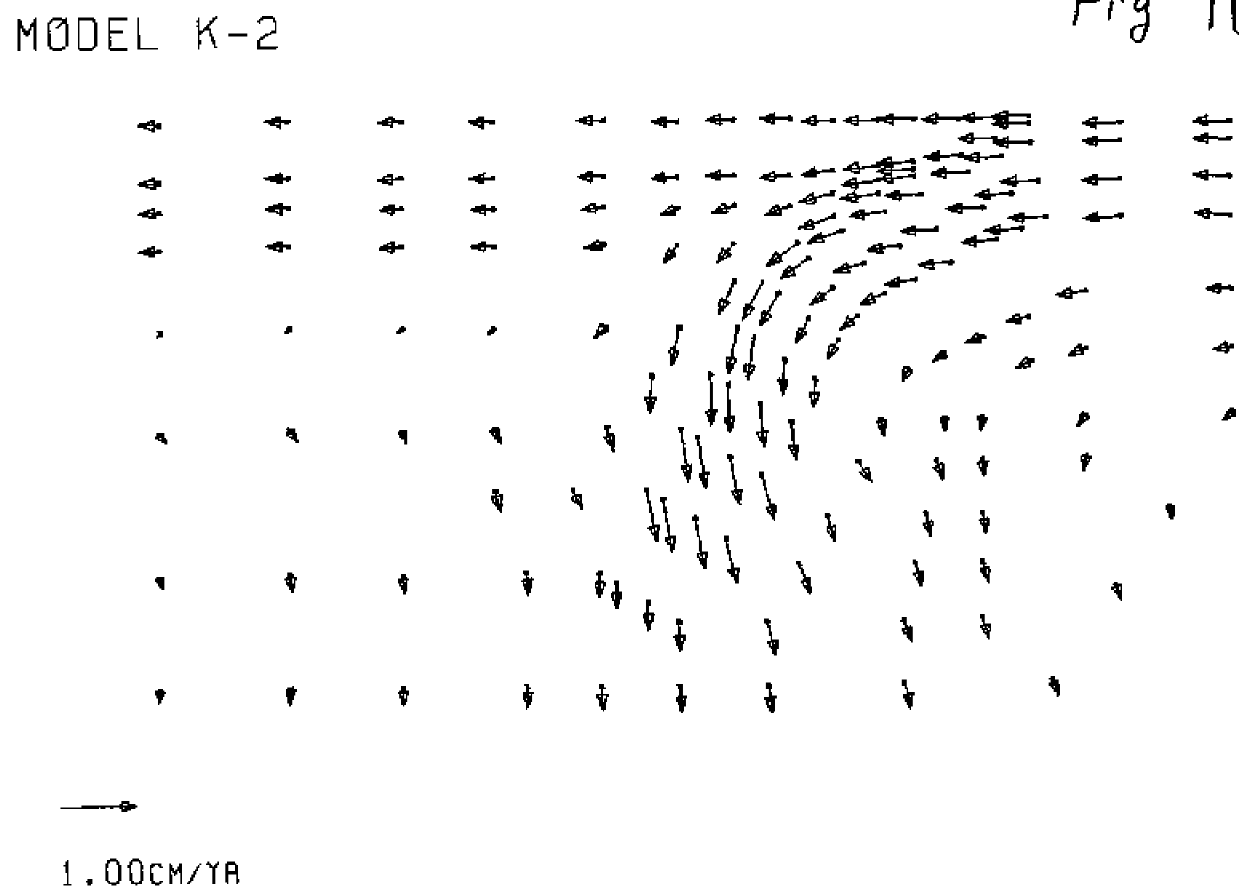


Fig. 9(e)

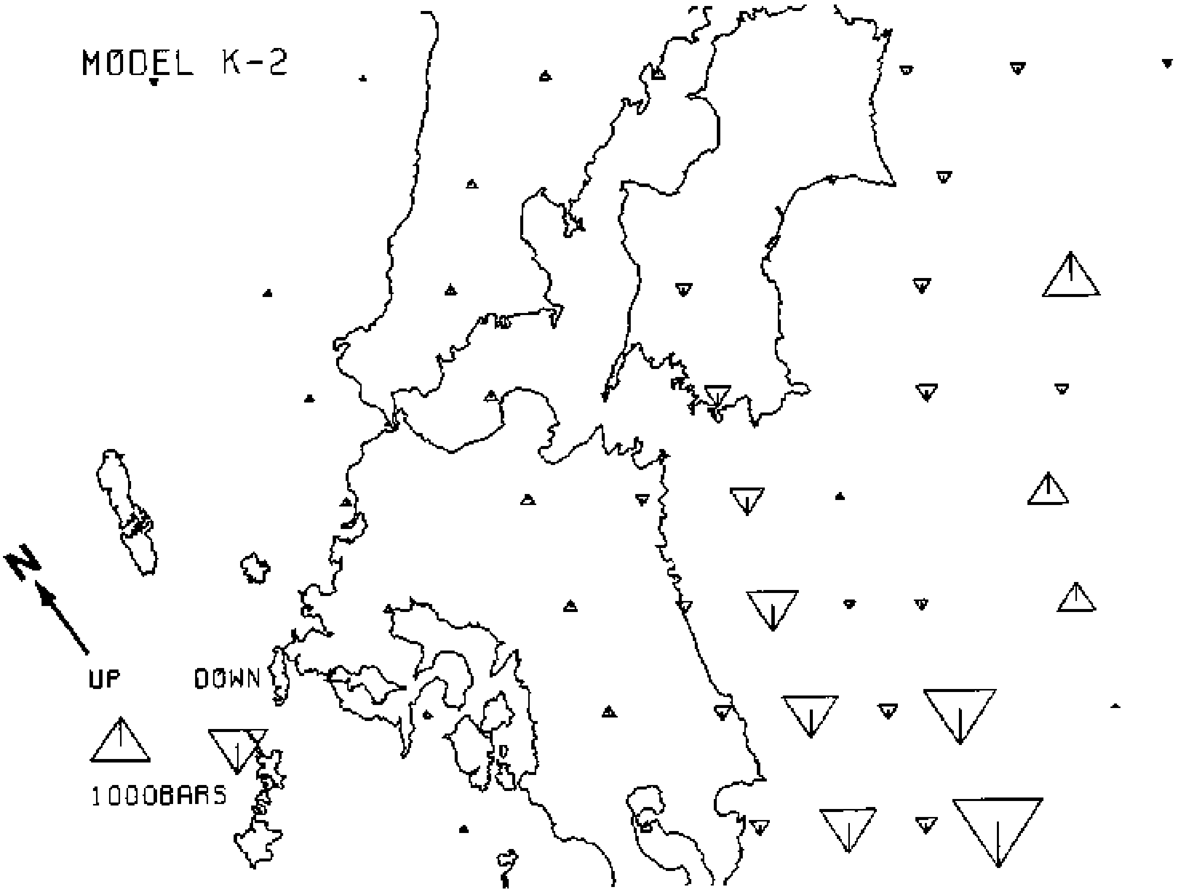


Fig. 10(a)

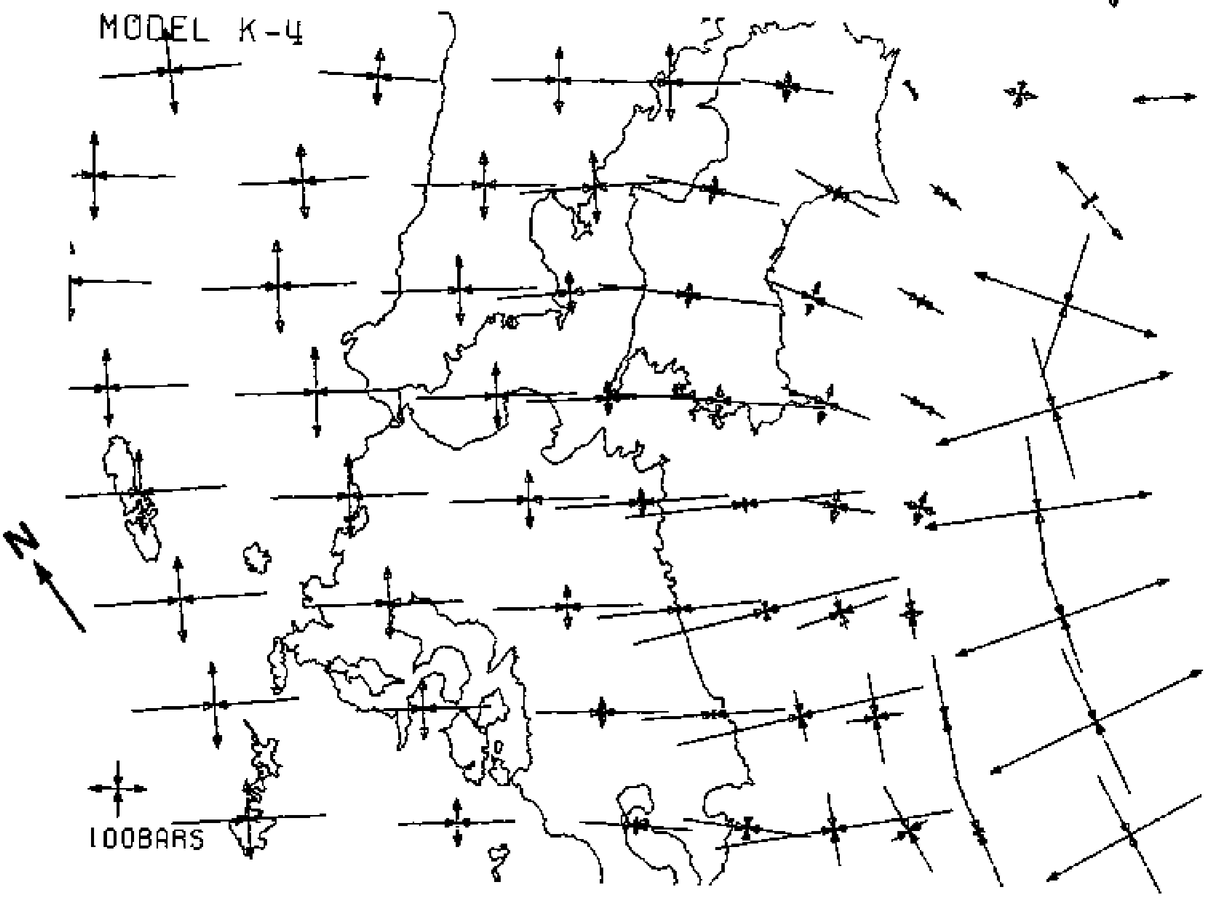


Fig. 10(b)

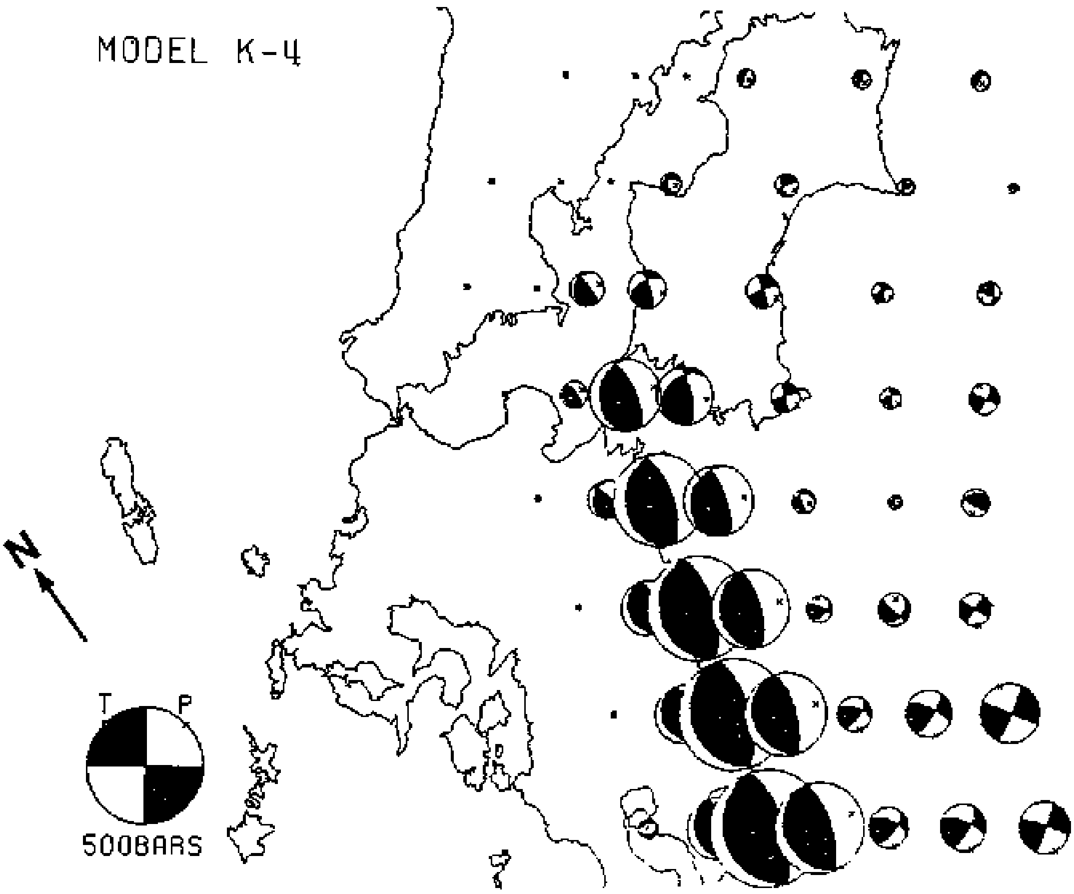


Fig. 10(c)

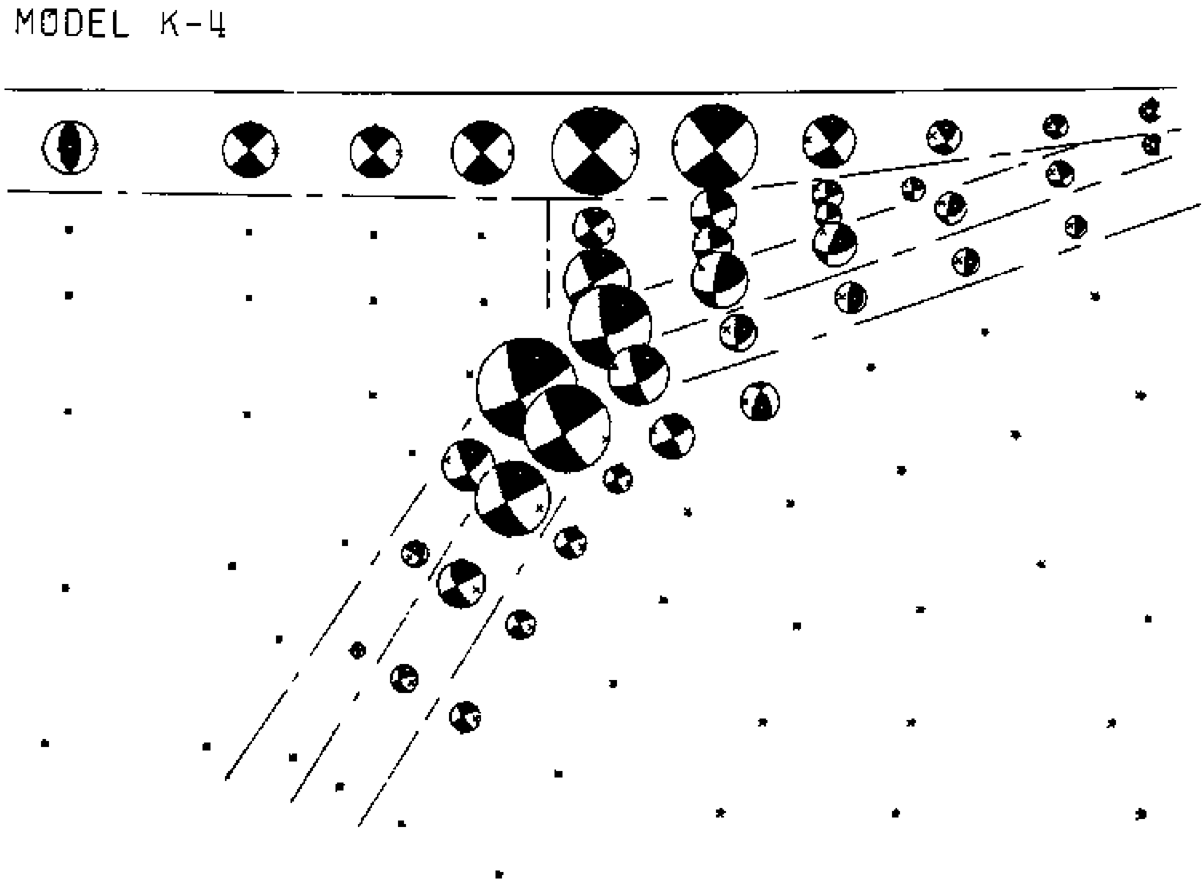


Fig 10(d)

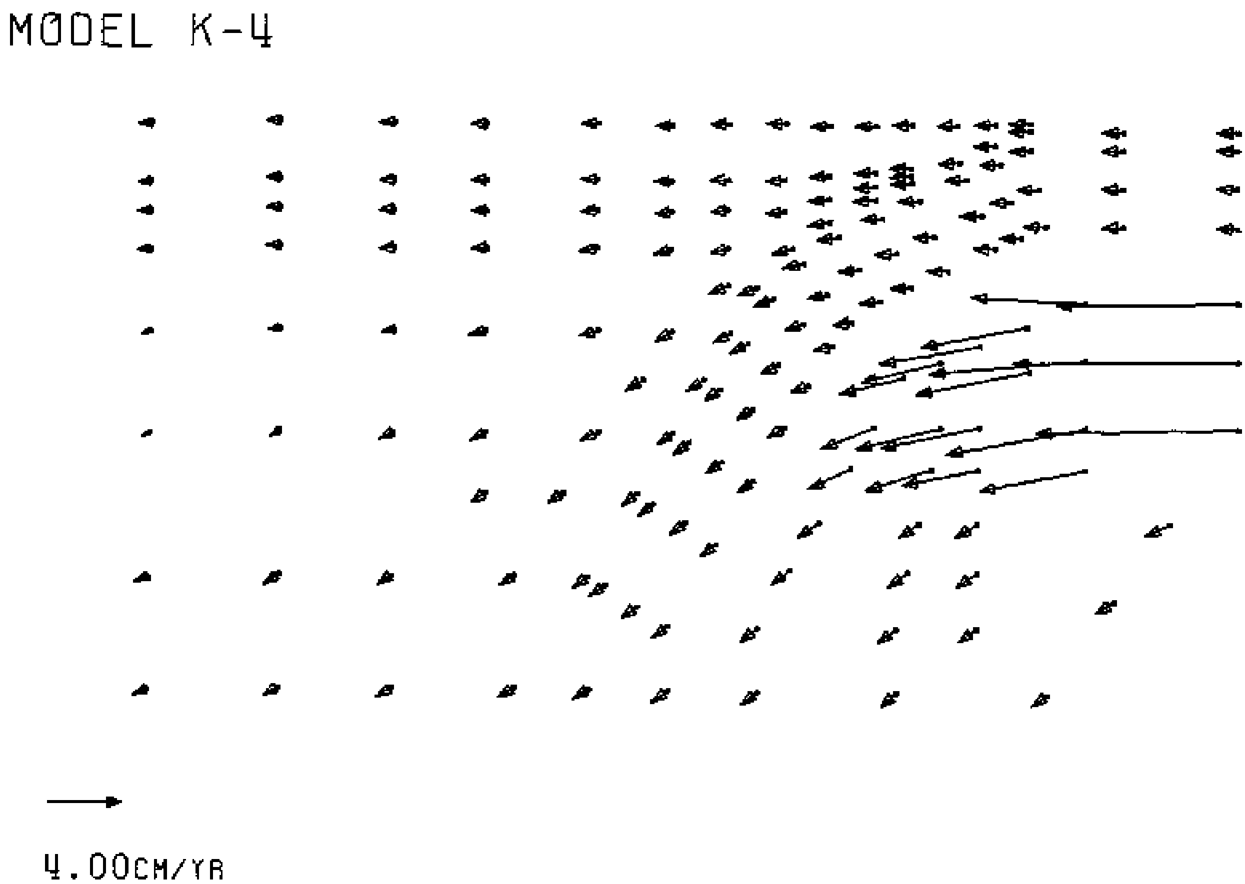


Fig 10(e)

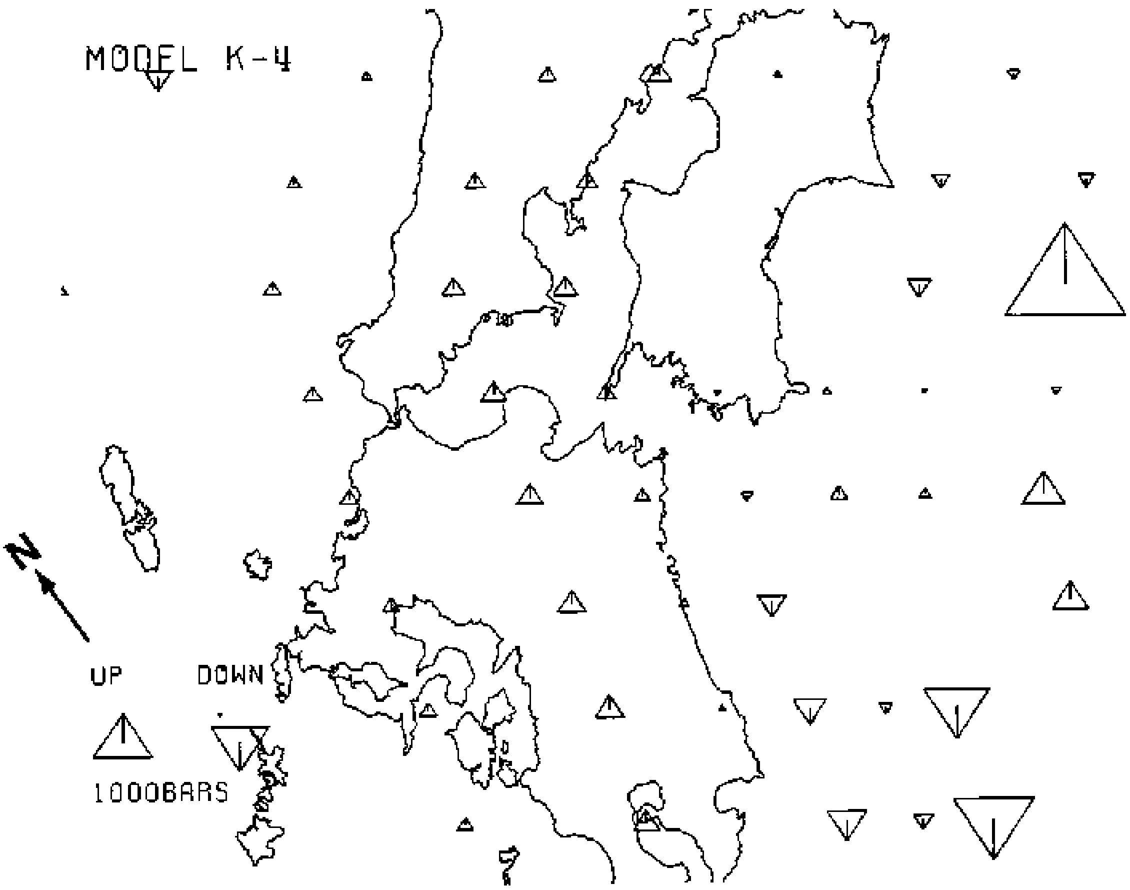


Fig. 11(a)

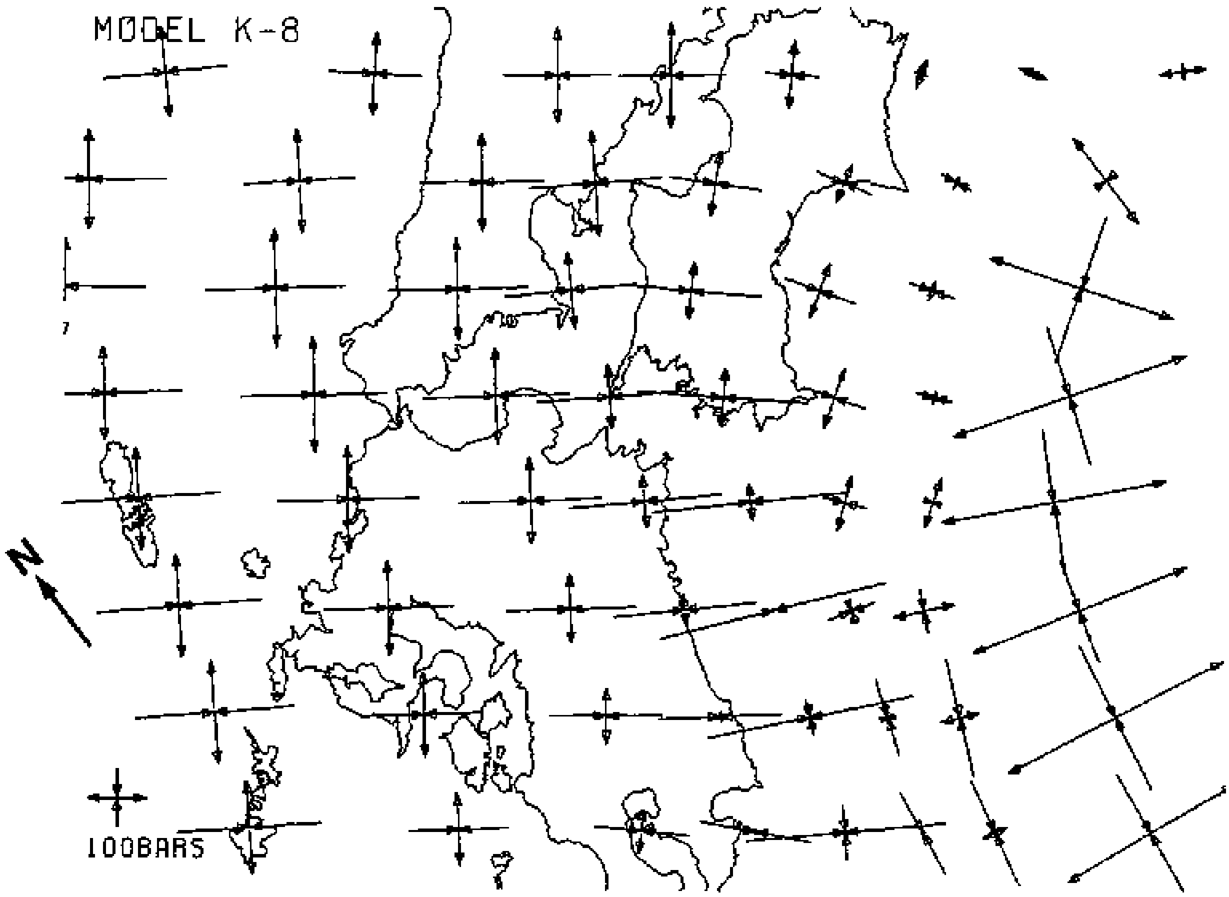


Fig. 11(b)

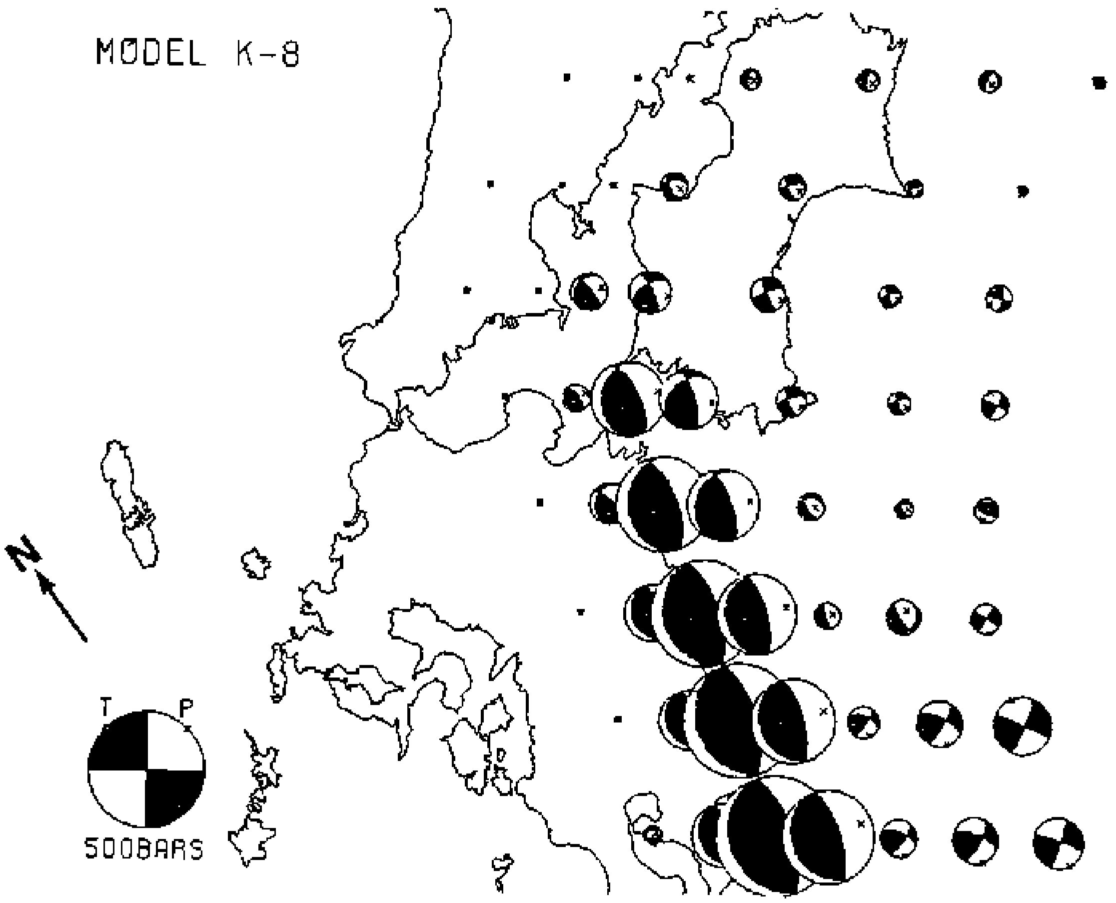


Fig. 11(c)

MODEL K-8

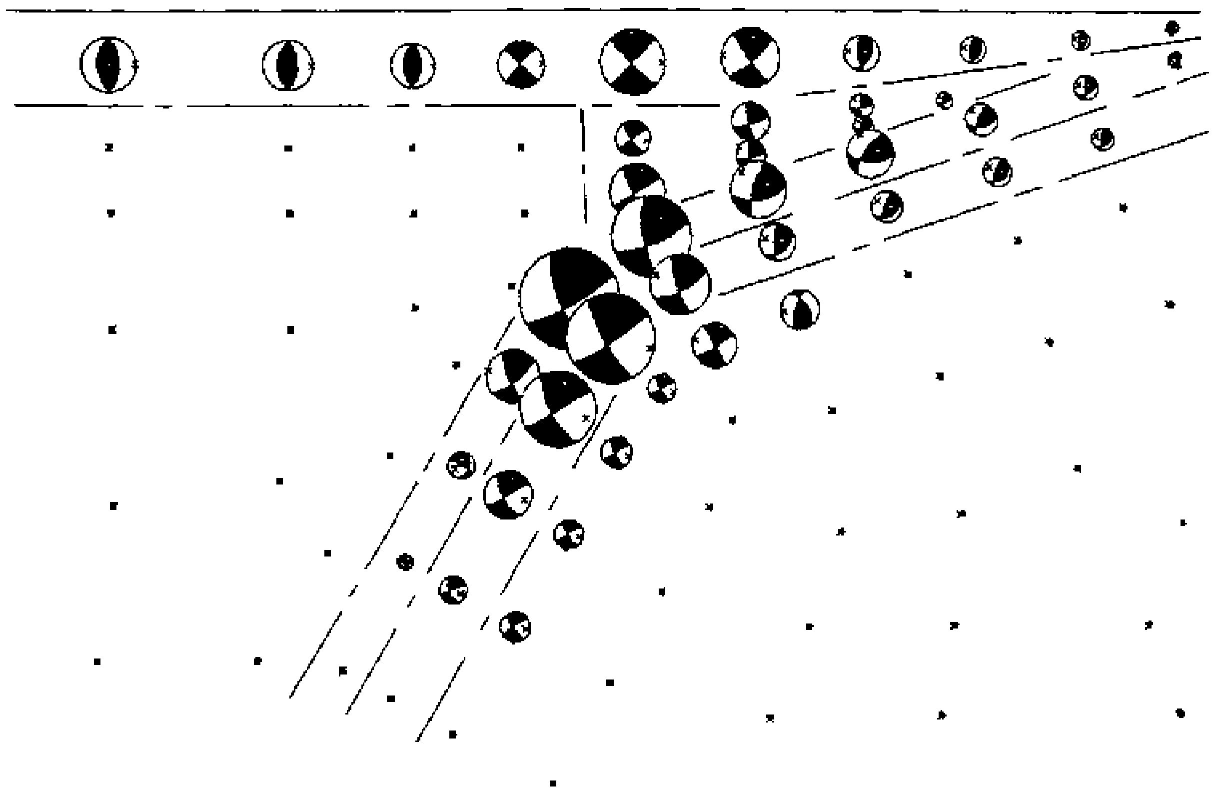


Fig. 11(d)

MODEL K-8

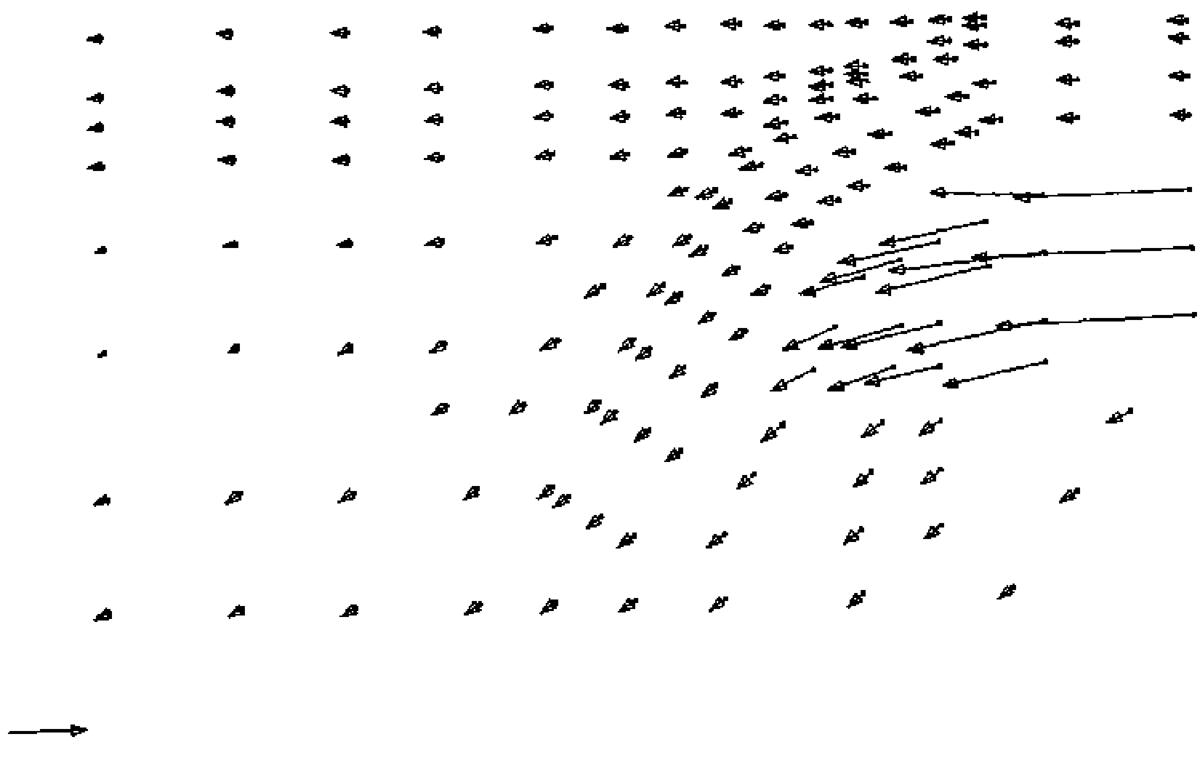


Fig. 11(e)

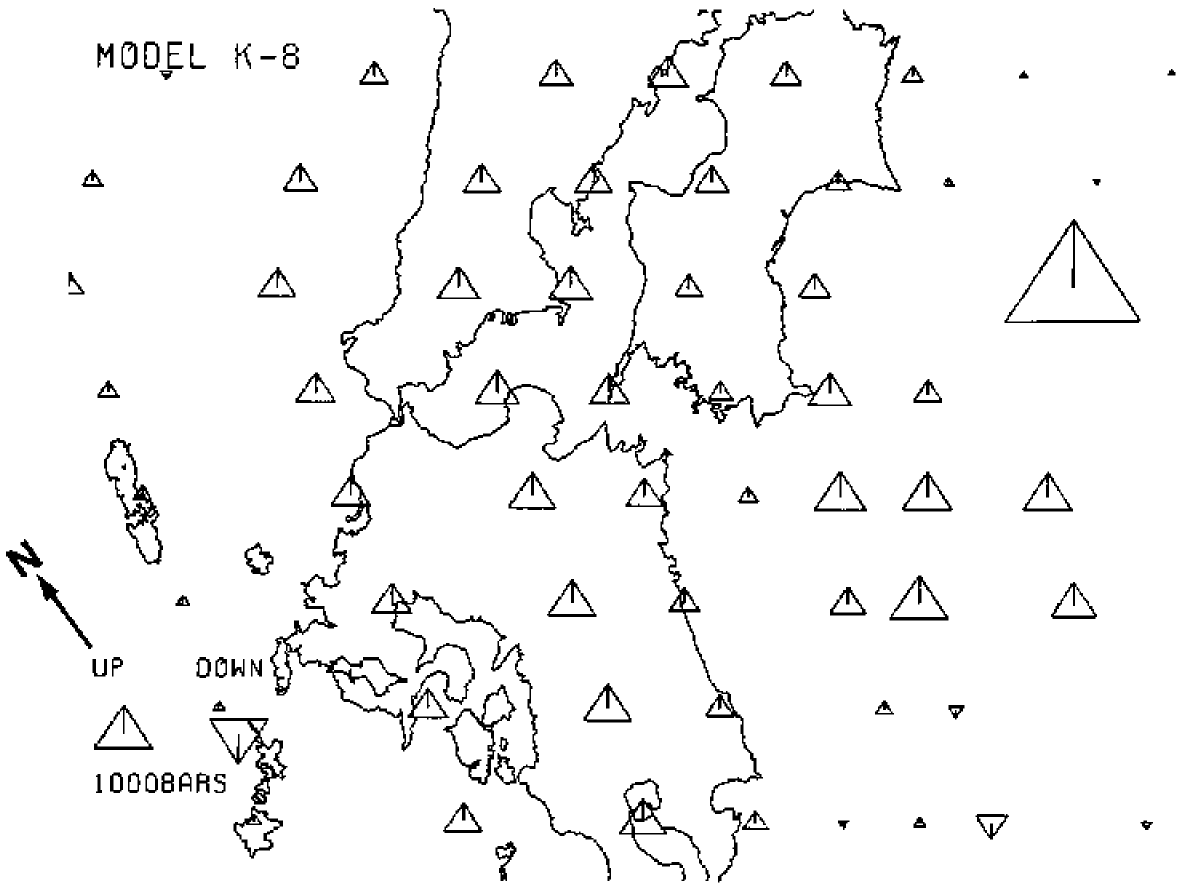


Fig. 12(a)

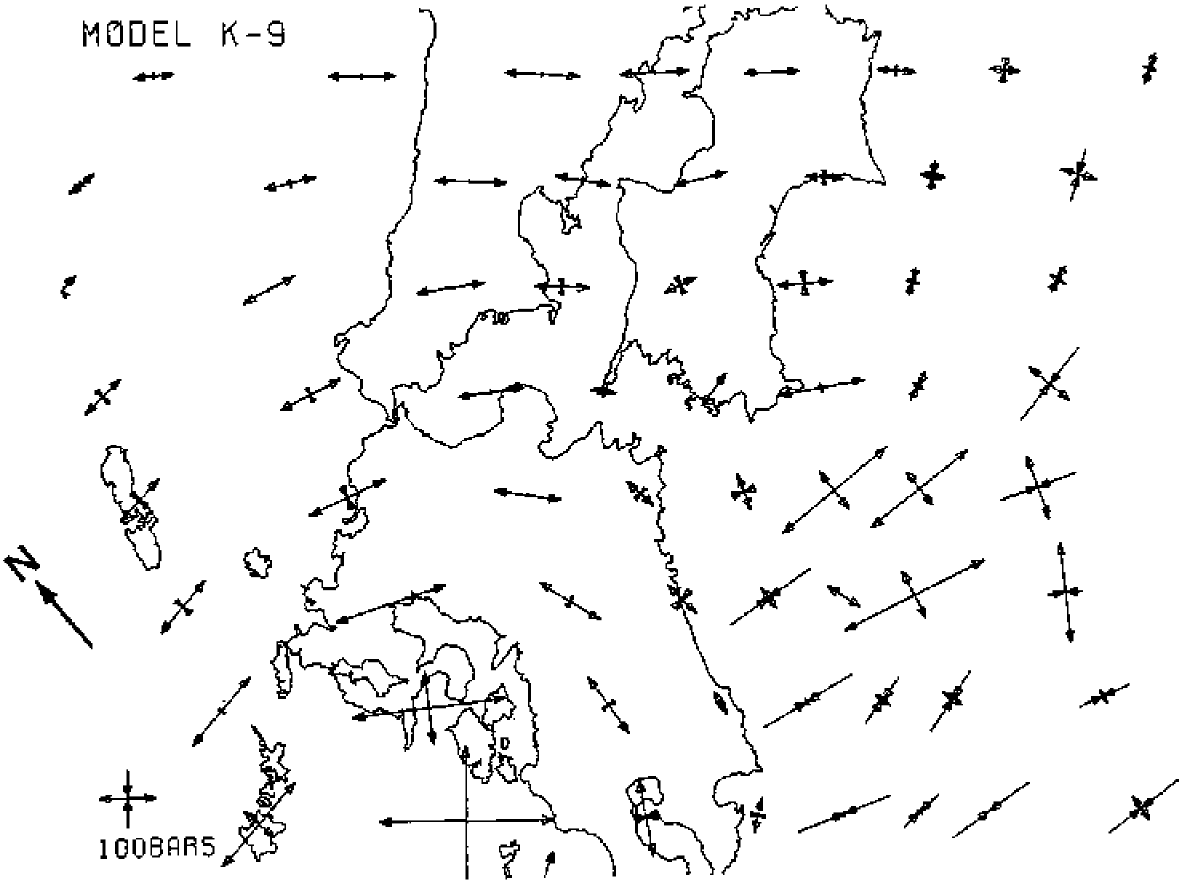


Fig. 12(b)

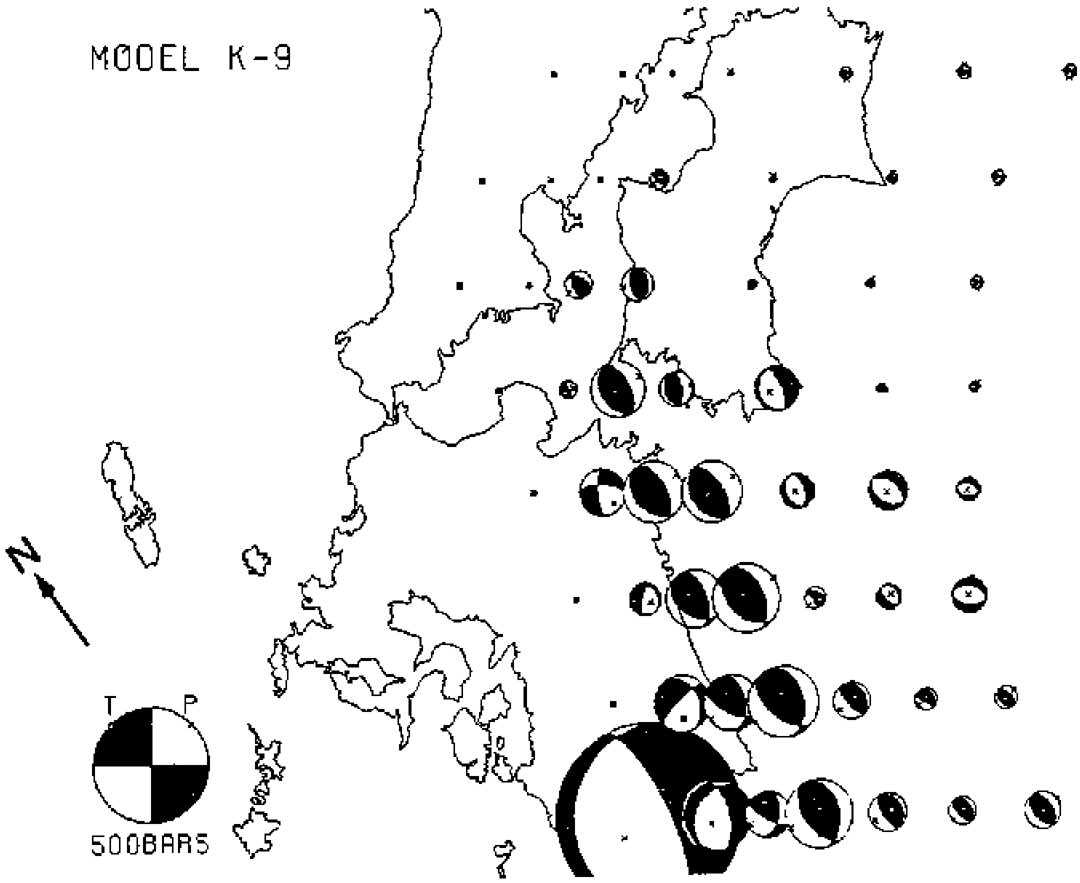


Fig. 12(c)

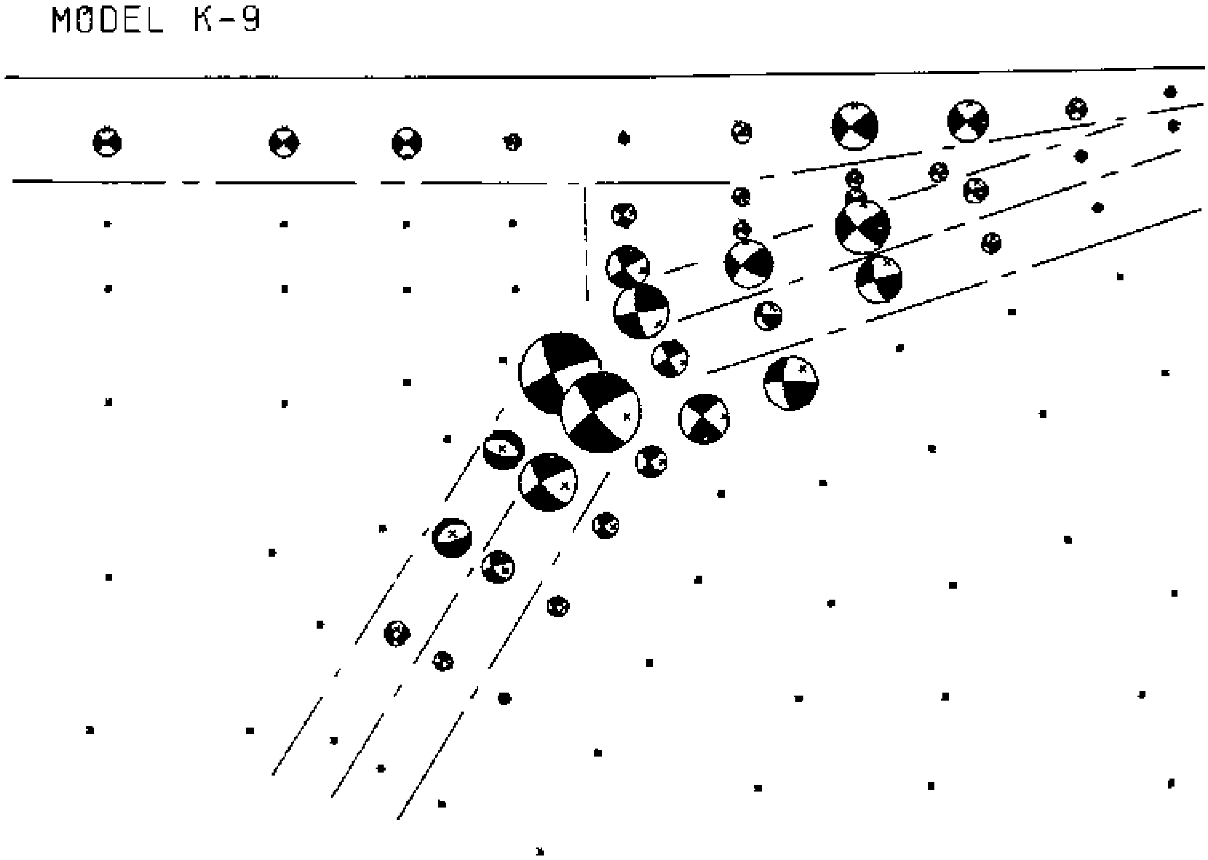


Fig. 12(d)

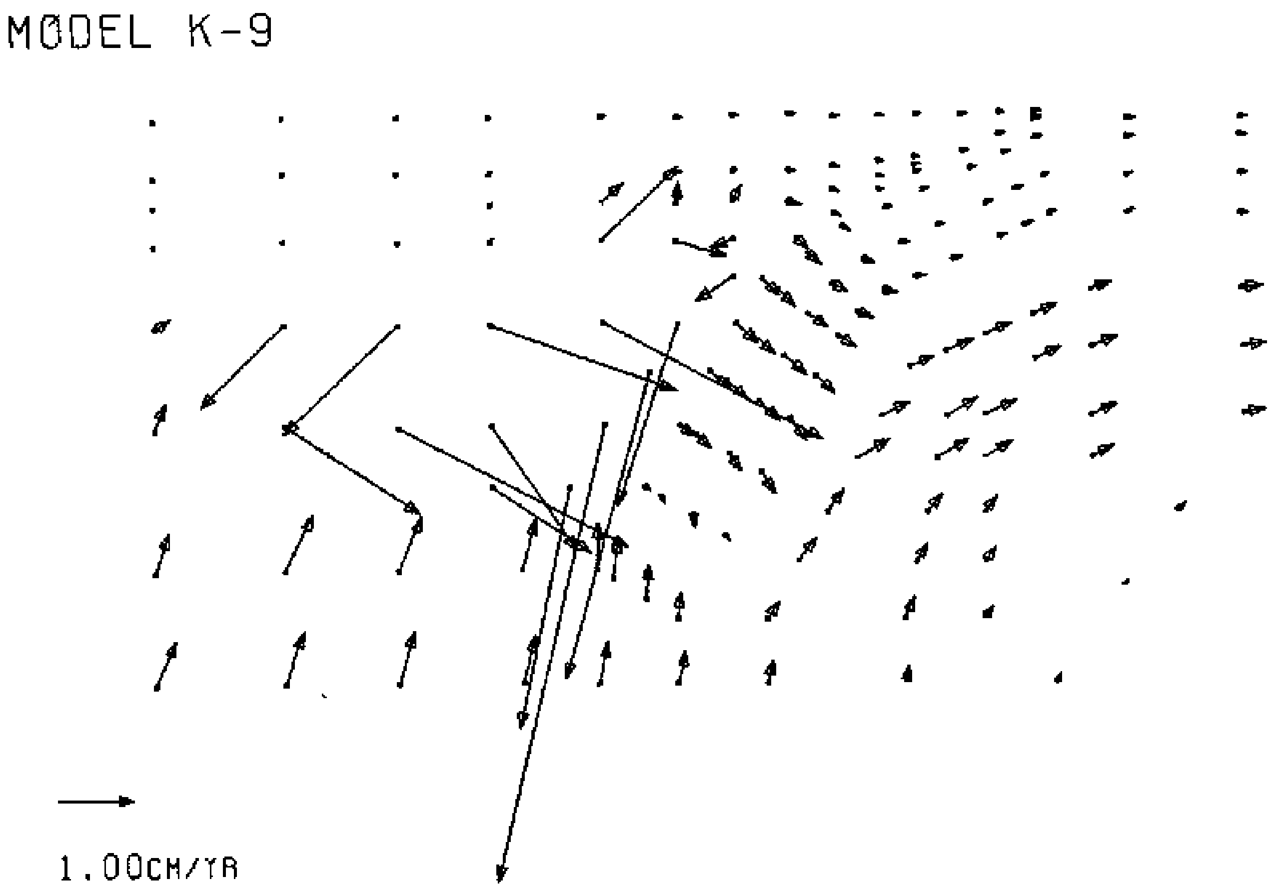


Fig. 12(e)

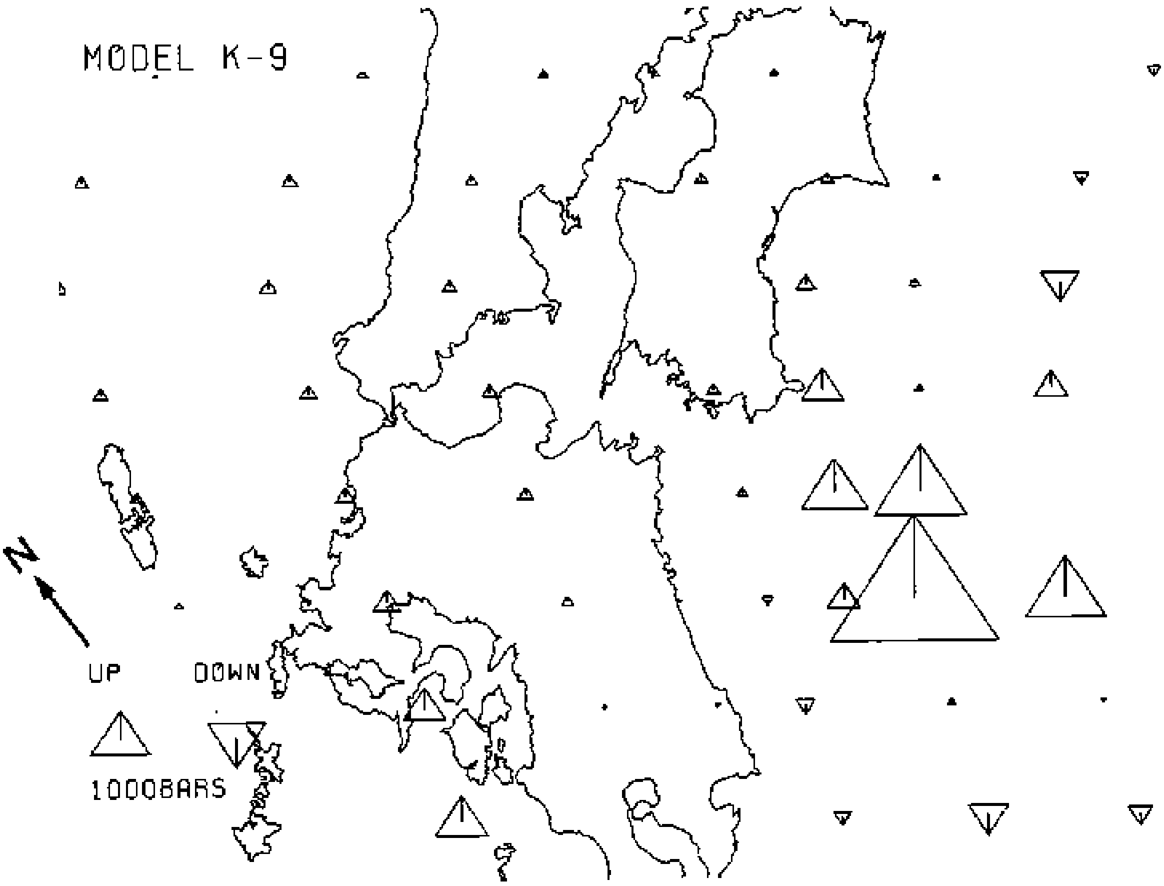


Fig. 13(a)

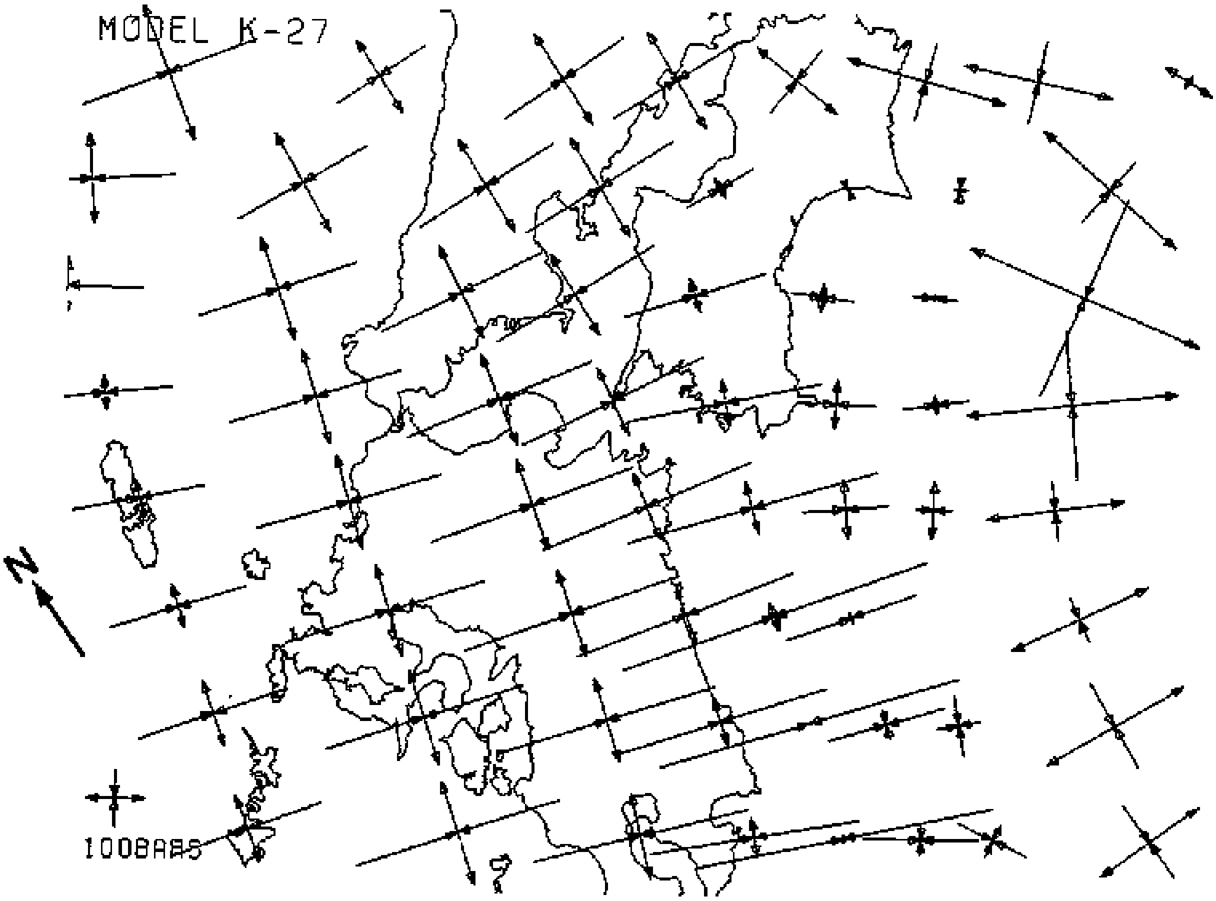


Fig. 13(b)

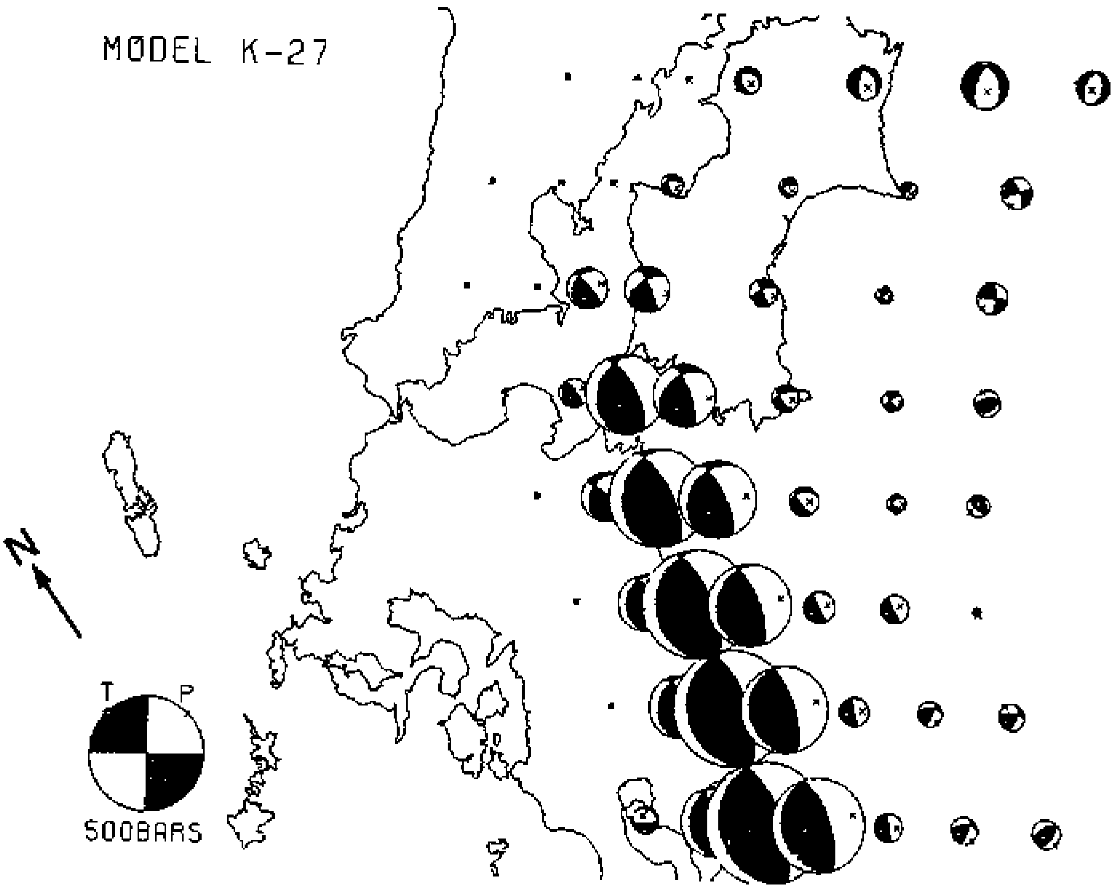


Fig. 13(c)

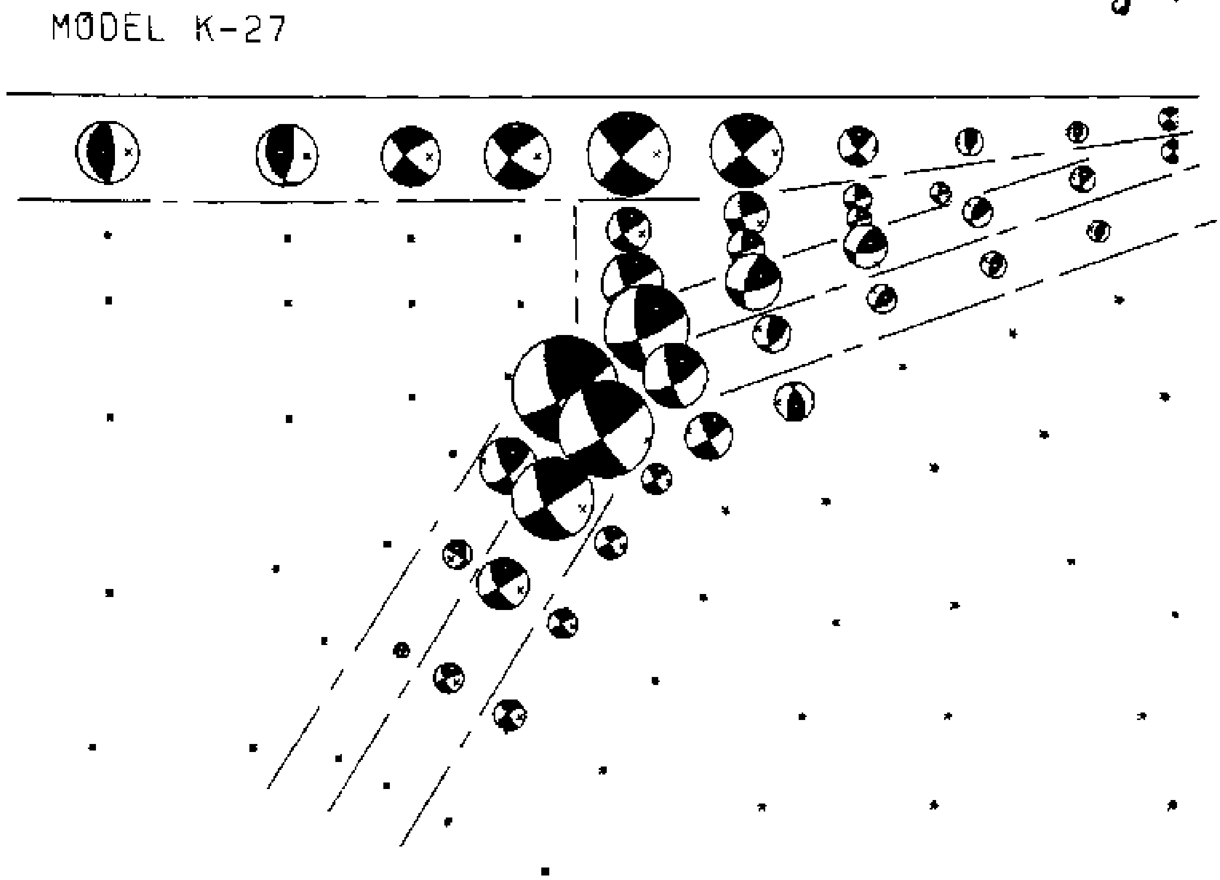


Fig. 13(d)

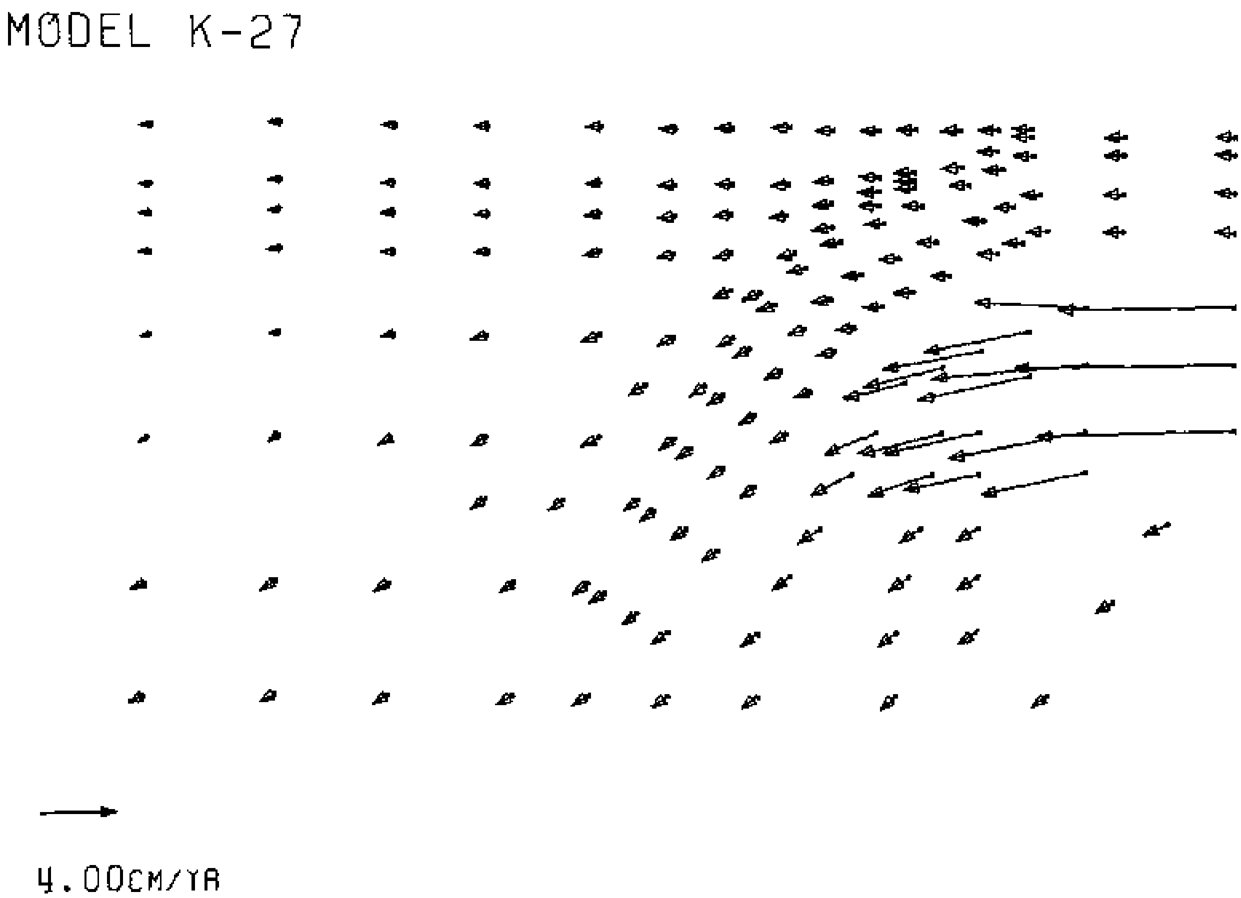


Fig. 13(e)