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Sea-floor mapping of the Sumisu Rift, Izu-Ogasawara (Bonin) Island Arc

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Abstract : The Sumisu Rift in the Izu-Ogasawara Island Arc has been mapped with SeaMARC II and 3.5-kHz echograms. The rift is an elongate graben separating the line of active volcanoes from a remnant arc. Volcaniclastic sedimentation dominates in the rift. Sediments collect in fault-block basins and in two basins on the rift floor, the North and South Basins. Echo-character mapping shows differences in bottom sediments between the basins. Variations in sea-floor sediment echo character are related to the proximity to the arc volcanoes and the presence of physical barriers that control sediment dispersal. Synrift sedimentation along active growth faults is observed in the South Basin.

1. Introduction

The Izu-Ogasawara (Bonin) Island Arc is located between Honshu and the Mariana Islands. Several small basins, first described by MOGI (1968), are found behind the volcanic line from Hachijojima to Nishinoshima Volcanoes. HOTTA (1970), in a crustal study in the northern Izu-Ogasawara Arc, reported that the small depressions are related to high-angle normal faulting. The nature of the basins was enigmatic until KARIG (1971, 1972) proposed that marginal basins in the Western Pacific were formed by the rifting of island arcs. KARIG and Moore (1975a) suggested that the small depressions in the Izu-Ogasawara Arc are incipient back-arc basins. The basins represent a 630 km line of semi-continuous rifting along the central Izu-Ogasawara Arc (TAYLOR *et al.*, 1984). HONZA and TAMAKI (1985) defined four rift basins (Hachijo, Sumisu, Torishima, and Nishinoshima back-arc depressions) which they named after nearby arc volcanoes (Fig. 1). This paper discusses the physiography and distribution of recent sediments and faults in the Sumisu Rift. The Sumisu Rift lies between 30° 30'N and 31° 30'N and between 139° 20'E and 140° 10'E. Although the rift narrows in the south its structures are continuous into the Torishima Rift (TAYLOR *et al.*, 1984).

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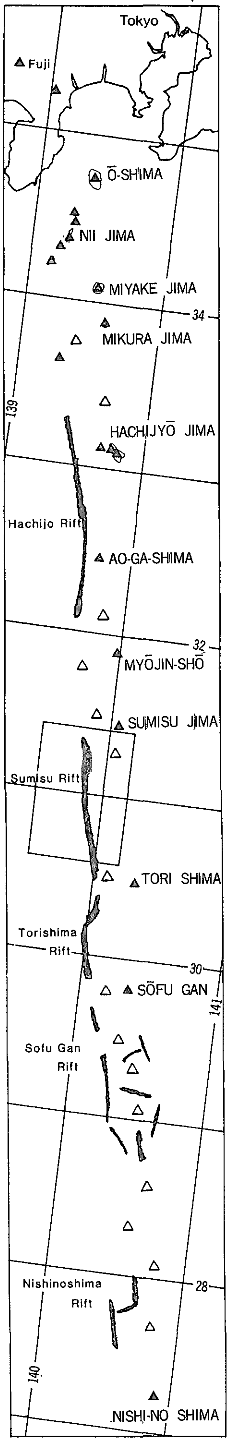
KARIG and MOORE (1975b) and CAREY and SIGURDSSON (1984) have proposed models for sedimentation marginal basins in which sediments deposited in the early stages of intra-arc basin opening would be dominated by coarse volcaniclastics derived from the proximal arc volcanoes. As the basin matures and widens sedimentation would be influenced more by detritus from marine organisms, montmorillonite clays, and wind-blown continental dust. KARIG and MOORE (1975b) estimated sedimentation rates in young troughs to be much greater than 100 m/m.y.

The thickness of the sediment layer in the rift system has been reported by several authors. HOTTA (1970) observed that the Hachijo Rift has a thin sediment cover except



on the western edge of the basin. HONZA and TAMAKI (1985) reported 500 m of sediments in the Nishinoshima Rift and 200 m in the Torishima Rift. Single channel reflection data from the Hawaii Institute of Geophysics (TAYLOR *et al.*,1984) show one second of sediments overlying downthrown blocks in the center of Sumisu Rift. HONZA *et al.* (1982) mapped the regional sea-floor sediment distribution in the Izu-Ogasawara Arc and reported Quaternary hemipelagic (?) sediments covering the Sumisu Rift, surrounded on the east and west by Quaternary volcaniclastic sediments.

This work is based on 3.5-kHz reflection data and SeaMARC II sidescan imagery and bathymetry data. The 3.5-kHz data were collected by the Hawaii Institute of Geophysics (R/V Kana Keoki, 1984) and the Geological Survey of Japan (R/V Hakurei Maru, 1979, '80, '84, '85). Track lines are shown in Fig. 2.

SeaMARC II (Sea Mapping And Remote Characterization) is a shallow-tow sidescan sonar system capable of high resolution seafloor imaging and bathymetry mapping for 5 km on either side of the ship's track (BLACKINTON *et al.*, 1983). The instrument uses an 11-kHz (port) and 12-kHz (starboard) signal with a fore-aft beam width of 2°. In 1984 the R/V Kana Keoki surveyed the Sumisu and Torishima Rifts with the SeaMARC II system. Processed sidescan and bathymetry data for the Sumisu Rift north of 30° 35'N is presented in this paper (Figs. 3 and 4).

2. Physiography

The Sumisu Rift is bounded on the east (active arc side) by a steep 1000-1500 m fault scarp and on the west (remnant arc side) by a

Fig. 1 Location of the Izu-Ogasawara rift system in the Izu-Ogasawara (Bonin) Island Arc (after TAYLOR *et al.*, 1984; HONZA and TAMAKI, 1985). The main rift segments are Hachijo, Sumisu, Torishima, Sofu Gan (southern rift segment of the Torishima Rift of HONZA and TAMAKI (1985)), and Nishino Shima. Subareal arc volcanoes (solid triangles) and submarine arc volcanoes (open triangles) delineate the Izu-Ogasawara Arc. The study area is outlined by the rectangle.

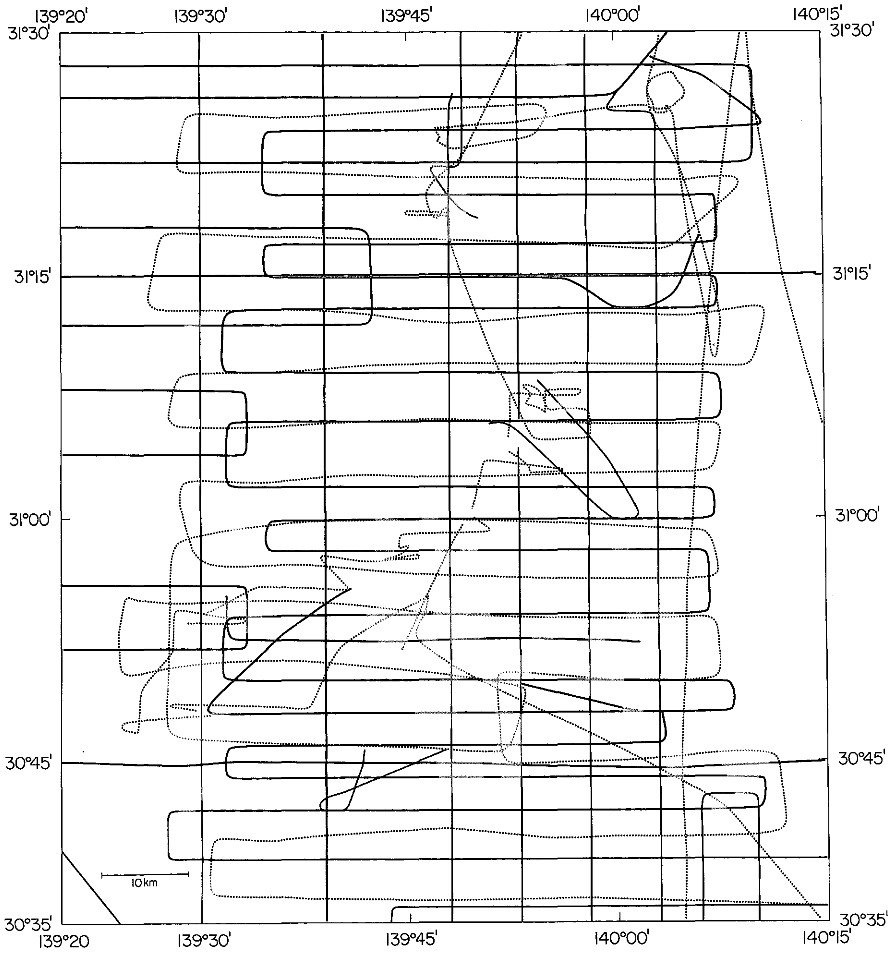


Fig. 2 Track chart of the Sumisu Rift region showing Hawaii Institute of Geophysics (R/V Kana Keoki, dotted lines) and Geological Survey of Japan (R/V Hakurei Maru, solid lines) track segments.

stepped, relatively gentle slope with numerous antithetic fault scarps. The approximate contact between regions offset by east-dipping (Sumisu Rift West Fault Zone-SRWFZ) and west-dipping (Sumisu Rift East Fault Zone-SREFZ) faults (the rift axis) is shown in Fig. 4. The rift is asymmetric, with a deep subgraben on its eastern side. Over 200 volcanic centers are found in the study area (Fig. 5). The volcanoes average 100-200 m relief, 1-3 km in diameter, and have a composition ranging from tholeiitic basalt to sodic rhyolite (FRYER *et al*, 1985). Intra-rift volcanoes separate the rift floor into two provinces: the Sumisu Rift North Basin (SRNB) and the Sumisu Rift South Basin (SRSB) (Fig. 4). The SRSB has a smooth floor which covers a wide area and has an average depth of 2200 m. In contrast the SRNB has two levels: a narrow lower level (shown in Fig. 4), which is smooth in the south becoming hilly in the north, and an upper level which is part of the faulted west slope of the graben.

Sumisu Jima is an active island arc volcano located just to the northeast of the SeaMARC II mosaic. The island is the subareal tip of a submarine caldera (MURAKAMI, 1986). The southern flank of Sumisujima Volcano covers

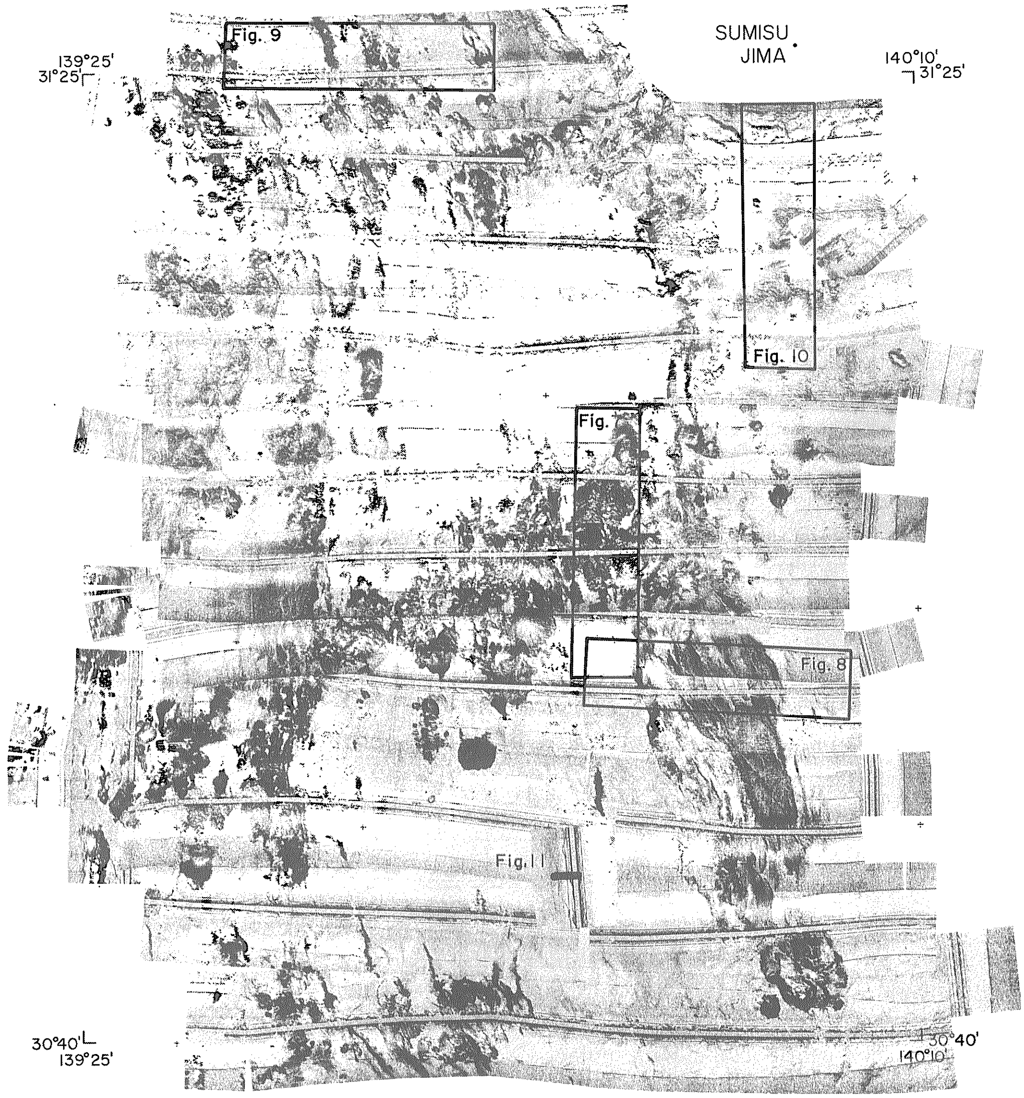


Fig. 3 Processed SeaMARC II mosaic of the Sumisu Rift. Individual files have been corrected for bottom detect errors and combined to produce the final mosaic. The ship track is shaded with an artificial grey shade. Enclosed areas and line segments refer to Figures 7 through 11.

the northeast corner of the mosaic. Twenty kilometers south of Sumisujima Volcano is a 350 m deep submarine volcano (hereafter referred to as "South Sumisu"). Tori Shima, an active subareal arc volcano, lies southeast of the SeaMARC II mosaic (Fig. 1).

3. Echo character and fault mapping

Echo soundings record acoustic returns from the sea floor and the distribution of various echotypes may be systematically mapped (e.g. DAMUTH, 1978 ; DAMUTH, 1980; NEMOTO and KROENKE, 1981 ; OKAMURA and NAKAMURA, 1981 ; DAMUTH *et al.*, 1983). Echo-character mapping of sediment is limited in its capabilities. Without bottom data (e.g.

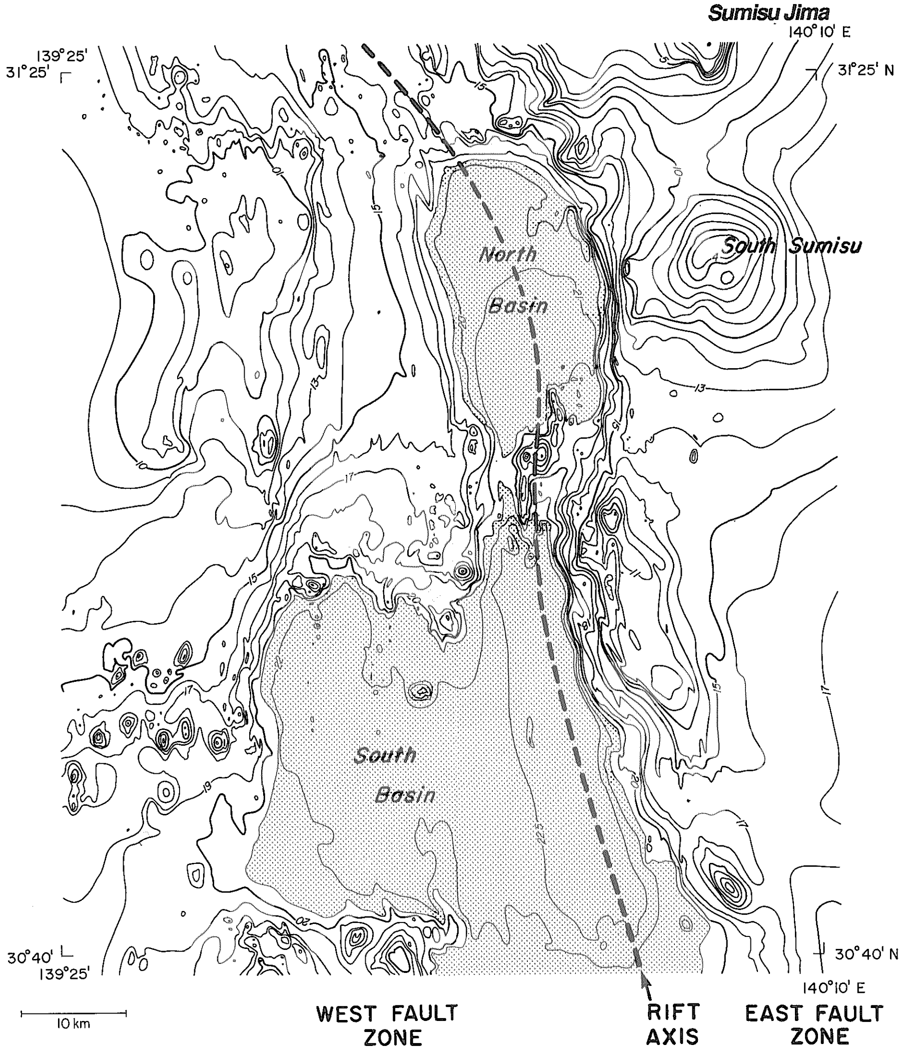


Fig. 4 SeaMARC II bathymetry of the Sumisu Rift (contour interval 100 m.). The South Basin and the deeper part of the North Basin are shaded. The approximate location of the rift axis is indicated with a dashed line.

core samples, bottom photographs) interpretation is qualitative. It is often impossible to determine the genetic origin of echotypes from the echo character alone (DAMUTH, 1980), although the echo character can be used to study sediment distribution and bottom processes such as turbidity flows and bottom currents (DAMUTH, 1980 ; EMBLEY, 1980; SWIFT, 1985). In this study the 3.5-kHz data proved useful in distinguishing differences in sediments, mapping faults, and identifying features on the SeaMARC II side-scan data.

Echograms from the Sumisu Rift were studied and classified based on the nature of subbottom reflectors (a similar method to that used by DAMUTH (1980). Echocharacter types and faults were plotted along the ships' tracks and then compared with the SeaMARC II sidescan mosaic. Normal faults that were

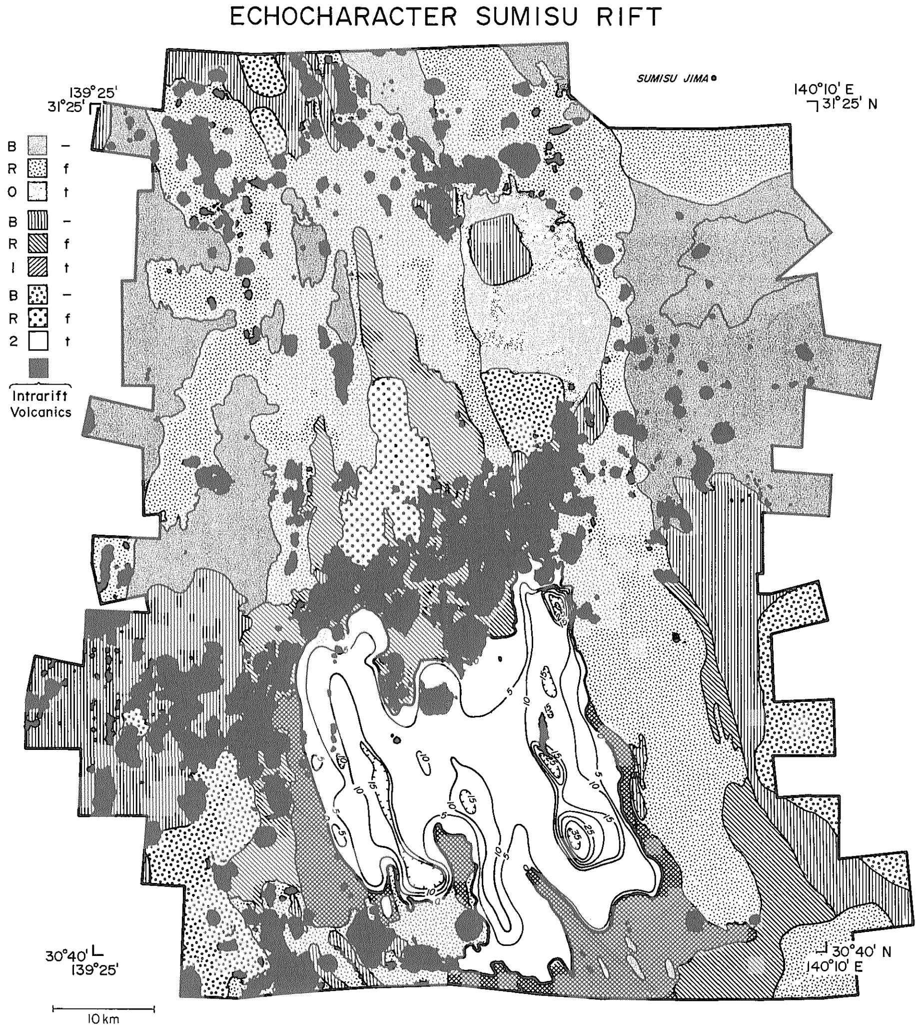


Fig. 5 Echo-character distribution in the Sumisu Rift based on 3.5-kHz echograms and SeaMARC II sidescan data (BR0-no subbottom reflectors, BR1-1 to 3 subbottom reflectors, BR2-greater than 3 subbottom reflectors, suffix "f"-echotype is interrupted by closely spaced faults, suffix "t"-transparent sediment patches overlay echotype). A combination of BR2t and BR2f echotypes is shown by an overlap of patterns. The distribution is controlled by the proximity of arc volcanoes and the presence of barriers to sediment transport. Contours in the South Basin refer to the thickness of the continuous transparent layer (contour interval is 5 m., assuming 10 msec = 7.5 m).

identified on the 3.5-kHz records were extrapolated between ships' tracks based on the SeaMARC II sidescan data (Fig. 6).

In the Sumisu Rift, where arc volcaniclastic sediments dominate, subtle changes in seafloor sediment type are often more apparent on the deeper penetrating 3.5-kHz records than on the 12-kHz SeaMARC II sidescan. However, areas of the sea floor with a rough bottom and therefore a high backscatter (e.g. coarse volcaniclastics, or exposed rock) and areas with a steep slope facing the ship's track and therefore high specular reflection (e.g. fault scarps) show significant contrast

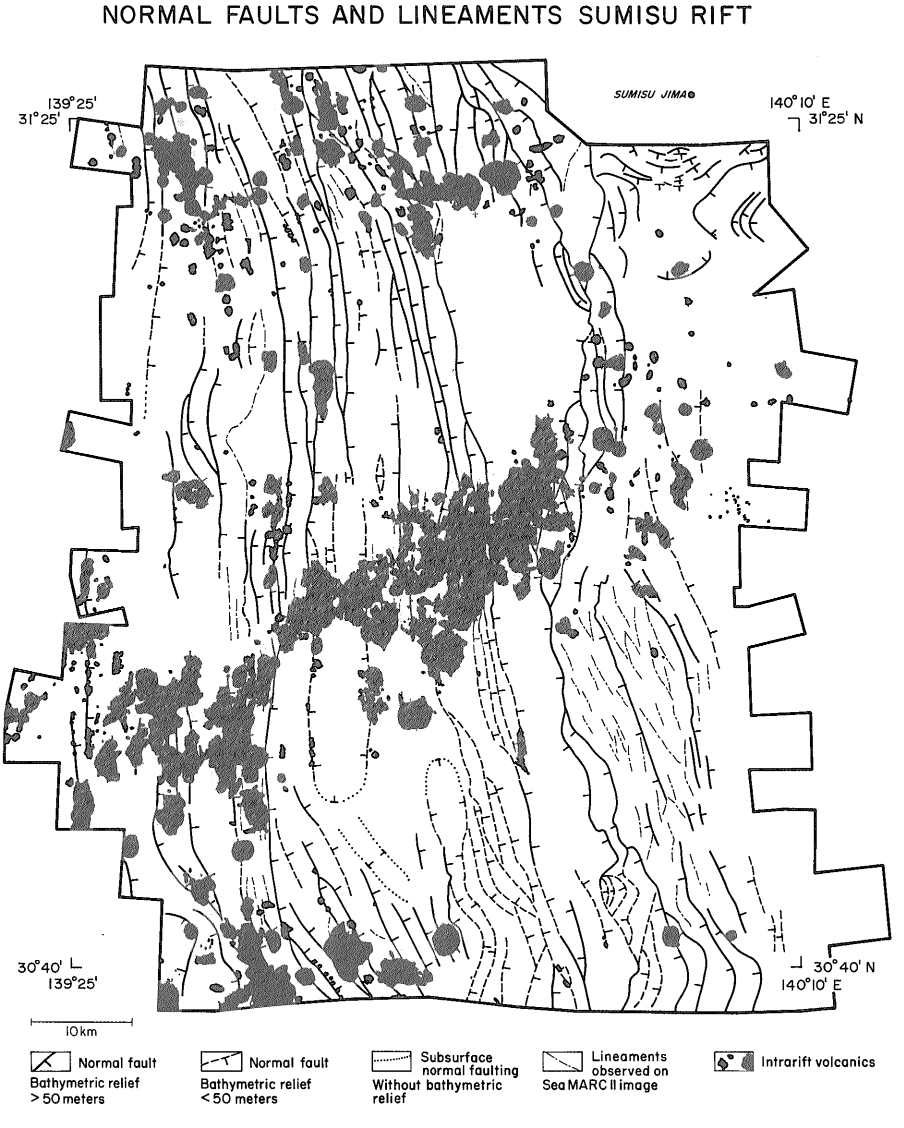


Fig. 6 Normal fault traces and lineations based on 3.5-kHz and SeaMARC II sidescan data. Subsidence of major blocks produces small sags in the overlying sediment pile (e.g. small grabens along the SRWFZ).

with flat lying sediments on the SeaMARC II imagery. If a 3.5-kHz echo-character type is bounded by these features, then the unit can be mapped using the SeaMARC II image as the contrast between features is distinct. For example, the boundary of the sediment in the SRSB is quite distinct because it is surrounded on the west, north, and east by large fault scarps or intra-rift volcanoes (Fig. 3).

Echotypes (Fig. 5), are notated with a prefix "BR" (Bonin rifts). The number following refers to the order of subbottom reflectors. A suffix "f" denotes that the echotype is not continuous but interrupted by closely spaced (i.e. more than 2 per 5km) fault scarps (along east-west ships'tracks, perpendicular to the general trend of rifting). Suffix "t" denotes that the unit is overlain by a transparent sediment layer of variable thickness.

Echotype BR0 (DAMUTH, 1980: Type IIB) is a prolonged echo with no subbottom reflectors. The sea floor is smooth (BR0) to heavily faulted (BR0f). The bottom reflection amplitude varies from weak to strong. The corresponding SeaMARC II sidescan image is dark to medium grey showing some structural features such as ridges and point reflectors. Echotype BR0 is found on the active island arc volcanoes, on the remnant arc, on intra-rift volcanoes, and along fault scarps. The prolonged echotype can be associated with two bottom types: exposed rock or coarse terrigenous material (sand/silt sediment) (DAMUTH, 1980).

Echotype BR1 (DAMUTH, 1980: Type IIA) has a strong bottom reflector, and a somewhat prolonged reflection with 1-3 subbottom reflectors. On 3.5-kHz records the contacts between BR0 and BR1 echotypes are often not distinct. Rather, there is usually a facies change characterized by a gradual increase in the number of subbottom reflectors.

Echotype BR2 (DAMUTH 1980: Type IB) has a distinct smooth bottom with multiple (more than 2) continuous subbottom reflectors. Echotype BR2t is characterized by multiple subbottom reflectors overlain by a continuous transparent layer of varying thickness. A strong reflector lies underneath the transparent layer followed by 4 to 6 weaker more discontinuous reflectors. The BR2t echotype is found only in the SRSB. Hemipelagic sediments, composed of fine-grained pelagic organics and silt detritus eroded from the surrounding footwalls, may explain the continuous SRSB transparent layer.

4. Discussion

4.1 Echo-character distribution

The small basins along the fault zones vary in echo character. Basins above approximately 1300m depth are dominated by a BR0 echotype. Below 1300m basins have BR1 and BR2 echotypes. With increasing depth and distance from the arc volcanoes the change in echo character from BR0 to BR2 may represent a facies change from coarse volcaniclastic sediments to sediments with an increased biogenous content similar to the model proposed by CAREY and SIGURDSSON (1984). Episodic influxes of pyroclastic or epiclastic sediments from volcanic eruptions, debris flows-turbidity currents, or changes in bottom currents may explain the layering.

The upper transparent echotype is found only in the deepest parts of the graben (Fig. 5). In the SRSB the transparent layer is smooth and continuous. The even distribution of the sediment layer implies that there are strong currents (relative to the particle size) that sweep across the basin floor. In the northern SRNB transparent sediments fill depressions between hills of BR0 echotype. Northwest of the SRNB transparent sediment is continuous and overlies a BR0 echotype.

Bottom-camera photographs and sediment-dispersal studies north of Hachijo Jima show that effects of the Kuroshio geostrophic current are found as deep as 1000 m (INOUCHI and KINOSHITA, 1981). The Kuroshiro Current flows from the Shikoku Basin into the North Pacific over the Izu Ridge (Izu-Ogasawara Arc). TAFT and FREITAG (1979) measured bottom current velocities over the Izu Ridge. They concluded that south of 32° 40'N the volume of transport in the northeast direction lessens in favor of flow to the south and recirculation in the Shikoku Basin. Although the Kuroshiro Current has deep-water motion over the Izu Ridge, it may have little effect on the movement of bottom sediments in waters as far south as Sumisu Rift.

Intra-rift volcanoes are shown on Fig. 5. Reflections on the 3.5-kHz echograms from the volcanoes appear as hyperbolae, the summits being point reflectors (diffraction points).

The subbottom echos are prolonged (BR0). The edge of a tilted fault block can appear similar to an intra-rift volcano on the wide beam (30°) echosounder records, but can generally be distinguished with the aid of the SeaMARC II data. The distribution of volcanoes in the rift graben and on the remnant arc is structurally controlled. The volcanoes are usually found at the foot of fault scarps. Except for a few of the large seamounts, the volcanoes are elongated parallel to the north-trending faults, and clusters of aligned vents are common. Most of the eruptions have been from central vents, but a few may be fissure eruptions.

The echo character of the sea-floor in the SRNB is similar to that of the undisturbed reflector lying under the transparent layer in the SRSB (Fig. 7B). The SRNB is over 100m above the SRSB. The intra-rift volcanoes between the SRNB and the SRSB appear to be a barrier to sediment transport. Sediment cores from the SRNB obtained by the Geological Survey of Japan contain more ash beds and coarse-grained sediments than do cores from the SRSB which are dominated by silt-sized sediments (Geological Survey of Japan, 1985). This may explain the difference in echo character between the two basins. Sedimentation in the SRNB is dominated by volcaniclastic debris shed from Sumisujima and South Sumisu Volcanoes. The intra-rift volcanic ridge between the basins restricts movement of coarse volcaniclastic ash into the SRSB.

4.2 Sumisu Rift East Fault Zone

The SREFZ has a complex structure on the sidescan image (Fig. 8A). On the 3.5-kHz record, rock exposed by normal faulting (footwall rock) has a BR0 echo character. The occasional point reflector on the echo record may be from the termination of sediment bedding planes. At the base of the exposed footwall lies the SRSB with a BR2t echo character to the west (a). A thicker transparent layer in the SRSB correlates with areas of fault-block subsidence. Terraced basins less than 2 km wide are found along the stepped fault zone (b). These sediment accumulations have white to grey shade on the SeaMARC II sidescan image. The small hyperbolic reflection on the 3.5-kHz record corresponds to a small ridge on the sidescan image. A "v" shaped structure on the SeaMARC II image (c) is formed by the contact between a bedding-plane ledge and a normal fault. The uplifted block is apparently down-faulted to the east (d). Forearc basin sediments with a BR2 echotype are blanketing the fault-block structures (e).

4.3 Sumisu Rift West Fault Zone

Basins along the SRWFZ (Fig. 9) are much broader than those on the SREFZ. The basin of BR2 echotype (a) is covered on the west by an additional sediment layer. A ridge of intra-rift volcanoes, associated with a fault, (b) separates the BR0 echotype basin from a BR1 echotype basin. The deepest basin (c) is bounded on the east by the SREFZ (d). The basin has a BR0t-echotype and overlies the rift axis. The variations in sediment echotypes between neighboring fault-block basins, which are separated by volcanic ridges or fault-block ridges, suggests that the ridges affect the distribution of sediment.

4.4 Sumisu Jima and South Sumisu

Sumisujima and South Sumisu Volcanoes have a BR0 echotype (Fig. 10). The flanks of the volcanoes show evidence of mass-wasting. On the SeaMARC II image, headwall scars of slumps are seen as highly reflective concentric arcs lying around the south ediface of Sumisujima (a). On 3.5-kHz and single-channel records there are offsets in the sea floor corresponding to the slumps. At (b) a rough area on the SeaMARC II sidesscan data is not obvious on the 3.5-kHz data except for a change in slope. This feature is thought to be a debris or lava flow originating near a flank volcano at (c). A region of rough bottom on the summit of South

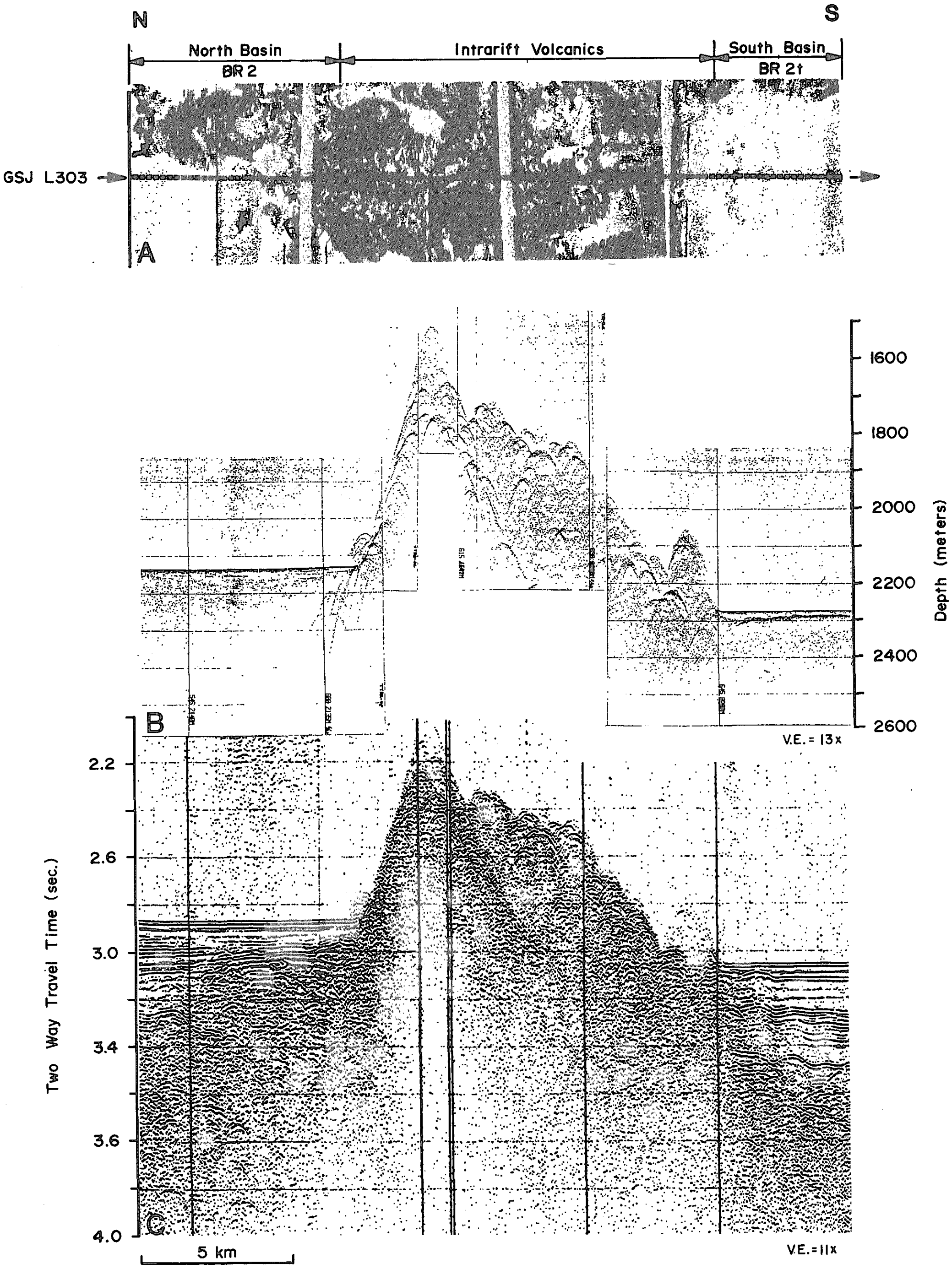


Fig. 7 Sumisu Rift North Basin (SRNB) and the Sumisu Rift South Basin (SRSB) (N-S profile) : 7A, SeaMARC II sidescan image ; 7B, GSJ 3.5-kHz record ; 7C, GSJ single-channel reflection record.

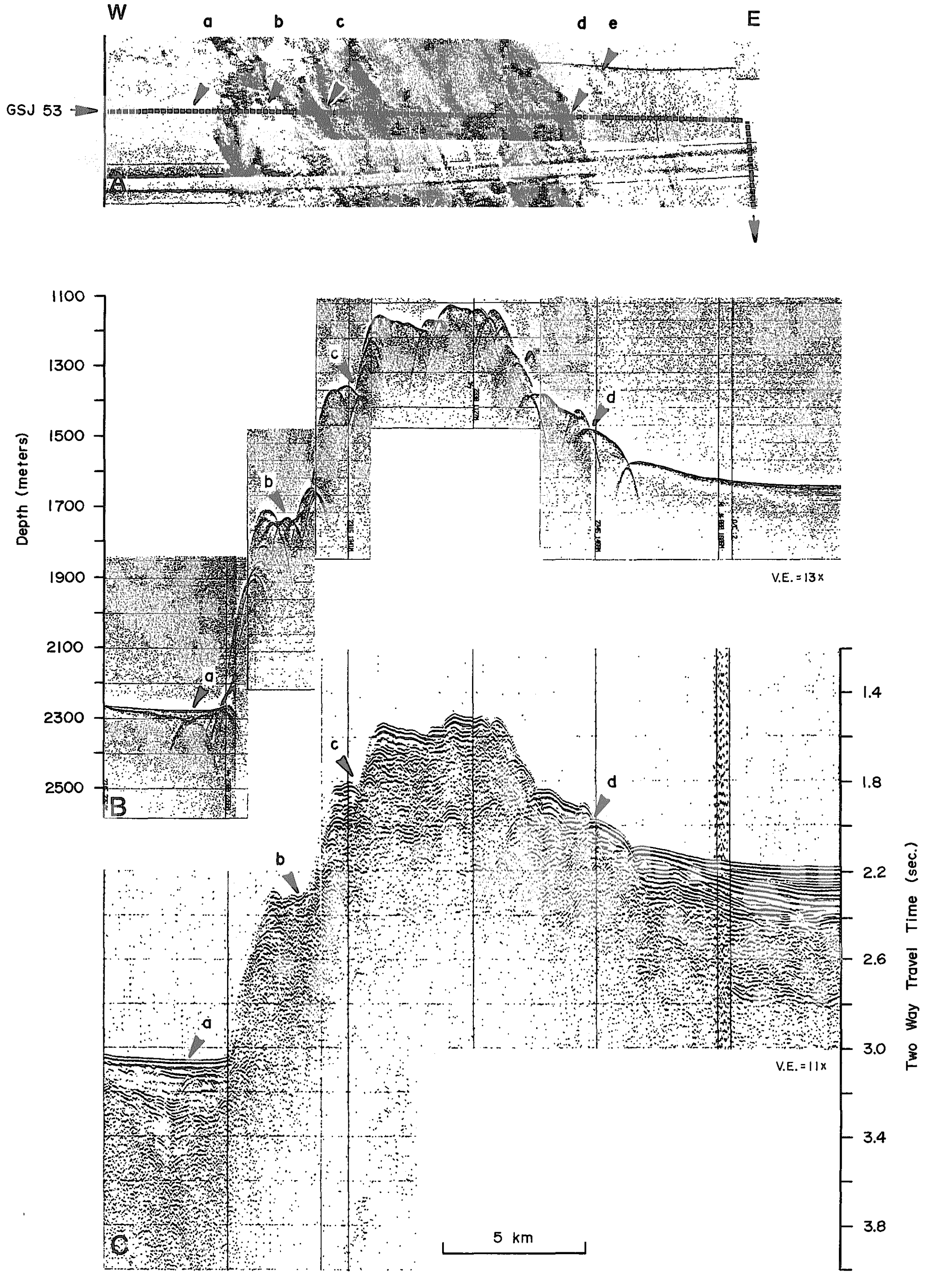


Fig. 8 Sumisu Rift East Fault Zone (E-W profile) : 8A, SeaMARC II sidescan image ; 8B, GSJ 3.5-kHz record ; 8C GSJ single-channel reflection record.

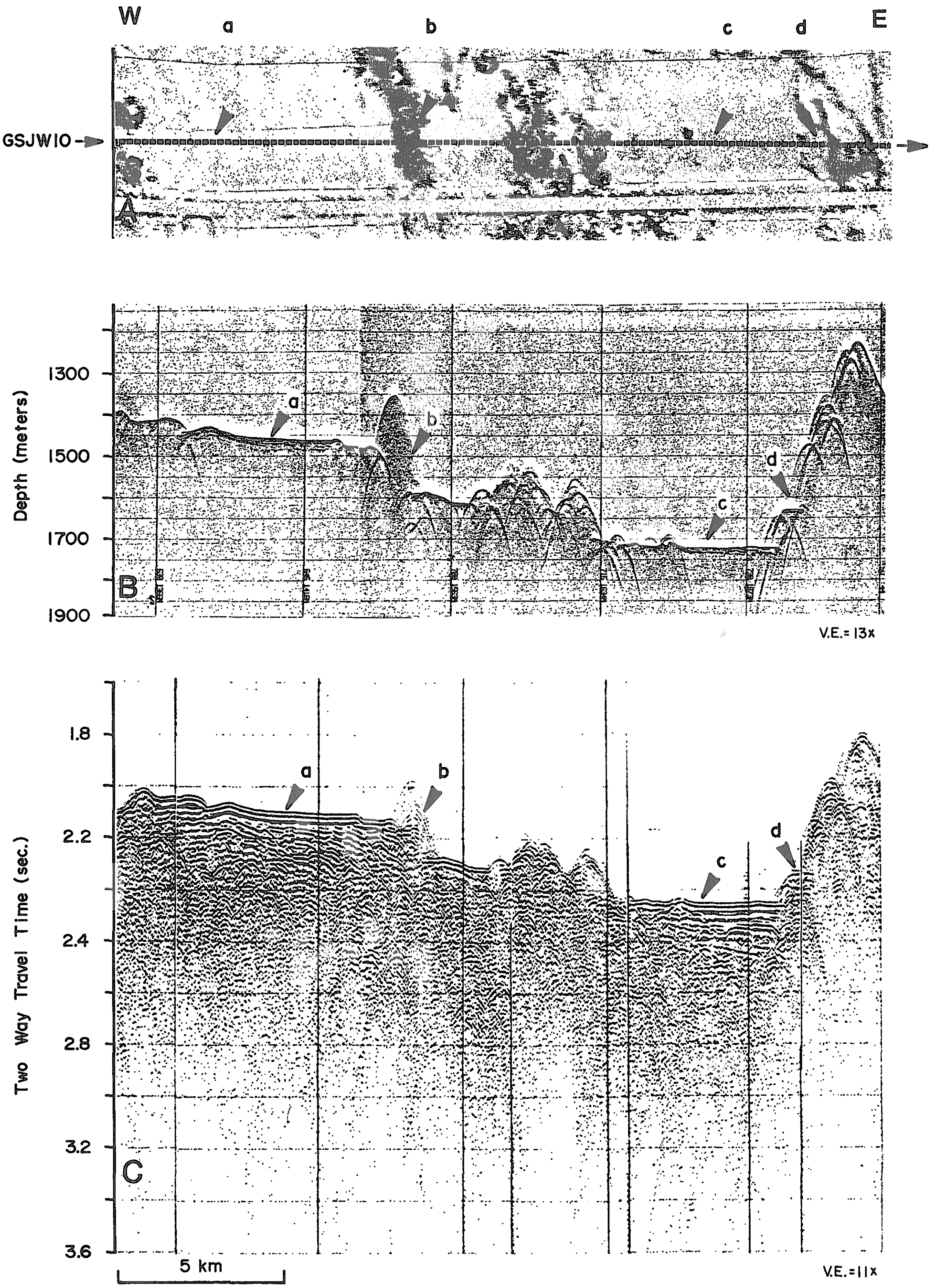


Fig. 9 Sumisu Rift West Fault Zone (E-W profile) : 9A, SeaMARC II sidescan image; 9B, GSJ 3.5-kHz record, 9C. GSJ single-channel reflection record.

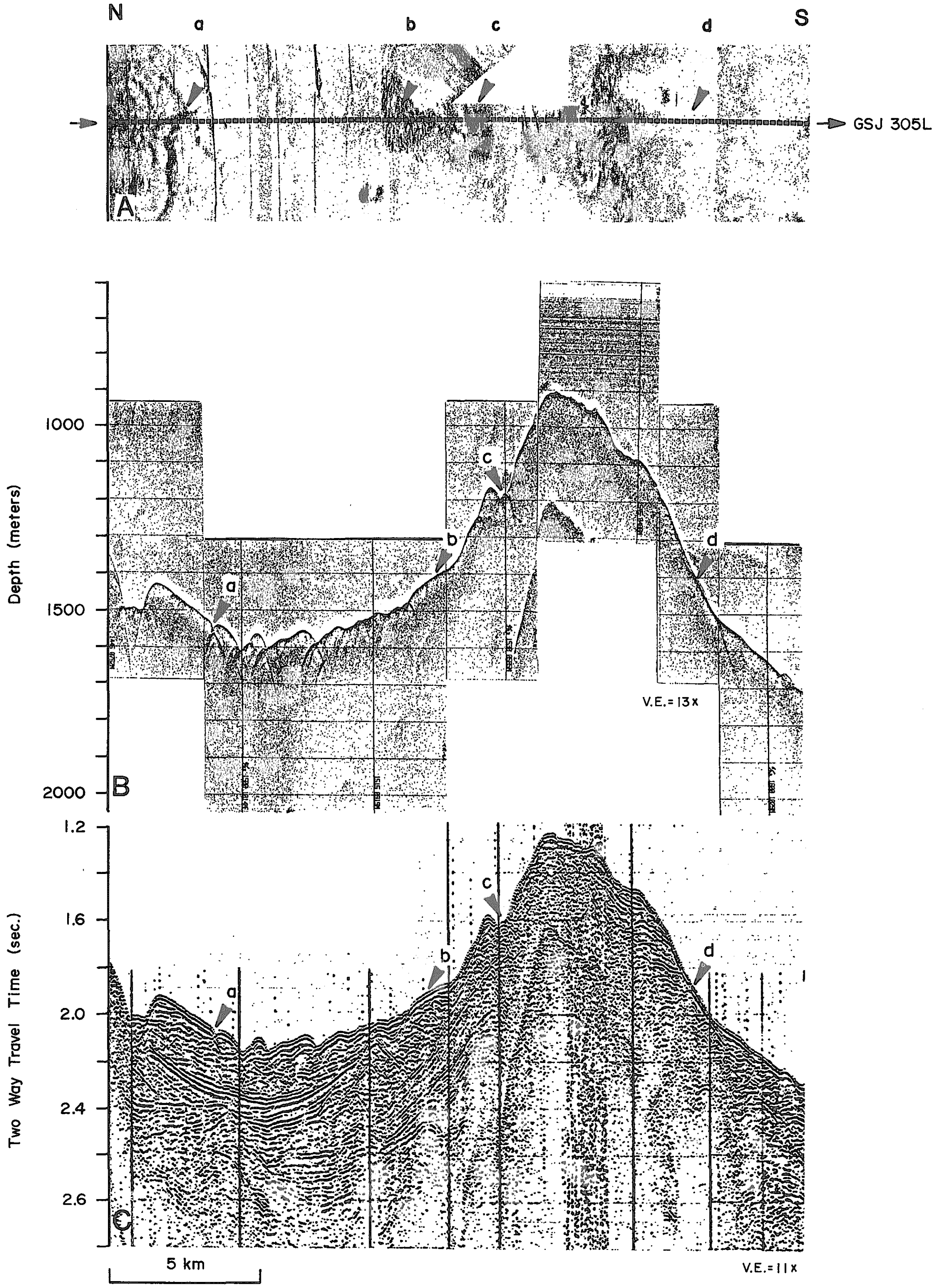


Fig. 10 Sumisujima and South Sumisu Arc Volcanoes (N-S profile) : 10A, SeaMARC II sidescan image ; 10B, GSJ 3.5-kHz record; 10C, GSJ single-channel reflection record.

Sumisu is seen on the SeaMARC II image (from (c) to (d)). The summit unit cannot be distinguished on the 3.5-kHz record, except that it corresponds to a change in slope. The summit unit is believed to be either exposed volcanic rock (suggested by single-channel seismic data) or coarse-grained volcaniclastic sediment.

4.5 Normal faults and lineaments

Fault scarps appear black on the sidescan image. In places where the ship track is perpendicular to small faults (less than 50m. bathymetric relief) the scarp appears as subtle discontinuities in the sidescan image on a small scale (large size) copies of the sidescan data (e.g. small faults in the SRSB). Small scarps are better imaged when the ship track is parallel to the fault scarp and on the down-dip side of the fault. Lineaments observed on the SeaMARC II sidescan image and mapped on Fig. 6 may be primary structures of exposed stratified rock or unmapped faults.

The distribution of normal faults in Fig. 6 indicates that the rift trend varies in the study area. It trends 345° in the south, shifts to 000° in the center, and returns to 345° in the north. Bathymetric relief along the faults is not constant. Relief of some faults lessens by bifurcation into smaller faults (e.g. eastern margin of SRSB). Some fault traces are buried by the NE-trending intra-rift volcanic ridge in the center of the rift. Large relief faults north of the volcanics are located to the east of the corresponding fault south of the volcanics. The volcanics may be localized along a right-lateral strike-slip fault which cuts through the center of the rift. Subsidence of fault blocks has formed growth faults in the overlying basins. In the SRWFZ narrow grabens have developed in the fault-block basins. Sediments in the SRSB are being faulted by a similar process. Subsidence of buried fault blocks creates small faults on the sea floor (Fig. 11). Transparent sediment fills the depressions on the downthrown side of the faults and is sometimes overlain by a thin layer of even more recent sediment (arrow). An isopach map of the transparent layer in the SRSB (Fug. 5) shows the areas of rapid subsidence in the SRSB.

5. Conclusion

The Sumisu Rift is a 120-km long intra-arc rift segment in the central Izu-Ogasawara Island Arc. Integration of closely spaced 3.5-kHz data and SeaMARC II sidescan imagery allows us to identify sediment types and geologic features, and to determine their distribution. The echo character of sea-floor sediments changes from a prolonged reflection to a multilayered reflection with increasing depth and distance from the arc volcanoes. This indicates a change in composition produced by a decrease in the coarse volcaniclastic constituents of the sediment. The change in echo character between neigh-

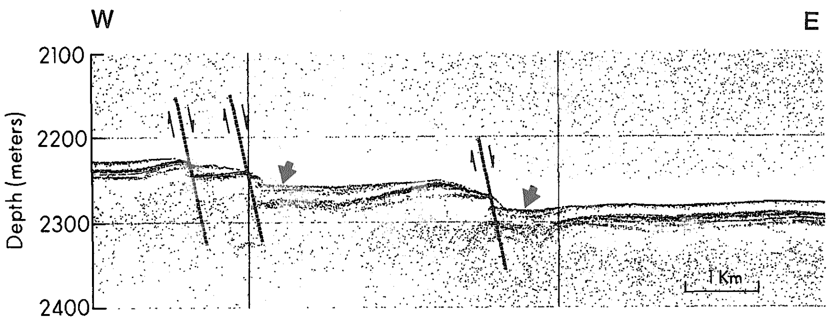


Fig. 11 GSJ 3.5-kHz record from the South Basin showing small growth faults in BR2t echotype sediment.

boring intra-rift basins that are separated by volcanic or fault-block ridges suggests that these physical barriers control the distribution of sediment. The distribution of transparent sediment found on the rift floor indicates recent faulting and current motion.

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伊豆・小笠原弧，スミスリフトの海底マッピング

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要　旨

伊豆・小笠原弧は本州とマリアナ諸島の間に位置し，その中の八丈島から西之島に至る火山列の背後に数個の小海盆の発達することが1960年代から知られていた．その後，1980年代になってから，それらの小海盆が伊豆・小笠原弧の中央弧に沿う断続的なリフティングであるといわれるようになり，各小海盆（リフト）は，近隣の島の名称を冠して，八丈，スミス，鳥島，及び西之島背弧凹地と命名された．この論文は，SeaMARK II 及び 3.5kHz 反射記録を用いた，スミスリフト海底の平面図化の結果をまとめたものである．本リフトは古島弧と活動性火山列を分けて細長いグラーベンであり，火山性砕屑物の堆積作用が優勢である．堆積物は，断層で生じた地塊の凹地やリフト内の南・北海盆に集まっている．音響的特性によるマッピングから，各海盆の堆積物の相違が明らかになった．堆積物の音響的特性の相違は島弧火山の近接性と堆積物の分散を規制している物理的バリヤーの存在に関係している．南海盆では，リフト形成と同時の堆積作用が観察される．

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