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Northern Part of the Tonga Region: A Complicated Subduction Closure

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Abstract. A detailed investigation of the morphology of the Wadati-Benioff zone based on the geometry of earthquake distribution allowed us to interpret the deep structure of the northern part of the Tonga region as a result of the complicated interplay of three different subduction systems (Tonga, Lau, Horne) and two deep-seated fracture zones (Niuafo'ou, Peggy). The Tonga system represents the active part of the recent subduction of the Pacific plate, and the Lau and Horne systems are considered to be buried paleoplates, activated by a deep collision with the Tonga system. The Niuafo'ou fracture zone forms the northern tectonic closure of the active Tonga subduction and is acting as a transform fault. The function of the Peggy fracture zone might be similar, forming the northern closure of the Lau paleosubduction. The active parts of both fracture zones reach a depth of more than 400 km.

Key words: Seismicity – Plate tectonics – Tonga island arc – Deep transform faults.

Introduction

The Tonga-Kermadec subduction seems to be one of the most impressive phenomena that substantially influenced the development of the plate concept of recent tectonic evolution of the Earth (Isacks et al., 1968). Although studied by various seismological methods in considerable detail (Sykes, 1966; Oliver and Isacks, 1967; Mitronovas et al., 1969; Sykes et al., 1969; Mitronovas and Isacks, 1971; Barazangi et al., 1972), the structure of this subduction zone appears to be much more complicated than these investigators have proposed, especially in some areas of high intermediate and deep seismic activity (Hanuš and Vaněk, 1978a and b). In this connection, the northern part of the Tonga region, with an interplay of three different subduction systems and two deep-seated fracture zones, can be considered as the most complicated area of the

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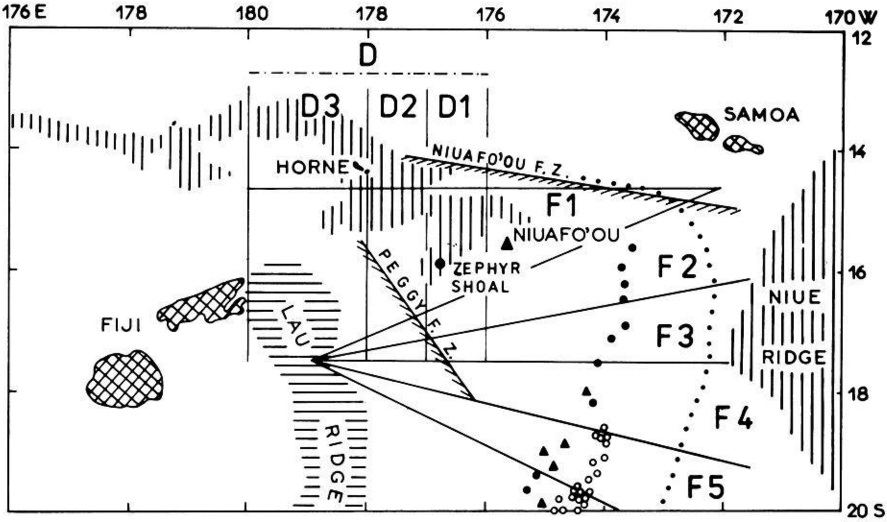


Fig. 1. Main structural elements and scheme of sections used for the study of the northern closure of the Tonga subduction zone. The Tonga-Kermadec trench is denoted by a *dotted line*, active volcanoes by *full triangles*, islands and submarine elevations associated with active volcanic chain by *full circles*, coral islands and reefs with associated submarine elevations by *open circles*

Tonga-Kermadec island arc, and, at the same time, as the northern closure of the recent Tonga subduction. The aim of the present paper is to investigate the detailed morphology of the Wadati-Benioff zone and to interpret the geometry of earthquake distribution in the area limited by 14°–19° S and 172° W–180°.

General Description

ISC data (Regional Catalogue of Earthquakes) for the seven years' period 1967–1973 were used as basic materials for studying the morphology of the Wadati-Benioff zone in the Tonga region. The ISC determinations, being based on world-wide observations, are burdened by the smallest random and systematic errors from all seismological data available. It appears that the accuracy given in the ISC bulletins is realistic and fully sufficient for studying the geometrical distribution of earthquakes in the regions of convergent plate margins.

The Tonga region was covered by a system of 22 sections approximately perpendicular to the axis of the Tonga-Kermadec trench, the scheme of which can be found in Hanuš and Vaněk (1978a). An analysis of the complete set of vertical sections, showing the depth distribution of earthquake foci in relation to the distance from the trench, reveals that the complicated geometry of the earthquake distribution cannot be interpreted by applying an elementary model of subduction. Assuming that the subduction zones preserve their simple plate-

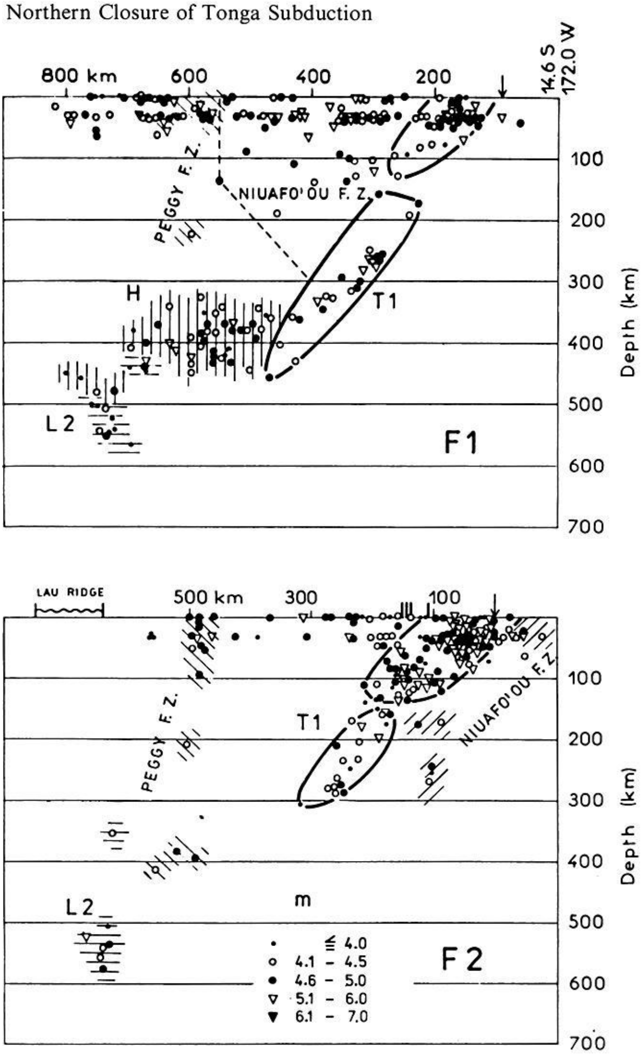


Fig. 2. Vertical Sects. *F*1 and *F*2 giving the distribution of earthquake foci in relation to the distance from the trench. For *F*1 the distance is plotted from the point 14.6° S, 172.0° W; m=ISC magnitude; active volcanoes are denoted by *full triangles*, islands and submarine elevations associated with active volcanic chain by *short vertical lines*, coral islands and reefs with associated submarine elevations by *short dotted lines*, position of the trench by *arrows*, the Lau Ridge by *wave-line*, the Wadati-Benioff zone *T* 1 by *full-line contour*, zones *L* 2, *H*, and fracture zones by *different hatching*

like shape the earthquake foci in the Tonga region can be associated with three interacting systems of subducted lithospheric plates: the recently subducting Tonga system *T* 1 and *T* 2 in the east, the remnant Lau system *L* 1 and *L* 2 in the west, and the remnant Horne system *H* in the north (Hanuš and Vaněk, 1978a).

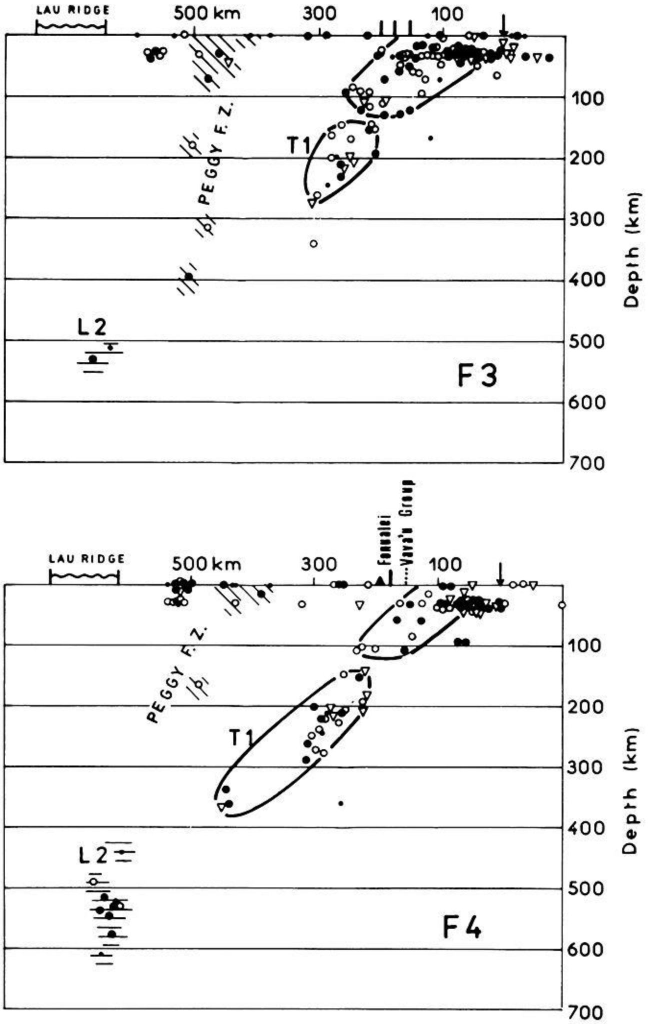


Fig. 3. Vertical Sects. *F*3 and *F*4. For key see Fig. 2

From the sequence of vertical sections, four northern sections *F*1–*F*4 of triangular shape are considered in the present paper. The position of these sections, together with the main structural elements of the northern part of the Tonga region, is given in Fig. 1, the depth distribution of earthquake foci being shown in Figs. 2 and 3.

It appears that the earthquake foci occurring in sections *F*1–*F*4 can be co-ordinated to the recently active Tonga zone *T* 1, to the Lau paleoplate *L* 2, and to the Horne system *H*. In addition, a group of shallow and intermediate earthquakes, westwards of the zone *T* 1, exists in section *F*1. Applying the principle of simple plate-like shape of lithospheric plates we conclude that these earthquakes cannot be geometrically associated with any of the above subduction zones. The specific distribution of the latter foci indicates that they belong to two active deep-seated fracture zones, the positions of which are plotted in Fig. 1; we denote them as the Peggy and Niuafo'ou fracture zones, respectively. The earthquakes associated with the Peggy fracture zone can be also found in sections *F*2, *F*3, and *F*4. In the next paragraphs the above-mentioned units will be treated in detail.

Systems of Subduction

(a) Tonga System

The general picture shown by the sequence of vertical sections confirms the existence of a well-defined Wadati-Benioff zone *T* 1 beginning in the vicinity of the Tonga-Kermadec trench. This zone is divided by an intermediate aseismic gap into two distinct seismically active parts. The gap appears to be spatially connected with the occurrence of active andesitic volcanism and can be interpreted as a zone of partial melting in the subducted Pacific plate (for details see Hanuš and Vaněk, 1978a).

The depth penetration of the zone *T* 1 changes along the trench, reaching a depth of 455 km in the northern part of the Tonga region (Sect. *F*1). Then it substantially decreases due to the hampering effect of the Niue Ridge (Sects. *F*2, *F*3) with a subsequent southward increase (Sect. *F*4) to a maximum depth of 565 km (see Fig. 4 in Hanuš and Vaněk, 1978 a). Both the intermediate and deep seismic activity are abruptly terminated in the north by the Niuafo'ou fracture zone, which evidently forms the northern tectonic closure of the Tonga subduction (Isacks et al., 1969). The Wadati-Benioff zone *T* 1 represents, in our interpretation, the active part of the recent subduction of the Pacific plate along the Tonga-Kermadec trench.

(b) Lau System

In the western part of the Tonga region numerous deep earthquakes occur, which cannot be geometrically co-ordinated to the Wadati-Benioff zone of the Tonga subduction. The epicenters of these deep earthquakes are arranged in a meridional belt, the course of which substantially differs from that of the Tonga-Kermadec trench. These earthquakes were co-ordinated to the Lau Ridge, a remnant arc according to Milsom (1970) and Karig (1972), which runs in the same meridional direction and is situated exactly above the belt of deep earthquakes in question (Hanuš and Vaněk, 1978a and b).

Of two zones distinguished as *L* 1 and *L* 2, only earthquakes belonging to *L* 2 occur in the northern part of the Tonga region (sections *F*1–*F*4). The Lau system is interpreted as a pair of buried paleoplates activated by a deep collision with the recently downgoing Pacific plate of the Tonga system of subduction (for details see Hanuš and Vaněk, 1978b).

(c) Horne System

In the complicated seismic pattern of the vertical section *F*1 a horizontal strip of earthquakes with focal depths between 300 and 500 km can be observed westwards of the zone *T* 1 (see Fig. 2), which belongs neither to the zones *T* 1 and *L* 2, nor to any of the fracture zones occurring in the northern part of the Tonga region.

After projecting the foci of the above-mentioned strip of deep earthquakes in the proper direction, the system appears to form a plate-like body dipping to the south. This is demonstrated by the meridional vertical sections *D*1–*D*3 in Fig. 4. For comparison, the foci belonging to the Tonga zone *T* 1 are also plotted in Section *D*1, as well as those co-ordinated to the Peggy fracture zone and to the Lau zone *L* 2 in sections *D*2 and *D*3, respectively. The average dip of this zone, denoted as zone *H*, is about 40° to the south, its thickness ranges between 50 and 80 km, and the focal depth of earthquakes located in the zone varies between 325 and 480 km.

Zone *H* may be tentatively interpreted as a remnant subduction zone belonging perhaps to one of the manifestations of the supposed extinct Pacific-Phoenix spreading centre (Winterer, 1976). The activation of zone *H* is caused by a deep collision with the recently subducting Tonga zone *T* 1, as demonstrated by the vertical Sect. *D*1 in Fig. 4 and by the horizontal projection of zones *T* 1, *H,* and *L* 2 in Fig. 5. The clustering of earthquake foci in section *D*1 does not allow a detailed co-ordination of individual events to respective zones *T* 1 and *H*. The position of the collision is marked by the hatched area in Fig. 5, its centre of gravity being at 15.9° S and 176.4° W at a depth of about 400 km.

If the above interpretation is correct, some traces of the corresponding ancient island arc should be found in the physiographic pattern of the Pacific ocean between Samoa and the New Hebrides island arc. However, geologic and petrologic data on the islands of the area in question are very scarce. According to Macdonald (1945) the rocks of the Wallis Islands undoubtedly belong to the alkaline suite of the central Pacific volcanoes. The Horne Islands consisting of deeply weathered andesite lavas and breccias, and minor amounts of Miocene limestones, marls, sandstones, and conglomerates (Aubert de la Rüe, 1935) might be a part of the supposed ancient island arc, this assumption being not in contradiction to chemical analyses of Lacroix (1941). Also the bathymetry of the ocean floor shows a large elevation in the east-west direction, the exposed part of which is represented by the Horne Islands (World Map, 1968; see the scheme in Fig. 1). Therefore, the activated paleoplate observed in the northern part of the Tonga region is provisionally denoted as the Horne system *H*. In this context it is not surprising that Sclater et al. (1972) found andesitic rocks on Zephyr Shoal, which is situated in the south-eastern part of the supposed Horne island arc.

It is not excluded that the Horne system may continue to the northern part of the New Hebrides island arc, being responsible for isolated deep shocks in the Northern Fiji Plateau and the andesitic volcanism of the Tikopea Island (Fryer, 1974).

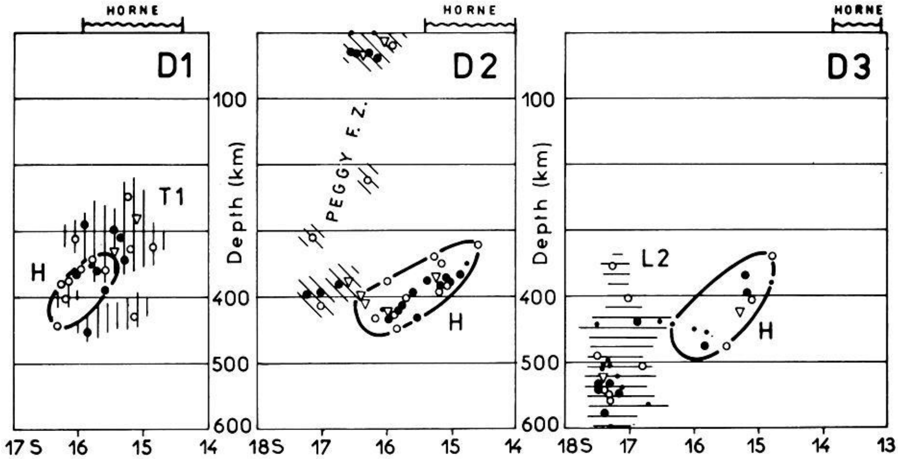


Fig. 4. Vertical Sects. *D*1–*D*3 for the Horne system, giving the distribution of earthquake foci in dependence on latitude; symbols as in Fig. 2. Zone *H* is denoted by *full-line contour*, zones *T* 1, *L* 2, and Peggy fracture zone by different hatching. For positions of Sections see Fig. 1

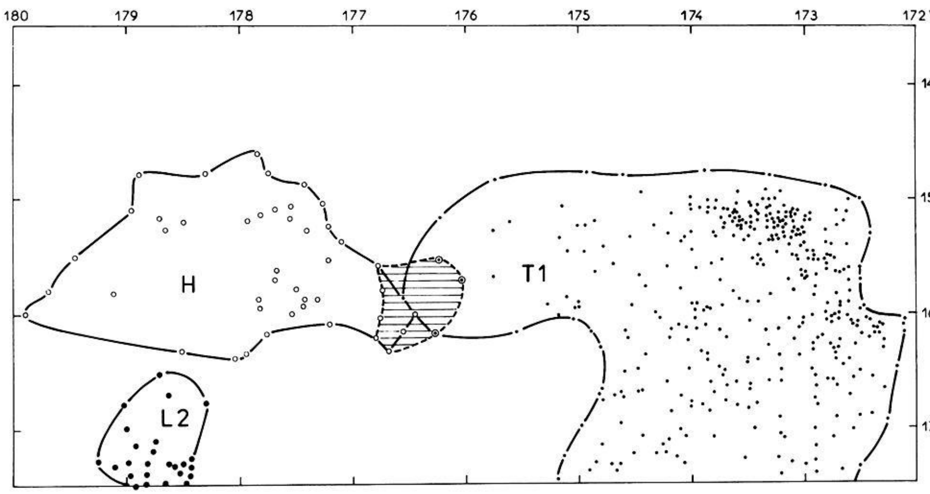


Fig. 5. Map of earthquake epicenters with delineation of three subduction systems in the northern part of the Tonga island arc. *T* 1: recent Tonga subduction; *L* 2: activated Lau paleosubduction; *H*: activated Horne paleosubduction; position of the deep collision is denoted by *horizontal hatching*

Deep Fracture Zones

In addition to the well-defined zones *T* 1, *L* 2, and *H*, two groups of shallow, intermediate and deep earthquakes can be observed westwards of the zone *T* 1 in the northern part of the Tonga region (see Figs. 2 and 3). In our interpretation, these earthquakes belong to two deep-seated fracture zones; they are denoted

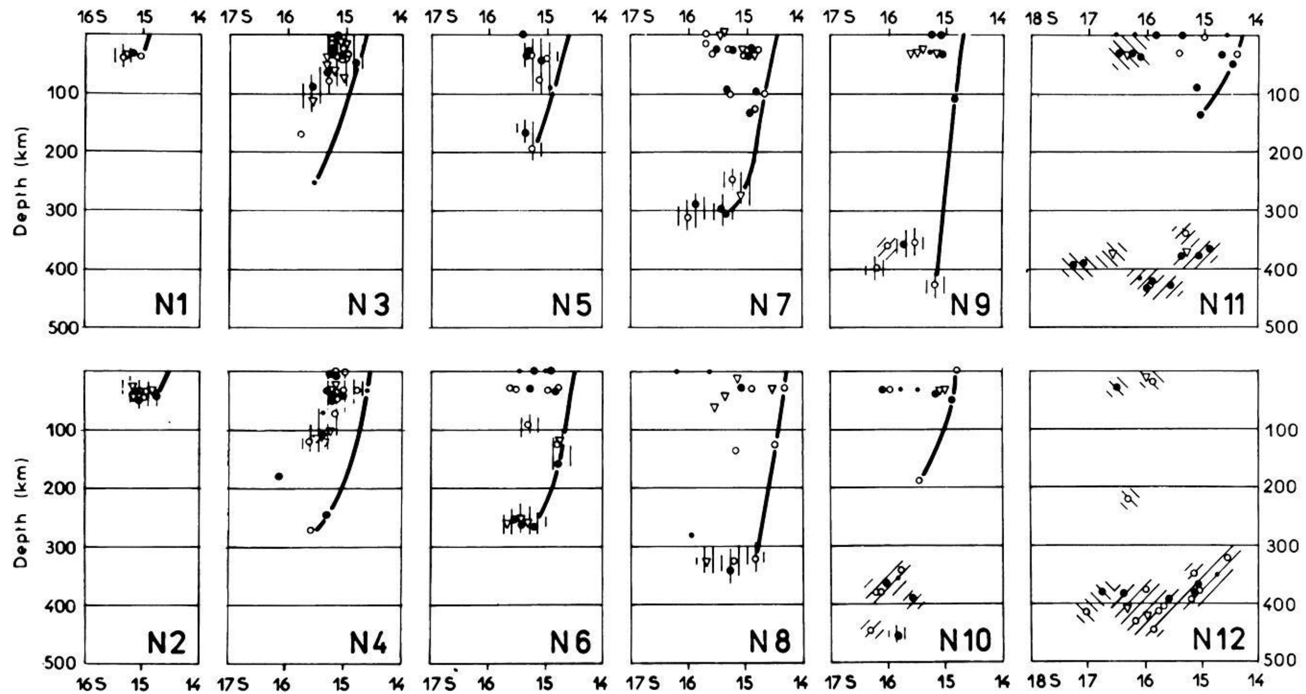
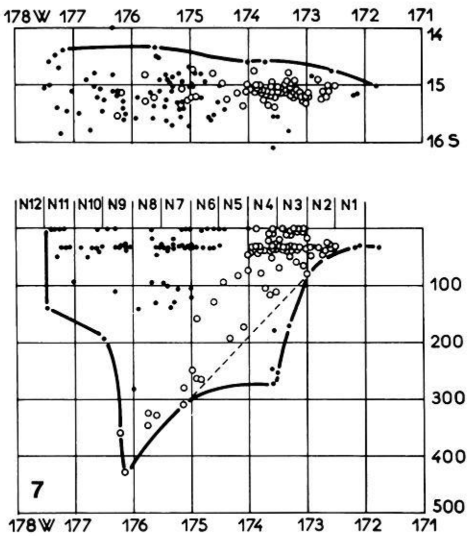


Fig. 6. Vertical Sects. $N1$–$N12$ across the Niuafo'ou fracture zone. Zone $T1$ is denoted by vertical hatching, zone H by NE-SW hatching, Peggy fracture zone by NW-SE hatching, and northern boundary of the Niuafo'ou fracture zone by a *full line*. For positions of Sections see Fig. 7



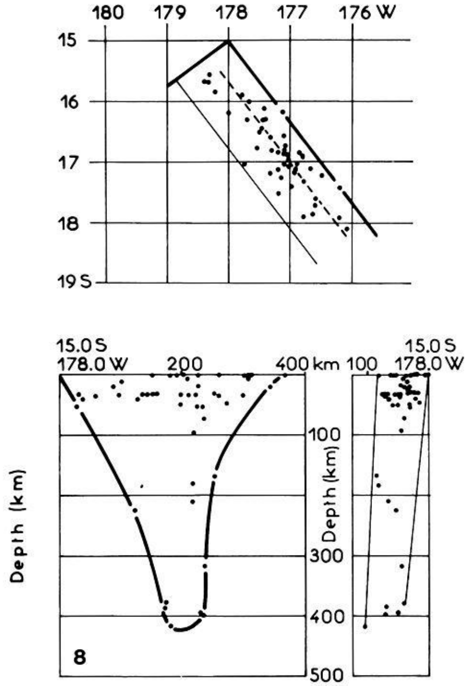


Fig. 7. Surface projection of the northern boundary and depth section along the Niuafo'ou fracture zone with associated earthquakes. Earthquakes belonging to both the fracture zone and subduction zone *T* 1 are denoted by *open circles*

Fig. 8. Surface projection, and vertical sections along and across the Peggy fracture zone, with associated earthquakes

as the Niuafo'ou and Peggy fracture zones, respectively, and their positions are shown in Fig. 1.

The *Niuafo'ou fracture zone,* the strike of which is almost in the east-west direction, evidently forms the northern tectonic closure of the active Tonga subduction zone *T* 1 and is playing the role of a transform fault (Isacks et al., 1969). In order to study the shape of the active part of the Niuafo'ou fracture zone, the associated activity is plotted in a sequence of meridional Sects. *N*1–*N*12 in Fig. 6 (for positions of sections see Fig. 7). After co-ordinating the individual shocks to appropriate zones, vertical sections *N*1–*N*12 give a clear picture of the northern boundary of the fracture zone. The southward dip ranges from 60° to 80°. The activity connected with the Niuafo'ou fracture zone reaches a depth of 430 km and disappears in Sect. *N*12. The surface projection of the northern boundary and the depth section along the fracture zone are shown in Fig. 7. It appears that in the eastern part the fracture zone cannot be distinguished from the subduction zone *T* 1, forming the northern closure of the downgoing Pacific plate. However, intermediate earthquakes in Sect. *N*3 and *N*4 indicate the occurrence of a mantle fracture with a northward dip under the zone of subduction. In the west, the active part of the Niuafo'ou fracture zone is abruptly terminated by a surface steeply dipping eastwards to the deepest part of the northern Tonga subduction.

The Niuafo'ou fracture zone was named after the Niuafo'ou Island, an active volcano situated in the area of the fracture zone. It follows from the conventional silica alkali plot of existing chemical analyses of Lacroix (1941) and Macdonald (1948) that the Niuafo'ou basalts can hardly be correlated with the alkaline suite of the central Pacific volcanoes, found on the Wallis Islands (Macdonald, 1945), or with the andesitic suite of the Tonga island arc (Ewart et al., 1973). The chemical composition of the Niuafo'ou basalts, which is similar to that of the East Pacific Rise tholeiites (Engel et al., 1965), seems to show a genetic relationship with the fracture zone.

The *Peggy fracture zone*, the position of which coincides with the Peggy Ridge (see the bathymetric charts in Sclater et al., 1972, and in Hawkins, 1974), is another active deep-seated fracture zone found in the northern part of the Lau Basin. The earthquakes associated with the Peggy fracture zone can be distinguished in all the vertical Sects. *F*1–*F*4 (see Figs. 2 and 3). The surface projection of the active part and two vertical sections along and across the Peggy fracture zone are given in Fig. 8. The fracture zone dips steeply to the south-west at an angle of about 85° and its seismic activity reaches a depth of more than 400 km. The chemical composition of rock samples dredged from the Peggy Ridge shows a marked affinity between these basaltic rocks and ocean-ridge type tholeiites (Sclater et al., 1972), indicating a possible genetic relationship with the Peggy fracture zone, a phenomenon observed also for the Niuafo'ou fracture zone.

The function of the Peggy fracture zone is disputable, but it might be similar to that of the Niuafo'ou fracture zone, forming the northern closure of the Lau paleosubduction. In this case, the original Lau subduction zone would have been inclined to the east, with a later tilting of the buried Lau paleoplates to the present position caused by a deep collision with the subsequent Tonga subduction (Hanuš and Vaněk, 1978b). This mechanism could also explain the process of formation of the uplifted Lau Basin.

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