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32. *The Accomodation of Plate Collision by Deformation in the Izu Block, Japan.*

By Paul SOMERVILLE,

Earthquake Research Institute.

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Abstract

A model is proposed which explains the intraplate deformation of the Izu block as resulting from the collision between the Philippine Sea plate and the Eurasian plate along the southern Fossa Magna. The collision produces two stress domains having contrasting orientations. The northeast Izu block whose motion is impeded by the collision accomodates as much as 0.4 cm/yr of the resulting NW-SE shortening by left lateral slip on the N-S striking Tanna fault and conjugate right lateral slip on the E-W striking Izu-Oshima fault. A further shortening of as much as 0.8 cm/yr, calculated from geodetic measurements, is accomodated directly by deformation across the collision zone. The combined effect of these two processes can adequately explain the convergence rate, measured along the Sagami trough using coastal terrace data and historical seismicity, of as little as 1.2 cm/yr, without resort to the subduction zone off the NE coast of the Izu Peninsula proposed by ISHIBASHI (1978). In the southwest Izu block, the difference in convergence rate between the outer Suruga trough (3 cm/yr) and the collision zone (approximately 1 cm/yr) produces shear strain parallel to the direction of relative plate motion. This shear strain is accomodated by slip on the network of NW striking faults in the Izu Peninsula and subduction along the inner Suruga trough which decreases northwards. The sense and rate of this shear strain are clearly reflected in the geodetically measured deformation of the Izu Peninsula during the past hundred years. The proposed model suggests explanations for various mechanical correlations between tectonic features of the Izu block, such as the presence of the Tanna fault, the Hiekawa Pass uplift region, and the Izu-Oshima fault in front of the zone of direct plate collision, and the observation that great earthquakes on the Sagami trough are followed by rupture on the Tanna fault.

Introduction

The Philippine Sea plate is colliding with the Eurasian plate in south central Honshu, where the Izu block abuts against the southern Fossa Magna (MATSUDA, 1978) as shown in Fig. 1. It has been proposed by ISHIBASHI (1978) that as a result of this collision process, a new subduction zone has begun to develop off the east coast of the Izu Peninsula. However, the 1978 Izu-Oshima earthquake has shed new light on the tectonics of the Izu block. Combining this new evidence with the wealth of information already accumulated, we show that the interplate collision along the boundary of the Izu block is reflected in the mechanisms of intraplate earthquakes and in other tectonic processes occurring within the Izu block.

We assume that the direction of motion of the Philippine Sea plate is northwest relative to the Eurasian plate (SENO, 1977a). This direction is not parallel to the trend of the Izu-Bonin arc, thereby violating the condition for the stability of the triple junction between the Japan trench, the Sagami trough and the Izu-Bonin trench (MCKENZIE and MORGAN, 1969; SENO, 1977a). In view of evidence that the triple junction has remained stable at least since the Miocene, KAIZUKA (1975) proposed that the Izu Inner Bar and the Izu-Bonin outer arc are moving northwards parallel to the trend of the Izu-Bonin trench in response to drag exerted by the Pacific plate. However, the direction of horizontal motion between the Izu block and Honshu during the 1923 Sagami trough earthquake was approximately N 30°W, in rough agreement with the approximately northwestward direction of relative motion of the Philippine Sea plate.

The plate boundary

We divide the boundary between the Philippine Sea and Eurasian plates into four segments as shown in Figs. 1 and 2. The southwestern segment along the outer Suruga trough is undergoing regular subduction at a rate of 3 cm/yr (SENO, 1977a), which is reflected in great shallow thrust earthquakes (KANAMORI, 1972; ANDO, 1975).

The second plate boundary segment lies along the inner Suruga trough and its tectonic extension landwards to the southern Fossa Magna. On this segment there is a gradual transformation from subduction to collision, accompanied by a corresponding gradual decrease in convergence rate. Such a decrease in convergence rate has been proposed by ISHIBASHI (1978).

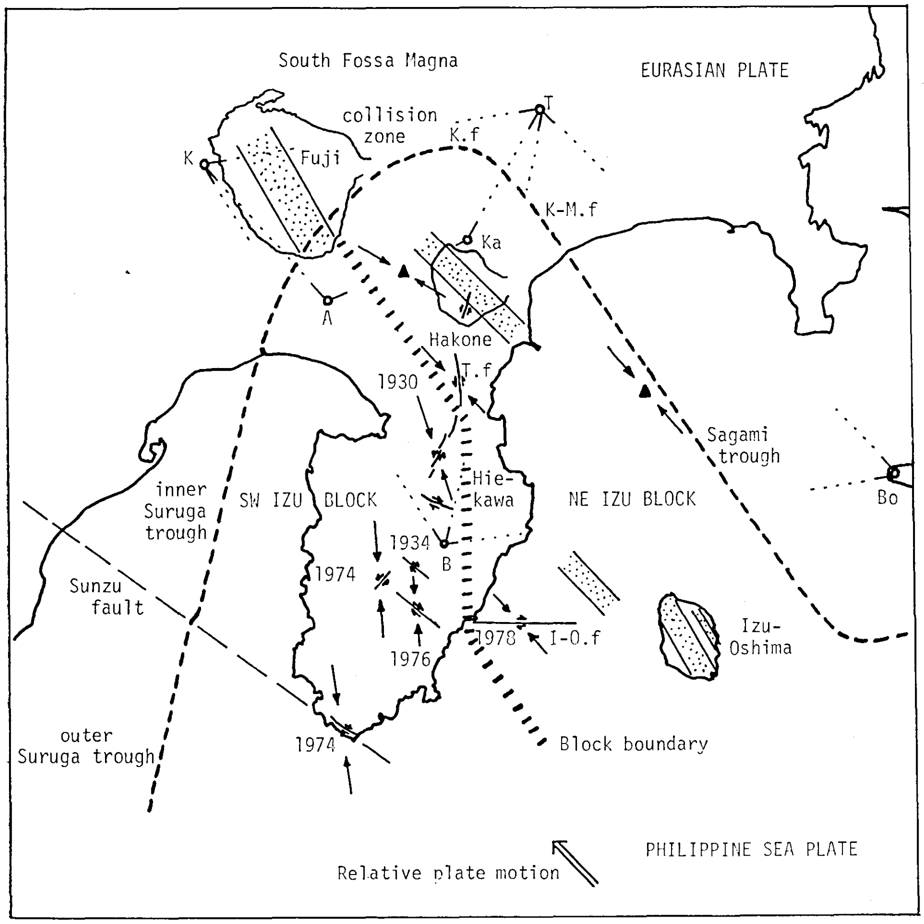

Fig. 1. Tectonic Map of the Izu Block. Arrows show compressional axes of a) earthquakes, whose fault planes (ABE, 1978) and year of occurrence are shown, and b) strain between 1924 and 1966 (NAKANE, 1973), measured geodetically between stations T, K and B; and T, B and Bo. Stippled zones are alignments of monogenetic volcanoes after NAKAMURA (1969 and personal communication, 1978).

K.f=Kannawa fault, K-M.f=Kozu-Matsuda fault, T.f=Tanna fault, I-O.f=Izu-Oshima fault, T=Tanzawayama, K=Kenashiyama, A=Ashitakayama, Ka=Kammuridake, B=Banjyodake, Bo=Bodaisan

The boundary between the first and second segments is chosen to be the Sunzu fault (TSUNEISHI and SUGIYAMA, 1978), which by our terminology marks the boundary between the inner and outer segments of the Suruga trough. MOGI (1977) suggested that the Irozaki fault at the tip of the Izu Peninsula is continuous with the fault that offsets the Suruga trough and with a fault (proposed on the basis of seismicity)

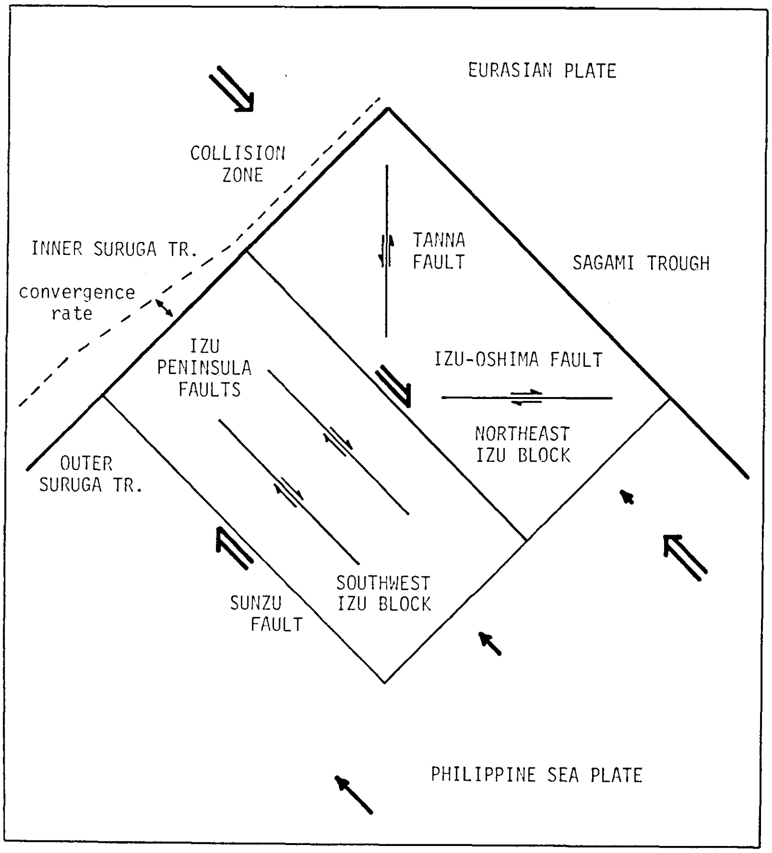

Fig. 2. Schematic Tectonic Map of the Izu Block.

near Yaizu on the western shore of Suruga Bay. Field evidence for this latter fault segment was subsequently described by TSUNEISHI and SUGIYAMA (1978). The sense of displacement is right lateral on all three segments of the Sunzu fault. TSUNEISHI and SUGIYAMA (1978) estimated a maximum displacement of 3.4 km since the Palaeocene near Yaizu, yielding a maximum slip rate of 0.017 cm/yr. The offset of the Suruga trough is approximately 2 km. During the 1974 Izu Hanto Oki earthquake, a surface displacement of 45 cm occurred on the Irozaki-median fault (MATSUDA and YAMASHINA, 1974). An average dislocation of 1.2 m was determined from levelling data by ABE (1978). Judging from the freshness of the Quaternary topography, MATSUDA and YAMASHINA (1974) estimated an average displacement rate of 0.01 to 0.1 cm/yr. It has been suggested by MOGI (1977) that the Irozaki fault is just one strand of a system of faults which marks a significant discontinuity in subduction rate between the inner and outer segments of the Suruga trough. However, the moderate rate of slip on the Sunzu fault suggests a predominantly second order discontinuity in slip rate as proposed above (i.e. a slip rate decreasing northward) rather than the first order discontinuity proposed by Mogi.

We temporarily bypass discussion of the third segment, the collision zone along the southern Fossa Magna, to examine the fourth segment which consists of the Sagami trough. Motion on this segment is dominantly right lateral strike slip, and to this extent it plays the role of a trench-trench transform fault connecting the Japan trench and the Nankai trough (KANAMORI and ANDO, 1973). However, there is also a component of thrust faulting which implies the role of a consuming plate boundary.

The rate of slip along the Sagami trough may be estimated from the rate of uplift of coastal terraces. Using the heights of the 6,000 year old Numa terrace measured by SUGIMURA and NARUSE (1954) and YONEKURA (1975), SENO (1977b) and SCHOLZ and KATO (1978) estimated the recurrence rate of the 1923 Sagami Bay earthquake to be 180-400 and 200-300 years respectively. MATSUDA et al (1978) found a recurrence interval of 800-1500 years for the Genroku terrace, which represents the combined effect of the 1923 and 1703 Sagami Bay earthquakes. Their estimate is derived from the height of the Numa terrace at Chikura on the southern tip of the Boso Peninsula, and the presence there of four clearly defined terraces. The uplift at Chikura was much larger than in other parts of the uplifted region, and was modelled by MATSUDA et al (1978) by a steep thrust fault along the Kamogawa submarine thrust (KASAHARA et al, 1973). Since this thrust contributed roughly two thirds of the uplift of the Genroku terrace, it appears that MATSUDA et al (1978) have, in effect, estimated the recurrence time of earthquakes on the Kamogawa thrust, which may not necessarily be the same as the recurrence time of Sagami trough earthquakes. Their estimate is similar to the value of 950-2500 years for the Kamogawa thrust component of the 1703 earthquake derived from the Chikura data by SENO (1977b). The relatively uniform height of the Numa terrace, when compared with the anomalously great height of the Genroku terrace at Chikura, suggests that the Genroku terrace may not accurately reflect the average rate of uplift.

The historical record of seismicity (USAMI, 1974) shows that the 1923 and 1703 earthquakes are the only ones of magnitude near 8 to have occurred along the Sagami trough during the past thousand years. The previous great Sagami trough earthquake of 818 in Usami's catalog is attributed to the Tone Valley by HAGIWARA (1972). Thus the historical seismicity is in approximate agreement with the upper limits of the recurrence times estimated by SENO (1977b) and SCHOLZ and KATO (1978). We therefore assume a recurrence interval of 400 years, and obtain a convergence rate of 1.2 cm/yr from the 4.8 m of slip of the 1923 Sagami Bay earthquake determined by MATSU'URA and IWASAKI (1978). If we had assumed a lower limit of 180 years for the recurrence time, we would have obtained a convergence rate of 2.65 cm/yr. The fault model of MATSU'URA and IWASAKI (1978) is preferred to previous ones determined by ANDO (1971) and KANAMORI (1971) because it was derived from the corrected triangulation data of SATO and ICHIHARA (1971) and satisfies both geodetic and seismological data.

The convergence rate of 1.2 cm/yr which we have assumed to be occurring along the Sagami trough is in rough agreement with an estimate of 0.75 cm/yr, derived below, for the rate of horizontal slip on the Kozu-Matsuda fault (Fig. 1), which is the landward extension of the Sagami trough. MACHIDA and MORIYAMA (1968) concluded that the rate of vertical displacement on this fault has been 0.2 cm/yr for the past fifty thousand years. This corresponds to a rate of horizontal motion of 0.75 cm/yr if we assume that the slip vector of the Kozu-Matsuda fault is the same as that of Matsu'ura and Iwasaki's model of the 1923 Sagami Bay earthquake.

These rates of horizontal motion on the Sagami thrust and the Kozu-Matsuda fault are considerably less than the 3 cm/yr assumed to be occurring along the outer Suruga trough, implying that motion of the Izu block is being impeded by collision along the southern Fossa Magna, and that shear deformation is occurring within the Izu block to accomodate the difference in convergence rate. This situation is illustrated schematically in Fig. 2. In what follows, we examine the manner in which intraplate faults in the Izu block accomodate the collision and shearing processes.

We now return to the third interplate boundary segment, which consists of the collision zone in the southern Fossa Magna. SUGIMURA (1972) delineated the northeastern boundary of the Philippine Sea plate north of the Izu Peninsula and estimated that a northward shift of 10-30 km had occurred during the past 0.3-0.5 m.yr. This corresponds to a rate of 2-10 cm/yr and was estimated from the rate of motion of the Philippine Sea plate. However, as we have just seen, the convergence rate inferred from coastal terrace data is considerably less than this value. Further, MATSUDA (1978) suggested that the motion of the Izu block has been partly absorbed within the block by intraplate faulting. This suggestion is quantitatively examined in what follows.

Faulting in the Izu block

In the collision process, the deformation of the Izu Peninsula is limited to block faulting, in strong contrast to the severe folding and

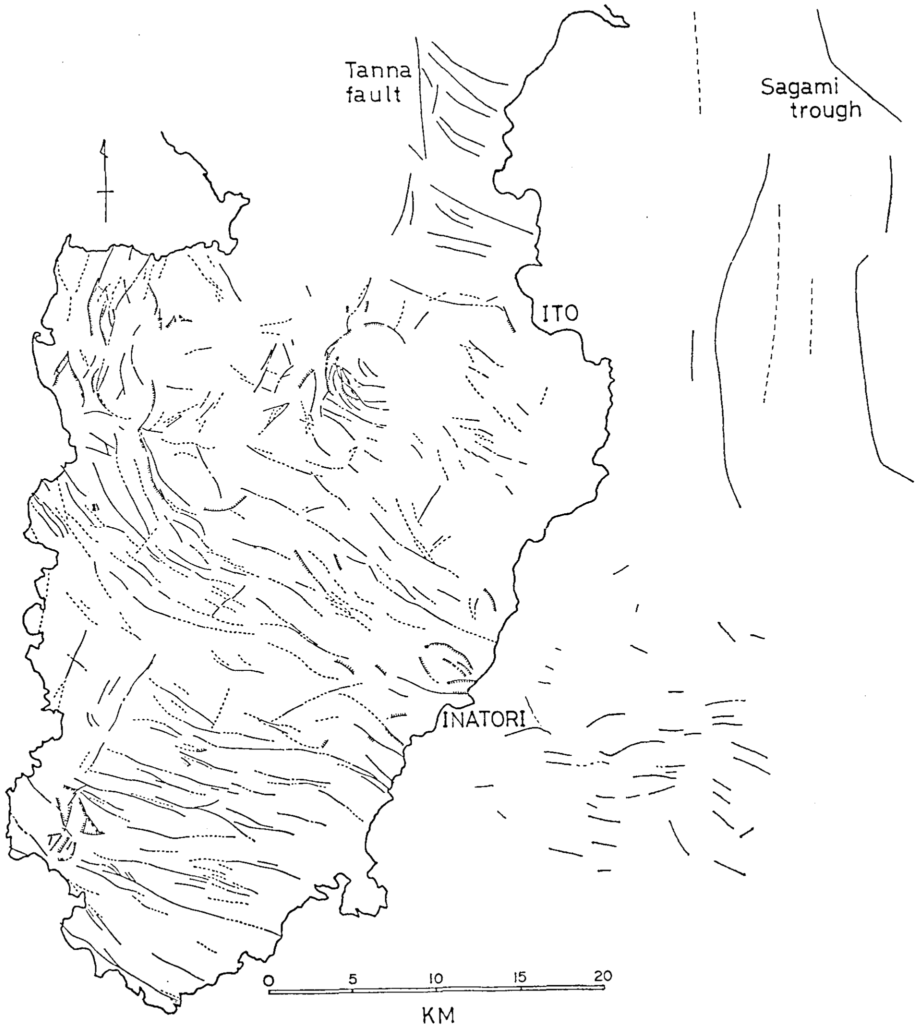

Fig. 3. Active Faults and Lineaments of the Izu Block. Faults in the Izu Peninsula after MURAI and KANEKO (1974), faults on land north of Ito and faults off Ito after KAIZUKA et al (1977), faults off Inatori after THE HYDROGRAPHIC OFFICE, MARITIME SAFETY AGENCY, 1978.

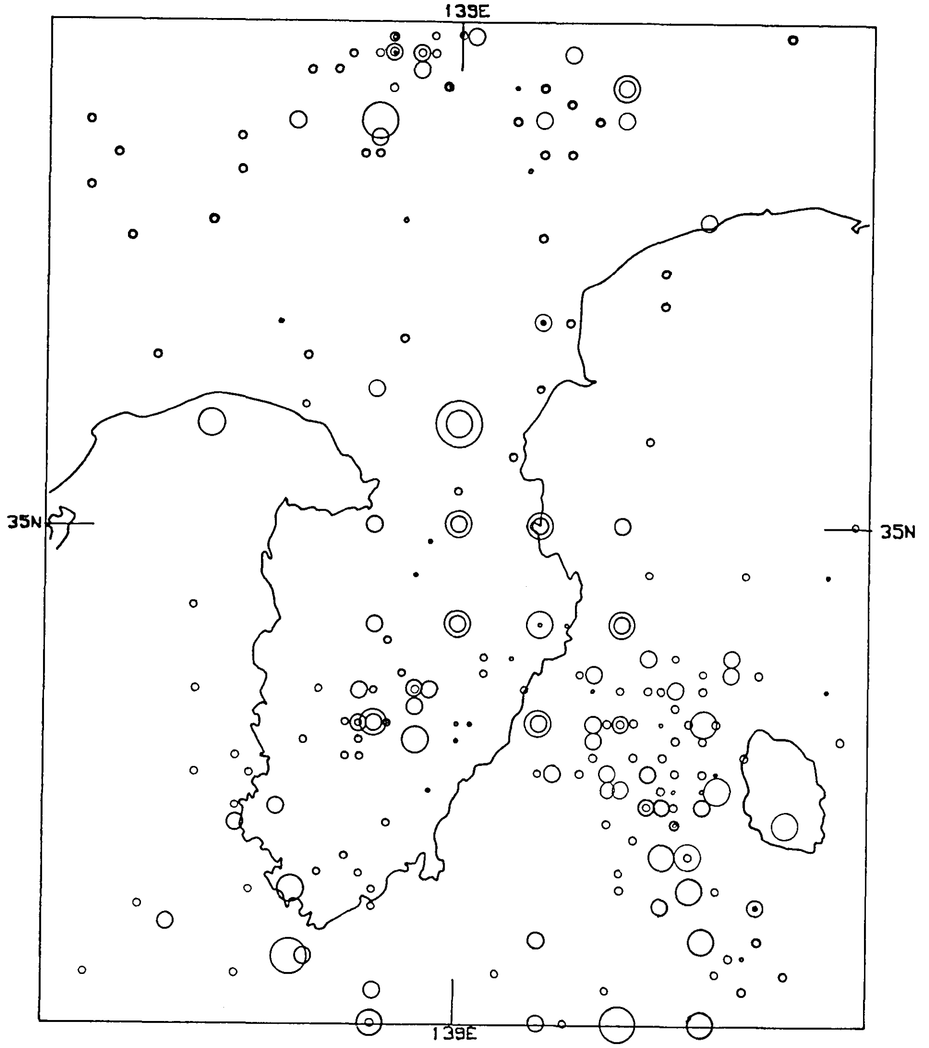

Fig. 4. Shallow Seismicity in the Izu Block, 1926-1977. Epicenters by J. M. A., map prepared by Dr T. Maki. Earthquakes having the same epicenter are not distinguished.

faulting deformation of the Miocene terrains in the collision zone north of the Izu block (MATSUDA, 1962). Active faults and lineaments in the Izu block are shown in Fig. 3. A distinct difference in strike between the northeast and southwest parts of the block is apparent, suggesting a difference in the orientation of stress in the two blocks. The strong contrast in the number of earthquakes across the boundary between the two blocks southwest of Izu-Oshima (Fig. 4) further suggests the existence of different stress regimes.

Historically, the only large earthquake known to have occurred in the Izu Peninsula before this century is believed to have occurred on the Tanna fault by virtue of its location (USAMI, 1966). This was the 841 earthquake with an estimated magnitude of 7.0.

A swarm of earthquakes occurred between the northern tip of Izu-Oshima and the Izu Peninsula in 1905 (OMORI, 1908), just north of the epicenter of the 1978 Izu-Oshima earthquake. The magnitude of the largest shock probably lies between 6.5 and the value of 7 estimated by USAMI (1966).

Since 1930, five destructive earthquakes, whose mechanisms have been summarised by ABE (1978), have occurred in the Izu Peninsula. The 1930 North Izu earthquake involved slip on the N-S striking Tanna fault and on a series of conjugate faults to the south with its dominant component striking roughly N 30°E. All four subsequent earthquakes, which occurred in the southern half of the Izu Peninsula, occurred on faults oriented roughly NW-SE or conjugate to this direction. The $M=5.5$ South Izu earthquake of 1934 occurred near the center of the Izu Peninsula. The $M=6.9$ Izu Hanto Oki earthquake of 1974 at the tip of the Izu Peninsula was followed by two months by the $M=4.9$ Amagi earthquake and in 1976 by the $M=5.5$ Kawazu earthquake.

The orientation of faults which have ruptured this century (Fig. 1) is in broad agreement with the orientation of faults and lineaments shown in Fig. 3, and also exhibits the difference in strike between the northeast and southwest blocks.

In Fig. 1 we show the principal horizontal stress orientations derived from the fault planes of Izu Peninsula earthquakes (ABE, 1978); the alignment of monogenetic volcanoes (NAKAMURA, 1969 and personal communication, 1978) which are suggested by Nakamura to reflect the principal compressive stress direction; and the strain which took place between 1924 and 1966 (NAKANE, 1973) which presumably reflects the complete cycle of deformation associated with the 1930 North Izu earthquake on the Tanna fault. This evidence all suggests that the northeast Izu block experiences a NW-SE stress field. This stress field is parallel to the direction of relative motion of the Philippine Sea plate and may be attributed to the collision of the Izu block with Honshu along the southern Fossa Magna. The difference in principal compressional stress orientations between the northeast and southwest blocks, which is evident in the set of earthquakes shown in Fig. 1, is also apparent in the mechanism solutions determined by ICHIKAWA (1970).

In the northwest corner of the Izu Peninsula, normal faulting occurs on faults striking NNE (Fig. 3), indicating horizontal WNW tension. This tensional stress may indicate that the Philippine Sea plate margin along the inner Suruga trough, experiencing relatively little resistance compared with the landward segment further north, is being dragged downward by the stronger subduction along the outer Suruga trough. We might therefore expect that across the northern shore of Suruga Bay there would be a strong contrast in convergence rate which would be reflected, for example, in right lateral strike slip motion normal to the Suruga trough. However, no such evidence for a discontinuity in convergence rate is apparent.

Relation of intraplate earthquakes to collisional deformation in the Izu peninsula

In the northeast Izu block, the Tanna fault which strikes N-S and undergoes left lateral strike slip is conjugate with the Izu-Oshima fault which strikes E-W and undergoes right lateral slip. These two faults are thereby accomodating the NW-SE compressional stress which was examined in the previous section. The maximum horizontal displacement of the Tanna fault during the 1930 North Izu earthquake was 3.5 m (MATSUDA, 1972), and the average horizontal displacement determined from triangulation data was 3 m (ABE, 1978). The average horizontal displacement associated with the 1978 Izu-Oshima earthquake was found to be 1.85 m from geodetic and seismological analysis (SHIMAZAKI and SOMERVILLE, 1978). The occurrence of two major earthquakes this century on faults between Izu-Oshima and the Izu Peninsula suggests that this fault system is equally as active as the Tanna fault.

If we infer from the 841 and 1930 North Izu earthquakes that a horizontal displacement of 3 m occurs once every thousand years on the Tanna fault, and assume a similar rate of motion on the Izu-Oshima fault, then these two faults may together accomodate a NW-SE shortening on the SW margin of the northeast Izu block of as much as 0.4 cm/yr. The contraction experienced by the segment of the collision zone northwest of the Tanna fault would be correspondingly reduced. This segment of the collision zone is oriented roughly normal to the direction of motion of the Izu block, suggesting that the resistance to convergence is greatest there. Thus the location of the Tanna and Izu-Oshima faults may reflect the position of the zone of direct collision, since they are accomodating crustal shortening in front of this zone.

According to the above calculation, the rate of convergence of this segment of the collision zone is being reduced from the value of 1.2 cm/yr, derived previously from the relative motion along the Sagami trough, to a value of 0.8 cm/yr, due to the shortening of 0.4 cm/yr afforded by the Tanna and Izu-Oshima faults.

Distance measurements derived from triangulation data (H. SATO, personal communication, 1978) suggest a rate of convergence of approximately this value across the collision zone in the interval 1924–1973 (Table 1). The Ashitakayama and Kammuridake stations (Fig. 1) on the Philippine Sea plate were assumed by SATO (1973) to have been unaffected by the 1930 North Izu earthquake. These measurements are therefore assumed to reflect the deformation occurring in the collision zone. If we assume that the maximum shortening occurred in the NW–SE direction, then the contractions between Ashitakayama and Kenashiyama, and between Kammuridake and Tanzawayama correspond to shortening rates of 0.80 and 0.66 cm/yr respectively. These two values are quite consistent, and are in good agreement with the value of 0.8 cm/yr estimated above on the basis of seismological data.

Table 1. Distance changes across the southern Fossa Magna. Crustal Dynamics Division, Geographical Survey Institute, 1978.

OBSERVATION POINTS	DISTANCE (m)	
Ashitakayama-Kenashiyama	34234.896	(1924)
	34234.510	(1973)
Kanmuridake-Tanzawayama	29672.066	(1924)
	29671.953	(1973)
Kanmuridake-Ashitakayama	19789.600	(1924)
	19789.578	(1973)

Geological evidence supports a shortening rate of this order. Shortening on the Kannawa fault itself (Fig. 1), which is assumed to constitute the plate boundary, is very small, since a vertical displacement rate of about 0.1 cm/yr (MACHIDA et al, 1975) is occurring on an almost vertical fault. However, in the southern Tanzawa Mountains north of the Kannawa fault, a 20,000 year old river terrace has been raised 60 meters (MATSUDA, personal communication, 1978). If we assume that this uplift represents a general uplift of the Tanzawa Mountains, and that an equivalent shortening has taken place, then we obtain a shortening rate of 0.3 cm/yr.

The activity of the collision zone is further demonstrated by the SE trending flank fissure eruption of Mt. Fuji in 1707, indicating NW-SE contraction, which followed the 1703 Sagami Bay earthquake (NAKAMURA, 1975). Further interpretation of this event will be made in a later section.

If it is assumed that convergence at a rate of 0.8 cm/yr is occurring across the collision zone, then a differential slip of 2.2 cm/yr must be occurring between the Sunzu fault and the collision zone. As in ISHIBASHI's (1978) model, this differential slip is being accomodated by right lateral strike slip motion on faults striking approximately NW-SE in the southern part of the Izu Peninsula. This strike slip motion is in turn accomodated by subduction whose rate decreases northward along the Suruga trough. Taking the maximum rate of displacement of 0.1 cm/yr estimated for the Irozaki-median fault by MATSUDA and YAMASHINA

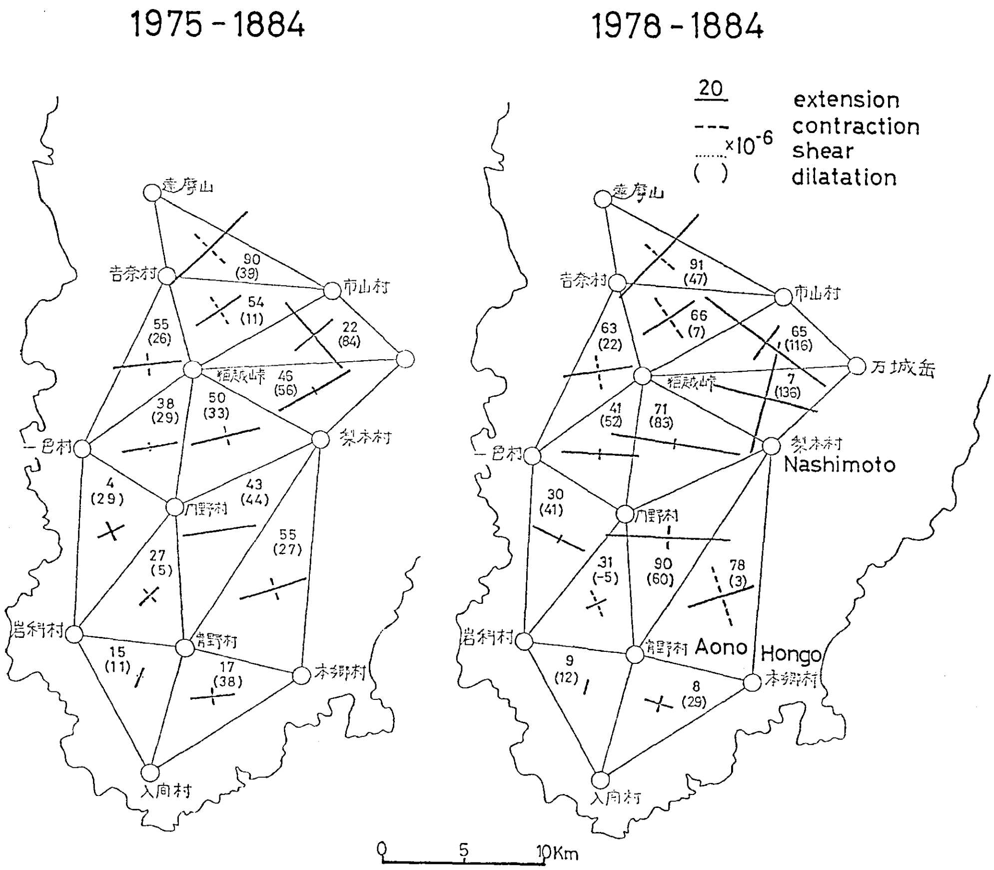

Fig. 5. Deformation of the Izu Peninsula during a) 1884-1975 and b) 1884-1978. CRUSTAL DYNAMICS DIVISION, GEOGRAPHICAL SURVEY INSTITUTE, 1978.

(1974), we require twenty-two equally active parallel faults distributed across the Izu Peninsula to accomodate this rate of differential slip. The faults and lineations shown in Fig. 3 indicate that such a rate of faulting motion may be taking place, although it would appear to be an upper limit of fault activity.

The geodetically measured deformation of the southern Izu Peninsula during the past one hundred years (CRUSTAL DYNAMICS DIVISION, GEOGRAPHICAL SURVEY INSTITUTE, 1978) provides strong confirmation of the sense and magnitude of the deformation proposed above. From Fig. 5 we see that extensions generally trend E-W and contractions N-S, indicating shear in a NW-SE (or NE-SW) direction. Choosing the largest triangle (Nashimoto-Aono-Hongo) for analysis, we find a shear strain of 5.5×10^{-5} oriented roughly WNW for the interval 1884-1975 (which excludes the Kawazu and Izu-Oshima earthquakes), and a shear strain of 7.8×10^{-5} with a similar orientation for the interval 1884-1978. These values represent rates of shear strain of 2.8 and 4.0 cm/yr averaged over the width of the Izu Peninsula (assumed to be 50 km). These values are in accord with the rate of 2.2 cm/yr deduced from the difference in the rates of convergence between the Sunzu fault and the collision zone. We conclude that shear deformation of the kind proposed in our model is in fact taking place.

Mechanical interrelationships in the tectonic activity of the Izu block

We have already noted that the Tanna and Izu-Oshima faults play the role of accomodating crustal shortening in front of the zone of direct plate collision. In this section we explore other relationships between tectonic phenomena in the Izu block.

Both of the two large earthquakes on the Tanna fault were preceded by great earthquakes on the Sagami trough by a few tens of years (Table 2). This may be explained by the fact that right lateral slip on the Sagami trough would impose a NW compressive stress on the northeastern Izu block because its motion is impeded by collision with Honshu in the southern Fossa Magna. This NW-SE compressive stress is then released by left lateral slip on the N-S striking Tanna fault. Such motion on the Tanna fault actually occurred at the time of the 1923 earthquake (IMAMURA, 1931).

Reasons for the apparent absence of an earthquake on the Tanna fault after the 1703 Sagami Bay earthquake have been suggested by

Table 2. Occurrence times of great Sagami trough earthquakes and Tanna fault earthquakes.

SAGAMI TROUGH		—	TANNA FAULT	
Year	Mag.		Year	Mag.
818	7.9		841	7.0
1703	8.2		—	
1923	7.9		1930	7.0

Nakamura (personal communication, 1978). Strain accumulated in the northern tip of the Philippine Sea plate as a result of the slip along the Sagami trough during the 1703 earthquake. This strain was released by the 1707 Nankai earthquake along the subducting part of the plate margin, including the Suruga trough, and by deformation along the colliding part resulting in the eruption of Mt. Fuji in the same year. This fissure eruption occurred on the southeast flank, indicating NW-SE contraction and NE-SW extension. Thus the absence of an earthquake on the Tanna fault is a consequence of the strain in the Izu block having been released entirely by interplate activity.

The short interval of time between the occurrence of the 1974 Izu Hanto Oki earthquake and the 1978 Izu-Oshima earthquake suggests that there may have been a causal mechanical relationship between the two events. YAMASHINA (1978) concluded that the 1974 earthquake enhanced the differential strain on faults in the central Izu Peninsula, thereby possibly triggering a sequence of earthquakes which culminated in the Kawazu earthquake of 1976. However it appears that the differential strain on the Izu-Oshima fault would have been little affected by either the Izu Hanto Oki or Kawazu earthquakes if we consider only the elastic response of an infinite half-space.

MOGI (1977) proposed that the occurrence of the Izu Hanto Oki earthquake allowed an increase in the subduction rate of the Philippine Sea plate, which was accomodated by increased subduction along the outer Suruga trough but which caused the build up of compressive strain in the Izu Peninsula. This compressive strain, oriented roughly northwest parallel to the direction of plate motion, would be released by right lateral slip on the E-W striking Izu-Oshima fault.

Anomalous uplift in the vicinity of Hiekawa Pass (Fig. 1) on the east coast of the Izu Peninsula was observed before both the 1930 North Izu earthquake (TSUBOI, 1931) and the 1978 Izu-Oshima earthquake (CRUSTAL DYNAMICS DIVISION, GEOGRAPHICAL SURVEY INSTITUTE, 1976). This anomalous area lies between the Tanna and Izu-Oshima faults, within the previously described NW-SE trending zone which is accomodating the largest amount of shortening in the collision process. The anomalous physical properties of this region are reflected in the fact that it is the site of the most recent volcanic activity in the Izu Peninsula.

The uplift which occurred in 1975-1976 has been interpreted in terms of expansion of a buried spherical magma reservoir (GEODETIC SURVEY PARTY, EARTHQUAKE RESEARCH INSTITUTE, 1976) using the model of MOGI (1958), and by creep dislocation models (ISHIBASHI, 1977; FUJII, 1977). It appears likely, however, that these episodes of crustal uplift are directly related to the stresses that generate the earthquakes that follow. The fact that the uplifts appear to have occurred rapidly, and remained after the earthquakes that followed, suggests non-linear plastic deformation at some critical stress of a volume having anomalous rheological properties which may be related to magmatism.

The area of anomalous uplift is located almost symmetrically between the Tanna and Izu-Oshima faults. Further symmetry exists in the location of the Hakone and Izu-Oshima stratovolcanoes (Fig. 1) at the ends nearest the plate boundary of the Tanna and Izu-Oshima faults respectively. Since volcanoes constitute weak spots which yield plastically at low stress levels, stress would be concentrated in the stronger material surrounding the volcano. We might therefore expect earthquakes to nucleate in this zone adjacent to the volcano and propagate unilaterally away from the volcano.

This sense of propagation occurred during the mainshock of the 1978 Izu-Oshima earthquake (SHIMAZAKI and SOMERVILLE, 1978) although the foreshock which occurred six seconds earlier appears to have propagated towards Izu-Oshima (SUDO et al, 1978). It appears, however, that rupture on the Tanna fault during the 1930 North Izu earthquake propagated towards Hakone volcano. The epicenter of the first of a series of shocks which constituted this earthquake was located near the southern end of the Tanna fault by IMAMURA (1931), and it is apparent from KUDO's (1978) study of Love waves recorded in Tokyo that rupture propagated either bilaterally or unilaterally northward, but not unilaterally southward away from the volcano.

Discussion and conclusions

The principal difference between the model proposed in this paper and that of ISHIBASHI (1978) lies in the rate of interplate convergence in the northeast Izu block and in the explanation of how it is being accomodated. Ishibashi proposes that convergence at a rate equal to that along the outer Suruga trough is taking place by subduction along the northeast coast of the Izu Peninsula. However, we have seen that the rate of motion of 1.2 cm/yr along the Sagami trough deduced from coastal terrace data and historical seismicity can be fully accounted for by the shortening of as much as 0.8 cm/yr measured geodetically across the Fossa Magna, and by crustal shortening of as much as 0.4 cm/yr due to slip on the Tanna and Izu-Oshima faults. This casts doubt on the existence of subduction along the northeast coast of the Izu Peninsula proposed by Ishibashi.

The slip rate of 1.2 cm/yr along the Sagami trough which we have used is compatible with both the elevation of coastal terraces and historical seismicity. However, if we allow a larger rate of convergence along the Sagami trough, then some other process, such as the subduction proposed by Ishibashi, is required to accomodate the motion of the Philippine Sea plate.

The 1978 Izu-Oshima earthquake is not readily explained by Ishibashi's model, since the Izu-Oshima fault cuts obliquely across the proposed subduction zone east of the Izu Peninsula in a direction which is not parallel to the orientation of his proposed transform belt. This casts doubt on the existence of the proposed subduction zone along the southeast coast of the Izu Peninsula, which is required in order to accomodate the transfer of a uniform convergence rate from the proposed subduction zone off the northeast coast of the Izu Peninsula to the outer Suruga trough. In the model proposed in this paper, the convergence rate decreases northwards and consequently a subduction zone off the southeast coast of the Izu Peninsula is not required.

The collision between the Philippine Sea plate and the Eurasian plate in south central Honshu is reflected in the mechanisms of intraplate earthquakes and other tectonic processes occurring in the Izu block. The collision is reflected in the reduced rate of motion along the Sagami trough (estimated to be as little as 1.2 cm/yr from coastal elevation changes and historical seismicity) compared with the value of 3 cm/yr along the outer Suruga trough estimated from the rotation rate of the Philippine sea plate and its rate of subduction as reflected in Nankai trough earthquakes. A considerable part (as much as 0.4 cm/yr) of the northwest motion of the northeast Izu block is accomodated by slip on the Tanna and Izu-Oshima faults: the remaining convergence is accomodated directly by strain across the collision zone itself, geodetically estimated to be as much as 0.8 cm/yr.

In the southeast Izu block, the difference in convergence rate between the collision zone and the outer Suruga trough produces NW-SE shear strain which is accomodated by slip on the network of NW-SE striking faults in the Izu Peninsula, and subduction along the inner Suruga trough which decreases northward. This sense and rate of shear deformation is clearly reflected in the geodetically measured deformation of the southern Izu Peninsula during the past hundred years.

The proposed model suggests explanations for various mechanical correlations between tectonic features of the Izu block, such as the presence of the Tanna fault, the Hiekawa Pass uplift region, and the Izu-Oshima fault in front of the zone of direct plate collision, and the observation that great earthquakes on the Sagami trough are followed by rupture on the Tanna fault.

In this paper, we have explained the consequences of the proposed northward decrease in convergence rate only in the Izu block itself. The implications for the region south of the Izu Peninsula are left for future investigation.

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32. 伊豆ブロック内の変形によるプレートの衝突の緩和

地震研究所　Paul SOMERVILLE

伊豆ブロックのプレート内変形を，フォッサマグナ南部におけるフィリッピン海プレートとユーラシアプレートとの衝突によって説明するモデルを提出する．両プレートの衝突により異なる方向性をもつ二つのストレス場が生ずる．北東伊豆ブロックでは，プレートの衝突によって，その運動が妨げられ，北西南東方向の圧縮歪を生ずる．この結果，0.4cm/年の短縮が南北走向の丹那断層での左ずれとそれに共役な東西走向の伊豆大島断層での右ずれとによって起きている．北西南東方向の短縮は衝突ゾーンでの変形によっても受け持たれている．測地データによればこの量は0.8cm/年に達する．上記二つの過程での短縮速度を加えることによって，相模トラフ沿いで海岸段丘や歴史地震の活動度から求められているプレートの収束速度，1.2cm/年をうまく説明することができる．このように考えれば，石橋（1978）の提唱する伊豆半島北東岸沖のサブダクションゾーンを必要としない．南西伊豆ブロックでは駿河トラフ南部（3cm/年）と衝突ゾーン（約1cm/年）とのプレートの収束速度の差によって，プレートの相対運動の方向にせん断歪を生ずる．このせん断歪は，伊豆半島内の北西南東方向の横ずれ断層群と，駿河トラフ北部でサブダクションが北へ向って減少することとで解消されている．このせん断歪の向きと速度とは，過去100年の測地データから求められる伊豆半島の変形に明らかに反映されている．直接プレートが衝突する地域の前面に丹那断層，冷川峠の隆起域，伊豆大島断層が存在することや相模トラフの巨大地震の後に丹那断層で地震が起ることなど，伊豆ブロックのテクトニックな諸特徴間の様々な力学的相関の説明を，ここに提唱するモデルは示唆している．