The Pliocene Stress Field and Tectonism in the Shin-Etsu Region, Central Japan

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(with 13 Figures)

1. Introduction

The stress state within the earth's crust is in general determined by gravitational stress due to the weight of overburden and tectonic stress related to the straining of the crust due to external forces (Ranalli, 1975). Regional geologic structures are controlled by the regional stress field covering the area, thus it is possible to consider the stress state from the characteristics of the tectonics of that province. The present paper describes the Pliocene tectonic stress state of the northern part of a large and important tectonic zone, the Fossa Magna, crossing the central part of Japan, from a geological point of view (Fig. 1). For this purpose, it is very important to know the relationships between the block movements of the basement rocks directly affected by the crustal tectonic stress state and the superficial folding structures of the covering layers. A discussion of this problem is also undertaken.

Fig. 1 Index Map: Enclosed area and dotted parts indicate the Shin-Etsu Region and alluvial plains and basins, respectively.
The recent tectonic stress field can be determined by various techniques; focal mechanism solutions of earthquakes, geodetic surveys of the crustal deformation and in-situ measurements of rock-stress, etc. Such methods are useful in estimating recent stress conditions, but it is difficult to know how old these conditions are. The stress field during earlier geologic times should be constructed by the geomorphological and geological methods. The former is very useful in Japan for Quaternary problems, but is not so for the Tertiary or even the Pliocene because Quaternary crustal movements have been very severe here. To discuss the Tertiary stress field, the distribution of dikes, faults and folds are very useful. Thus, in the study of the history of stress change, it is considered important to draw kinematic pictures of the development process of tectonics.

Summary of the arguments mentioned above is schematically represented as follows:

2. General Trend of Dikes and Tectonic Stress Fields

NAKAMURA (1977) proposed a method for determining stress state using dike distribution, called the "dike method", which has been applied in this study. The dike method is based on the recognition of the preferred orientation of radial and parallel dike swarms as a result of large-scale magma fracturing.

Considering that dikes are formed in tension fractures of the earth's crust, they have a tendency to develop in a direction normal to the minimum principal axis of compression. Moreover, the general trend of dike swarms can be interpreted to show the orientation of the maximum horizontal compressive axis of the region because dikes intrude almost vertically.

The orientation of tectonic stress which has existed in recent geological times in the upper crust of volcanic regions can be identified from such volcanic features as the distribution of flank craters indicating the trend of the underground, radial, dike swarm (NAKAMURA et al., 1977).

The orientation of tectonic stress determined by the dike method is generally consistent to the results obtained using other well-known methods of estimating the recent state of crustal stress, such as the focal mechanism solutions of earthquakes, geodetic measurements of crustal deformation and in-situ measurements of stress, and studies of active faults and folds. Among techniques for studying the past state of regional stress in
the upper crust, analyses of faults and folds of various scale is useful, as well as is the dike method. However, the dike method is superior to other methods for dating purpose as well.

Compilations of tectonic stress orientation in Japan based on the available data using various techniques have been presented by ANDO et al. (1973), NAKAMURA & UI (1975) and HUZITA & OTA (1977). Fig. 2 is a stress trajectory map showing a horizontal stress field, which has been compiled with the addition of new data (SHIONO, 1977). With the exception of the southern part of Central Japan, the Kanto region, stress trajectories of maximum compression are slightly curved but linear and, as a whole, in the direction of east-west trend. Such stress states suggesting east-west horizontal compression is attributable to the subduction of the Pacific Plate along the Japan Trench (MATSUDA, 1977).

![Stress trajectory map of the recent stress field in Japan](image)

Fig. 2 Stress trajectory map of the recent stress field in Japan, compiled from ANDO et al. (1973), NAKAMURA & UI (1975), HUZITA & OTA (1977) and SHIONO (1977). In the southern part of Central Japan, these trajectories show a radial pattern radiating from the northern part of the Izu Peninsula.

1; trajectories of maximum horizontal stress (compressive), deduced from seismic waves (2), active faults (3) and dikes (4). Arrows: directions of oceanic plate movements.

3. Pliocene Stress Field Inferred from Dikes

An attempt was made to determine the Pliocene stress field in the Shin-Etsu Region in the central part of Honshu Island, using Pliocene dikes, the intrusion of which have close connection with the volcanism of the Nishi-Yama stage mainly distributed in the central part of the sedimentary basin (CHIHARA, 1974; SHIMAZU et al., 1977). The Kakkadasan (101), Yoneyama (102) and Arakurayama (103) areas are examined for this purpose (Figs. 3 and 4). Brief descriptions of these three areas are as follows:
Fig. 3 Dominant dike-directions of the Pliocene and Pleistocene in the northern part of Central Japan.
101, 102 and 103 are the symbol numbers of the Pliocene dikes, and correspond to those in Fig. 4. Pleistocene dikes are referred to by Nakamura & Ut (1975).

Fig. 4 Rose-diagrams showing azimuthal distribution of Pliocene andesite dikes in the Shin-Etsu Region. The total number (and dominant direction) of each dike swarm is 30 (N85°E), 33 (N75°W) and 20 (N60°W), respectively.

101. Kakudasan Area
The Kakuda Mountainland composed of the Kakuda Formation (Shirai et al., 1976) is rich in various kinds of effusive and intrusive andesite rocks which partially have pillow structures. The volcaniclastic rocks are interfingered with mudstone and sandstone alternations of the latest Miocene (later Shiiya stage) and the Pliocene (Nishiyama stage). The effusives are distributed in the core of an anticlinal axis trending north to south. Dikes of andesite are developed in the west side of the Kakuda Mountainland and show a dominant direction of N85°E. The number of dikes is 30 in all.

102. Yoneyama Area
The Pliocene volcaniclastic rocks of the Yoneyama Formation lie unconformably on
the Middle Miocene mudstones which are folded with the axes trending north to south (YONEYAMA RESEARCH GROUP, 1976). The volcanism of this district started at the end of the Late Miocene and continued until Pleistocene, and products composed of olivine-, pyroxine- and hornblende-andesite have cyclically accumulated (CHIHARA, 1974). Intrusive rocks show dotty distribution. There is a total of 33 dikes in this province, all of which have been examined and found to have an average strike of N75°W.

103. Arakurayama Area

Pyroclastics and lavas called Togakushi or Arakurayama Volcanics are intercalated with the mudstones and sandstones of the Plio- and Pleistocene formations (TAKEISHITA, 1974). They are part of the folded structures of the Hikage and Orihashi Synclines. Dikes distributed in this area petrographically consist mostly of calc-alkalic andesites and high-alumina tholeiitic rocks, so-called basalts (TAKEISHITA, 1975). 20 dikes were examined and their dominant direction was found to be N60°W.

Considering that dikes are dilated cracks or fractures filled by magma, the stress field existing during the main volcanism in each province was found to be as follows: The directions of the maximum horizontal compression was N85°E in the Kakuda Area (101), N75°W in the Yoneyama Area (102) and N60°W in the Arakurayama Area (103).

As for the northern part of the Fossa Magna region, the Pliocene stress field shown by dikes are for the most part consistent with that deduced from the distribution of folds (KOMATSU, 1967) and faults (TAKEUCHI, 1977). Moreover, it is significant that in the Pleistocene stress field in this region can be traced back to the Pliocene by means of the preferred orientation of dikes.

Fig. 5 Stress trajectory map of Pleistocene~Recent stress field in the Shin-Etsu Region. Stress directions obtained from seismic waves and active faults are quoted from ANDO et al. (1973) and HUZITA & OTA (1977). Pleistocene~Recent stress field in this region can be traced back to the Pliocene by means of the preferred orientation of dikes.
Shin-Etsu Region the directions of maximum ($SH_{max}$) and the minimum horizontal compression ($SH_{min}$) are nearly the same as those of the recent stress field (Fig. 5). Such results suggest that the recent regional tectonic stress state which has principal axes of $SH_{max}$ in the east-west trend and $SH_{min}$ in the north-south trend had already appeared at the end of Late Miocene and has continued through the Plio- and Pleistocene.

4. Stress History and Structural Development

4-1. Neogene Stress History

The orientation of the tectonic stress field during the Miocene in the southern part of Northeast Honshu has already been examined on the basis of the dike method. According to the analytical results of Hori & Takeuchi (1977), the axes of the “principal” stress $SH_{max}$ and $SH_{min}$ have been found to be the north to south and east to west trends, respectively, in the Inner Belt of Northeast Honshu, including the Shin-Etsu Region, through the Miocene (Fig. 6). However, the direction of $SH_{max}$ and $SH_{min}$ changed abruptly in the latest Miocene. The change of tectonic stress field from the E-W tensional state to the E-W compressional one is well expressed in tectonism (Takeuchi, 1977).

4-2. Tectonic Development in the Neogene

The tectonic history of the Shin-Etsu Region is summarized below, making reference

Fig. 6  Orientation of the Miocene stress field estimated from dikes (Hori & Takeuchi, 1977; with the addition of new data by courtesy of Mr. K. Mizuguchi)
to the results of IKEBE et al. (1972), MORITA et al. (1973), TAKESHITA (1974), TAKEUCHI (1977) and SHIMAZU et al. (1977).

The Shin-Etsu Region had been a sedimentary basin in the southwestern part of the Inner Belt of Northeast Japan, where the thick Neogene sediments have moderately folded to form one of the most productive oil-fields in Japan. Since intensive deep drilling and geophysical surveys have been carried out for the purpose of oil prospecting, the subsurface structures have recently become remarkably clear.

The basement complex of the basin consists of Paleozoic and Mesozoic sediments and pre-Tertiary granitic rocks. The Neogene “Green Tuff Region” originated as grabens bounded by faults, which obliquely cut the old structures formed in the Cretaceous. “Green Tuff” was abundantly erupted in these grabens of the northern and southern parts of the Shin-Etsu Region during the Early Miocene.

Almost whole areas of the region were covered by sea and thick mudstone deposited during the maximum transgression. Submarine eruptions of alkali basalts took place along the margin of the sedimentary basin. Besides, volcanic activity was high in the Tsugawa-Aizu province and in the eastern part of the region, being characterized by bimodal volcanism of rhyolites and basalts. In the northern Fossa Magna, volcanic activity was vigorous, and quartz-diorites intruded within the “Central Belt.” In the Late Miocene, the activity of dacite occurred along the margin of the Central Belt of Upheaval.

Accompanied by differential subsidence due to block faulting of the geological basement, differentiation of the sedimentary basin which became shallower and narrower started in the late Middle Miocene.

At the end of the Late Miocene, a significant change in sedimentary structures and volcanic activity occurred. Starting in the Pliocene (Nishiyama stage), the paleocurrent system began to be controlled by the structural trend called to “Niigata trend.” In other words, folding of the oil-Tertiary is considered to have begun to increase after the latest Miocene (Shiiya stage). Since the Pliocene, volcanic activity has been localized in space, but thick piles of calc-alkaline andesites were formed in the Yoneyama, Arakurayama and other areas. In the Early Pleistocene, volcanic activity of andesite took place in upheaved land areas along the margin of the Shin-Etsu Region.

Most of the deformations of the sedimentary covers were completed by severe tectonic movements which took place at the end of the Late Miocene and proceeded during and after the Pliocene. This tectonism was caused by block movements associated with reverse dip-slip faulting, which is due to the compressive stress resulting from a force acting oblique to the long axis of the “Green Tuff Region”.

4-3. Folding Process from the Viewpoint of Tectonic Stress

The characteristics of structural features and folding patterns developed in the Shin-Etsu oil-field are well shown in the structural profiles of KATAHIRA (1974) based on the detailed surveys and numerous drilling data for oil prospecting. These are summa-
rized briefly as follows:

One of the characteristics of the folding patterns in this oil field is the development of asymmetrical anticlines associated with thrusts along overturned limbs and wide synclinal structures among these anticlines. In most cases, the folding of covering Neogene layers is considered to be strongly affected by the westward tilting movements of the basement fault blocks, and most of the main anticlines occurred along the boundaries between tilted blocks. These basement blocks are inferred to have cylindrically curved, not simply vertical surfaces because they moved not only vertically but also rotationally.

Fig. 7 shows schematic models of the movements of basement fault blocks in two different states of tectonic stress (after Kitamura, 1963; Matsuda, 1977). In a tensile state, tilting blocks occur in the basement divided by normal faults. Considering the sedimentation of the overlying layers under the influences of tilting block movements of the basement, wedge-shaped strata might be formed, becoming thick tilting downwards of the hanging wall blocks (Fig. 7a). In an E-W compressional state, on the contrary, cylindrical faults of reverse dip-slip type are inferred to develop in the basement, so overlying sediments might become thicker in the direction of the downward tilt of the foot wall side of each fault block (Fig. 7b).

Some tectonic features such as followings should be noticed for successful configuration of the folding process: Typical examples of buckling folds can be found in the Matsudai district of the Niigata area (Uemura & Shimohata, 1972) and in midway up the Saigawa River in the Nagano area (Takeuchi & Sakamoto, 1976). Such folds are formed directly in the horizontal compressional states. Besides, in the Niitsu district, one of the main oil fields of the Niigata area, a typical bending fold can be seen as Niitsu Anticline, which is considered due to the pushing up of the tilting basement blocks (Collab. Research Group for Niitsu Anticline, 1976). Various styles of anticlinal structures developed in this region can be attributed to the differences in thickness of Neogene strata and/or depth of the basement blocks. The overlying layers having different thickness are expected to have behaved somewhat differently responding to block movements of the basement.

Above facts suggest followings. States of tectonic stress are not always continuous nor uniform between the basement and the sedimentary cover. It is the basement rocks, not the Neogene sedimentary cover to respond directly to the regional crustal tectonic stress. Within the sedimentary cover, there exist both regional tectonic stress and local one resulted from block movements of the basement.

By the way, it is very significant that the folding of the Neogene strata has started when the regional crustal stress field abruptly changed nearly 90 degrees from the E-W tensile state with SHmin of E-W trend into the E-W compressional one with SHmax of E-W trend.

Such right-angled change in arrangement of stress-axes could occur the fundamental change to reactivate or rejuvenate the former normal faults as reverse faults.

In the Matsushiro earthquake swarm area, Asano et al. (1973) found a clear example
Fig. 7 Neogene tectonism and regional tectonic stress field in the Inner Belt of the Northeast Japan Arc.
(a) Tensional tectonism: In the upper crust of the earth, normal faulting proceeds in response to the tensional state of regional stress, which is characterized by the direction of $\text{SH}_\text{min}$.
(b) Compressional tectonism: Reverse faulting is likely to appear in a compressional stress field characterized by the direction of $\text{SH}_\text{max}$.
In both cases, preferred orientations of stress indicators (earthquakes, faults and dikes) are shown in the upper parts. The schematic profile showing block faulting with cylindrical surfaces is also given in each lower part.

of "reactive" fault along the western boundary of the Nagano intermountain basin. The crustal structure of this basin was revealed by seismic prospecting crossing the boundary in the direction of northwest-southeast. The sedimentary layers with a velocity of 4.0 km/sec become thick discontinuously with a head of 3000 m in the west of the boundary. While, the younger sediments with velocities less than 4.0 km/sec are rather thick in the Nagano Basin just east of such underground structural discontinuity.

When the quite opposite stress field occurred, it is very important to the newer folding whether the initial deflection and wavelength of folding, which is essential to the buckling
process, has been prepared or not. The anticlinal flexures (step-like monoclinal structures) formed in the former tensional tectonism played a role of initial deflection and decided a dominant wavelength of buckling folds in the newer compressional tectonism. So, it is obvious that the embryos of the folds in this region had been constructed in the former tectonics during the Miocene times.

Figs. 8 show 9 are schematic profiles and Fig. 10 gives a relation diagram, summarizing the folding process of the Neogene strata in the Shin-Etsu Region.

The folding process of this region is not the result of simple “bending” nor “buckling” but is rather combined process of both in the complicated tectonic history of a sedimentary basin. Such process can be explained as follows:

From the Early to Late Miocene, this region was in a tensional state in the E-W direction, and tensional tectonics had been formed. A vast amount of volcaniclastics of the early Miocene was closely associated with fissure eruptions in the trend of north to south.

In and after the maximum transgression of the Middle Miocene, one by one normal faults of the basement trending north to south became so active that differentiation of sedimentary basins due to differential subsidence proceeded. At the same time, gentle anticlinal flexures due to “bending” is considered to have developed within the sedimentary cover along the boundaries of each basement block.

At the end of the Late Miocene, the regional tectonic stress field changed into an E-W compressional state, which resulted in the start of compressional tectonism. The tilting block movements of the basement associated with reverse faults began to take place, and most of these faults are inferred to be “reactivated” ones which had originated at the time of the tensional state.

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Fig. 8 Interpretative schematic profile for the folding process of the Neogene strata in the northern Fossa Magna region. See text.
Fig. 9 Idealized geologic section across the Niigata sedimentary basin from east to west. See text.
1: latest Miocene~Pleistocene sediments,
2: Early~Late Miocene sediments,
3: basement rocks,
4: boundary between basement blocks.

Fig. 10 Schematic diagram for explanation of the folding process with respect to the relationship between the block movements of the basement and its influences on the overlying strata.

The overlying layers are also affected by the lateral compressive stress as well as the basement and tend to be "buckled" into a more or less regular sinusoidal form. It is significant in this case that such an initial wavelength had already been reflected as anticlinal flexures formed during former tensional tectonism.

Along with the buckling process, there is bending moment due to reverse block faulting in the basement, so that the initial deflections are amplified and modified into asym-
metrical folds. "Green Tuff" and Miocene granitic rocks would behave as rigid bodies the same as pre-Tertiary basement rocks.

5. A Proposal —Chikumagawa Tectonic Line—

After UTADA (1973), three parallel zones of hydrothermal alteration activity can be recognized in the Central Belt of the northern Fossa Magna (see Fig. 11). This hydrothermal activity occurred during the latest phase of Miocene volcano-plutonic activity within the Central Belt and ceased just before the earliest of Pliocene volcanism. During the Late Miocene, the northern half of the Central Belt was more uplifted than the southern half, and the boundary between them is very clear in the summit level map (Fig. 12). Therefore, it is not unreasonable to assume that there existed a fault zone trending northwest to southeast along the present-day Chikumagawa River during the Late Miocene. Paying attention to the distribution of the hydrothermal alteration zones showing discontinuity between the two blocks separated by this zone, it can be also assumed that the nor-
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Fig. 12 A map showing the distribution of the main faults which were formed or rejuvenated in the Quaternary period and their close relationship to the geomorphology of Central Japan. The contours show summit-level with 100 m interval. 1: strike-slip fault, 2: thrust fault, 3: "Chikumagawa Tectonic Line." This figure is quoted from HUZITA et al. (1973, Fig. 1) with slight addition.

thern block of the Belt dislocated toward the northwest against the southern block. As it is, at the front of the western edge of the northern block of upheaval, the folded structure of the Neogene strata is thrown into confusion. According to the topographic map illustrated by OKAYAMA (1968), this line is significant as the geomorphological boundary between Central and Northern Japan (Fig. 13). However, there is no topographical evidence that this fault zone has been active during the Quaternary period. Consequently, remarkable lateral block movement with a sinistral displacement is concluded to have occurred after the hydrothermal activity ceased, or possibly during the Pliocene. In the Pliocene, regional, stress field discussed here, left-lateral strike-slip faulting with a northwest to southeast trend is reasonably expected. The name of "Chikumagawa Tectonic Line" is proposed for the assumed fault zone mentioned above. Further studies are expected to add clarity to this problem.
Fig. 13 A map showing the distribution of the main tectonic lines occurring along the boundaries between large geologic bodies (OKAYAMA, 1968; with slight revision). ML: Median Line, Sr: Suruga-Bay Line, Sg: Sagami-Bay Line. B: boundary between Central and Northern Japan. B: Chikumagawa Tectonic Line. 1: alluvial plains and basins, 2: Quaternary volcanoes, 3: lines of topographic discontinuity.

6. Summary and Conclusions

(1) The dike method for determining the regional stress field was applied in the Shin-Etsu Region. The recent E-W compressional state can be followed up to the end of the Late Miocene through the Pliocene. During the Miocene, however, this region had been subjected to an E-W tensional state.

(2) The tectonic development of the region can be understood based on the above-mentioned stress history, by which the following process can also be constructed. In the tensional stress field during the Miocene, normal faulting of the basement of the regionally subsiding sedimentary basin resulted in blocky differential subsidence, which formed some initial heterogeneities in the sediments deposited in the basin. In the following compressional tectonism, such pre-existing sedimentary structures as embryos have
developed into asymmetrical anticlines.

(3) Such a kinematic picture is presented showing the normal faults rejuvenated as reverse faults owing to the nearly right-angled change in the arrangement of the axes of tectonic stresses (SHmax and SHmin). The possible mechanism of folding should be examined in relation to the change in the regional stress field.

(4) The abrupt change of the tectonic stress state at the end of the Late Miocene obtained by dike method is expected to be recognized in the “Green Tuff Region” because the studied area is a representative part of the Inner Belt of the Northeast Japan Arc.

(5) The existence of the “Chikumagawa Tectonic Line” is assumed according to Pliocene tectonic movements. This line suggests left-lateral block movements of the basement blocks, which resulted in the severe folding of the sedimentary cover in the northern part of the Fossa Magna.

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