Geofísica Internacional (1994), Vol. 33, Num. 1, pp. 45-51

Thermal history of the NE Japan frontal arc since the Late Miocene inferred from vitrinite reflectance

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Received: December 9, 1992; accepted: April 30, 1993.

RESUMEN

Se estiman los gradientes paleogeotérmicos a partir de las relaciones reflectancia de vitrinita-profundidad (-z) para sedimentos del Mioceno Tardío en las áreas de Tanakura y Hirono del noreste de Japón. Ambas áreas se han situado en la región antearco desde hace 15 Ma y no han sido afectadas por magmatismo. Estos sedimentos debieron haber sufrido disturbios térmicos locales limitados, y por ello resultan adecuados para estudiar las condiciones paleogeotérmicas a una escala regional.

El levantamiento que se llevó a cabo en la región, entre el Mioceno Tardío y el Plioceno Temprano dió como resultado una discordancia angular entre las rocas miocénicas y pliocénicas y causó el enfriamiento de los sedimentos del Mioceno, lo que pudo haber retardado y detenido en forma efectiva el proceso de carbonización. Las relaciones -z de los sedimentos por tanto, revelan el gradiente geotérmico entre la depositación y el destechamiento. El gradiente paleogeotérmico estimado es de 64± 11° en Tanakura y de 45± 10° en Hirono. Los gradientes actuales son de 30° y 18° respectivamente, lo cual indica que la temperatura en el subsuelo fue mayor en el Mioceno Tardío que en el presente, debajo del ante-arco.

Un enfriamiento de escala regional a través del arco parece haber tenido lugar a partir del Plioceno y durante todo el Cuaternario, tal como lo sugiere la firma geoquímica de las rocas volcánicas del frente volcánico (Ban *et al.*, 1992). Un retroceso hacia el occidente del frente volcánico (Ohguchi *et al.*, 1989) es consistente también con el enfriamiento regional.

PALABRAS CLAVE: Reflectancia de vitrinita, historia térmica, arco de islas, noreste de Japón.

ABSTRACT

Paleogeothermal gradients are estimated from the vitrinite reflectance-depth (R_0-z) relations of Middle to Late Miocene sediments in the Tanakura and Hirono areas, Northeast Japan. Both areas have been situated in the frontal arc since 15 Ma and have been free from magmatism. Thus, the sediments would have undergone a limited amount of local, thermal disturbances, and are suitable for a study of regional-scale paleogeothermal conditions.

Late Miocene to Early Pliocene uplift resulted in an angular unconformity between the Miocene and Pliocene rocks and caused cooling of the Miocene sediments that would have retarded and effectively stopped coalification. The R_0-z relations of the sediments therefore reveal the paleogeothermal gradient between deposition and unroofing. The estimated paleogeothermal gradient is 64 ± 11° C km^{-1} at Tanakura and 45 ± 10° C km^{-1} at Hirono. The present gradients are respectively 30° and 18° C km^{-1}, indicating that subsurface temperature was higher in the Late Miocene than at present under the frontal arc.

Cooling from the Pliocene through Quaternary appears to have been of regional scale across the arc, as is also suggested by the geochemical signature of volcanic rocks erupted at the volcanic front (Ban *et al.*, 1992). Westward retreat of the volcanic front (Ohguchi *et al.*, 1989) is also in accord with the regional cooling.

KEY WORDS: Vitrinite reflectance, thermal history, island arc, Northeast Japan.

INTRODUCTION

Geothermics is an important clue to island arc dynamics, and has been investigated mainly on the basis of heat flow measurements (e.g., Uyeda, 1972). However, such geophysical measurements only represent a snapshot: island arcs have their own history. The NE Japan arc, as an example, experienced a sequence of tectonic events in the Late Cenozoic such as spreading and subsequent subduction-initiation in the back arc (Jolivet and Tamaki, 1992; Nakamura, 1983; Kobayashi, 1983). The geothermal regime must have varied together with the tectonics. The secular change of arc magmatism suggests such variations under the arc. The volcanic front has migrated back and forth across the NE Japan arc during the Cenozoic (Ohguchi *et al.*, 1989; Ohki *et al.*, 1993). Sato *et al.* (in preparation) document the variation of production rates of volcanic materials in the arc since the mid Tertiary. They found that the rate has changed up to two orders of magnitude. These observations suggest that the estimation of geothermal history provides an important clue to island arc dynamics.

The analysis of the thermal history of NE Japan has been undertaken recently by the petrology of volcanic rocks (Ban *et al.*, 1992; Yoshida 1992) and by the studies of organic maturation (Suzuki, 1989). Ban *et al.* and Yoshida calculate the silica-normalized abundance of LIL elements in Cenozoic volcanics and show tentative results of spatio-temporal variations of the depth of an isotherm that determines the element abundances. Suzuki measured vitrinite reflectance, the most widely used parameter of organic diagenesis, of coaly particles in Neogene sediments, and he suggested that the gross pattern of the distribution of paleogeothermal gradient in the Middle Miocene did not differ from that of the present. However, a significant part of his data was obtained in the volcanic arc of NE Japan in the exploration of metallic ores that are often formed at thermally abnormal loci. The maximum temperature to which coal was exposed exerts a strong control on vitrinite reflectance (Hood *et al.*, 1975; Barker and Pawlewicz, 1986). Therefore Suzuki's estimation might be biased by local anomalies.

In this paper an attempt is made to estimate ancient geothermal gradients in the NE Japan arc from vitrinite reflectance. The Tanakura and Hirono areas are selected around the Abukuma mountains, that have been situated in the frontal arc since 15 Ma (Figure 1). The Miocene sequence in the studied areas was uplifted in Early Pliocene resulting in an angular unconformity. Due to the associated unroofing and cooling of the Miocene strata, coalification would have stopped so that an analysis of these strata enables us to estimate geothermal gradient in the Miocene.

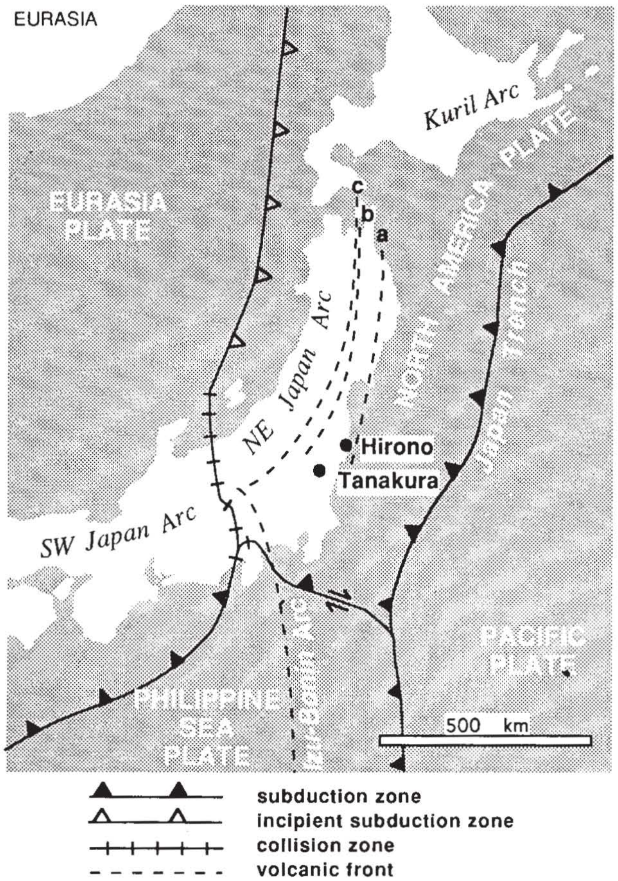

Fig. 1. Map showing the location of the Hirono and Tanakura areas and the position of volcanic front at and after 15 Ma (Ohguchi *et al.*, 1989). (a): volcanic front at 16-15 Ma, (b): in the Late Miocene (8-5 Ma), and (c): 15-8 Ma and 0-5 Ma.

METHOD

The monotonic increase of the reflectance of vitrinite, a constituent of coals, through diagenesis has permitted quantitative reconstructions of the burial and temperature histories of stratigraphic sequences. There are a number of methods for correlating vitrinite reflectance R_O with the degree of thermal stress undergone by strata containing the vitrinite. The present study uses Middleton's approach (Middleton, 1982a, b; Middleton and Schmidt, 1982):

$$R_o^a = B\int_0^t \exp\,[b\,T(t)]\mathrm{d}t \qquad (1)$$

which is simple and approximates recent more sophisticated formulations (Morrow and Issler, 1993). In this equation, t is the time since deposition and $T(t)$ is the temperature at which the coal was exposed. Middleton proposes the coefficients,

$$a = 5.5,\ \ b = 0.069°\ \mathrm{C}^{-1} \text{ and } B = 2.8\times 10^{-5}\ \mathrm{Myr}^{-1}. \qquad (2)$$

$T(t)$is approximated by the equation

$$T = T_o + gz \qquad (3)$$

where z is the burial depth, and T_o and g are respectively the surface temperature and geothermal gradient. From equations (1) and (3) we have

$$\log R_o = \frac{1}{a}\log\left[\int_0^t \exp(bgz)\mathrm{d}t\right] + \frac{bT_o + \log B}{a}$$

If the geothermal gradient and the depth do not significantly change, this reduces to

$$\log R_O = (b/a)gz + \text{const.} \qquad (4)$$

Since coalification is much more sensitive to temperature than to time, R_O is determined mostly by the maximum temperature which the coal experienced (Hood *et al.*, 1975). Thus the reflectance records the maximum burial temperature (Yamaji, 1986). The linear correlation of log R_O with depth z represented by equation (4) is commonly observed in sedimentary basins (Dow, 1977).

Cooling due to uplift and erosion of overlying sediments effectively stops coalification. In this case, the reflectance gradient

$$\Gamma = (\log R_o) / z$$

is related to the thermal gradient before the uplift through the equation

$$g = (a/b)\Gamma \qquad (5)$$

This is the upper limit for the bed temperature between the deposition and uplift, because of the irreversibility of coalification.

GEOLOGICAL BACKGROUND OF STUDIED AREAS AND RESULTS

Tanakura area

Coal particles (> #200 mesh) were collected from cuttings of a bore-hole that penetrates the Akasaka and Kubota formations in the Tanakura area. The bore-hole is at proximity to a syncline axis so that dips of strata are very gentle. The formations consist of Middle to early Late Miocene paralic sediments that cover Mesozoic metamorphic rocks (Figure 2). The formations yield calcareous nanofossils from CN5a to CN8 zones (Amano and Takahashi, 1986) which are dated at 14–8 Ma (Oda, 1986).

The formations were uplifted at the Miocene-Pliocene boundary and the non-marine Nikogi formation unconformably covers the Miocene sequence (Otsuki, 1975). The formation is correlated with the Gauss normal epoch (~3 Ma) (Tohoku Agricultural Administration, 1986).

Figure 3a shows the linear regression between log R_o and depth with a reflectance gradient of $\Gamma = 0.81 \pm 0.14$ km^{-1}, where the accuracy is represented by one sigma. Using the coefficients (2) and the formula (5), the Γ is converted to the thermal gradient at 64 ± 11° C km^{-1}. The present geothermal gradient is 30° C km^{-1} (Tohoku Agricultural Administration, 1986), significantly lower than the paleogeothermal gradient.

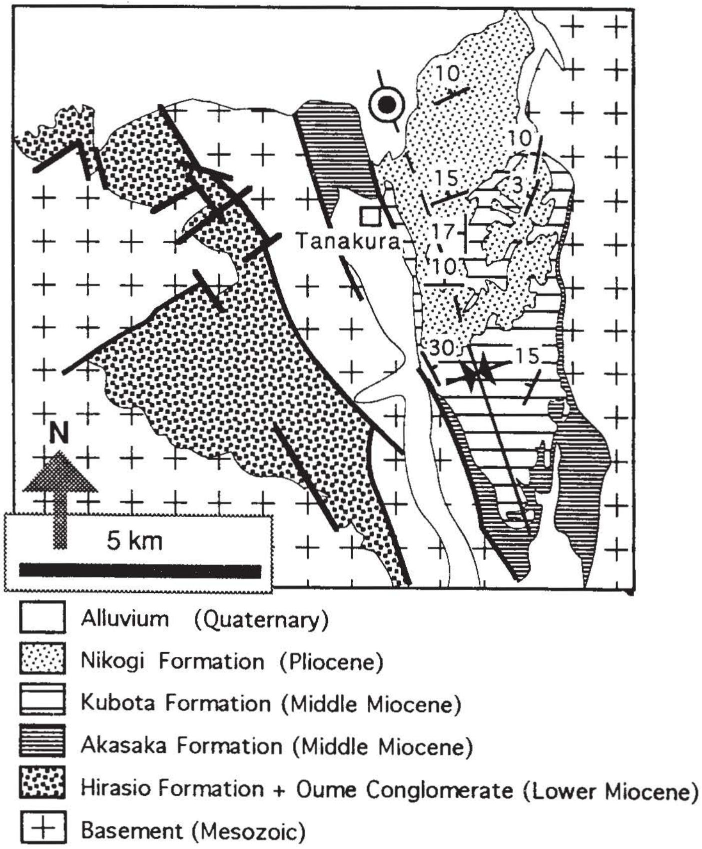

Fig. 2. Geologic map of the Tanakura area (Otsuki, 1975). Circle: bore-hole site.

Hirono area

The Lower Miocene Yunagaya group is overlain by the Pliocene Hirono Formation with a sharp angular unconformity in this area (Sugai *et al.*, 1957). The lowermost part of the group consists of a thin volcanic breccia that yields K-Ar and fission track ages of 20.9 and 23.4 Ma respectively (Kimura, 1988). The breccia is immediately overlain by shallow marine, non-volcanic sediments. Planktonic fossils indicate that the marine sediments were deposited from ~18 to 16 Ma (Koizumi, 1986; Yanagisawa *et al.*, 1989). The Yunagaya group is covered by the Hirono formation that yields a variety of fossil plankton which is correlated to 3.5–4 Ma (Taketani *et al.*, 1986). The group was uplifted at the end of Miocene or Early Pliocene (Yanagisawa *et al.*, 1989). Thrusting along the Futaba fault vertically tilted the group in the Hirono area (Figure 4). The thickness of the stratigraphic section that was truncated by the faulting is not well constrained, but the equation (4) is linear with respect to depth z so that the missing section does not affect the estimated paleogeothermal gradient—it only affects the constant in the equation. Therefore, we use the stratigraphic thickness as z in the equation. Measurement of vitrinite reflectance of the Yunagaya group therefore allows an estimation of the maximum geothermal gradient in the Miocene.

Figure 3b shows the measured reflectance versus depth that is approximated by stratigraphic thickness. The linear regression of the data gives a slope $\Gamma = 0.57 \pm 0.13$ km^{-1} which is converted to a temperature gradient of 45 ± 10° C km^{-1}. Nakamura and Wakita (1982) show the present geothermal gradient as 18° C km^{-1}. The paleogeothermal gradient before the Pliocene was therefore higher than at present.

DISCUSSION

The maximum paleogeothermal gradient for Tanakura occurred in the Late Miocene to early Pliocene, and would represent a regional geothermal state, as the area has been free from volcanism since early Middle Miocene (~15 Ma).

For the Hirono it is less clear than for Tanakura when the temperature reached its maximum, because of the long period between deposition and uplift. Although there was volcanic activity in the NE Japan fore-arc at 21-25 and 15-16 Ma, small volcanoes were produced tens of kilometers away from the studied areas. Thus regional rather than local paleogeothermal gradients are estimated. Figure 5 shows the inferred thermal history. In the Tanakura and Hirono cases, the paleogeothermal gradient in the Miocene was greater than at present, though the estimated gradients represent the upper bound in the period between the maximum burial and uplift. Subsurface temperature appears to have fallen through the Pliocene to Quaternary in these areas.

Cooling appears to have occurred on a regional scale across the arc as secular changes in arc-volcanism exhibit

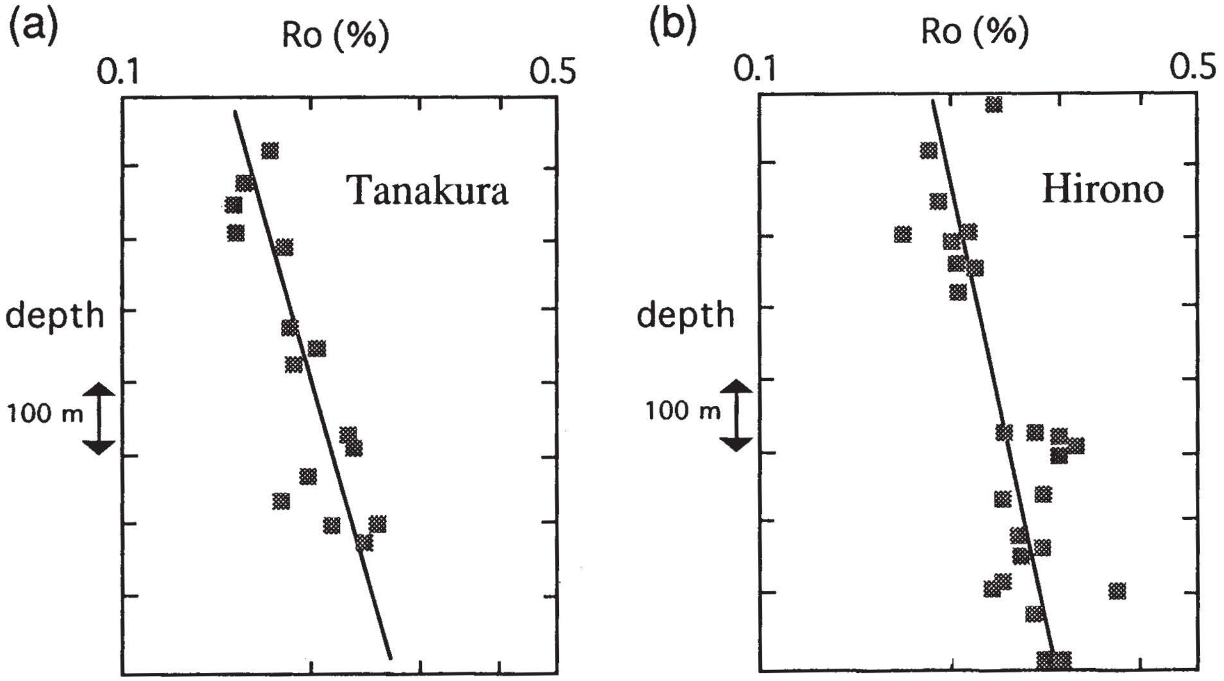

Fig. 3. Vitrinite reflectance versus depth for the Tanakura (a) and Hirono (b) samples.

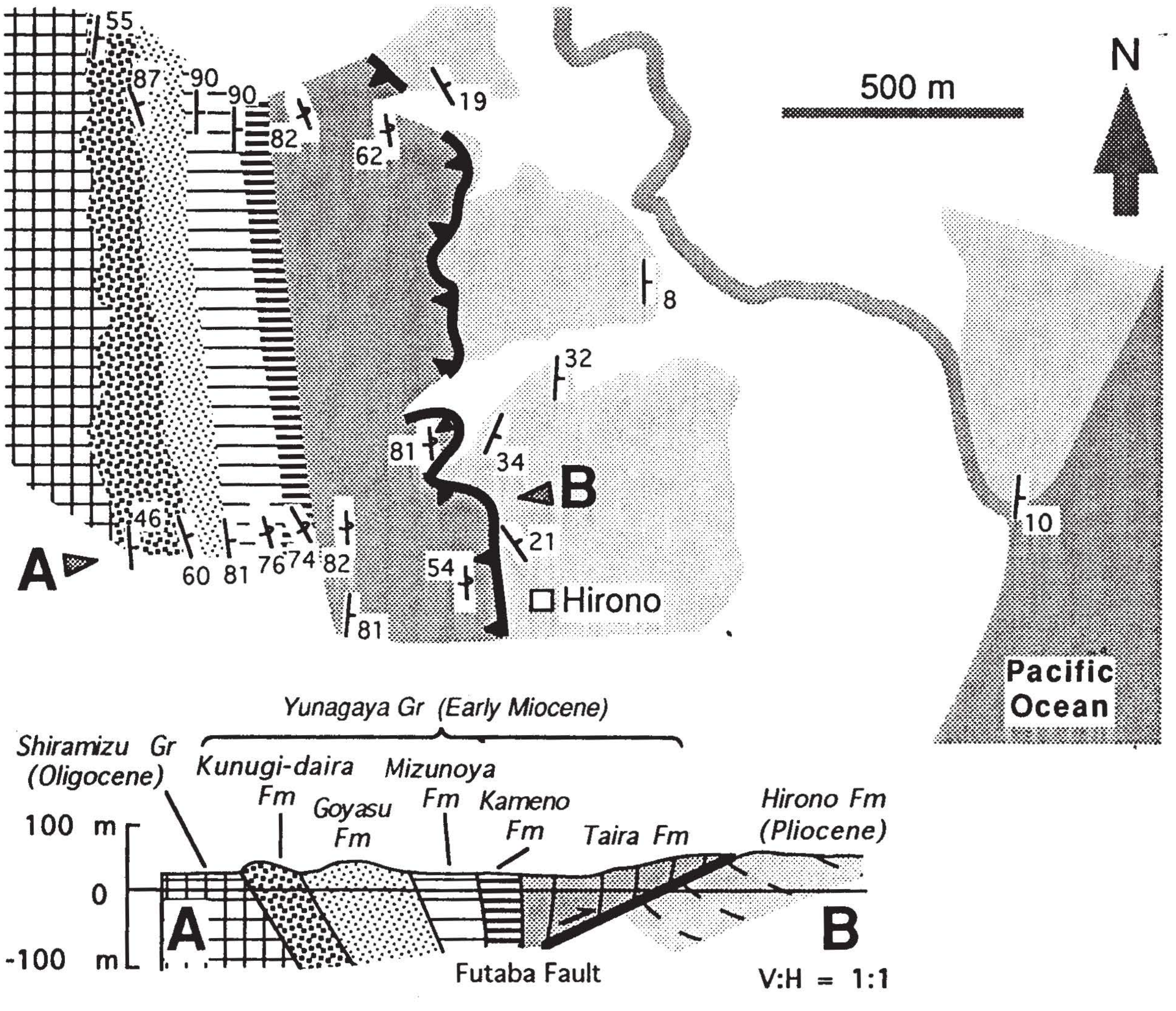

Fig. 4. Geologic map of the Hirono area (Taketani *et al.*, 1986).

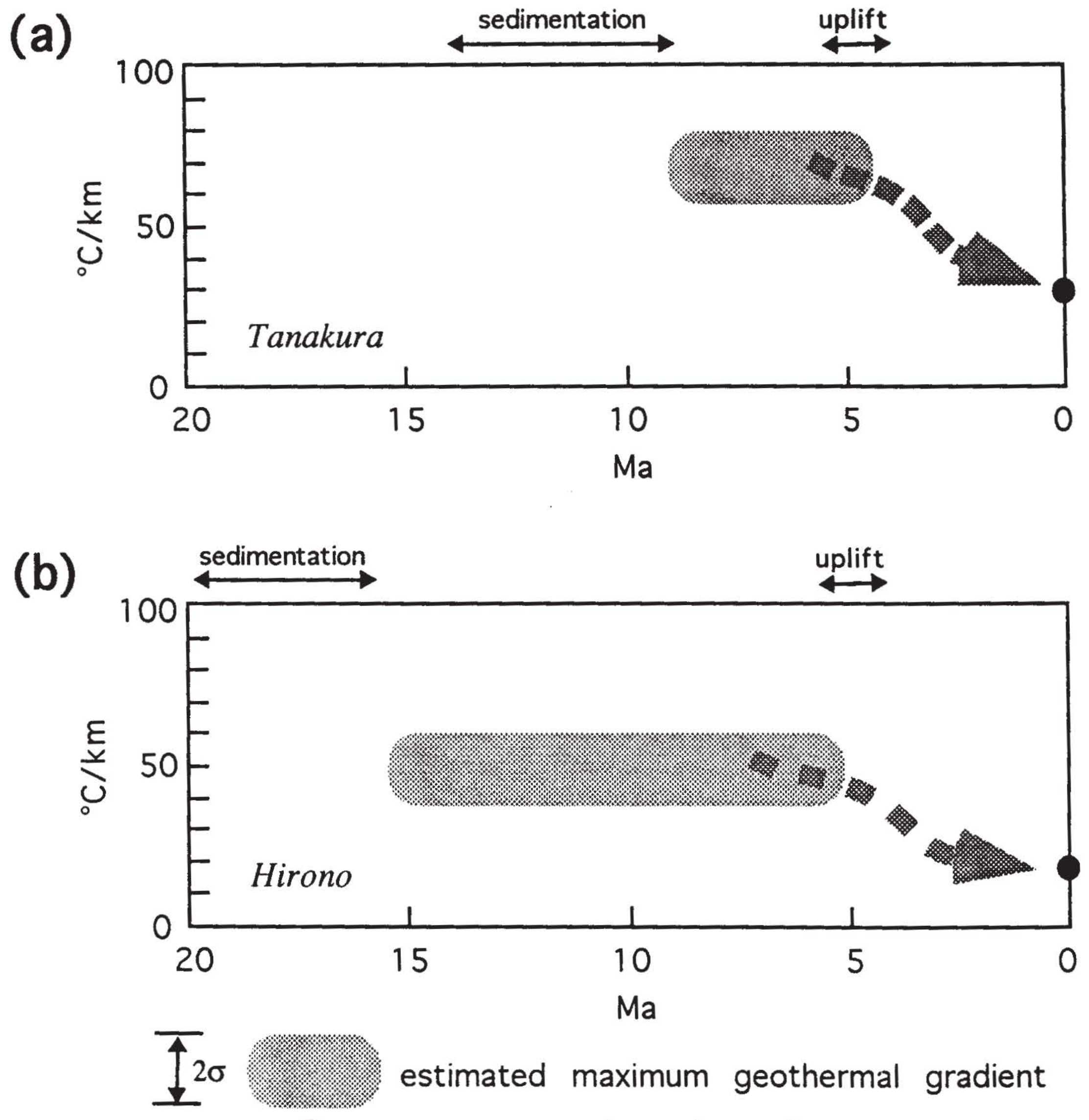

Fig. 5. Maximum paleogeothermal gradients in the Tanakura (a) and Hirono (b) areas estimated from vitrinite reflectance-depth relations. Indicated is the period in which the maximum gradient must have occurred and it is not meant to imply this gradient acted over the whole period. Closed circles represent the present geothermal gradient.

parallel trends. The silica-normalized K_2O content of volcanics at the present volcanic front shows a gradual increase through the Plio-Pleistocene, suggesting a cooling of their source region (Ban *et al.*, 1992). In the same period, the volcanic front retreated westward (Ohguchi *et al*, 1989). Volcanic activity, as estimated from production rate, also waned (Sato *et al*, in preparation). The regional cooling may be the surface expression of a secular change in the underlying mantle wedge.

Many factors control variation in temperature of the wedge. Davies and Stevenson (1992), who take temporal changes into account in numerical modelling, stressed the role of subduction dip angles and the mechanical coupling between the slab and asthenosphere. However, little is known about the temporal variation of the coupling under NE Japan. The volcanic front lies above the subducting slab with a depth of about 110 km that is thought to be determined by pressure-dependent dehydration of the slab

(Tatsumi, 1986). The shallowing of the slab is suggested by the observation of the westward migration of the front (Ohguchi *et al.*, 1989) and by the inference of insignificant migration of the Japan trench after Middle Miocene (Lallemand *et al.*, 1992). Therefore, the observed cooling from the Pliocene may represent the decrease in the subduction dip angle.

ACKNOWLEDGMENTS

I am grateful to Drs. N. Kitamura, H. Nakagawa, K. Otsuki, T. Yoshida and H. Sato for discussions and encouragement. The Tanakura samples were provided from Mr. J. Miyakita of the Tohoku Agricultural Administration. Thanks are also due to the anonymous reviewers for the improvement of the manuscript.

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