



# Clockwise and Anticlockwise Rotation of Viti Levu, Fiji -in Relation to the Tectonic Development of the North and the South Fiji Basin

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神戸大学博士論文

Clockwise and Anticlockwise Rotation of Viti Levu, Fiji  
—— in Relation to the Tectonic Development  
of the North and the South Fiji Basin

(ビチレブ島(フィジー)の時計廻り及び反時計廻り回転  
—— 北フィジー海盆, 南フィジー海盆の拡大と関連して)

Hiroo INOKUCHI

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## abstract

Samples for paleomagnetic study were collected from 40 sites in Viti Levu, Fiji. Reliable paleomagnetic directions were obtained from 22 sites after magnetic cleaning. These data cover the age between late Eocene to Pliocene. Geological study indicates that Viti Levu can be structurally divided into three stages; Stage 1 (late Eocene to early Oligocene), Stage 2 (early to middle Miocene) and Stage 3 (late Miocene to Pliocene). The mean paleomagnetic direction (D,I) for each stage is  $(-10^{\circ}, -48^{\circ})$  in Stage 1,  $(-66^{\circ}, -26^{\circ})$  in Stage 2 and  $(-32^{\circ}, -46^{\circ})$  in Stage 3, respectively.

Expected directions of the geomagnetic field in the past were calculated from the Australian apparent polar wander path and were subtracted from the obtained paleomagnetic directions in geological sequence. Then, the tectonic movement in and around the island of Viti Levu with respect to the Australian Plate was estimated since late Eocene. The followings were concluded: (1) A clockwise rotation of about  $45^{\circ}$  took place during late Oligocene, (2) an anticlockwise rotation of about  $75^{\circ}$  have occurred since late Miocene, and (3) the Euler poles of these rotations were situated in or near Fiji.

A tectonic history of the Fiji region since late Eocene, possible to explain the episodes of clockwise and anticlockwise rotations of Viti Levu, is as follows: Clockwise rotational movement in late Oligocene was closely related to the formation of the South Fiji Basin and anticlockwise rotational movement since late Miocene was closely

related to the formation of the North Fiji Basin. The clockwise rotation of Viti Levu had taken place, being accompanied with a progress of fan-shape spreading in the northern half of the South Fiji Basin, in which a system, R-R-R triple junction of plates, was involved. Subsequent anticlockwise rotation of Viti Levu was the movement explained as "ball bearing" rotation accommodated by antithetical transform faults accompanied with the spreading of the North Fiji Basin.

## I Introduction

Fiji is one of the island nations located in the southwest Pacific. The largest island, Viti Levu, and the second largest island, Vanua Levu, are encircled by about 320 smaller islands. Several types of topographic unit border and subdivide a surrounding area of Fiji (Fig. 1) suggesting that the tectonic history of this area is not simple. Within a region between the New Hebrides and the Tonga-Kermadec trench-island arc systems (simply "the Fiji region"), there are three basins, i.e. the North Fiji Basin, the South Fiji Basin and the Lau Basin - Harve Trough. The North Fiji Basin and the South Fiji Basin are divided by the Hunter Fracture Zone and the South Fiji Basin and the Lau Basin - Harve Trough are divided by the Lau-Colvill Ridges. Fiji islands join the Hunter Fracture Zone and the Lau Ridge. Explanations of the origin and development of complex physiographic and geologic structure in the region have been made by several earth scientists within the framework of the theory of plate tectonics (e.g. Chase, 1971; Green and Cullen, 1973; Kroenke, 1984; Brocher, 1985-a). It could be summarized from their discussion that; (1) two major plate, i.e. the Australian and the Pacific Plates, have been converged at the Fiji region since Paleogene, (2) the plate boundaries in the convergence region were repeatedly reorganized accompanied by various tectonic events, e.g. back-arc spreading, roll-back of trenches and initiation, termination of trenches and so on. The situation of Fiji islands should be repeatedly changed by such reorganizations of the

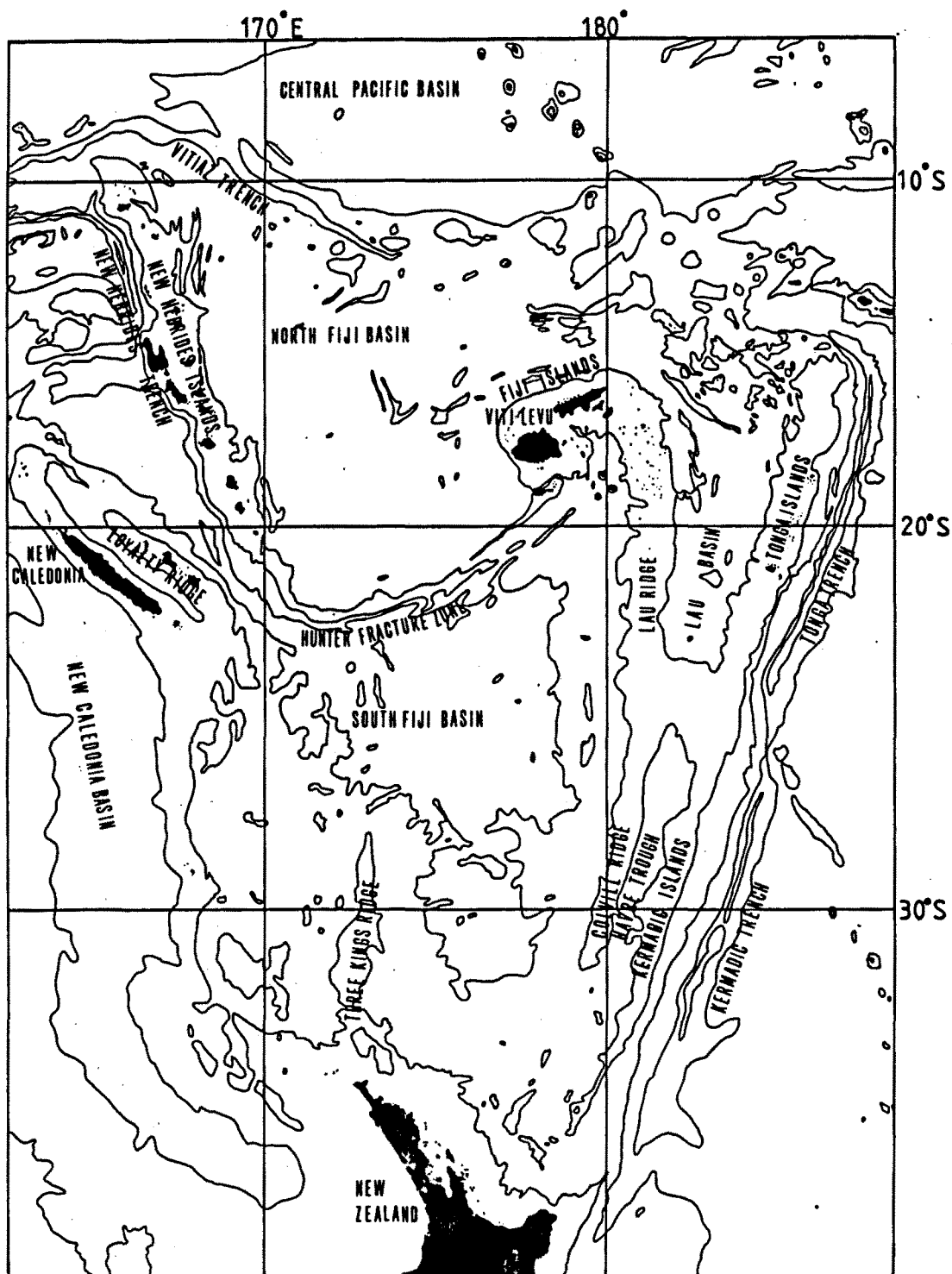


Fig. 1 Simplified bathymetric map of the adjacent sea of Viti Levu, Fiji..

Water depth is shown by every 2000m contour. Data for the map are taken from the International Hydrographic Organization (1982).

the plate boundaries. Therefore, it must be important to throw light on the tectonic history of Viti Levu in order to understand the tectonic history of the Fiji region, where the oceanic plates have converged since Paleogene and the tectonics of the region may be a clue to solution of a number of fundamental problems (Uyeda, 1986) in understanding the subduction tectonics.

Paleomagnetic study of Viti Levu is particularly useful in unraveling the tectonic history in and around the island, because paleomagnetic methods are generally useful to detect and measure the relative movement and rotation of different tectonic units on both a global and subcontinental scale. Viti Levu is the most suitable island for paleomagnetic study in Fiji islands, because the oldest rocks (late Eocene) in Fiji crop out in Viti Levu and various volcanic and sedimentary rocks, ranging from late Eocene to Pleistocene, are widely distributed in the island (Rodda, 1967). The remanent magnetization of rocks from Viti Levu, Fiji has been described by several authors (Tarling, 1967; James and Falvey, 1978; Malahoff et al., 1982-b). Malahoff(1970) made a speculative proposal that the Fiji Platform had undergone anticlockwise rotation based on earthquake distribution and submarine morphology, and some of the paleomagnetic results of these authors seem to support this hypothesis (James and Falvey, 1978; Malahoff et al., 1982-b).

The present paper gives further results from some sites almost the same as some of these authors', and also from different sites. The purpose of the present study is to investigate more thoroughly the direction of the magnetiza-



tion of rocks distributed in Viti Levu from late Eocene to Pliocene, and to infer precisely tectonic movements in and around Viti Levu in this period, based on the paleomagnetic results.

## II Outline of geology and sampling sites

### II-1 Outline of geology

The geology of Fiji has been studied by Rodda (1967, 1974, 1975) and is reviewed by Rodda and Kroenke (1984). According to his studies and their review, the geology of Viti Levu could be summarized as follows:

Fig. 2 is a simplified geological map and Fig. 3 stratigraphical columns of the island. The oldest rocks in Fiji are found in western and southern Viti Levu and are those of the formations classified as the lower Wainimala Group. These rocks include dacite tuffs interbedded with upper Eocene (Tertiary b) limestones and pillow basalts and were intruded by a lower Oligocene tonalite stock near Nadi, a member of the lower Colo Group, dated at 34 Ma. An unconformity is believed to separate the lower and upper Wainimala Groups in both western and southern Viti Levu, although no boundary has been mapped between the two subgroups in western Viti Levu. The Wainimala Group is composed of island-arc tholeiite and forms the exposed basement of the island. An angular unconformity in southeastern Viti Levu between rocks of the Wainimala Group and the overlying Savura Volcanic Group led to the suggestion that the Wainimala Group there could be Eocene in age. It appears that may be a lacuna in Oligocene and lower Miocene in Viti Levu, so the Wainimala Group rocks of southern and southwestern Viti Levu could be latest Eocene or earliest Miocene in age.

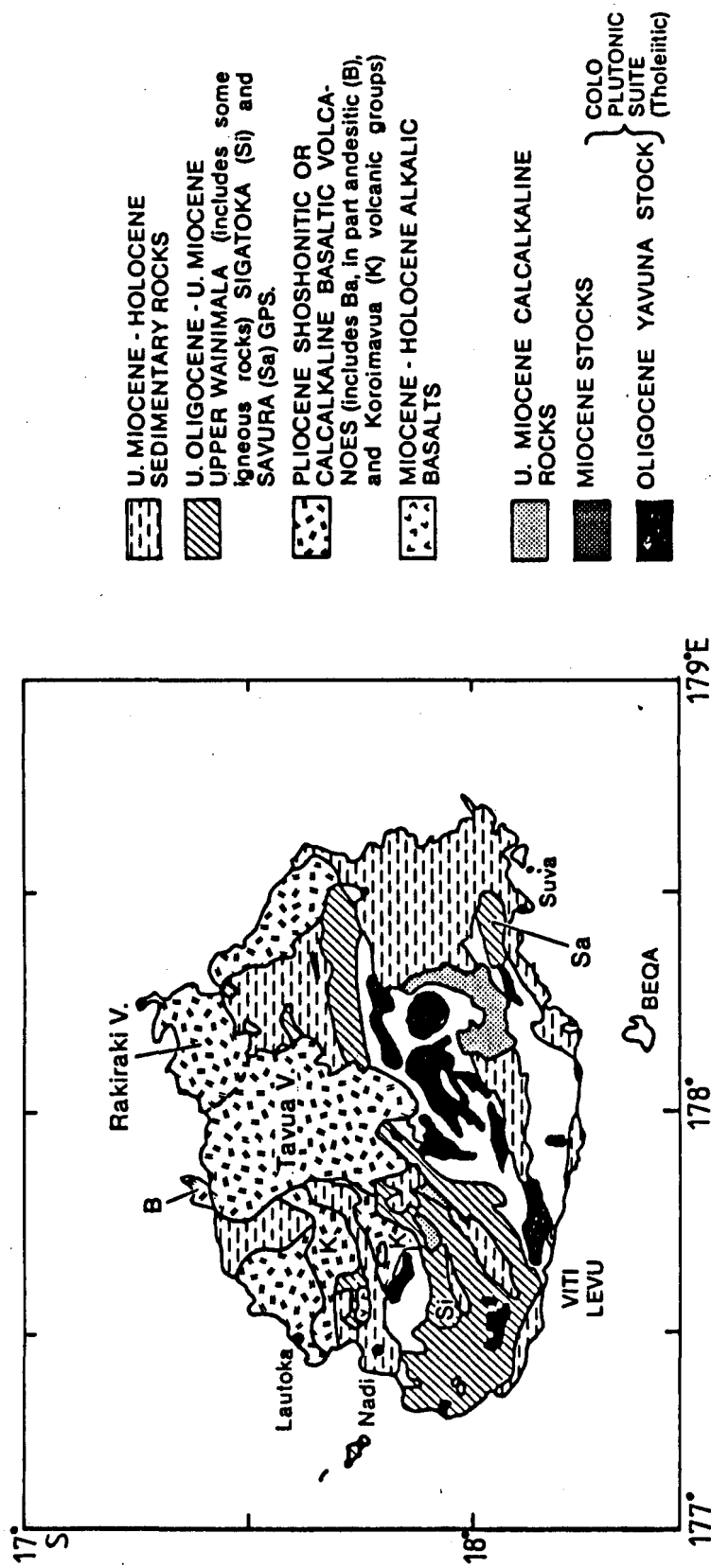


Fig. 2 Simplified geological map of Viti Levu, Fiji after Rodda and Kroenke (1984).  
Blank areas are known or considered likely, to be lower Wainimala Group (Rodda and Kroenke, 1984).

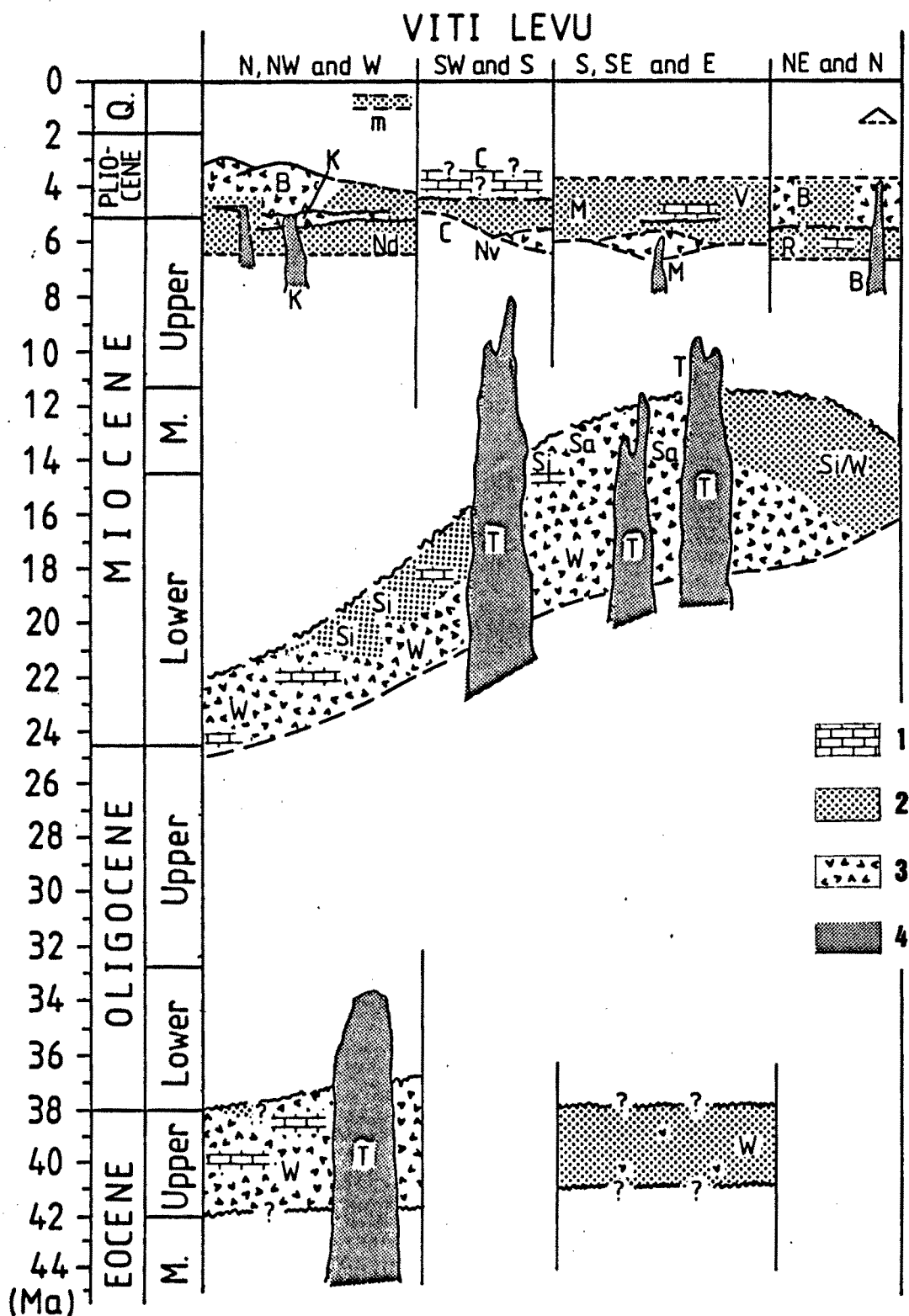


Fig. 3 Diagrammatic stratigraphic column of Viti Levu, Fiji after Rodda (1982). Chronostratigraphic scale is from Harland et al. (1982). The tops of intrusions indicate ages. B : Ba Group, C : Cuvu Sedimentary Group, K : Koroimavua Volcanic Group, M : Medrausucu Group, Nd : Nadi Sedimentary Group, Nv : Navosa Sedimentary Group, R : Ra Sedimentary Group, Sa : Savura Volcanic Group, Si : Sigatoka Sedimentary Group, T : Colo Plutonic Suite, V : Verata Sedimentary Group, W : Wainimala Group. 1 : Limestone, 2 : Fine-grained epiclastic and worked volcanoclastic rocks, 3 : Flows and coarse volcanoclastics, 4 : Volcanic plugs and stocks and plutonic stocks.

Gabbro and tonalite stocks of Colo Platonie Suite were intruded in two periods, in Oligocene and in middle and late Miocene. The plutons, ranging from 12.3-7.5 Ma in age were emplaced synorogenically into anticlinal folds across southern Viti Levu; widespread greenschist metamorphism occurred at the same time.

The Sigatoka Sedimentary Group is latest Oligocene to middle Miocene and probably older than all Miocene Colo stocks, and overlies some of the volcanic rocks of the Wainimala Group in the west. The Savura Volcanic Group, basalt to rhyolite, is thought to be also middle Miocene and rests unconformably on rocks of the Wainimala Group in the southeast.

The rocks of these Groups are unconformably covered by Mio-Pliocene sedimentary rocks with some andesite of the Ba, Nadi and Navosa Sedimentary Groups and the Medrausucu Group. Calc-alkaline andesite were erupted in southeastern Viti Levu, and probably farther west, between 6 and 5.5 Ma.

A belt of younger eruptive and intrusive rocks ranging in age from 5.5 to 3 Ma trends E-NE across northern Viti Levu. The belt contains the Koroimavua and Ba Volcanic Groups and includes associated monzonite and olivine monzonite stocks and sills. The Koroimavua Volcanic Group is early Pliocene and overlies the Nadi Group. The Ba Volcanic Group is mostly basalt with some andesite and other differentiates and originated from several volcanic centers in the north. Two of the volcanoes are the Tavua Volcano in northern Viti Levu and the calc-alkaline Rakiraki Volcano in the northeast. The rocks of the Group are mostly Pliocene

to Pleistocene, but some of the basal rocks may be upper Miocene.

The Verata Sedimentary Group in the east and the Cuvu Sedimentary Group in the southwest are both Pliocene with probably some Pleistocene strata in the east of Viti Levu.

## II-2 Sampling sites

Orientated rock samples for paleomagnetic study were collected from 19 sites in 1982 and from 21 sites in 1985, in Viti Levu. The following are the brief descriptions of the sampling sites with the ages of rocks and Fig. 4 shows their approximate locations on the map of the island of Viti Levu.

Site 82-1: Excavated cliff of a playing field at Narere. A part of the Suva Marl, fine grained calcareous sandstone with rare tuffs. Three samples were taken, the highest of which was at the level predicted for the Gilbert-Gauss boundary by the line of regression through the K-Ar dates on tuffs lower in the sequence (Rodda et al., 1985). The samples 1 to 3 are respectively at 33.6, 30.9 and 37.5 m (of siltstone only) above the Purple Marker in the Standard Sequence of the Suva Marl (Rodda, 1986).

Site 82-2: In Wainibuku Creek. Trachytic basalt flow within basaltic rudite, some of which contains the more usual olivine basalt called Nasinu Basalt, and classified as the Savura Volcanic Group. As it is overlain by strata

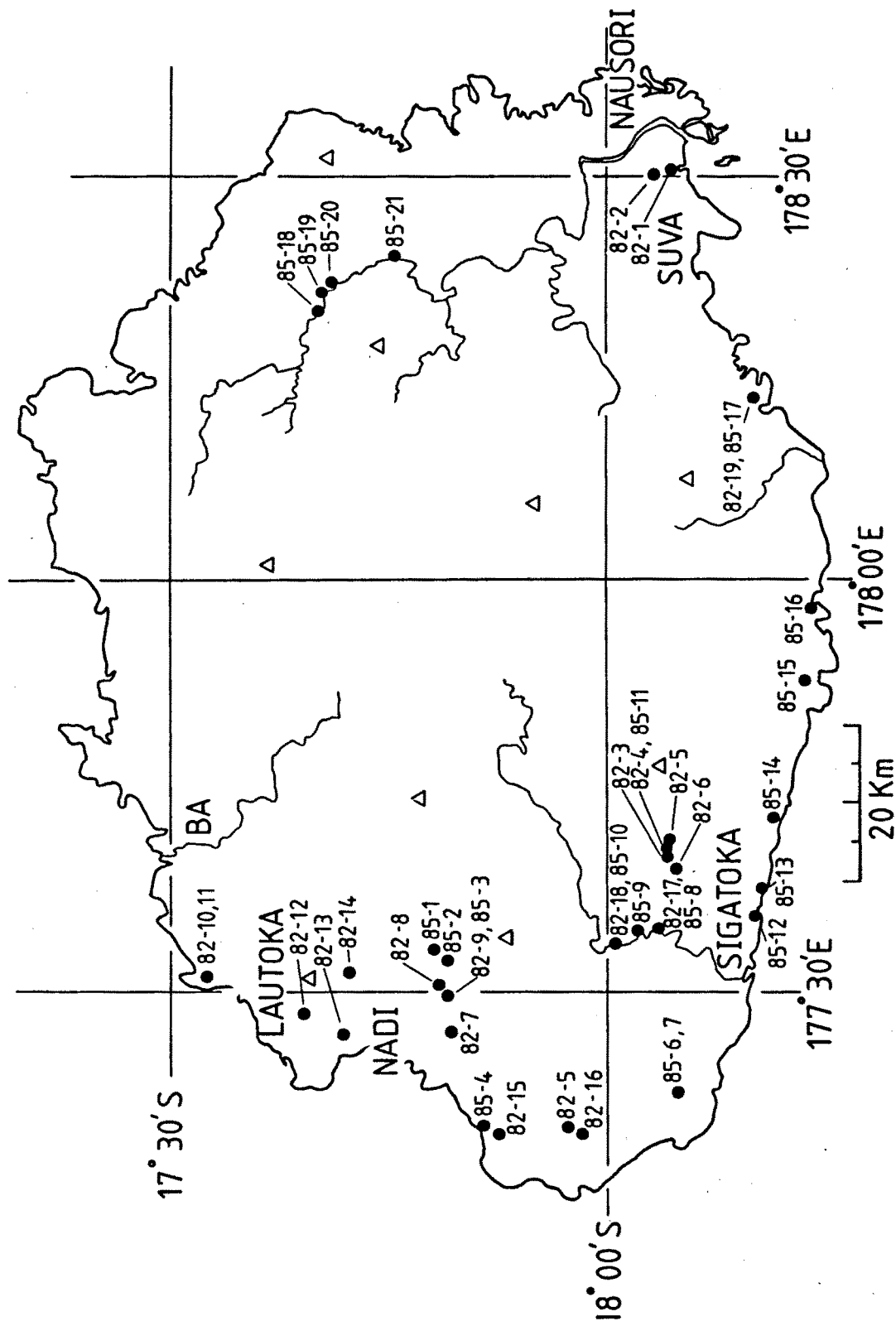


Fig. 4 The map of Viti Levu, Fiji, showing locations of paleomagnetic sampling sites. Numerals are site numbers.

of latest Miocene to earliest Pliocene, the age is geologically in the range of latest Oligocene to early middle-Miocene. The K-Ar date at 6.49 Ma given by Yaskawa et al. (1985) seems to be too young as compared with the geological presumption, though it is not in conflict with the observed stratigraphy.

Site 82-3: By Balenabelo Road. Impure limestone associated with volcanics and volcaniclastics; being a member of the Wainimala Group. The limestone crops out on the road and ridges nearby and it has been dated at middle Miocene (Coleman, 1974), probably early middle-Miocene or about 14 Ma.

Site 82-4: By Balenabelo Road, in a creek east of site no. 82-3. Basalt (possibly pillowed) of probably about the same age as the limestone of site no. 82-3.

Site 82-5: By Balenabelo Road, as above but on a ridge about 0.5 km past the creek. Probably pillowed basalt.

Site 82-6: By Balenabelo Road, excavation beside the road about 0.5 km south of site no. 82-3. Rhyolite or dacite, being possibly an intrusive within the Wainimala Group.

Site 82-7: By Vatutu Road, 1 km north-west of Vatutu Village and beside Nawaka Creek. Sandstone and siltstone of the basal part of the Nadi Sedimentary Group, the age of which is given as NN. 11 by Wilcoxon (Easton, 1973).

Site 82-8: (17° 49.1'S, 177° 30.8'E) near Namulomulo. Foraminiferal limestone of the Wainimala Group, dated at late Eocene (Cole, 1960).

Site 82-9: Beside Namosi Creek near Namulomulo. Volcanics of the Wainimala Group, partly pillowed. It crops out



immediately below strata of the Nadi Sedimentary Group, and is presumed to be of late Eocene age.

Site 82-10: A roadcut on Kings Road about 12 km north of Lautoka. A flow of augite-olivine basalt belonging to Nacilau Volcanics of the Ba Volcanic Group. It was dated at 4.73 Ma but thought to be somewhat younger (Whelan et al., 1985).

Site 82-11: A roadcut near a disused quarry and 1 km north of site no. 82-10 along Kings Road. Geological description is as for the site no. 82-10.

Site 82-12: (17°39.2'S, 177°28.1'E) beside Varage Creek. Partly pillowed basalt or shoshonite lava of Saru Shoshonite, Koroyanitu Volcano, the Ba Volcanic Group. The age was radiometrically determined at 5.04 Ma (Yaskawa et al., 1985).

Site 82-13: In Lomolomo area and the proposed quarry site at the west end of Sabeto Range. Massive plug-fed lava of Sabeto Volcanics, the Koroimavua Volcanic Group. The age in thought to be as for eruptive rocks from nearby dated at 5.4 Ma (McDougall, 1963).

Site 82-14: (17°42.6'S, 177°31.9'E) beside Nawainiu Creek. One of the centers for Sabeto Volcanics. Augite-biotite micromonzonite, Nawainiu Creek Intrusives of the Koroimavua Volcanic Group. Possibly one of the dykes intruding steeply dipping beds of the Nadi Sedimentary Group. It was dated at 4.9 Ma (Rodda and Kroenke, 1984).

Site 82-15: By Queens Road near Yako. Basalt with common zeolite amygdales, called Dakadaka Basalt by Skiba (1964), probably belonging to the Sigatoka Sedimentary

Group.

Site 82-16: By Queens Road near Navutu turnoff at Kubuna River bridge. Intrusive rock (gabbro?) of the Colo Plutonic Suite. The age is thought to be approximately 10 Ma.

Site 82-17: At 16 km from the east end of Sigatoka River bridge along Kavanagasau Road, on the side of the hill Navuwa. Possibly a plug of massive dacite of the Wainimala Group. The age is probably middle Miocene.

Site 82-18: At 23 km from the east end of Sigatoka River bridge along Kavanagasau Road. A dyke of porphyritic andesite intruding strata of the Sigatoka Sedimentary Group. The age is possibly middle Miocene and may be about 14 Ma.

Site 82-19: Mau Quarry. Hornblende andesite plug, Mau Andesite Member of Veisari Sandstone, the Medrausucu Group. It was dated at 5.85 Ma (Gill and McDougall, 1973).

Site 85-1: Beside Nawaka Creek about 2 km upstream from site no. 82-7. Mudstone of the older Wainimala Group; being presumed to be of Eocene age.

Site 85-2: Beside Namosi Creek, near Yavuna Village. Dolerite, Yavuna Stock, a member of the Oligocene Colo Suite, intruded within strata of the lower Wainimala Group. It was dated at 34 Ma (McDougall, 1963).

Site 85-3: Beside Namosi Creek near Namuromuro and very close to site no. 82-9. Sandstone and mudstone of the lower Wainimala Group. Their ages are presumed to be of late Eocene.

Site 85-4: A roadcut about 500 m south of Yako Village along Queens Road and near to site no. 82-15. Calcareous sandstone including fragments of volcanic rocks, being a member of the Sigatoka Sedimentary Group. The age is thought to be early Oligocene to early Miocene.

Site 85-5: By Queens Road near Navutu turnoff and close to site no. 82-16. Hornblende gabbro of the Miocene Colo Suite. The age is thought to be approximately 10 Ma.

Site 85-6: A roadcut about 500 m northwest of Semo Village along Queens Road. Volcanic rock (basalt-andesite) intruding into sedimentary rocks of site no. 85-7. The age could be between 7 and 9 Ma.

Site 85-7: By Queens Road, the same outcrop with site no. 85-6. Mudstone intruded by the rock of site no. 85-6 and its age must be expected to be a little older than the intrusion at site no. 85-6.

Site 85-8: At about 18 km from the east end of Sigatoka River bridge along Kavanagasau Road and very close to site no. 82-17. Dacite of the Wainimala Group. The age is probably middle Miocene.

Site 85-9: By Kavanagasau Road near Raiwaga Village. Sandstone of the Sigatoka Sedimentary Group and probably early to middle Miocene.

Site 85-10: Hillside cliffs of Mavua Village along the river Sigatoka, regarded as nearby the same place with site no. 82-18. Geological description is as for the site no. 82-18.

Site 85-11: Riverbed outcrop in Raunisosole Creek by Balenabelo Road, the same place with the site no. 82-4.

Geological description is as for the site no. 82-4.

Site 85-12: A roadcut along Queens Road, west of Sovi Bay.

Volcanic sandstone of the upper Wainimala Group. The age is somehow around 9 to 11 m.y. B.P.

Site 85-13: A roadcut cliff of well bedded sandstone by Queens Road in between Vatukarasa and Namada Villages, being to the Miocene Wainimala Group. The age is almost the same with the site no. 85-12.

Site 85-14: A very fresh roadcut along Queens Road, the west of and close to Votua Village, east of Naviti Resort. Andesite with columnar and platy joints could be a sill whose age cannot be specified yet, but it is a member of the upper Wainimala Group, and its origin could be either Nubu or Naboto Volcano.

Site 85-15: A roadcut about 500 m east of Man Friday Turnoff along Queens Road. Tuff of probably a bottom member of the Miocene Wainimala Group.

Site 85-16: By new Queens Road, about 800 m south of Korovou village. Tuvanatu Tuff, probably a bottom member of the Miocene Wainimala Group.

Site 85-17: Mau Quarry. Sampling places are not same with the former site no. 82-19, but geological description is as for the site no. 82-19.

Site 85-18: A roadcut along the Kings Road about 1 km north of Wailevu Village. Lawalevu Sandstone of the Wainimala Group. The age was given as N 8 or N 9.

Site 85-19: A roadcut along the Kings Road in Naqia Village and beside Wailou Creek. Lawalevu Sandstone of the Wainimala Group consisted mainly of limestone and partly

of sandstone. The age is as for the site no. 85-12.

Site 85-20: By Kings Road, about half a kilometer southeast of site no. 85-19. Mudstone of the same formation with that of site nos. 85-18 and 85-19.

Site 85-21: By Kings Road, outcrops of massive Wailotua Limestone beside the road in Wailotua village. It might be a part of a huge mass of the Eocene coral reef.

### III Paleomagnetic measurements

#### III-1 Sample collection

More than five rock samples for the paleomagnetic study were collected in each site in Viti Levu using a magneto-compass for orientation. They were later drilled and cut into cylindrical specimens 2.5 cm both in diameter and in length in the laboratory. As the strike direction of each sample was measured from magnetic north with a magneto-compass, the geomagnetic declination of  $13.0^\circ$  in 1982 and  $13.2^\circ$  in 1985, inferred for the island of Viti Levu from the IGRF-80<sup>1</sup> and IGRF-85<sup>2</sup> respectively, was added in order to obtain the true strike direction from geographic north.

The orientation of bedding plane of the rock-body, from which paleomagnetic samples were collected, was measured at each site. If the rock-body have moved after its acquisition of original magnetization, then orientation correction is needed for such movement. If original horizontal of the rock-body can be defined, for example by determining the bedding plane in the body, then this plane can be measured in terms of its strike and dip. The samples collected from this body can then be rotated back to their original, pre-tilt, positions. The measurement of orientation of bedding plane was done as follows: In case of layered sedimentary rocks, the bedding orientation was determined with the mean

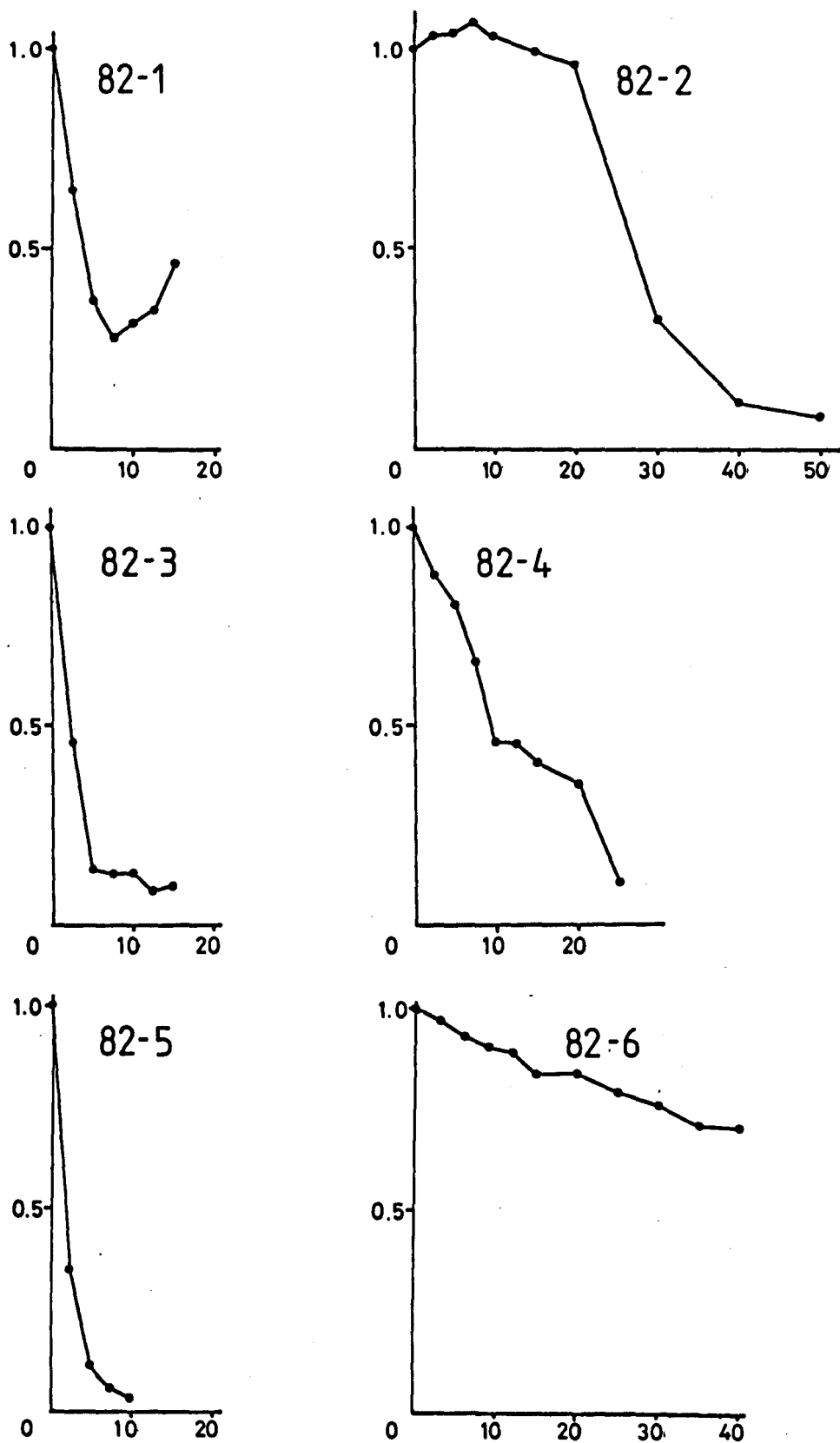
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1. IAGA Division I Working Group 1 (1981)
  2. IAGA Division I Working Group 1 (1985)

of orientation of several layers. In case of massive rocks, it was estimated with the bedding orientation of structurally associated strata, although in some cases it was unsuccessful to determine the original position of the body by any methods.

### III-2 Measurements and results

The measurement of direction and intensity of natural remanent magnetization (NRM) was done with a SCT cryogenic magnetometer for almost all the specimens and with a spinner magnetometer for the especially strongly magnetized specimens of some volcanic rocks. The spinner magnetometer was designed for measurement of strong magnetization, using a compensating pick-up coil system in a magnetic shield, since it is difficult to measure the magnetization stronger than  $1 \times 10^{-5} \text{Am}^2$  with the cryogenic magnetometer with a maximum sensitivity of  $1 \times 10^{-11} \text{Am}^2$ .

All the specimens were demagnetized in an alternating field in the following way: A few specimens from each site were progressively demagnetized in steps (Fig. 5, 6, and 7) until a stable direction of magnetization was reached. The remaining specimens from the same site were then demagnetized in the field which had been thus determined. For those sites where the direction of magnetization in the specimens continued to change on application of higher fields, several more specimens were progressively demagnetized to determine the peak alternating field at which the



**Fig. 5** The examples of normalized demagnetization curves.  
The abscissa shows the peak intensity of alternating field in mT.



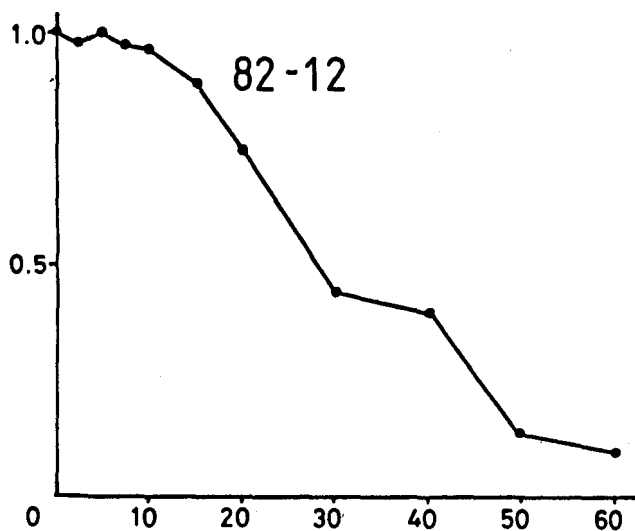
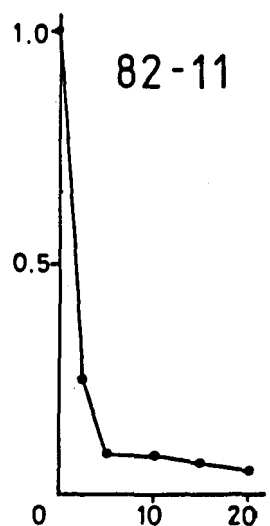
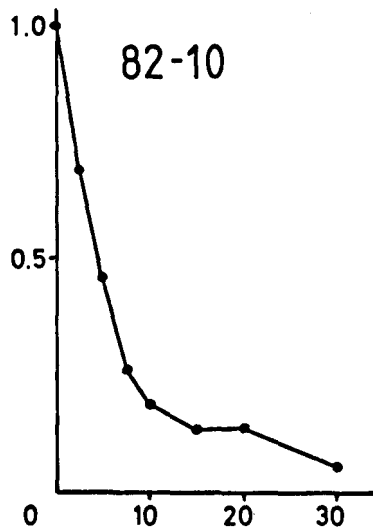
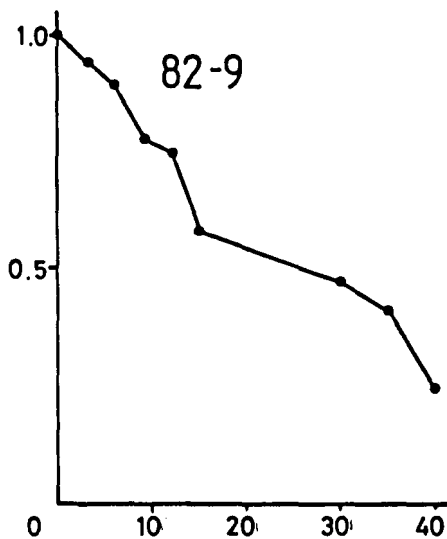
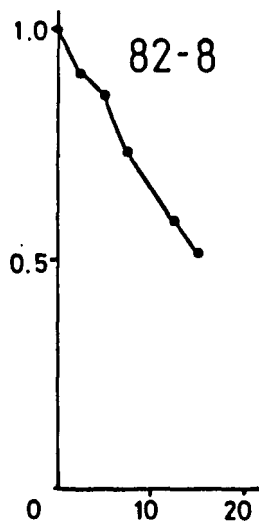
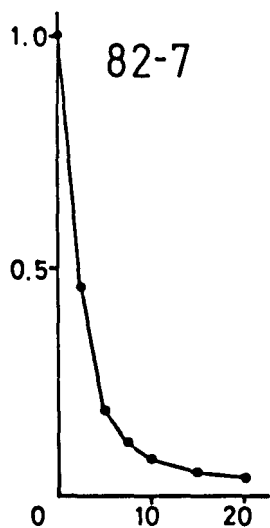


Fig. 5 (continued)

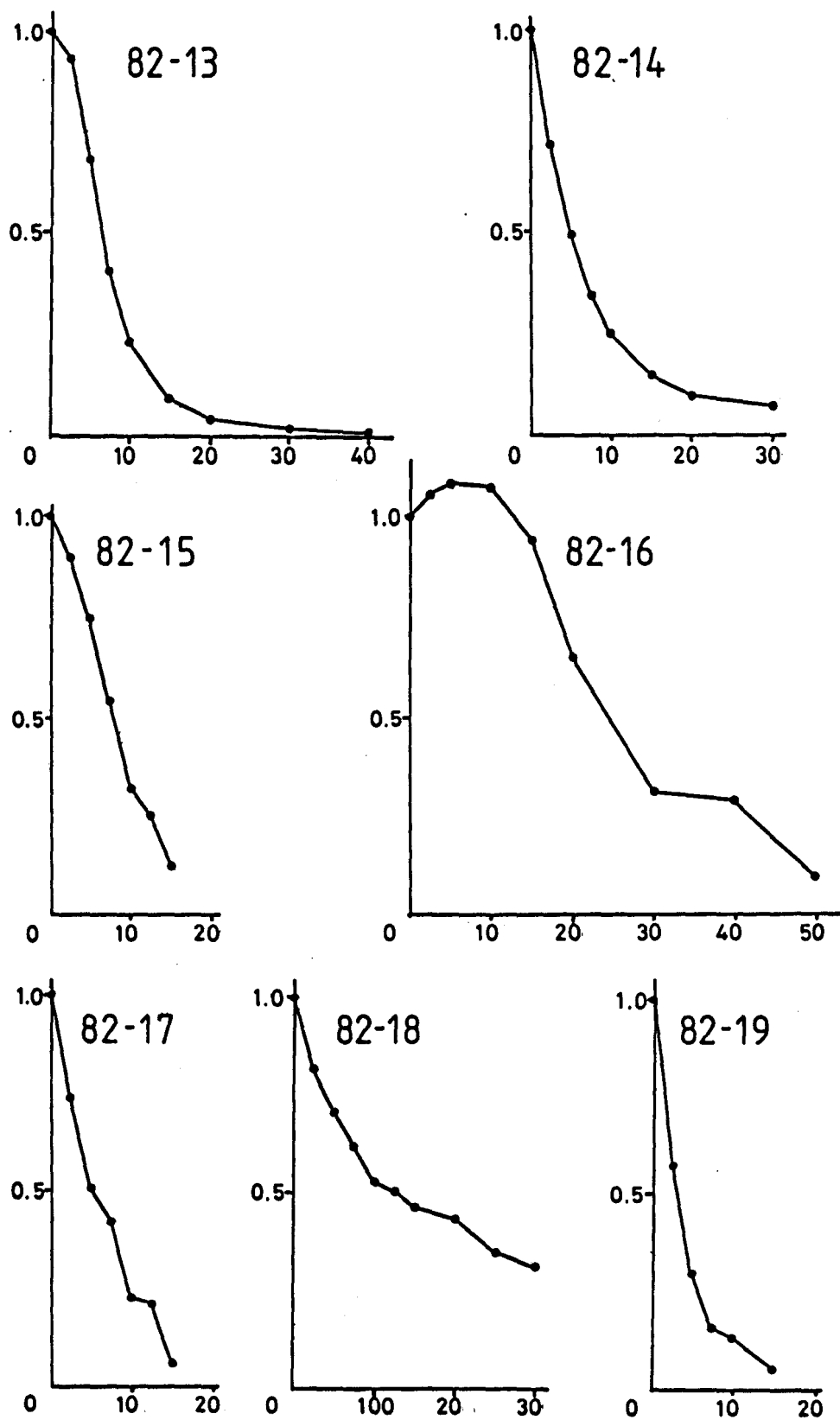


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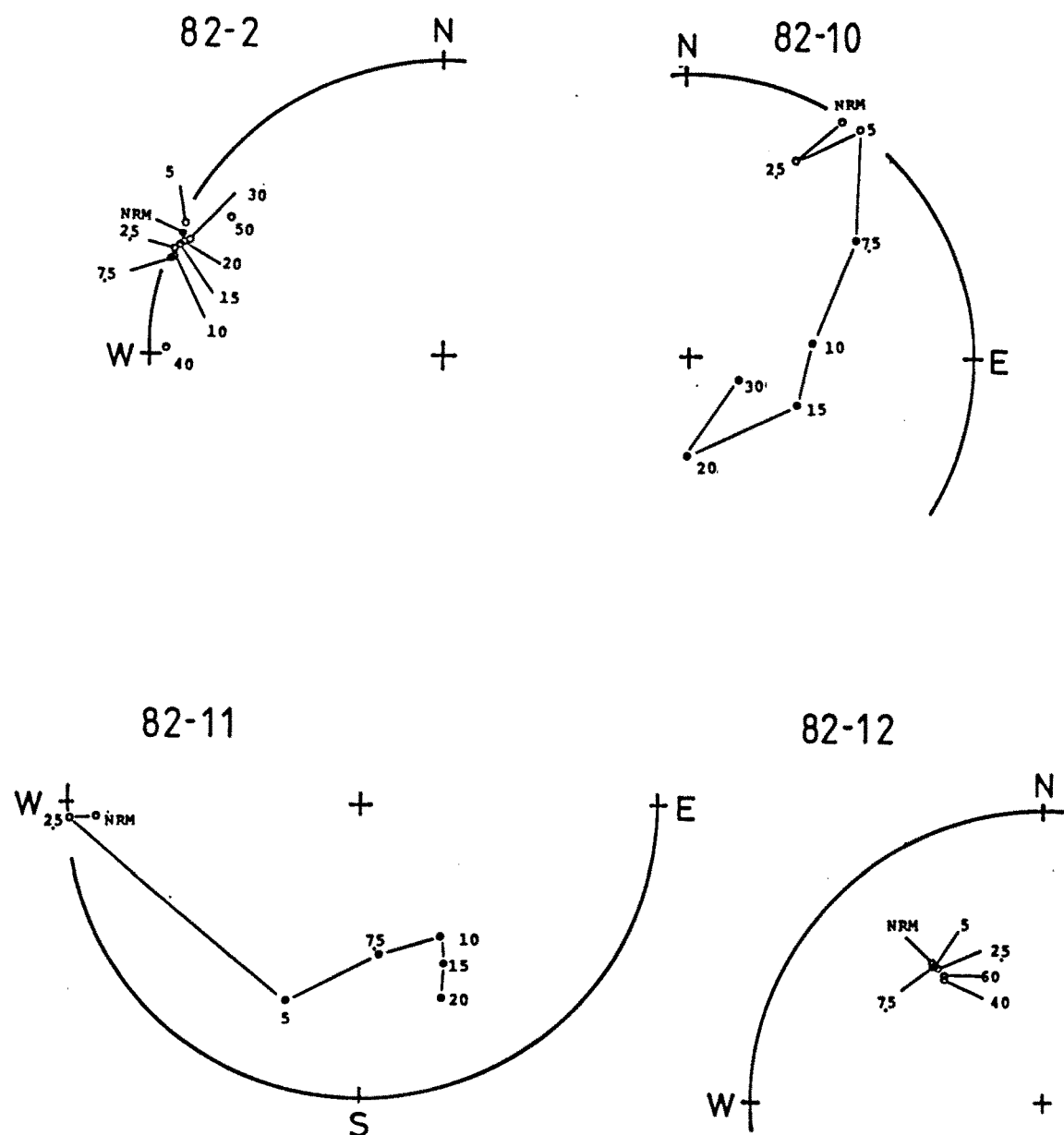


Fig. 6 The examples of the direction change through step-wise alternating magnetic field demagnetization shown by the equal area projection.

A number by the side of a point presents the peak intensity of alternating field in mT. Positive dips are shown by solid circles and negative dips by open circles.

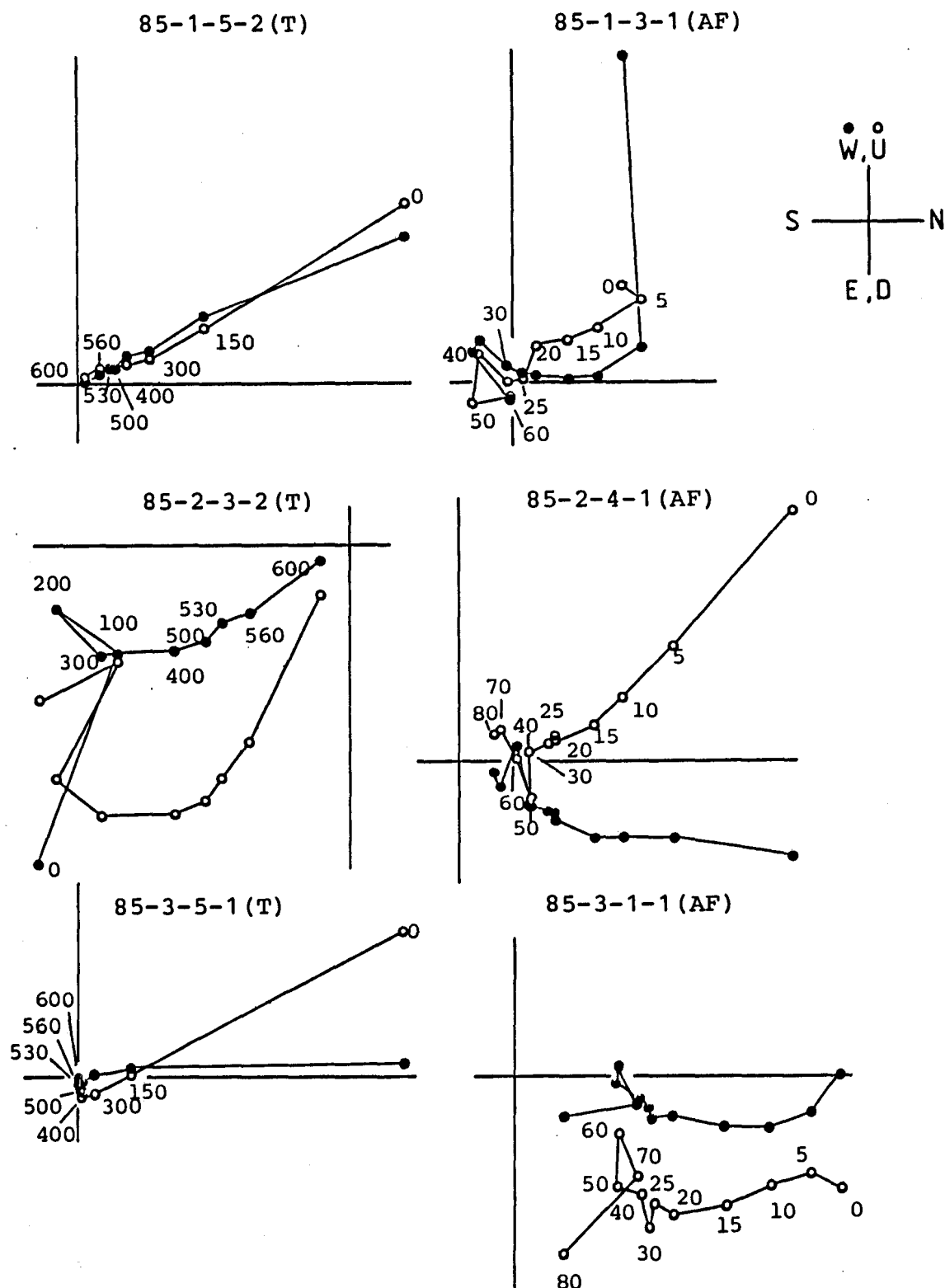


Fig. 7 Typical examples of the direction change of remanent magnetization projected on two orthogonal planes (Zijderveld, 1967) corresponding to progressive thermal (T) and alternating field (AF) demagnetization.

Solid and open circles represent horizontal (East-West and North-South) and vertical (Upward-Downward and North-South) components of magnetization, respectively. Numerals show temperatures of thermal demagnetization in °C or peak intensity of alternating magnetic field in mT.

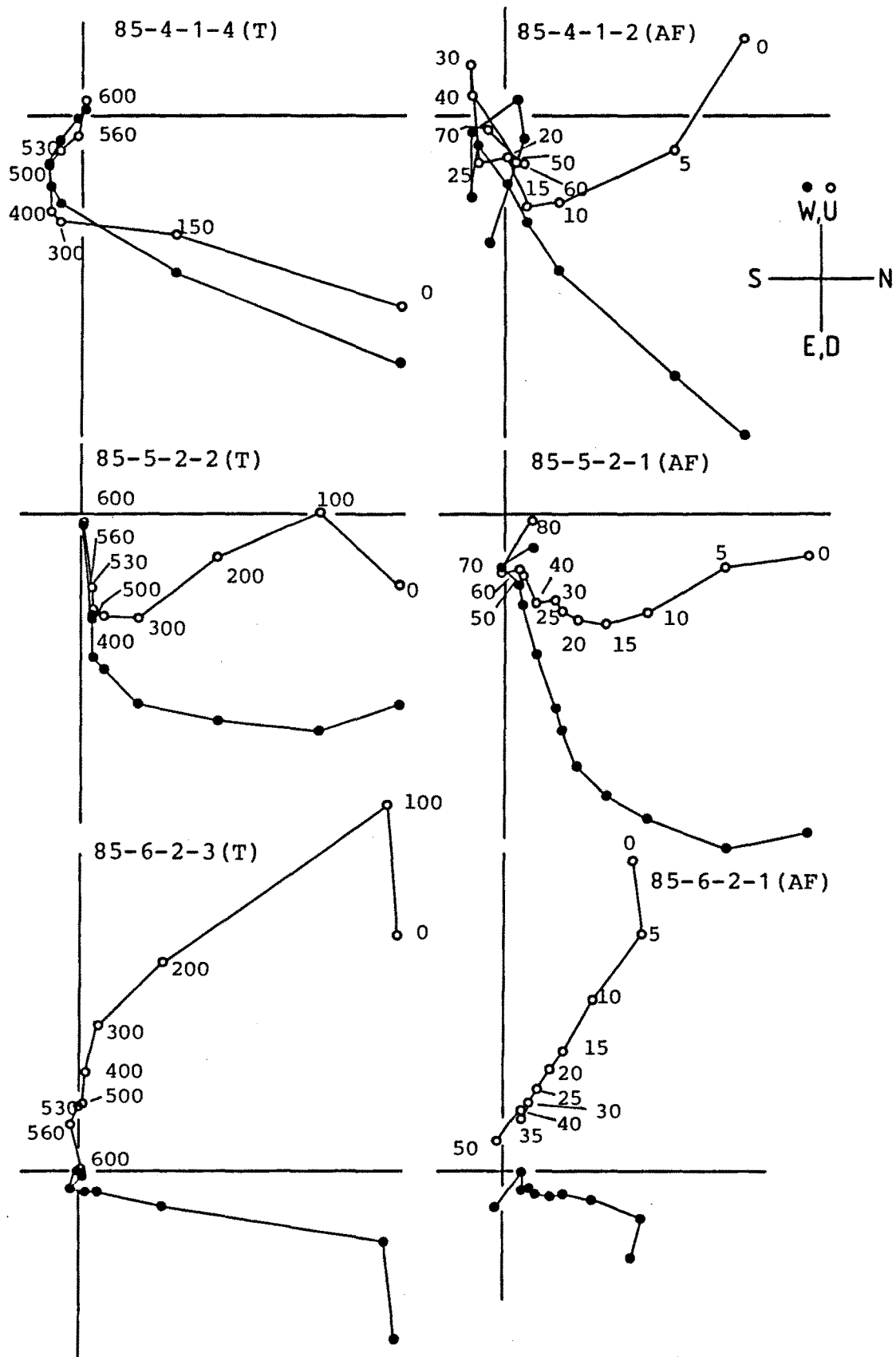


Fig. 7 (continued)

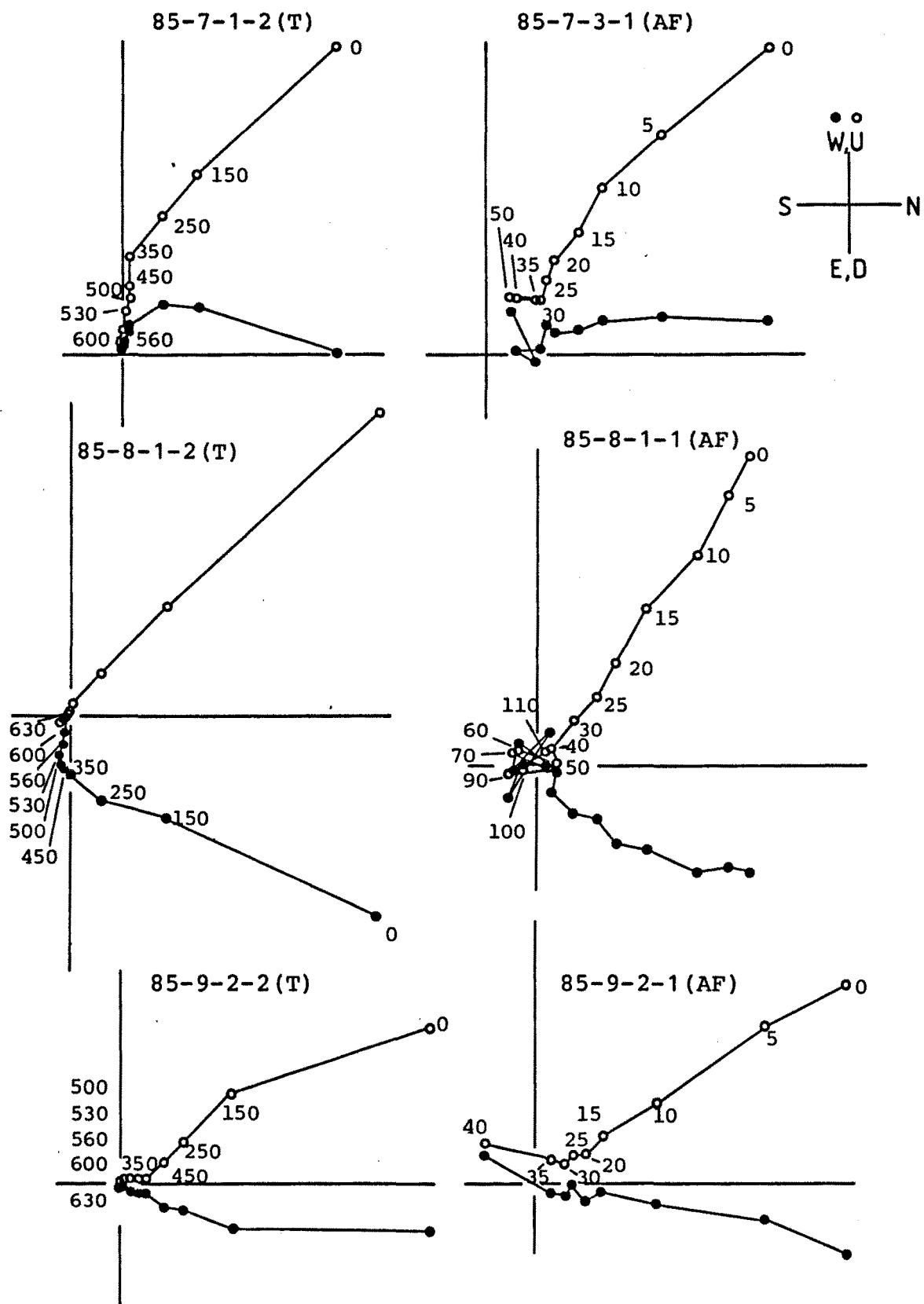


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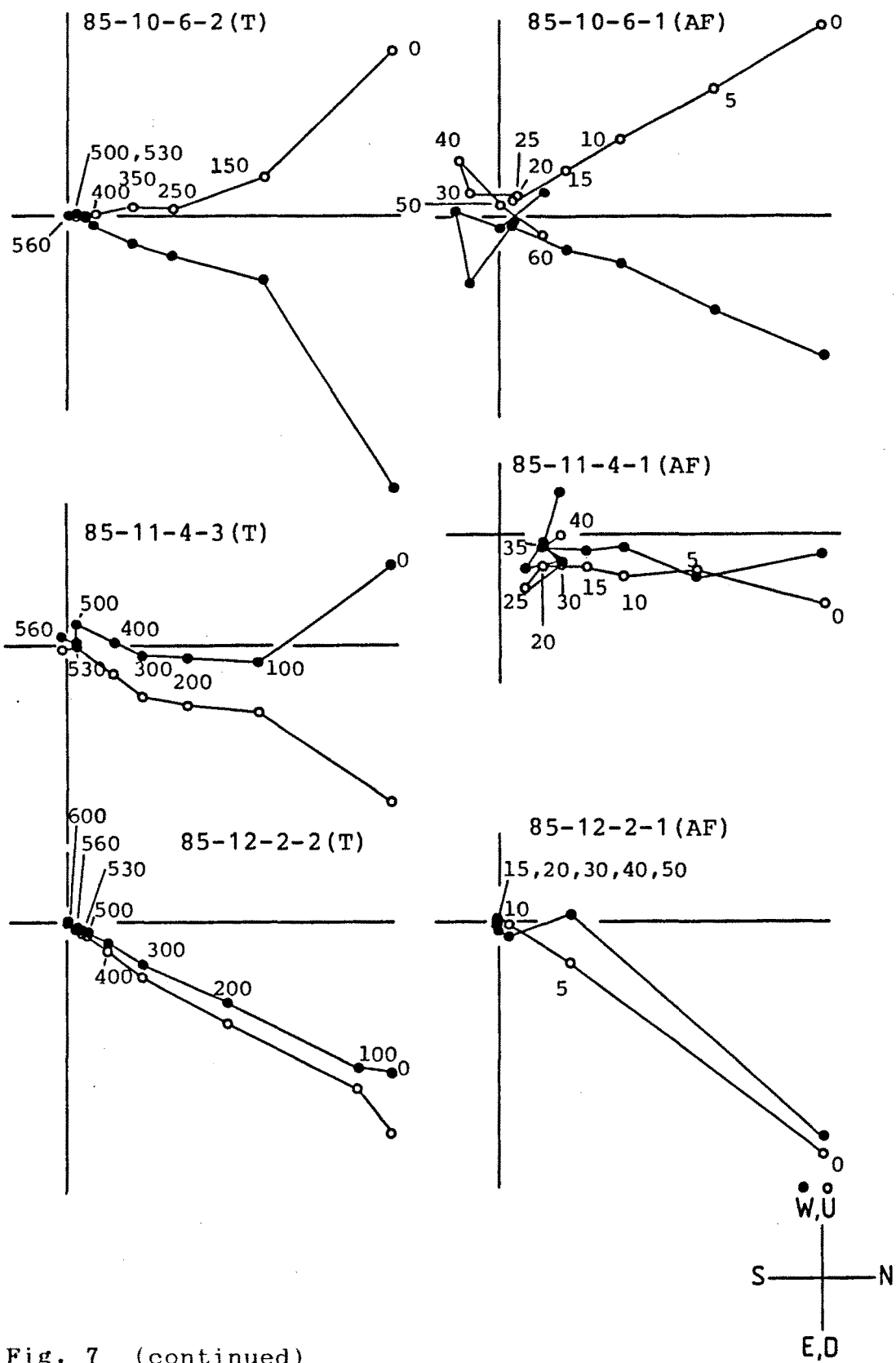


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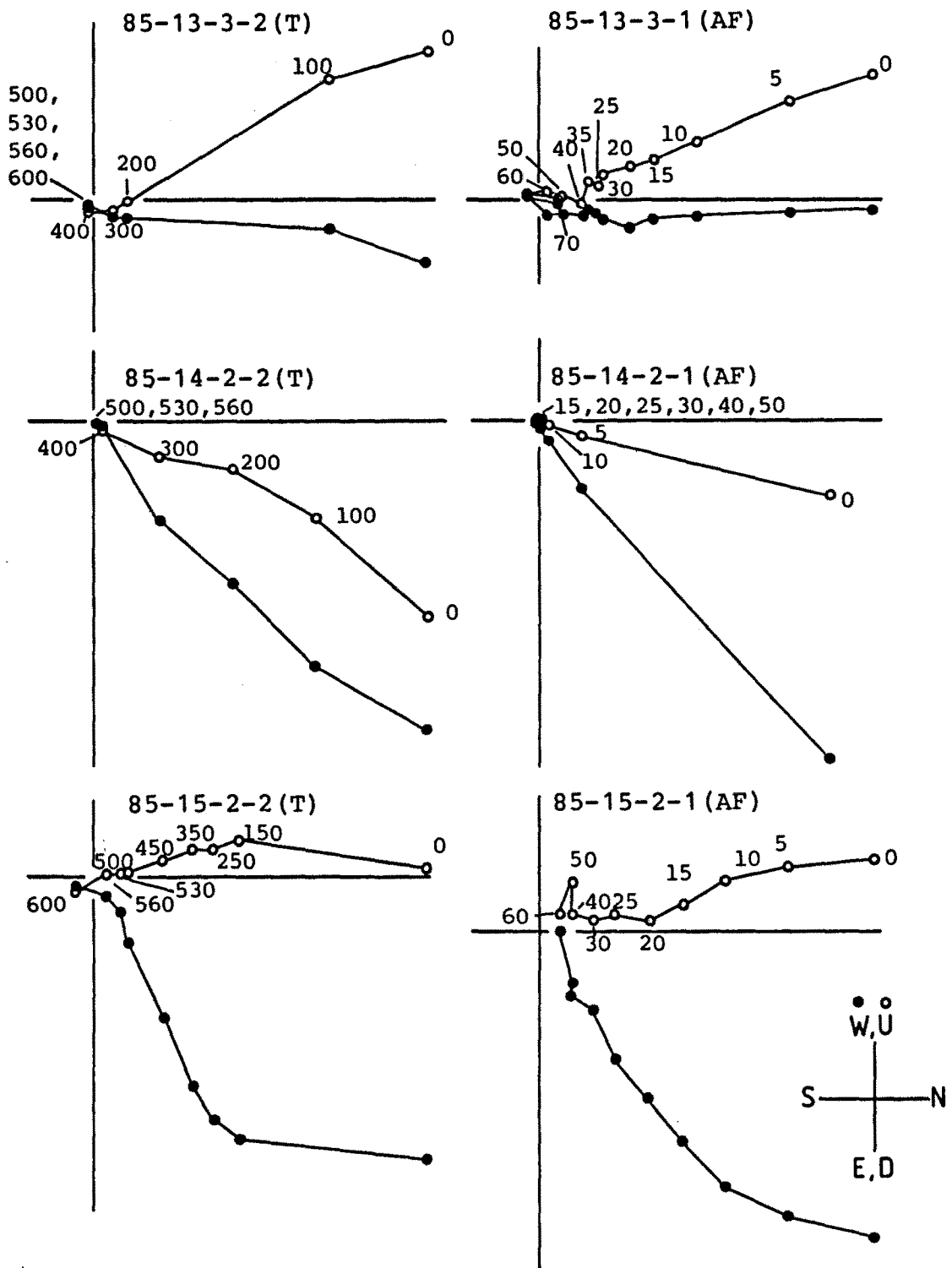


Fig. 7 (continued)



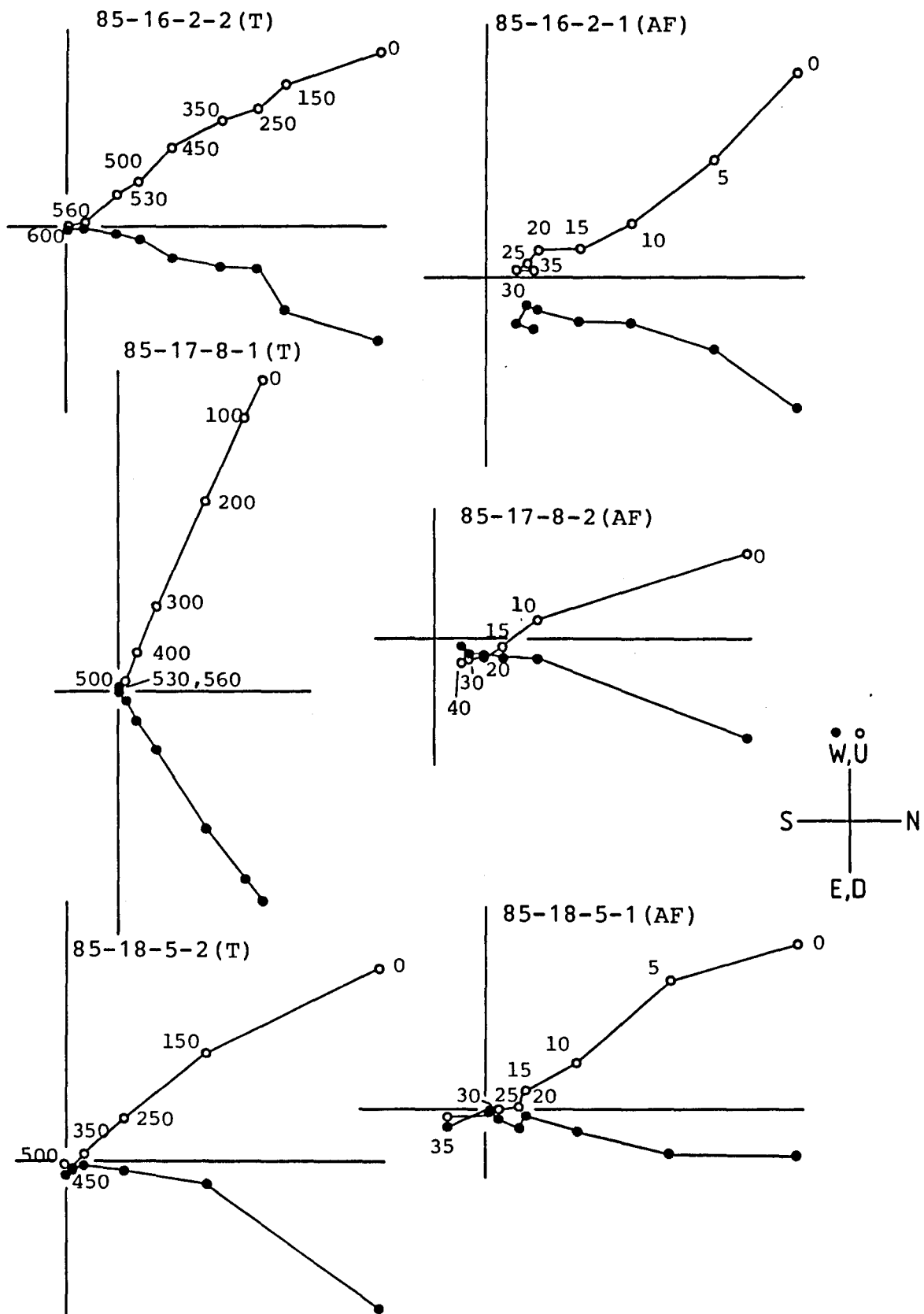


Fig. 7 (continued)

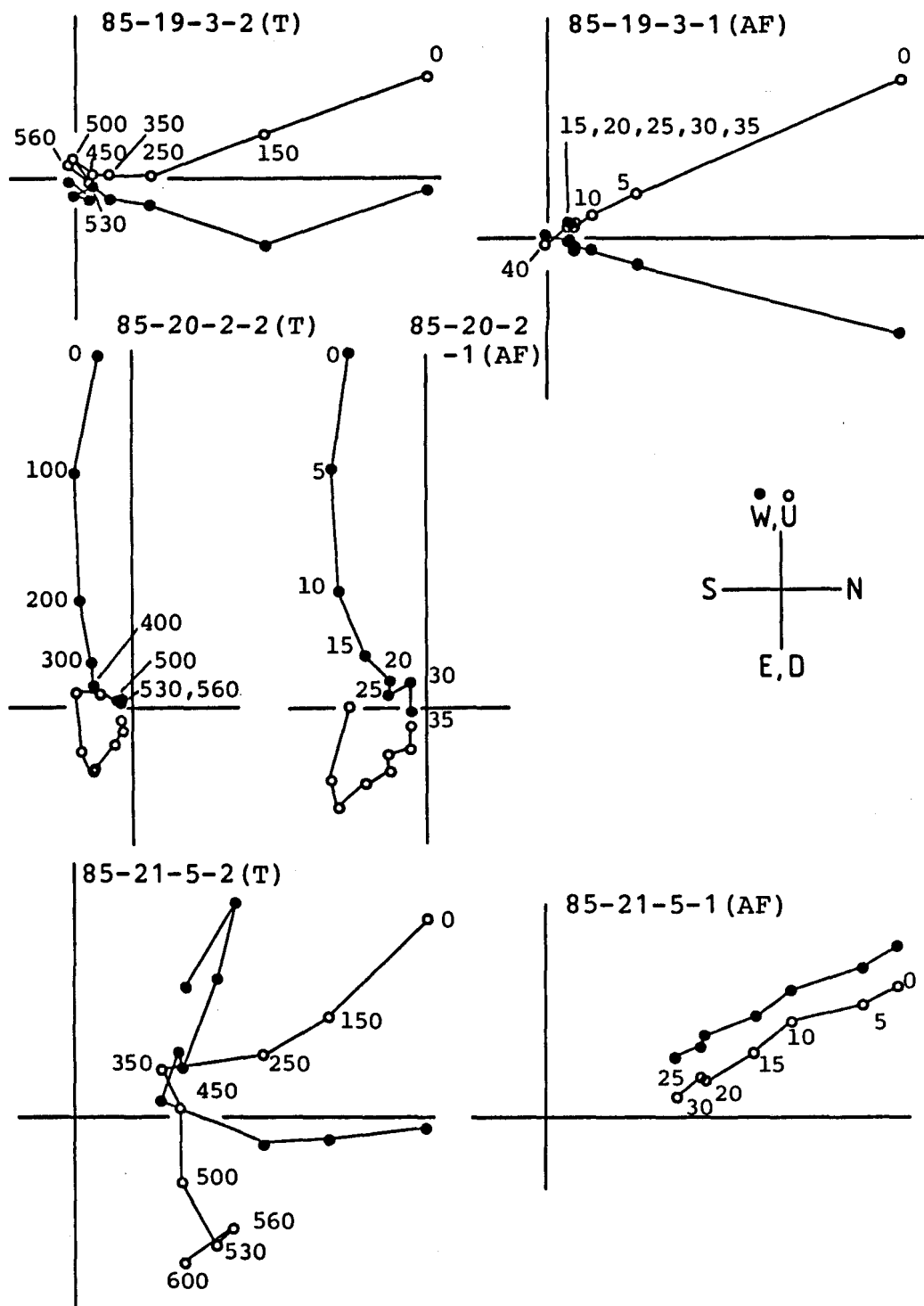


Fig. 7 (continued)

dispersion was least.

Concerning the site where the dispersion of magnetic vectors was not improved through the above-mentioned AF demagnetization procedure, the thermal demagnetization was attempted on the specimens from the site. That is the specimens were progressively heated up to the temperature at which the intensity of magnetization of the specimens was reduced to five per cent of the original one or the dispersion of magnetic vectors was least.

The mean direction of magnetic vectors, its estimated precision parameter  $k$  and the semiangle  $\alpha_{95}$  of cone of 95 % confidence for the mean direction (Fisher, 1953) were calculated from the direction of stable magnetization of specimens thus obtained at each site, and are presented in Table 1 and 2 with the mean intensities of stable magnetization.

The volume susceptibility  $\kappa$  of each specimen is calculated from the value obtained in the following way. After being demagnetized completely, each specimen was installed in the sample holder of the cryogenic magnetometer, in which the ambient geomagnetic field was stably trapped with the superconducting shield, and the intensity of magnetization induced in the weak field trapped around the specimen was measured.

As the index of the specimen's capability of maintaining a stable remanence, the Königsberger ratio  $Q_r$  was calculated as  $Q_r = \text{NRM} / \kappa H$ , where  $H$  is the geomagnetic field at each sampling site, inferred from the IGRFs. As the quantity describing stability against alternating fields, median

destructive field (MDF), the demagnetizing field required to reduce the initial NRM intensity by half, was determined for each specimen. In Table 1 and 2 are given the mean Konigsberger ratio and the mean MDF for all the specimens at each sampling site.

Table 1 Paleomagnetic results for Viti Levu (1)

| Site       | N  | demag. | D<br>(°) | I<br>(°) | M<br>(10 <sup>-2</sup> A/m) | $\alpha_{95}$<br>(°) | k     | $\kappa$<br>(10 <sup>-4</sup> ) | MDF<br>(mT) | Qr   | G.S.<br>( $\mu$ m) | rock           |
|------------|----|--------|----------|----------|-----------------------------|----------------------|-------|---------------------------------|-------------|------|--------------------|----------------|
| 82-1-1     | 6  | 5mT    | 18.7     | -54.2    |                             | 19.4                 | 15.6  |                                 |             |      |                    |                |
| -2         | 6  | 5mT    | 111.2    | 30.5     |                             | 12.0                 | 31.9  |                                 |             |      |                    |                |
| -3         | 5  | 5mT    | 19.5     | -54.6    |                             | 12.3                 | 40.0  |                                 |             |      |                    |                |
| 82-1*(1)17 |    | 5mT    | -32.5    | -52.0    | 1.9                         | 12.6                 | 9.0   |                                 | 3.8         |      |                    | siltstone      |
| 82-2       | 7  | 15mT   | -64.5    | -4.7     | 194.0                       | 5.4                  | 125.9 | 90.9                            | 27.2        | 6.9  | 15-20              | basalt         |
| 82-3       | 19 | 0      | 148.9    | 10.7     | 0.2                         | 3.0                  | 126.1 | 0.0                             | 2.3         | 17.6 |                    | limestone      |
| 82-4       | 1  | 0      | -162.2   | 23.5     | 238.0                       |                      |       | 3.1                             | 9.3         | 1.9  | 8-10               | basalt         |
| 82-5       | 14 | 0      | -38.0    | -4.4     | 130.4                       | 3.7                  | 116.4 | 68.2                            | 2.0         | 6.0  | 50-100             | basalt         |
| 82-6       | 5  | 6mT    | 1.0      | -59.2    | 21.9                        | 9.8                  | 61.9  | 6.7                             | 32.0        | 9.3  | 20-50              | volcanics      |
| 82-7       | 9  | 5mT    | -41.7    | -26.2    | 185.0                       | 2.4                  | 461.2 | 219.2                           | 2.2         | 3.0  |                    | sandstone      |
| 82-8       | 15 | 3mT    | -1.4     | -3.8     | 0.1                         | 8.9                  | 19.4  | 0.0                             | 15.5        | 6.7  |                    | limestone      |
| 82-9       | 10 | 3mT    | 28.3     | -6.5     | 31.5                        | 13.7                 | 13.4  | 3.5                             | 26.0        | 3.9  | 20-30              | volcanics      |
| 82-10      | 8  | 7.5mT  | 123.5    | 46.4     | 60.3                        | 15.3                 | 14.1  | 201.7                           | 4.5         | 1.0  | 50-100             | basalt         |
| 82-11      | 8  | 0      | 165.4    | 54.2     | 86.8                        | 13.9                 | 16.8  | 250.3                           | 1.7         | 0.6  | 8-12               | basalt         |
| 82-12      | 16 | 0      | -16.0    | -39.6    | 879.3                       | 7.5                  | 25.2  | 135.0                           | 28.0        | 20.2 | 5-20               | basalt         |
| 82-13      | 6  | 0      | 24.1     | 51.8     | 1003.7                      | 18.4                 | 14.2  | 236.0                           | 6.5         | 14.6 | 10-30              | volcanics      |
| 82-14      | 7  | 5mT    | 8.7      | -31.8    | 137.1                       | 3.5                  | 298.4 | 201.4                           | 4.8         | 1.8  | 50-100             | micromonzonite |
| 82-15      | 7  | 10mT   | 65.8     | 39.6     | 156.4                       | 11.4                 | 29.0  | 58.7                            | 8.0         | 6.6  | 4-10               | basalt         |
| 82-16      | 12 | 0      | 140.7    | -8.2     | 28.2                        | 62.9                 | 1.4   | 28.9                            | 23.0        | 1.1  | 2-4                | gabbro         |
| 82-17      | 7  | 9mT    | -1.2     | -16.1    | 32.7                        | 16.3                 | 14.7  | 114.1                           | 5.0         | 1.2  | 10-20              | dacite         |
| 82-18      | 7  | 6mT    | 25.6     | -30.9    | 33.5                        | 8.5                  | 51.4  | 74.8                            | 12.5        | 1.0  | 15-25              | andesite       |
| 82-19      | 11 | 6mT    | -22.7    | -36.9    | 48.1                        | 6.0                  | 58.9  | 122.5                           | 3.0         | 1.1  | 40-60              | andesite       |

N : number of specimens, demag. : peak field of optimum demagnetization,

D : declination of remanent magnetization, I : inclination of remanent magnetization,

M : intensity of remanent magnetization,  $\alpha_{95}$  : semiangle of cone of 95% confidence,

k : precision parameter,  $\kappa$  : volume susceptibility, MDF : median destructive field,

Qr : Koenigsberger's ratio, G.S. : grain size.

\*(1) Both stable normal and reversed polarity samples in the Site no. 82-1 are included. The reversed directions were inverted just in the opposite directions as the normal in calculation of the mean direction (see text).

Table 2 Paleomagnetic results for Viti Levu (2)

| Site  | N  | demag. | D<br>(°) | I<br>(°) | M<br>(10 <sup>-3</sup> A/m) | $\alpha_{95}$<br>(°) | k     | $\kappa$<br>(10 <sup>-4</sup> ) | MDF<br>(mT) | Qr   | G.S.<br>( $\mu$ m) | rock        |
|-------|----|--------|----------|----------|-----------------------------|----------------------|-------|---------------------------------|-------------|------|--------------------|-------------|
| 85-1  | 8  | 300°C  | -39.5    | -9.3     | 1.1                         | 18.9                 | 9.5   | 14.0                            | 10.0        | 1.4  | 5-50               | mudstone    |
| 85-2  | 6  | 300°C  | 144.4    | 58.0     | 23.4                        | 10.2                 | 44.4  |                                 | 4.3         |      | 20-150             | dolerite    |
| 85-3  | 10 | 550°C  | 40.0     | 80.9     | 0.1                         | 18.6                 | 7.7   | 3.4                             | 44.0        | 4.7  | 5-20               | sedimentary |
| 85-4  | 11 | 500°C  | 143.7    | 49.0     | 1.5                         | 14.9                 | 10.3  | 111.3                           | 12.0        | 0.3  | 10-100             | sandstone   |
| 85-5  | 8  | 500°C  | 71.8     | 40.2     | 36.3                        | 8.2                  | 46.5  |                                 | 22.0        |      | 10-250             | gabbro      |
| 85-6  | 7  | 10mT   | 20.0     | -67.7    | 7.6                         | 16.7                 | 14.0  | 3.5                             | 20.0        | 13.4 | 20-100             | volcanics   |
| 85-7  | 4  | 15mT   | -9.2     | -61.0    | 11.2                        | 9.7                  | 90.3  | 65.4                            | 12.0        | 1.6  | 5-100              | mudstone    |
| 85-8  | 6  | 530°C  | 92.7     | 7.4      | 7.3                         | 14.8                 | 21.5  | 90.4                            | 16.0        | 2.0  | 5-20               | dacite      |
| 85-9  | 9  | 15mT   | 5.5      | -33.0    | 8.7                         | 3.9                  | 173.6 | 93.4                            | 7.5         | 1.2  | 20-200             | sandstone   |
| 85-10 | 10 | 0      | 13.3     | 2.8      | 31.1                        | 22.0                 | 5.8   | 53.9                            | 18.0        | 1.9  | 5-200              | andesite    |
| 85-11 | 12 | 10mT   | 8.1      | 11.7     | 11.1                        | 23.9                 | 4.2   | 149.0                           | 4.0         | 0.5  | 10-80              | basalt      |
| 85-12 | 12 | 0      | 42.3     | -10.8    | 53.2                        | 30.0                 | 3.0   | 211.5                           | 4.0         | 0.8  | 10-40              | sandstone   |
| 85-13 | 6  | 500°C  | 114.5    | 65.0     | 0.1                         | 18.6                 | 13.9  | 73.8                            | 8.0         | 0.2  | 5-150              | sandstone   |
| 85-14 | 11 | 20mT   | 116.3    | 31.8     | 0.3                         | 17.9                 | 7.5   | 140.3                           | 2.7         | 0.7  | 4-40               | andesite    |
| 85-15 | 13 | 15mT   | 61.6     | -11.9    | 9.2                         | 3.0                  | 193.5 | 88.1                            | 16.5        | 0.6  | 8-100              | tuff        |
| 85-16 | 13 | 0      | 15.9     | 0.5      | 1.8                         | 39.5                 | 2.1   | 6.9                             | 10.0        | 0.9  |                    | tuff        |
| 85-17 | 18 | 5mT    | 19.7     | 8.4      | 13.7                        | 30.0                 | 2.3   | 230.4                           | 2.6         | 1.2  | 5-250              | andesite    |
| 85-18 | 12 | 0      | 21.6     | -16.3    | 3.7                         | 29.3                 | 3.2   | 20.2                            | 6.6         | 0.6  | 10-100             | sandstone   |
| 85-19 | 12 | 0      | -13.9    | -31.0    | 8.4                         | 27.1                 | 3.5   | 22.4                            | 3.8         | 1.2  | 20-100             | sandstone   |
| 85-20 | 11 | 30mT   | -60.3    | 45.5     | 1.4                         | 23.5                 | 4.7   | 38.8                            | 7.2         | 0.9  | 10-100             | mudstone    |
| 85-21 | 11 | 0      | 6.8      | -30.3    | 0.0                         | 17.0                 | 7.7   | 0.0                             | 17.5        | 1.0  | 2-10               | limestone   |

N : number of specimens, demag. : temperature or peak field of optimum demagnetization,  
D : declination of remanent magnetization, I : inclination of remanent magnetization,  
M : intensity of remanent magnetization,  $\alpha_{95}$  : semiangle of cone of 95% confidence,  
k : precision parameter,  $\kappa$  : volume susceptibility, MDF : median destructive field,  
Qr : Koenigsberger's ratio, G.S. : grain size.

## IV Paleomagnetic consideration

### IV-1 Reliability of results

The magnetic and microscopic properties of the samples do not show any particular characteristics indicating either remarkable stability of magnetization or useless instability (see in Table 1 and 2), except for the site no. 82-12. Stable magnetization was observed in some sedimentary rocks and, on the contrary, unstable magnetization was in some volcanic rocks. In many cases, instability of NRM may be due to weathering of rocks in this island as suggested by Tarling (1967).

The Königsberger ratio  $Q_r$  is usually in the range of 2 to 20 in volcanic rocks and  $>3$  in sedimentary rocks. The ratios shown in Table 1 and 2 are not so good and not too small according to this range. The values of median destructive field MDF in Table 1 and 2 are rather low on the whole, and some of these low MDF samples show good grouping of the direction of their remanent magnetization after AF demagnetization. This indicates the presence of some magnetically unstable components, i.e. an isothermal or viscous remanent magnetization, that could be removed by the applied adequate alternating field.

Microscopic studies show that all the samples contain more or less of a magnetic spinel phase mineral, presumably titanomagnetite, but almost none of a rhombohedral or a hexagonal mineral. The peripheral region of some titanomagnetite might have been altered into titanomaghemite by low

temperature oxidation, as the color of peripheral region is observed to be slightly different from that of the inner part of the mineral under the microscope.

The grain size of magnetic minerals, not too big nor very small as shown in Table 1 and 2, does not seem to show any correlation with other stability indices. Since the indices of magnetic stability have no clear correlation with each other, it may be the best way to estimate the reliability of the direction of magnetization with the value of  $\alpha_{95}$ .

#### IV-2 Characteristic paleomagnetic directions

Reliable paleomagnetic directions were obtained from twenty two sites, adopting the following four criteria to evaluate the reliability of the result from each site.

- (1) Each site has to have at least three individual orientated samples, from which a few specimen are made for measurement.
- (2) The value of  $\alpha_{95}$  has to be smaller than  $20^\circ$  in each site.
- (3) The mean direction of magnetization in each site has not to coincide with the present geomagnetic field before tectonic correction.
- (4) The mean direction of magnetization in each site has not to be a record of transition of geomagnetic field.

The criterion (1) was adopted to reject the site in



which only one or two orientated samples were available for experiment. Although, more than five orientated rock samples were collected from each site as mentioned in the section of "sample collection", some samples were broken in the process of making a cylindrical specimen and some specimens were smashed into fragments by explosion during heating for thermal demagnetization. Thus, the number of three in the criterion (1) needed in the present study. Since, the directions of magnetization of the rocks from the site no. 85-15 are widely spreaded from the mean direction, this site was rejected by the criterion (4).

The mean direction in each age was calculated using the reliable site-mean directions of corresponding age. The directions after tectonic correction were used for calculation of the mean, while no tectonic correction was done in some sites, in which it was hard to obtain available data for tectonic correction. The reversed polarity directions were inverted just in the opposite directions as the normal in calculation of the mean direction in each age. Polarities were judged from the sign of the inclination value of magnetization. The positive inclination must have been observed in the reversed polarity time, as the present inclination is negative in Fiji, in southern hemisphere.

Two major unconformities in late Oligocene and in late Miocene are recognized in Viti Levu from the geological studies as mentioned in the section of "Outline of geology". With these unconformities all the paleomagnetic data were divided into three time stages, based on the radiometric and geologic ages of the rock samples. Stage 1 is late Eocene

Table 3 Paleomagnetic directions for each age

|   | D<br>(°) | I<br>(°) | $\alpha_{95}$<br>(°) | P         | Site  | V. G. P.     |             | $\alpha_{95}$<br>(°) |
|---|----------|----------|----------------------|-----------|-------|--------------|-------------|----------------------|
|   |          |          |                      |           |       | Long.<br>(°) | Lat.<br>(°) |                      |
| Stage 1 (Late Eocene - Early Oligocene) |          |          |                      |           |       |              |             |                      |
|   | -1.4     | -3.8     | 8.9                  | N         | 82-8  | 172.9        | 74.1        |                      |
|   | 22.2     | -44.8    | 13.7                 | N         | 82-9  | 65.3         | 67.8        |                      |
|   | -47.3    | -60.6    | 18.9                 | N         | 85-1  | 47.1         | 43.3        |                      |
|   | -35.6    | -58.0    | 10.2                 | N         | 85-2  | 46.6         | 52.7        |                      |
|   | 169.4    | 56.6     | 18.6                 | R         | 85-3  | 21.6         | 68.5        |                      |
| mean                                    | -10.1    | -47.9    | 29.4                 | (Ns = 5)  |       | 35.1         | 72.1        | 28.2                 |
| Stage 2 (Early - Middle Miocene)        |          |          |                      |           |       |              |             |                      |
|   | -64.5    | -4.7     | 5.4                  | N         | 82-2  | 93.8         | 25.0        |                      |
|   | 161.3    | 10.6     | 3.0                  | R         | 82-3  | 119.9        | 68.0        |                      |
|   | -33.0    | -2.1     | 3.7                  | N         | 82-5  | 111.6        | 53.6        |                      |
|   | -67.9    | -37.1    | 9.8                  | N         | 82-6  | 73.2         | 26.3        |                      |
|   | 65.8     | 39.6     | 11.4                 | R         | 82-15 | 58.4         | -14.1       |                      |
|   | 102.5    | 11.1     | 14.9                 | R         | 85-4  | 86.4         | 13.6        |                      |
|   | 71.8     | 40.2     | 8.2                  | R         | 85-5  | 60.4         | -8.9        |                      |
|   | -36.0    | -37.3    | 9.7                  | N         | 85-7  | 76.9         | 56.0        |                      |
|   | 92.7     | 7.4      | 14.8                 | R         | 85-8  | 85.3         | 3.7         |                      |
|   | 121.9    | 43.5     | 18.6                 | R         | 85-13 | 69.1         | 35.9        |                      |
|   | 106.3    | 19.4     | 17.9                 | R         | 85-14 | 83.2         | 18.5        |                      |
| mean                                    | -66.0    | -25.7    | 18.8                 | (Ns = 11) |       | 80.3         | 26.1        | 18.1                 |
| Stage 3-1 (Late Miocene)                |          |          |                      |           |       |              |             |                      |
|   | -39.2    | -26.9    | 2.4                  | N         | 82-7  | 87.6         | 52.3        |                      |
|   | -30.3    | -50.8    | 9.5                  | N         | 85-6  | 55.6         | 59.4        |                      |
| mean                                    | -35.5    | -38.9    | ---                  | (Ns = 2)  |       |              |             |                      |
| Stage 3-2 (Early Pliocene)              |          |          |                      |           |       |              |             |                      |
|   | -32.5    | -52.0    | 12.6                 | N         | 82-1  | 54.8         | 57.3        |                      |
|   | 123.5    | 46.4     | 15.3                 | R         | 82-10 | 66.4         | 37.4        |                      |
|   | 165.4    | 54.2     | 13.9                 | R         | 82-11 | 32.7         | 68.7        |                      |
|   | -16.0    | -39.6    | 7.5                  | N         | 82-12 | 67.9         | 74.3        |                      |
| mean                                    | -29.8    | -49.3    | 16.7                 | (Ns = 4)  |       |              |             |                      |
| Stage 3 (Late Miocene - Pliocene)       |          |          |                      |           |       |              |             |                      |
| mean                                    | -32.0    | -45.9    | 12.5                 | (Ns = 6)  |       | 63.0         | 59.3        | 13.2                 |

Data are after tectonic correction.

D : declination of remanent magnetization, I : inclination of remanent magnetization,  $\alpha_{95}$  : semiangle of cone of 95% confidence, P : polarity of remanent magnetization, Ns : number of site for calculation of mean direction in each stage, V.G.P. : virtual geomagnetic pole, Long. : longitude of the position of V.G.P., Lat. : latitude of the position of V.G.P.

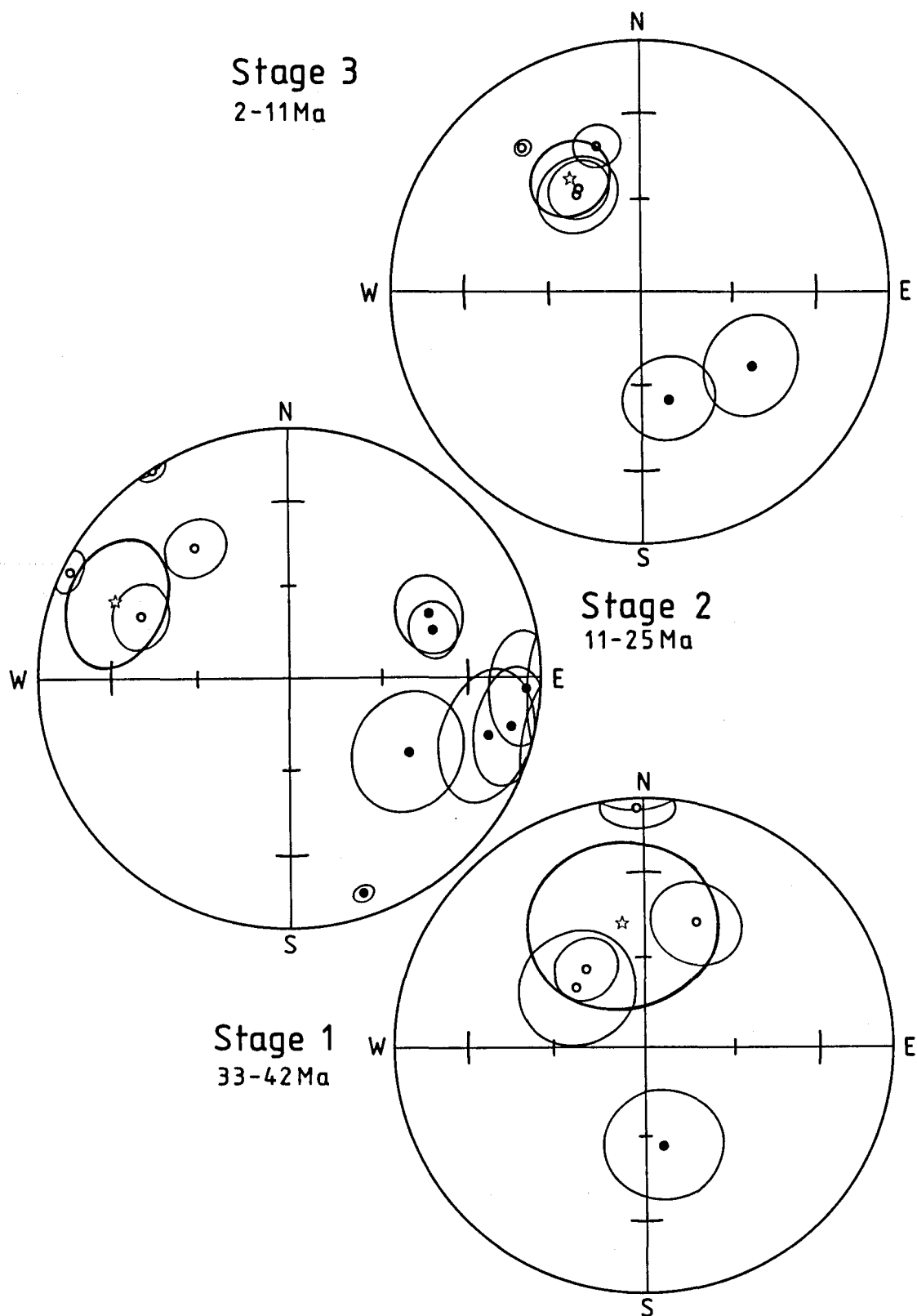


Fig. 8 A summary of characteristic directions of magnetization in each stage by equal area projection.

Site-mean directions and 95% confidence circles are represented by dots and thin line, respectively. The mean directions in each stage and 95 % confidence circles are shown by a star and a thick line, respectively. Positive inclinations are shown as black dots and negative inclinations as open dots. stage 1 : late Eocene-early Oligocene, stage 2 : early-middle Miocene, stage 3 : late Miocene-Pliocene.

to early Oligocene, Stage 2 is early to middle Miocene and Stage 3 is late Miocene to Pliocene. Two boundaries of the three stages correspond to the major unconformity. The mean paleomagnetic direction for each stage is tabulated in Table 3 and shown in Fig. 8.

#### **Stage 1 (late Eocene to early Oligocene)**

The rocks from five sites of the lower Wainimala Group and the Colo Stock have preserved reliable paleomagnetic records. The declination of the mean paleomagnetic direction in this stage is deflected to the west by ten degree from the present geocentric dipole field ( $D=0.0^\circ$ ,  $I=-33.0^\circ$ ). Although these directions lie within 95% confidence level, the reliability of this paleomagnetic direction can be confirmed by the presence of both normal and reversed polarities in this stage as well as by the good agreement between both paleomagnetic directions from igneous rocks and from sedimentary rocks. The reliability of the mean direction is also ascertained through the evidence that the directions before tectonic correction from all the sites in this stage are different from the present geomagnetic field.

#### **Stage 2 (late to middle Miocene)**

The declination of the mean direction ( $-66.0^\circ$ ,  $-25.7^\circ$ ) from reliable eleven sites is clearly deflected to the west, and the inclination is similar to that of the present geocentric axial dipole field. The eleven reliable paleomagnetic directions in this stage are mainly obtained from both volcanic and sedimentary rocks of the Lower

Wainimala Group, the Sigatoka Sedimentary Group and the Savura Volcanic Group, and also obtained from some of the Colo Plutonic Suite.

The site-mean directions are grouped into two separate clusters in antipodal directions, i.e.  $(-50.2^\circ, -21.0^\circ)$  and  $(103.8^\circ, 27.6^\circ)$ . These two directions are regarded as of normal or of reversed polarity according as the inclination is negative or positive as mentioned already, while the declinations are deflected to the east or to the west, respectively. Thus, these paleomagnetic directions must correctly represent the direction of the ancient geomagnetic field.

### Stage 3 (late Miocene to Pliocene)

The declination of the mean direction  $(-32.0^\circ, -45.9^\circ)$  in this stage is also clearly deflected to the west but the value is smaller than that in Stage 2. Six reliable paleomagnetic directions from both volcanic and sedimentary rocks of the Ba Volcanic Group, the Medrausucu Group and the Nadi Sedimentary Group were used in calculation of the mean value.

The mean direction from four sites of early Pliocene (see Table 3) is comparable with that from the previous work. Paleomagnetic direction of Viti Levu in early Pliocene  $(22^\circ, -37^\circ)$  had been compiled by James and Falvey (1978) using their own data with Tarling's data (1967). The circle of 95% confidence level of this study satisfactorily overlaps that of their studies.

The samples from the site no. 82-1 were collected in

order to find whether the Gilbert-Gauss boundary occurred at the expected stratigraphic level. A change from reverse to normal polarity was found to lie between samples 82-1-1 and 82-1-2 (Table 1). The age of this level was presumed by an extrapolated regression line as 3.46 Ma (Rodda et al., 1985), being in reasonable agreement with current polarity time scales (Cox and Dalrymple, 1967; Mankinen and Dalrymple, 1979; Harland et al., 1982).

Characteristics of the paleomagnetic results from late Eocene to Pliocene from Viti Levu are summarized as follows:

- (1) The paleomagnetic direction in each stage is held in its original condition.
- (2) The declination is largely deflected to the west in Stage 2. On the other hand, the declination in Stage 1 is deflected toward north-north-west. The changes in declination took place in late Oligocene and also later than late Miocene.
- (3) The changes in inclination is not remarkable between these stages.

#### IV-3 Rotation of Viti Levu

The position of the mean virtual geomagnetic pole with 95% confidence level in each stage was computed with the virtual geomagnetic pole in each site and shown in Table 3 and Fig. 9. The virtual geomagnetic pole in each site was calculated with the site mean direction of magnetization,

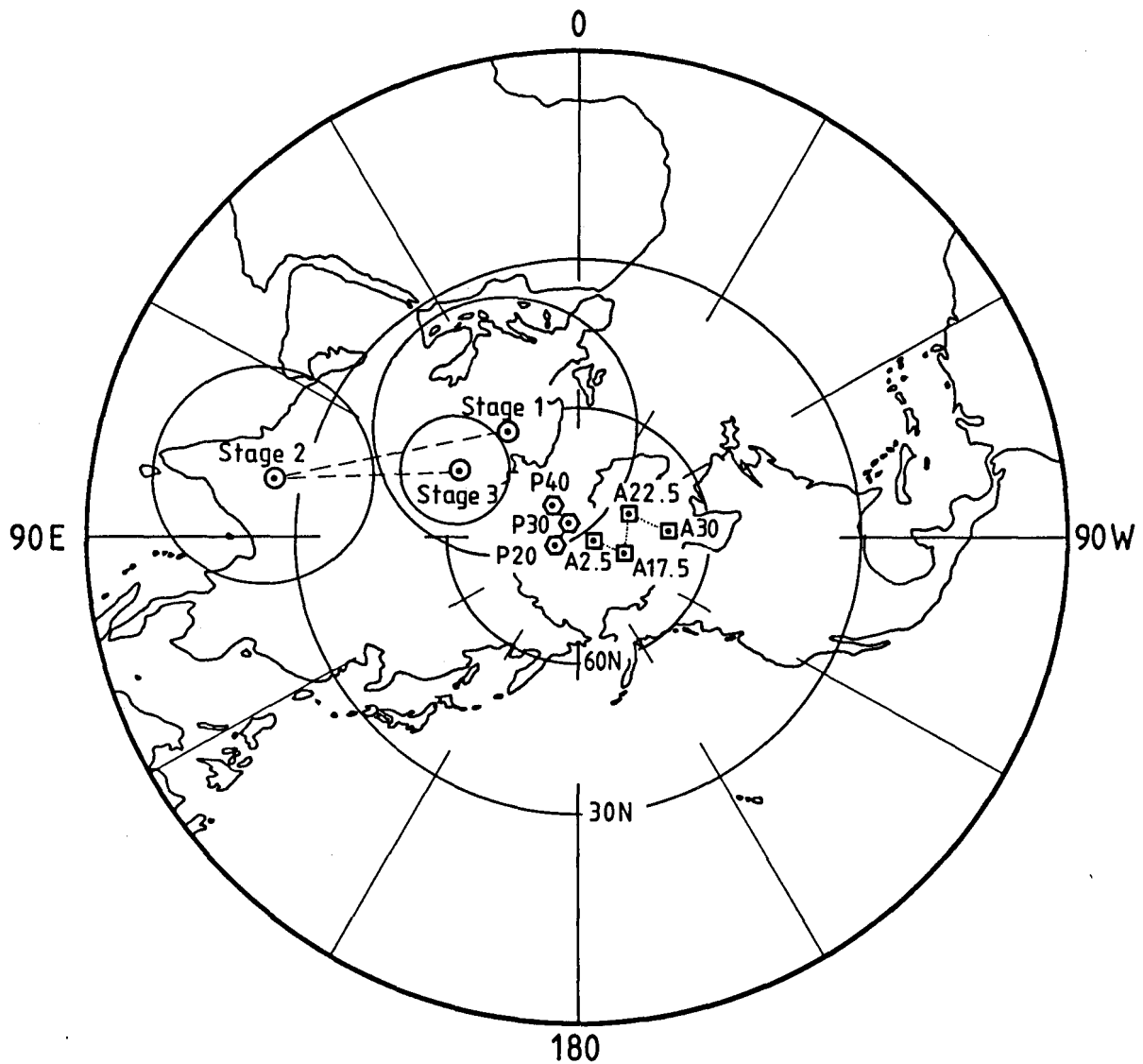


Fig. 9 Virtual geomagnetic poles of Viti Levu from Late Eocene to Pliocene.

The mean pole positions for each stage (stage 1 : late Eocene-early Oligocene, stage 2 : early-middle Miocene, stage 3 : late Miocene-Pliocene) are shown by circles with a circle of  $\alpha_5$ . Apparent polar wander path with ages in millions of years for the Pacific Plate (Suarez and Molnar, 1980) and the Australian Plate (McElhinny et al., 1974) are expressed by hexagons and squares, respectively.

assuming that the geomagnetic field has been geocentric axial dipole. Several studies have been carried out to estimate the Australian apparent polar wander path (e.g. McElhinny et al., 1974; Irving and Irving, 1982; Idnurm, 1985 and so on). The apparent polar wander path from Australia by McElhinny et al. is most suitable for further discussion in this study, because the density of virtual geomagnetic pole positions is higher in the duration from late Eocene to Pliocene than the other authors' and the paleomagnetic sampling sites by McElhinny et al. are mostly spread in the eastern Australia. It does not seem, however, that there is such fundamental difference between the result of McElhinny et al. and that of the others as it has influence on the discussion in the present study. The apparent polar wander path from the Pacific Plate by Suarez and Molnar (1980) is used in further discussion in the present study. Reliability of this apparent polar wander path was sufficiently discussed in their paper from the pelagic sediment distribution and using a set of continental paleomagnetic data etc.

The paleomagnetic direction change is caused both by tectonic movement and by apparent polar wander. If no tectonic movements in and around Viti Levu have taken place with respect to the Pacific Plate or the Australian Plate, the apparent polar wander path from Viti Levu should precisely agree with that from either the Pacific Plate or the Australian Plate. Comparing the apparent polar wander path from Viti Levu with that from the Australian Plate by McElhinny et al. or the Pacific Plate by Suarez and Molnar,

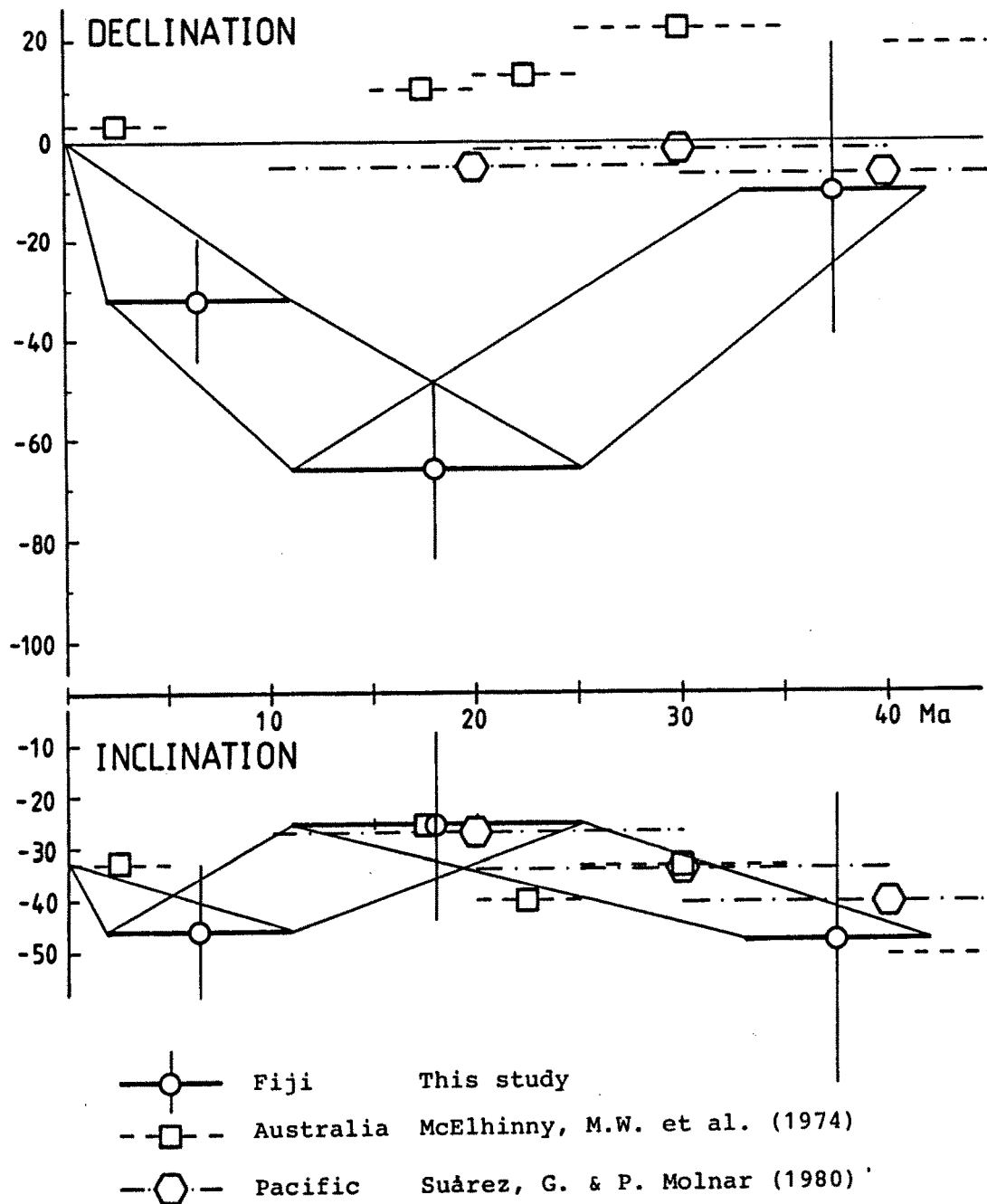


no agreement was found as shown in Fig. 9. This indicates that relative tectonic movement of Viti Levu has taken place with respect to both the Pacific Plate and the Australia plate.

Making a point ( $178.0^{\circ}\text{E}$ ,  $17.75^{\circ}\text{S}$ ), the representative of Viti Levu, the geomagnetic declinations and inclinations were calculated in several ages from the above-mentioned polar wander paths and these calculated declinations and inclinations were plotted in Fig. 10 as a function of the age. The amount of tectonic movement (rotation and parallel movement to the meridian) of Viti Levu can be estimated from this Figure, with respect to the Pacific Plate or the Australian Plate.

Considerable discrepancies between the paleomagnetic and calculated declinations of Viti Levu indicate that the island of Viti Levu rotated relatively as a micro plate. Moreover, twice rotational movements are detected from the change of declination. The poles of these rotations can be situated in Fiji or not so far from Fiji, because the paleomagnetic inclination of Viti Levu is very similar to both calculated inclinations from the Australian Plate and from the Pacific Plate as shown in Fig. 10, and this fact also means that the tectonic movement parallel to the meridian is hardly detected as the movement relative to either the Australian Plate or the Pacific Plate.

The anticlockwise rotation of about  $75^{\circ}$  of Viti Levu with respect to the Australian Plate since late Miocene is estimated from the evidence that the paleomagnetic declination of Viti Levu in Stage 2 is  $-66^{\circ}$  and, contrary, the



**Fig. 10** Change in declination and inclination of paleomagnetic direction of Fiji as a function of the age.

Mean paleomagnetic directions in each stage are shown by circles. The declination and inclination error bars corresponding to the  $\alpha_{95}$  and shown by thin lines. Calculated declination and inclination both from the Australian Plate (McElhinny et al., 1974) and from the Pacific Plate (Suarez and Molnar, 1980) are represented by squares and hexagons, respectively. Time intervals in averaging data of Viti Levu, Australia and Pacific are shown by age bars.

calculated declination from the Australian Plate from 15 to 20 Ma is  $+10^\circ$ . Intermediate value of difference in declination from late Miocene to Pliocene supports the existence of this anticlockwise rotation of Viti Levu: That is, the value of  $-35^\circ$  was obtained from the difference between the paleomagnetic declination of Viti Levu ( $D=-32^\circ$ ) in Stage 3 and the calculated declination of Viti Levu from the Australian Plate ( $D=+3^\circ$ ) from 0 to 5 Ma. Paleomagnetic result in Stage 3 may show characteristic directions acquired during the period of rotation of Viti Levu.

The clockwise rotation of Viti Levu in late Oligocene is estimated in the same manner. The value of the declination of Viti Levu expected from the Australian Plate in this period is  $20^\circ$  as a result of calculation of the mean value of calculated declinations in this period, i.e.  $22^\circ$ ; 25-35 Ma and  $19^\circ$ ; 40-50 Ma. The value of  $-30^\circ$  was obtained by subtracting this mean value from the paleomagnetic declination ( $-10^\circ$ ) of Viti Levu in Stage 1. The difference between these values ( $-30^\circ$  in Stage 1 and  $-75^\circ$  in Stage 2) suggests that the clockwise rotation of  $45^\circ$  took place during the late Oligocene (33-25 Ma).

## V Discussions about tectonic implications

As mentioned in the preceding section, the followings are concluded with the paleomagnetic results from late Eocene to Pliocene in Viti Levu: (1) the clockwise rotation of  $45^\circ$  of Viti Levu took place during late Oligocene, (2) the anticlockwise rotation of  $75^\circ$  of Viti Levu has taken place since late Miocene, and (3) the Euler poles of these rotations are situated in or near Fiji. These rotations must closely relate to the origin and development of complex physiographical and geological structure in the Fiji region. The timing, the amount and the direction of these rotation must be important as a clue to the origin and the driving force of these rotations.

A tectonic history from late Eocene to present in the Fiji region will be described under the construction possible to explain these rotations. The Australian Plate is chosen as a reference frame in this paleogeographic reconstruction (Fig. 12). Relative plate motion between the Pacific and the Australian Plates was computed from the rotation poles and the angular velocities of the plates determined by Gordon and Jurdy (1986). Calculated relative motion between the two plates since 42 Ma at the position of Fiji is presented by a convergent vector (8.6-8.8 cm/yr) directed almost perpendicular to the meridian in the hot spot reference frame. Reliability of this motion is also confirmed by the fact that both tendency of the inclination change with respect to the age and the absolute values of inclination at the reference point in Viti Levu calculated

from the Australian virtual geomagnetic poles are very similar to those from the Pacific plate. The agreement of paleomagnetic inclinations can replace with the agreement of paleolatitudes. For consistency the ages of all magnetic anomalies and chronostratic scale are reassigned to conform with the time scale by Harland et al. (1982) and are then rounded off to the nearest million years. For following discussion, informations of the volcanism are mainly referred to Kroenke (1984) and Rodda and Kroenke (1984) and the magnetic lineation patterns are referred to Malahoff et al. (1982-a).

#### Early history (~ 42 Ma)

The structure between New Caledonia - the Norfolk Ridge and the Australian Continent had been fundamentally formed before 43 Ma (Fig. 11). Seafloor spreading in the eastern margin of the Australian Continent began in late Cretaceous, displacing the eastern margin of the Australian Continent formed in the period from late Paleozoic to early Mesozoic (Kroenke, 1984). Formation of the New Caledonia Basin, displacing New Caledonia and the Norfolk Ridge to the north-east, seems to have been completed by early Paleocene (Kroenke, 1984). Formation of the Tasman Basin, displacing the Lord Howe Rise to the east continued to early Eocene (Weissel and Hays, 1977). Direction of the plate motion for the Pacific plate changed in 43 Ma (Morgan, 1972; Clague and Jarrard, 1973; Gordon and Jurdy, 1986).

#### Late Eocene - Early Oligocene (42-33 Ma)

Island-arc tectonism along the Vitiaz Ridge began in the period from late Eocene to early Oligocene and were probably caused by new subduction zone along the Vitiaz Trench, underthrusting of the Pacific Plate beneath the Australian Plate (Kroenke, 1984). The initiation of new subduction zone may relate to reorganization of the plate boundary between the Australian Plate and the Pacific Plate supervening on the change of the motion of the Pacific Plate. Following formation of frontal arc in the Vitiaz in the period from late Eocene to early Oligocene, volcanism began along the Vitiaz Arc and continued to early Miocene. On Viti Levu, Vitiaz Arc magmatic activity is represented by a tonalite intrusion into the lower Wainimala Group (Rodda and Kroenke, 1984).

#### Late Oligocene (33-25 Ma)

The timing (33-25 Ma) and the amount (45°) of clockwise rotation of the Viti Levu are a clue to the origin of rotation (Fig. 12-a and b). The South Fiji Basin formed during late Oligocene by back-arc spreading marginal to the Lau-Tonga arc-trench system (Kamp, 1986). Magnetic anomaly lineations 12 to 7A have been widely mapped (Watts et al., 1977; Davey, 1982; Malahoff et al., 1982-a) and anomaly 13 has been locally identified (Malahoff et al., 1982-a), indicating that the sea floor producing between 34 Ma and 27 Ma involved a R-R-R triple junction. The clockwise rotation of Viti Levu with its northwest limb took place and the fan shaped northern half of the South Fiji Basin were formed

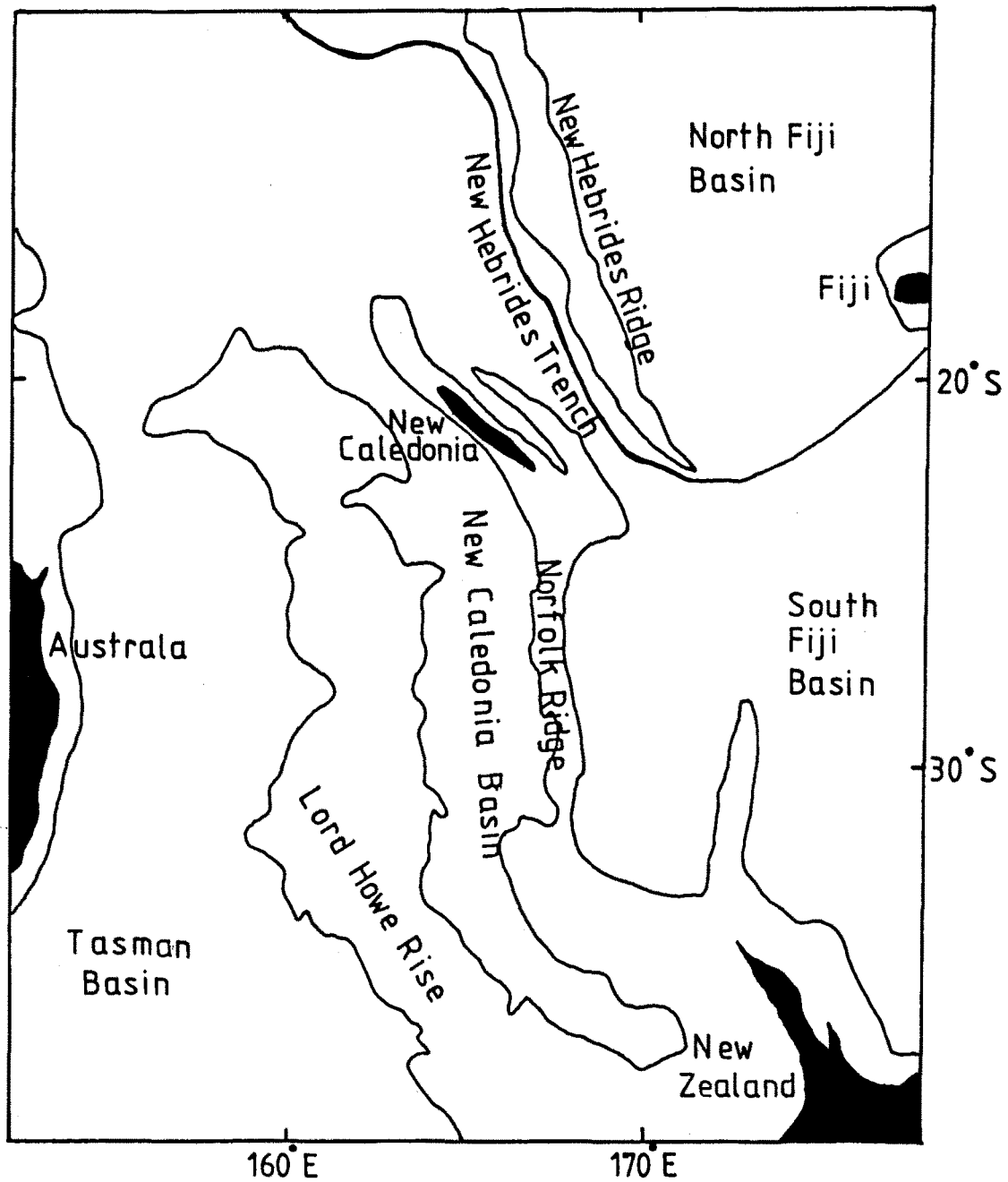


Fig. 11 Principal physiographic features between the Australian continent and the Fiji region.

with the progress of spreading of the South Fiji Basin from a system involving a triple junction (Fig. 12-b). The angle between the direction of anomaly 12 in the central part of eastern limb and that in the central part of north western limb is approximately  $45^{\circ}$ . This angle agrees with the amount of the rotation of Viti Levu. Clockwise rotation of Viti Levu and formation of the South Fiji Basin can be explained by introducing more plate boundaries, e.g. spreading ridges, between the Australian Plate and the Pacific Plate margins.

#### Early - Middle Miocene (25-11 Ma)

Reorganization of the boundary between the Australian Plate and the Pacific Plate was completed in the early Miocene (Kroenke, 1984). A brief period of volcanic activity and the deposition of coarse, clastic sediment in the period from early to middle Miocene in the Vitiaz Arc and Viti Levu may be related to reactivation of a southwest-dipping subduction zone beneath the Vitiaz-Fiji Arc. (Kroenke, 1984; Rodda and Kroenke, 1984). Passive arc volcanism in the period from early to middle Miocene in the Vitiaz-Fiji Arc seems to be influenced by a oblique subduction and/or by a collision of the Ontong-Java Plateau to the Vitiaz Trench. This possibility is suggested from plate reconstruction using the data of rotation poles and angular velocities of the Australian Plate and the Pacific Plate by Gordon and Jurdy (1986). Oblique subduction is inferred from the evidence that WNW-ESE trend of the Vitiaz Trench is almost parallel to the relative plate motion and the



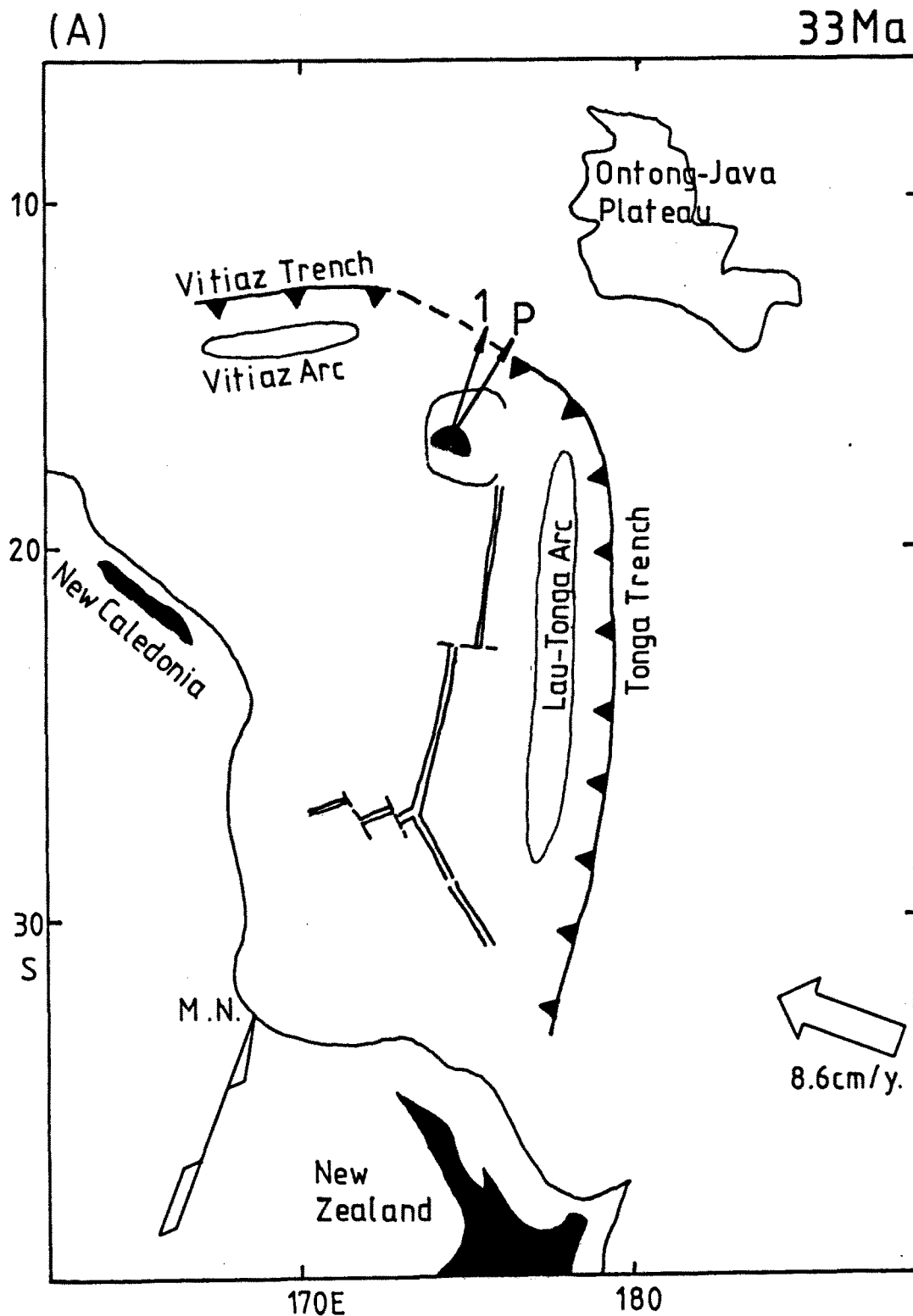


Fig. 12 Schematic diagrams of tectonic evolution of the Fiji region in coordinate system fixed with respect to the Australian Plate.

Arrows show obtained paleomagnetic directions of Viti Levu for each stage (1: stage 1, late Eocene - early Oligocene, 2: stage 2, early-middle Miocene, 3: stage 3, late Miocene - Pliocene). Present north direction with respect to Viti Levu is represented by an arrow, P. Ticks show the location of the upper plate in a subduction zone. The failed subduction is shown with unfilled ticks. Sea floor spreading

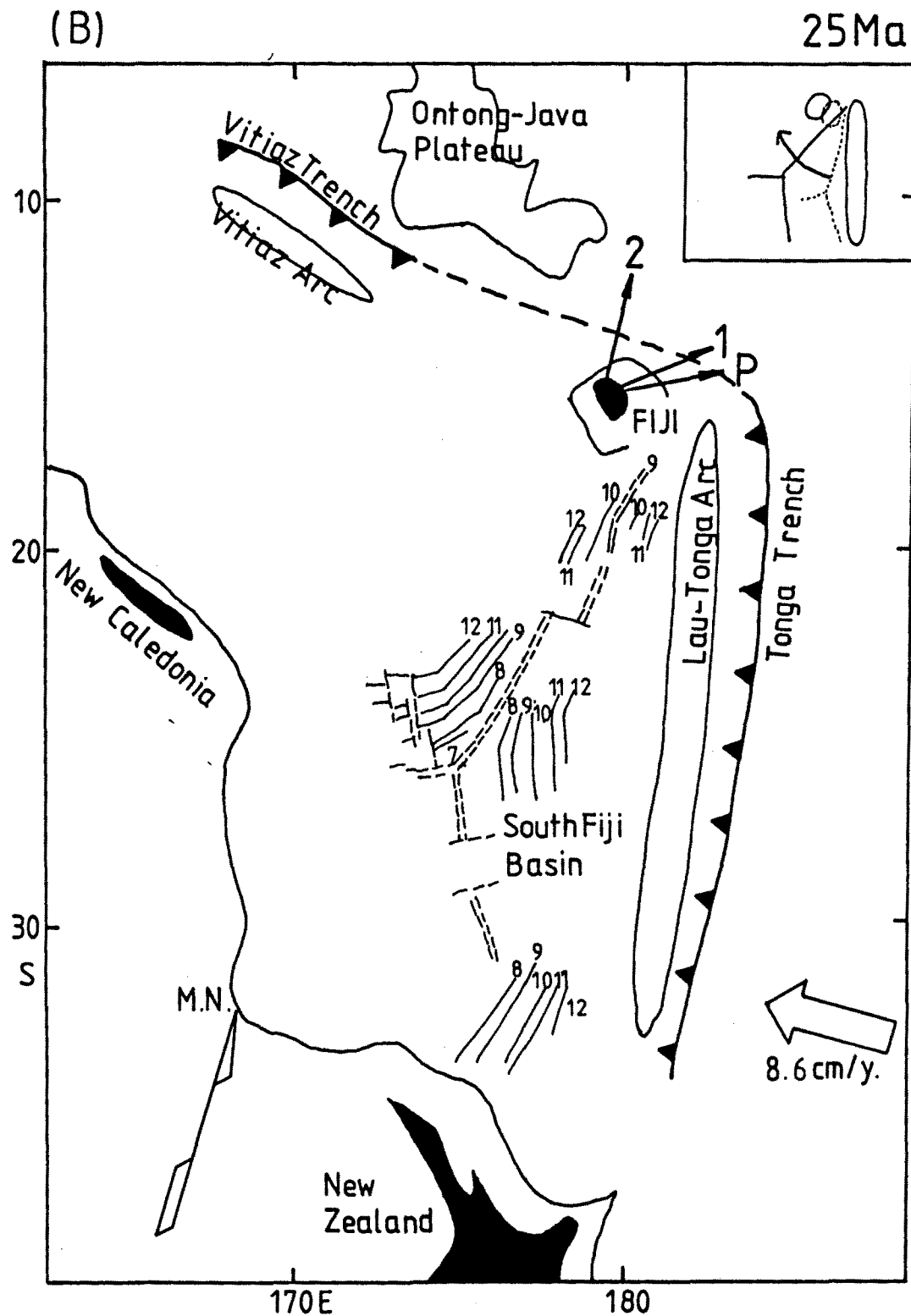


Fig. 12 (continued) centers are shown by double ruled lines, transform fault zones are by thick single-ruled lines, and by dashed lines where uncertain or inactive. Magnetic anomaly lineations are shown by thin lines with anomaly numbers taken from Malahoff et al. (1982-a). The directions and rates of relative motion between the Australian Plate and the Pacific Plate are taken from Gordon and Jurdy (1986) and shown by unfilled arrows. The north direction represented to the virtual geomagnetic north pole from McElhinny et al. (1974) is shown by an arrow in the west of the New Zealand.

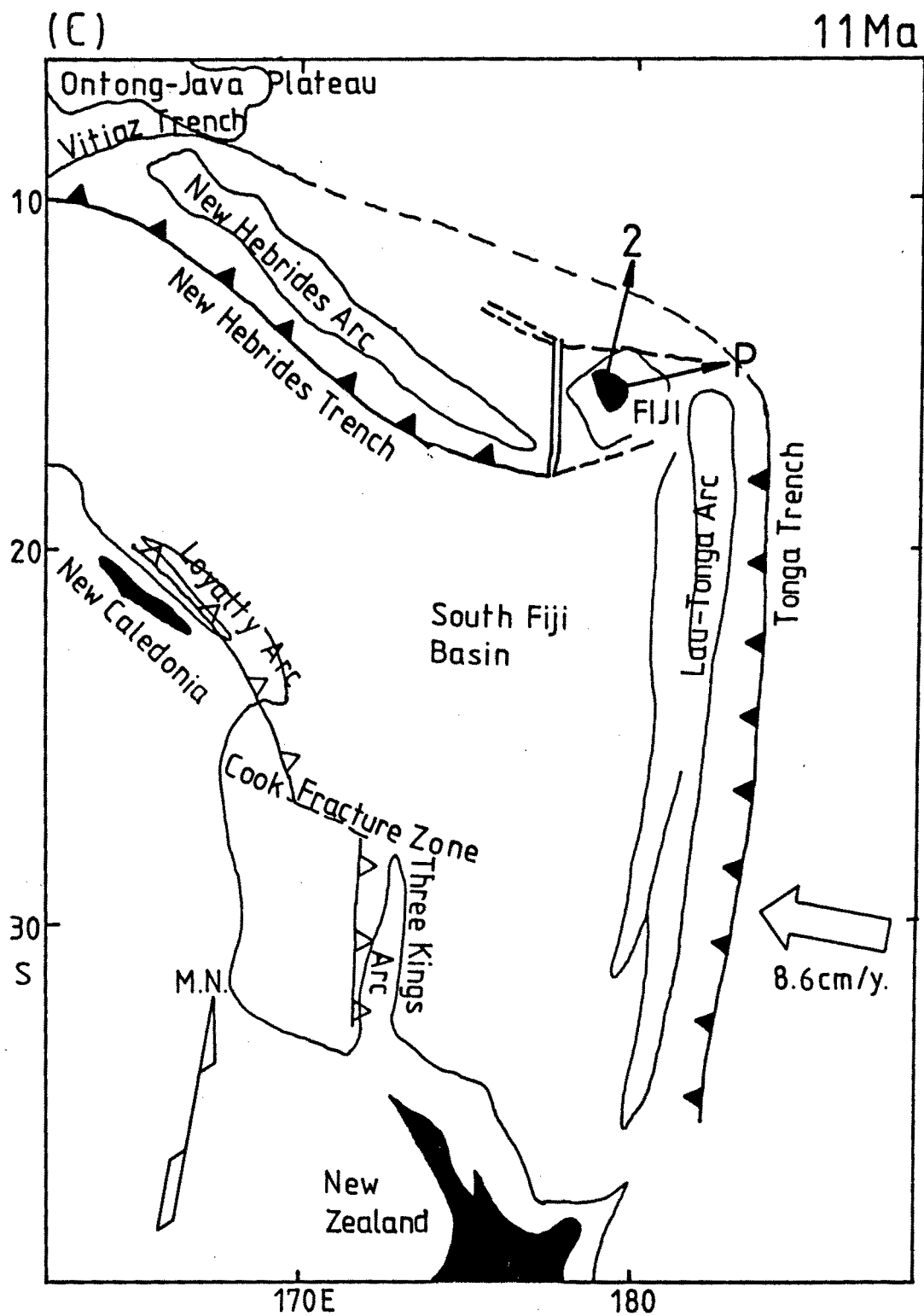


Fig. 12 (continued)

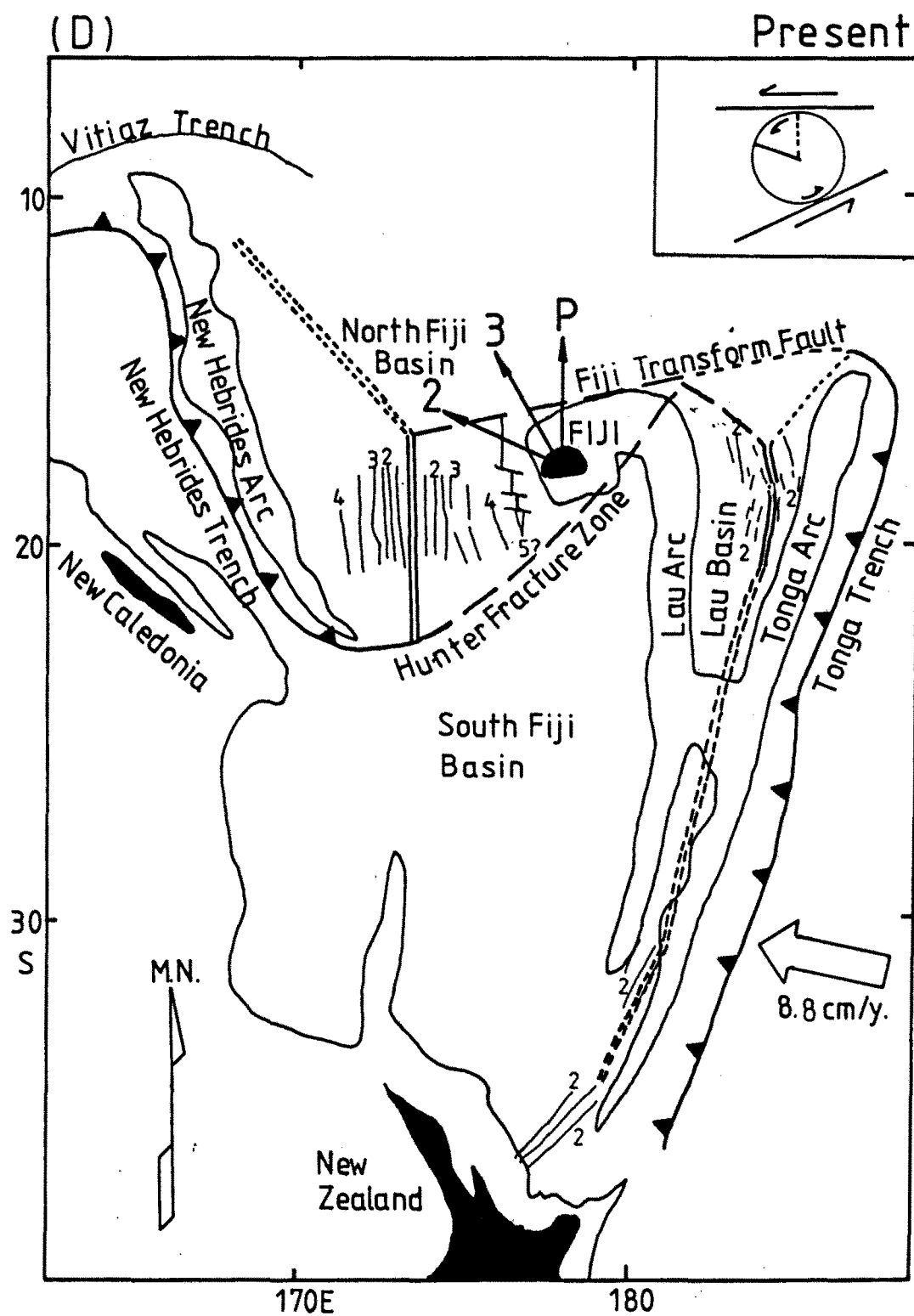


Fig. 12 (continued)

collision is inferred from paleo-position of the Ontong-Java Plateau (Fig. 12-b and c).

The onset of volcanic activity along the combined Lau-Tonga volcanic axis occurred close to the boundary between Oligocene and Miocene and continued to Miocene (Kroenke, 1984). Although convergence between the Australian Plate and the Pacific Plate was absorbed beneath the Lau-Tonga Arc throughout most of Miocene, the Three Kings Arc and the Loyalty Arc may have been the site of subduction from middle to late Miocene (Kroenke, 1984). An age from middle to late Miocene (15-9 Ma) for the volcanism along the Three Kings Ridge has been suggested on the basis of evidence from DSDP Site 206.

The missing western limb of the South Fiji Basin, magnetic anomaly sequence 7-13, was probably subducted under the Three Kings Ridge's complex in the period from middle to late Miocene. Trench morphology indicating northeast ward subduction is recognized in a seismic reflection profile taken across the South Loyalty Basin southwest of the Loyalty Ridge (Dubois et al., 1974). The subduction zone along the Loyalty Ridge and the Three Kings Ridges seemed to be joined by a transform fault forming the Cook Fracture Zone.

#### **Late Miocene - Present (11-0 Ma)**

A complex reorganization of plate boundaries occurred in late Miocene. The anticlockwise rotation of Viti Levu may be related to the reorganization. The collision of the Ontong-Java Plateau at the Vitiaz Trench may have stopped

subduction along the Vitiaz Trench, in close to middle and late Miocene boundary (Brocher, 1985-b). This collision probably led to a subsequent reversal of the subduction polarity to the southwest of the New Hebrides Arc to accommodate the ongoing convergence between the Australian and Pacific Plates. (Brocher, 1985-b). The ongoing divergence of the currently active trenches has been accompanied by back-arc spreading in the North Fiji Basin (Malahoff et al., 1982-a). The movement of the New Hebrides trench-arc system was estimated from paleomagnetic data that the New Hebrides Arc showed clockwise rotation of  $30^\circ$  since late Miocene (Falvey, 1978). N-S orientated magnetic anomalies from 1 to 4 or 5 (0 - 8 or 10 Ma, respectively) are mapped in the southern portion of the North Fiji Basin (Malahoff et al., 1982-a). Although the location, azimuth, and rate of spreading of the ridges in the northern region of the basin are still uncertain (Brocher, 1985-b), the North Fiji Basin have been formed since late Miocene involving a R-R-F triple junction (Fig. 12-c and d). The existence of E-W orientated transform fault, i.e. Fiji Transform Fault, in the north of Fiji was suggested based on bathymetry (Green and Cullen, 1973; Yaskawa et al., 1984) and seismotectonics (Eguchi, 1984). Both the Fiji Transform Fault and NE-SW trending the Hunter Fracture Zone in the south of Fiji were identified as left-lateral shearzones based on focal mechanism solutions of shallow earthquakes (Eguchi, 1984). The  $75^\circ$  anticlockwise rotation of Viti Levu since late Miocene can be explained as "ball bearing" rotation accommodated by antithetical transform faults, i.e. the Fiji Transform Fault

and the Hunter Fracture Zone, as shown in Fig. 12-d. The possibility of such mechanism was discussed in the Western North America (Beck, 1976). The dimension of rotational rigid block is not certain, however it is suggested that one of the possible boundary is a transform fault zone situated in the west of Viti Levu (Brocher and Holmes, 1985).

N-S trending magnetic lineations comprising anomalies 1-2' (0-3.5 Ma) are mapped over much of the Lau Basin. Although the tectonics of the northern portion of the Lau Basin is still uncertain, the initial rifting of the Lau-Tonga Trench and the ongoing divergence of currently active trenches have been accompanied by back-arc spreading in the Lau Basin since the time between late Miocene and early Pliocene (Weissel, 1977; Malahoff et al., 1982-a). A back-arc spreading has been also recognized in the Havre Trough (Malahoff et al, 1982a), south of the Lau Basin. The view, that the age of spreading is young, has been supported by the seismotectonic study, geological study of the island and, besides, by the following facts in this area: (1) The acoustic basement is shallow and rough, (2) the heat flow is high and variable, and (3) the sediment cover is thin (Weissel, 1977).

Present plate boundaries are described by Brocher (1985-b) as follows; (1) convergent boundaries include the Tonga-Kermadec Trenches where the Pacific Plate is consumed and the New Hebrides Trench where the Australian Plate consumed, (2) divergent boundaries are N-S trending sea-floor spreading in both the North Fiji Basin and the Lau Basin, and (3) translational boundaries are the Fiji

Transform Fault which connects the spreading center in the North Fiji Basin and the Tonga Trench and the Hunter Fracture Zone which bounds the northern margin of the South Fiji Basin.



## VI Conclusions

Remanent magnetization of the rocks collected from Viti Levu were measured. Reliable paleomagnetic data obtained from 22 sites can be divided into three stages on the basis of the geological evidence; i.e. ( $D = -10^\circ$ ,  $I = -48^\circ$ ); late Eocene - early Oligocene, ( $D = -66^\circ$ ,  $I = -26^\circ$ ); early-middle Miocene and ( $D = -32^\circ$ ,  $I = -46^\circ$ ); late Miocene - Pliocene. The paleomagnetic field calculated from the Australian apparent polar wander path were subtracted and then the tectonic movement of Viti Levu with respect to the Australian Plate were estimated. It was concluded that; (1) the clockwise rotation of about  $45^\circ$  took place during late Oligocene, (2) the anticlockwise rotation of about  $75^\circ$  have occurred since late Miocene, and (3) these Euler poles are situated in Fiji or near Fiji.

To explain the origins of these rotation of Viti Levu possible tectonic history of the Fiji region was proposed with plate tectonic concept. Clockwise rotation in late Oligocene was closely related to the formation of the South Fiji Basin and anticlockwise rotation since late Miocene was closely related to the formation of the North Fiji Basin. Mechanism of the two rotational movements seems to be different. Fan-shape of the northern half of the South Fiji Basin were formed and the clockwise rotation of Viti Levu took place with a progress of the spreading of the basin from a system involving the R-R-R triple junction. The anticlockwise rotation of Viti Levu was explained as "ball bearing" rotation accommodated by antithetical transform

faults accompanied with the spreading of the North Fiji Basin.

The importance of the Fiji region is that it is one of a few places where oceanic plates have converged since Paleogene. The history of the Fiji region suggests that the modes of reorganization of the plate boundaries were various in such a convergence zone. Such a consideration of the region's history based on paleomagnetic data will lead to better understanding of the process of intra oceanic plate collision.

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## References

- Beck, M. E., Jr., Discordant paleomagnetic pole positions as evidence of regional shear in the western Cordillera of North America, *Am. J. Sci.*, 276, 694-712, 1976.
- Brocher, T. M., (ed.), "Investigations of the Northern Melanesian Borderland", *Circum-Pacific Council for Energy and Mineral Resources Earth Sci. Ser.*, 3, Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, 199pp, 1985-a.
- Brocher, T. M., On the formation of the Vitiaz trench lineament and North Fiji Basin, in Brocher, T. M. (ed.) "Investigations of the Northern Melanesian Borderland", *Circum-Pacific Council for Energy and Mineral Resources Earth Sci. Ser.*, 3, Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, 13-33, 1985-b.
- Brocher, T. M., and R. Holmes, The marine geology of sedimentary basins south of Viti Levu, Fiji, in Brocher T. M. (ed.) "Investigations of the Northern Melanesian Borderland", *Circum-Pacific Council for Energy and Mineral Resources Earth Sci. Ser.*, 3, Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, 123-138, 1985.
- Chase, C. G., Tectonic history of the Fiji Plateau, *Geol. Soc. Am. Bull.*, 82, 3087-3109, 1971.
- Clague, D. A. and R. D. Jarrard, Tertiary Pacific plate motion deduced from the Hawaiian-Emperor chain, *Geol. Soc. Am. Bull.*, 84, 1135-1154, 1973.

- Cole, W. S., Upper Eocene and Oligocene larger foraminifera from Viti Levu, Fiji, *Prof. Pap. U. S. Geol. Surv.*, 374-a, 1960.
- Coleman, P. J., Pers. comm., 1974, in Yaskawa et al., 1985.
- Cox, A. V., and Dalrymple, G. B., Statistical analysis of geomagnetic reversal data and the precision of potassium-argon dating, *J. Geophys. Res.*, 72(10), 2603-2614, 1967.
- Davey, F. J., The structure of the South Fiji Basin, *Tectonophys.*, 87, 185-241, 1982.
- Dubois, J., C. Ravenne, A. Aubertin, J. Louis, R. Guillaume, J. Launay, and L. Montadert, Continental margins near New Caledonia, in Burk, C. A., and C. L. Drake (eds.) "The geology of continental margins", Springer-Verlag, New York, 521-535, 1974.
- Easton, W. H., Geology of Sawa-i-lau, Nanuya and Verona islands, Fiji, *S. Pac. Pet. NL, rep.*(Unpublished), 1973.
- Eguchi, T., Seismotectonics of the Fiji Plateau and Lau Basin, *Tectonophys.*, 102, 17-32, 1984.
- Falvey, D. A., Analysis of paleomagnetic data from the New Hebrides, *Bull. Aust. Soc. Explor. Geophys.*, 9(3), 117-123, 1978.
- Fisher, R. A., Dispersion on a sphere, *Proc. Roy. Soc. London, A*, 217, 295-315, 1953.
- Gill, J. B., and I. McDougall, Biostratigraphic and geological significance of Miocene - Pliocene volcanism in Fiji, *Nature*, 241, 176-180, 1973.

- Gordon, R. G. and D. M. Jurdy, Cenozoic global plate motions, *J. Geophys. Res.*, 91(B12), 12389-12406, 1986.
- Green, D., and D. J. Cullen, The tectonic evolution of the Fiji region, in Coleman, P.J. (ed.) "The Western Pacific : Island Arcs, Marginal Seas, Geochemistry", Univ. Western Australia Press, Nedlands, 127-145, 1973.
- Harland, W. B., A. V. Cox, P. G. Llewellyn, C. G. A. Pickton, A. G. Smith, and R. Walters, "A geologic time scale", Cambridge Univ. Press, Cambridge, 131pp, 1982.
- IAGA Division I Working Group 1, International Geomagnetic Reference Fields: DGRF 1965, DGRF 1970, DGRF 1975 and IGRF 1980, *EOS Trans. Am. Geophys. Un.*, 57, 120-121, 1981.
- IAGA Division I Working Group 1, International Geomagnetic Reference Field revision 1985, *J. Geomag. Geoelectr.*, 37(12), 1157-1163, 1985.
- Idnurm, M., Late Mesozoic and Cenozoic paleomagnetism of Australia --I. A redetermined apparent polar wander path, *Geophys. J. R. astr. Soc.* 83, 399-418, 1985.
- International Hydrographic Organization, "General Bathymetric chart of the oceans(GEBCO, 5-10)", Canadian Hydrographic Service, Ottawa, Canada, 1982.
- Irving, E., and G.A. Irving, Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana, *Geophys. Surv.*, 5, 141-188, 1982.
- James, A., and D. A. Falvey, Analysis of paleomagnetic data from Viti Levu, Fiji, *Bull. Aust. Soc. Explor. Geophys.*, 9, 115-117, 1978.

- Kamp, P. J. J., Late Cretaceous-Cenozoic tectonic development of the southwest Pacific region, *Tectonophys.*, 121, 225-251, 1986.
- Kroenke, L. W., "Cenozoic Tectonic Development of the Southwest Pacific", *U.N. ESCAP, CCOP/SOPAC Tech. Bull.*, 6, 126pp, 1984.
- Malahoff, A., Gravity and magnetic studies of the New Hebrides island arc, *New Hebrides Condominium Geological Survey, Special Rpt. Brit. Oversea Geol. Surv., Pt. Vita. New Hebrides*, 67pp, 1970.
- Malahoff, A., R. H. Feden, and H. S. Fleming, Magnetic anomalies and tectonic fabric of marginal basins north of New Zealand, *J. Geophys. Res.*, 87(B5), 4109-4125, 1982-a.
- Malahoff, A., S. R. Hammond, J. J. Naughton, D. L. Keeling, and R. N. Richmond, Geophysical evidence for post-Miocene rotation of the island of Viti Levu, Fiji, and its relationship to the tectonic development of the North Fiji Basin, *Earth Planet. Sci. Lett.*, 57, 398-414, 1982-b.
- Mankinen, E. A., and G. B. Dalrymple, Revised geomagnetic polarity time scale for the interval 0-5m.y. BP, *J. Geophys. Res.*, 84(B2), 615-626, 1979.
- McDougall, I., Potassium-argon ages of some rocks from Viti Levu, *Nature*, 198(4881), 677, 1963.
- McElhinny, M. W., B. J. J. Embleton, and P. Wellman, A synthesis of Australian Cenozoic paleomagnetic results, *Geophys. J. R. astr. Soc.*, 36, 141-151, 1974.

- Morgan, W. J., Plate motions and deep mantle convection, *Mem. Geol. Soc. Am.*, 132, 7-22, 1972.
- Rodda, P., Outline of the geology of Viti Levu, *N. Z. J. Geol. Geophys.*, 10, 1260-1273, 1967.
- Rodda, P., Fiji, in Spencer, A. M. (ed.) "Mesozoic-Cenozoic orogenic belts", *Spec. Publ. geol. Soc Lond.*, 4, 425-432, 1974.
- Rodda, P., Fiji, in Fairbridge, R. W. (ed.) "The encyclopedia of world regional geology, part 1", Dowden, Hutchinson & Ross, Stroudsburg, PA, USA, 278-282, 1975.
- Rodda, P., Fiji, in Stratigraphic Correlation between sedimentary Basins of the ESCAP Region, Vol.VIII; "ESCAP Atlas of Stratigraphy", *U.N. ESCAP, Miner. Resour. Dev. Ser.*, 48, 13-21, 1982.
- Rodda, P., The standard sequence of the Suva Marl revised and completed, *Rep. Miner. Resour. Dep. Fiji*, 54, 1986.
- Rodda, P., N. J. Snelling, and D. C. Rex, Radiometric age data on rocks from Viti Levu, Fiji, *N. J. Geol. Geophys.*, 10, 1248-1259, 1967.
- Rodda, P., and L. W. Kroenke, Fiji : A fragmented arc, in Kroenke, L. W. (ed.) "Cenozoic Tectonic Development of the Southwest Pacific", *U.N. ESCAP, CCOP/SOPAC Tech. Bull.* 6, 87-109, 1984.
- Rodda, P., I. McDougall, R. A. Cassie, D. A. Falvey, R. Todd, and J. A. Wilcoxon, Isotopic ages, magnetostratigraphy and biostratigraphy from the early Pliocene Suva Marl, Fiji, *Bull. Geol. Soc. Am.*, 96, 529-538, 1985.



- Skiba, W. J., Geological studies in southwest Viti Levu, *Mem. Geol. Surv, Fiji*, 1, 1964.
- Suarez, G., and P. Molnar, Paleomagnetic data and pelagic sediment faces and the motion of the Pacific plate relative to the spin axis since the late Cretaceous, *J. Geophys. Res.*, 85(B10), 5257-5280, 1980.
- Tarling, D. H., The paleomagnetism of some rock samples from Viti Levu, Fiji, *N. Z. J. Geol. Geophys.*, 10(5), 1235-1247, 1967.
- Uyeda, S., Facts, ideas and open problems on trench-arc-backarc systems, in Wezel, F. C. (ed.) "The origin of arcs", Elsevier Sci. Pub. B. V., Amsterdam, 435-460, 1986.
- Watts, A. B., Weissel, J. K. and Davey, F. J., Tectonic evolution of the south Fiji marginal basin. in Talwani M. and W.C. Pitman (eds.), "Island arcs, deep sea trenches and back-arc basins", Am. Geophys. Union, *Maurice Ewing Ser.*, 1, 419-427, 1977.
- Weissel, J. K., Evolution of the Lau Basin by the growth of small plate, in Talwani, M., and W. C. Pitman (eds.) "Island arcs, deep sea trenches, and back-arc basins", , Am. Geophys. Union, *Maurice Ewing Ser.*, 1, 429-436, 1977.
- Weissel, J. K. and D. E. Hayes, Evolution of the Tasman sea reapprised, *Earth Planet. Sci. Lett.*, 36, 77-84, 1977.

- Whelan, P. M., J. B. Gill, E. Kollman, R. A. Duncan, and R. E. Drake, Radiometric dating of magmatic stages in Fiji, in Scholl, D. W., and T. L. Vallier (eds.) "Geology and offshore resources of Pacific island arcs - Tonga region", *Circum-Pacific Council Energy Mineral Resources Earth Sci. Ser.*, 2, Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, 415-440, 1985.
- Yaskawa, K., N. Isezaki, T. Miyata, H. Nishimura, T. Kojo, S. Takahashi, N. Skinner, G. Heys, P. Rodda, and B. Rao, Preliminary report on the paleomagnetic study of Viti Levu island, Fiji, *Prompt Rep. First Sci. Surv. S. Pac., Res. Center S. Pac. Kagoshima Univ.*, 137-141, 1984.
- Yaskawa, K., H. Inokuchi, J. Matsuda, S. Takahashi, N. Isezaki, T. Miyata, B. Rao, and P. Rodda, Paleomagnetism of rocks from the island of Viti Levu, Fiji, *Kagoshima Univ. Res. Center S. Pac., Occasional Papers*, 5, 1-12, 1985.
- Zijderveld, J. D. A., A. C. demagnetization of rocks: analysis of results, in D. W. Collinson, K. M. Creer, and S. K. Runcorn (eds) "Method in paleomagnetism", Elsevier, Amsterdam, 1967.