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STRUCTURAL CHARACTERISTICS AND TECTONICS OF AN ACTIVE ISLAND ARC : THE NEW HEBRIDES

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The New Hebrides island arc (see fig. 1) is lying in the South-West Pacific Ocean, at the boundary of the Indo-Australian and Pacific plates. It is striked NNW-SSE in an inverse S shape with its northern extremity directed westwards and its southern extremity eastwards.

A trench which is interrupted close to the bigger islands, Espiritu Santo and Malekula, a Benioff plane continuous all along the arc, oriented east and dipping steeply beneath the Pacific plate, and a volcanism in the islands, define the boundary of the plates. The chain of islands is 300 - 1600 meters altitude looking at east down to the Fiji plateau which is 3.000 meters deep and, at west beyond the trench, the North Loyalty plateau, 4.000 meters deep, divided by the d'Entrecasteaux rise with some heights close to the sea level.

A lot of data (seismic-reflection, bathymetry and magnetism) have been gathered by ORSTOM with a location by celestial fixes for Coriolis, Danaïdes and Kimbla cruises, the latter thanks to the collaboration of the New South Wales University, or by satellite navigation for Austradec cruises (from 1972 to 1976). Some data have been communicated by Woods Hole Oceanographic Institution (Chain), by the Mobil Oil and Gulf Oil Companies. We present transverse profiles to define the structural units of the arc and a few longitudinal profiles which bring into evidence discontinuities.

I. - STRUCTURAL UNITS OF THE ARC

A structural concept of an arc has been set by Karig and Sharman (1975), with respect to a transverse section, with the following units : trench - accretionary prism - upper slope discontinuity - frontal arc - volcanic line - active marginal basin - remnant arc. Cross-sections in the New Hebrides arc lead to better determine these units as shown on the fig. 2 which represents a seismic reflexion profile near the area retained for a drilling project (IPOD).

The accretionary prism is also called the "imbricate zone" for dredgings brought into evidence elements coming from the arc (Luyendyk et al 1974, Dugas et al 1976). In the frontal arc we discern the summit of the trench slope here called "the fore-horst" and the basin. At last we previously brought into evidence that the marginal basin was a horst and trough zone (Dubois et al, 1975, 1976). It is possible that the horsts and troughs zone is the first stage of a marginal basin. The structural units of the New Hebrides arc are : <u>trench</u> - <u>imbricate zone</u> - <u>upper slope discontinuity</u> - <u>frontal arc consisting in a fore-horst and a basin</u> - <u>active volcanic line</u> - <u>horst and trough zone</u> -

The magnetic profiles (fig. 3A, 3B, 3C) point out the structural units. On the whole arc, anomalies with short wavelength (10 to 20 km) and high amplitude (several hundred of gammas) characterizing heterogeneous areas with low depth bodies, attributed to volcanic intrusions or faults.

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The narrow and dissymmetrical trench has its western scarp generally steeper than its eastern scarp. It looks deeper north (about 9.000 meters) than south. There is no trench in the middle part though the Benioff plane is existing (Dubois 1969, Dubois et al 1973, Pascal 1974). It is not sharply magnetically marked. We can observe a regular decreasing of the magnetic field from west to east to a minimum at 20 km east of the trench. The difference in phase between bathymetric minimum and magnetic minimum is due to the orientation of the magnetic field.

The imbricate zone spreads along from the trench to the second slope break or upper slope discontinuity. It looks narrower northern than southern as the trench does. A comparison between the profiles leads to determinate in the central zone of the arc an imbricate zone which, if it exists, seems uplifted (see fig. 3B, C907 profile). The magnetic field over the imbricate zone increases middly with a low amplitude (a hundred gammas at most) and large wavelength anomalie corresponding to a relief effect.

The frontal arc is lying between the imbricate zone and the volcanic line. It is a basin whose the edge, towards the summit of the trench slope, is often faulted. We propose to call that edge the "fore-horst of the frontal arc". It is wider in the central area of the arc and abnormally uplifted to 1.600 meters on Santo island ; but, near Epi island, it is very narrow. Several magnetic anomalies of a few hundred gammas in amplitude and short wavelength (about 10 km) mark the frontal arc. They bring into evidence irregularities in the basin basement.

The volcanic line is joining the active volcanoes and is the boundary between the frontal arc and the horst and through zone at the rear of the arc. It looks like a volcanic front. The distance between the trench and the active volcanic line (or front) is 125 - 135 km except in its extremity where it is smaller. It is one of the shortest known and characterizes a young arc. Along this line, active or recently extinct volcanoes and intrusions can be seen. This line is pointed out by well marked magnetic anomalies of high amplitude and short wavelengths and by a neat gravimetric anomaly (Luyendyk and al 1973).

Lastly horst and trough zone or rifted trough zone can be observed at the rear of the arc. It is about 60 km wide. The shapes of this zone were previously studied (Dubois et al 1975) : three magnetic anomalies of short wavelength (20 km) and high amplitude (500 to 2.000 gammas) mark it. Apparently interrupted in the central area of the arc, its existence, though deformed, can be proved by narrow troughs on the east flank of Maewo and Pentecost islands and the three characteristical magnetic anomalies. These islands look like abnormally uplifted horsts (fig. 3B, C907-906 profile). The inter-arc basins north and south of Aoba island, which are not extensional basins (Luyendyk et al 1974) seems to be down faulted frontal basins.

Geological models derived from magnetic profiles (fig. 4) confirm these structural units. They indicate high susceptibilities, so intrusions, beneath the fore-horst of the frontal arc where igneous rocks have been dredged by Luyendyk et al (1974), Dugas et al, this volume and beneath the volcanic line and the horsts at the rear of the arc. The treatment of data includes first a reduction to N magnetic pole (Galdeano 1974), second an upwards prolongation of the profiles (Galdeano 1974) or filtering (Behannon and Ness 1965). The reduction to the N pole eliminates theoretically the difference in phase between the bodies and the observed anomalies giving thus with accuracy their location. The upwards prolongation or the filtering eliminates the higher frequences of the variations due to the surface causes.

II. RECENT TECTONIC STRETCHING

Tectonic features over the New Hebrides arc are not only related to the present subduction. Basements of different ages and characters are observed in islands, along the volcanic line in northern and southern parts of the arc, and on each side of this line in the middle part. Their ages are Oligocene in Santa Cruz islands (Craig et al, in press), Oligocene - lower Miocene in Torres islands (Greenbaum et al 1975), lower to middle Miocene in Santo and Malekula (Mitchell and Warden 1971), Miocene but mainly upper Miocene to lower Pliocene in Maewo and Pentecost (Mallick and Neef 1974), and probably Miocene in southern islands.
On these basements, a volcanism from 5 m.y. old to present day is observed along the volcanic line and can be related to the present subduction (Dugas et al this volume).

From the faulting in these Pliocene to Recent islands and from the seismic reflexion profiles, three main trends are inferred(see fig. 8) :

-first, NNW-SSE parallel to the trench shown by the morphology, the magnetic anomalies and the seismicity.

-second, approximately W-E, transverse to the arc. This is the most common magnetic trend (Malahoff 1970). It is associated with a seismic trend. It is lying North of Santo in extension of Hazel Holme and d'Entrecasteaux fractures, in southern Santo along the extension of Aoba axis, and in northern Malekula along the extension of WNW-ESE axis of Ambrym. These trends seem to be stretched beyond the trench.

-third, NNE-SSW, very oblique to the arc, shown by the morphology in association with seisms alignments. This trend crosses the whole arc and shifts the structural units. That, particularly marked at the rear of the arc, looks like "en echelon" system. On the frontal arc it gives form of grabens south of Ambrym, in Efate (Teouma graben). On Ambrym one of morphological extension must be attributed to it but is magnetically masked by the other E-W axis.

Another trend, NW-SE, is mainly seen in Efate island. This direction seems to be a WNW-ESE direction, curved towards the north, in connection with the trench which is also curved, and with the narrowness of the arc in this area; but it can also be a direction influenced by the basement.

Our magnetic measurements are in agreement with the surveys from Malahoff(1970). The E-W trend is outstanding on the whole arc. The NNW-SSE trend, parallel to the trench is shown in magnetic anomalies associated with the structural units specially beneath : fore-horst, volcanic line, horst and trough zone.

In addition to these magnetic trends, a NW-SE magnetic direction may be observed, north of Banks islands, in Espiritu Santo, Malekula and Efate islands. This trend is specially seen in the biggest islands of the arc where the magnetic anomalies have a longer wavelength and a lower amplitude involving deeper bodies. These structures appear to be an extension of d'Entrecasteaux rise (Lapouille and Dugas 1975). As it was not possible to obtain N-S elongated models from magnetic anomalies in this central part of the arc, near Santo and Malekula islands, some E-W trends must be deduced and have an origin older than the present subduction. The existence of E-W oriented magnetic bodies is confirmed, on AUS 110 N-S profile, by its high variations. In the same way magnetic variations, slightly higher than on AUS 110 profile can be seen on AUS 112 bis NW-SE profile. On a crossing profile with the exception of the fore-horst of the frontal arc, high magnetic anomalies can only be seen from the volcanic line towards the rear arc; so the volcanic line is also called the ctual volcanic front.

Shallow seismicity data (0 to 50 km depth) over the New Hebrides (fig. 5) is related to present day tectonics. It is observed over the whole arc but a part of the seismicity is not directly related to the Benioff plane. Many studies (Dubois 1969, Dubois et al 1973, Pascal 1974) have shown a Benioff plane oriented east and dipping very steeply (about 70°). As its continuity has been recently proved (ORSTOM-CORNELL project) we can assume a tectonic origin for that part of the shallow seismicity at the back of the Benioff zone (fig. 6).

A geographical distribution of released seismic energies between 0-50 km depth (fig. 7) points out isoenergetic zones parallel to the trench and confirm one of the tectonic trends. Besides they bring into evidence a more energetic stripe beneath the frontal arc at the boundary of the fore-horst and the basin. This stripe is wider (about 100 km) in the middle of the arc than in northern and southern parts (about 50 km). As it is the same over Tonga arc it must be connected to the subduction rather than the local structures. Another narrow energetic stripe can be observed at the rear of the arc, approximately 150 km from the trench in horst and trough zone with a lower energy than the former. A less marked seismicity spreads over both sides of the arc, eastwards to 200 km from the trench, and westwards, only to 50 km. The seisms of these latter zone are sparsed and release weak energy.

Some focal mechanisms have been determined on surface seisms by Johnson and Molnar (1972) and by Pascal (1974). We shall distinguish firstly overlapping mechanisms, secondly shearing mechanisms. The overlapping mechanism appear more numerous in the middle part of the arc near the biggest islands and d'Entrecasteaux zone which is involved into the subduction. It also exists in the south of the arc facing southern island of the Loyalty islands, and at the extremities of the arc. The compression must be strongest in these areas. The shearing mechanisms are observed particularly between the central and southern part of the arc and close to the fore-horst of the frontal arc. They bring into evidence NNE-SSW and NNW-SSE fractures with a differential uplift. The shear direction is interpreted as a reaction to stresses.

The E-W trend is also confirmed by seisms alignments.

III - VOLCANISM AND TECTONICS

On the tectonic map (Fig. 8) we can note that active volcanoes are located in the very vicinity of a structural seismically active fault intersecting the volcanic line. As examples : Gaua is set on a W-E North Santo fault, Aoba on a ENE-WSW fault, Ambrym which has two morphological axis of extension at the intersection of two faults, one WNW-ESE, the other NNE-SSW, Tanna on a NNE-SSW fault. The faults crossing Lopevi and South of Epi are not easily seen because the arc is narrower and active or extinct volcanoes are abundant there. Besides small grabens (Luyendyk et al 1974 and fig. 2), magnetic anomalies (Malahoff 1970, and AUS 112 bis profile on Fig. 2), show that structural discontinuities are in that area. Other volcanoes seem to be in the extension of the NNE-SSW faults Vanua Lava, northern Efate, Erromango and Anatom.

The presence of extrusions as Merig (Banks islands) aged of 1.1 m.y. (Mallick and Ash 1975) and volcanoes as Mere Lava (Banks islands) in the horst and trough zone show that the volcanic line can be considered as a front of the actual volcanism.

As the alkalinity of lavas is related to a deep origin, this character marks a deep fault. But this alkaline character is either occasional on a volcano as Lopevi either constant on Aoba and Ambrym. Consequently we shall consider three groups of lavas ; (see fig. 9) :

- mainly alkaline lavas but high alumina too : Ambrym and Tanna (active volcanoes), Aoba and Gaua (extinct volcanoes).

- high alumina and tholeïtic lavas with a few alkaline lavas : Lopevi and Karua (active volcanoes), western Epi and Tongoa (extinct volcanoes).

- high alumina and tholeïtic lavas of all other volcanoes (extinct volcanoes).

The lavas of the first group, as suggested by Colley and Warden (1974), must reveal the tapping of magma from a deeper level under tensional conditions. The faults beneath these volcanoes must be deeper than the others.

IV - GEODYNAMIC STRESSES

Let us find out the relations between the observed tectonics and stresses. First in the edge of two A and B plates (see fig. 10) in a subduction, we can observe, with respect to Hank's notes (1970) in the plate :

- a vertical component Pb resulting from the weight of the slab A, or its drawing into a medium less dense than the asthenosphere,

- a horizontal component Nb resulting from the force applied by reaction of the subducting plate into the subducted plate.

The surface breaks observed on the outer slope of the trench, in the plate A, involve a tectonic readjustment due probably to the condition change of the plate A, as it comes near the trench (Dubois et al 1976). It would become from an elastic condition into a plastic condition when its radius of curvature is diminishing.

On the plate B, we can observe a N'b tension opposite to Nb whose vertical component Nv is oriented upwards. The intensity of Nv is dependent on that of N'b and of the friction coefficient of both plates. It produces an uplift of the plate B edge which might be a flexure (infinite plate with free edge) if B is elastic. But along the arc we can observe an uplift of the fore-horst : Torres, Santo (Robinson 1969), Malekula and Efate islands. On western Efate an uplift rate of 1 meter / 1.000 years since 200.000 years has been measured by Bloom (oral communication). Another argue of this uplift is the existence of overlapping mechanisms (see fig. 7) consequently to the down going of rises into the subduction zone. The value of Nb increases but we have to add another resistance due to the buoyancy. The fore-horst of the frontal arc may be explained by this mechanism.

The faulting of the horst and trough zone would have been created by another mechanism (Dubois et al 1975). They can only be found in the curved parts of the arc, excluding the middle part and are in agreement with the Fitch's (1972) transcurrent faults.

The transverse and oblique faults of the arc may be explained through a simple compressional mechanism. If we assume the opposite stresses which are in presence in both sides of the subduction, they induce in a square element of the plate B two shearings along both diagonal planes. These diagonal planes agree exactly with the NNE-SSW and WNW-SSW trends.

General diagram of the forces in an islands arc

In regard to the arc, the tectonics is complicated by the existense of extension and compression zones varying in place and in time (Mercier et al 1976, in the Egean arc, Dubois et al 1975, in the New Hebrides arc).

Andrews (1972), Andrews and Sleep (1974), Sleep (1975) have computed the stress distribution of a two dimensional model through the flow function of a medium whose variations in viscosity are known. In these models the reduced parameters are the distribution of densities and viscosities, the boundaries conditions, and the velocities of the slab shift. More recently viscosity models with variations from 10^{23} poizes in the lithosphere to 10^{20} poizes in the asthenosphere were made by Sleep (1975). The flow function and shearing are computed for 21 models. The 9 to 12 models where the subduction rate is 7 to 8 cm/year may be applied to the New Hebrides (see fig. 12). Besides that repartition as function of the slab length could have varied in time and in space.

The block faulting of the fore-horst of the frontal arc and of the horst and trough zone are in agreement with the tectonic model of alternate zones with compression and extension. The shift of the volcanic line (Mallick 1973) in time confirm also the variation of the stress repartition in time.

In the New Hebrides arc, the thrust westwards appears higher in the Northern part where the slab is deeper and the trench narrower than in the southern part. We can explain this difference by the presence of the Fiji islands which would act as an obstacle. The shift of the southern part of the Fiji plateau and of the southern New Hebrides arc would then be readjusted by the creation of transcurrent faults and expansion zones.

V - CONCLUSIONS

An active island arc can be defined through structural units, a tectonic and volcanism with associated magnetics and seismicity. The structural units are deduced from morphological, magnetic and seismic criteria. The shallow tectonics of the arc follows three trends :

- first, parallel to the trench indicated by morphology, magnetics and seismicity,

- second, transverse to the arc mainly indicated by magnetics and seismicity,

- third, oblique to the arc indicated by seismicity and morphology.

The active volcanism is found at the intersection of the volcanic line with the transverse and oblique faults.

Several mechanisms must be considered in relative stresses in an arc : mechanisms producing an uplift of the fore-horst of the frontal arc, transcurrent faults in curved parts, and shearing mechanisms. In addition to these mechanisms, alternate compression and extension zones occurs over the whole arc.

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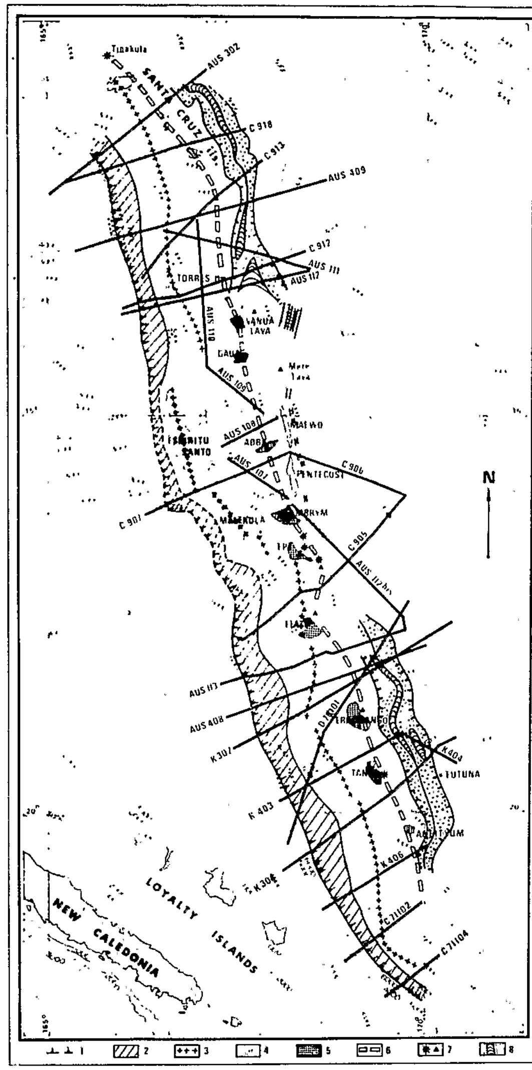


Fig. 1 - The New Hebrides arc and profiles - 1 : subduction, 2 : imbricate zone, 3 : summit of the trench slope, 4 : older volcanics, 5 : Pliocene-Recent volcanics, 6 : active volcanic line, 7 : active and extinct volcanoes, 8 : horst and trough zone.

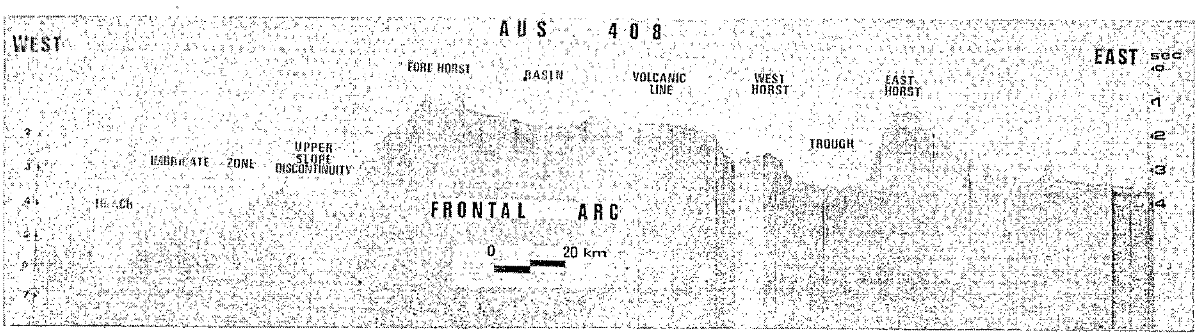


Fig. 2 - Seismic reflexion profile crossing the New Hebrides arc with structural units.

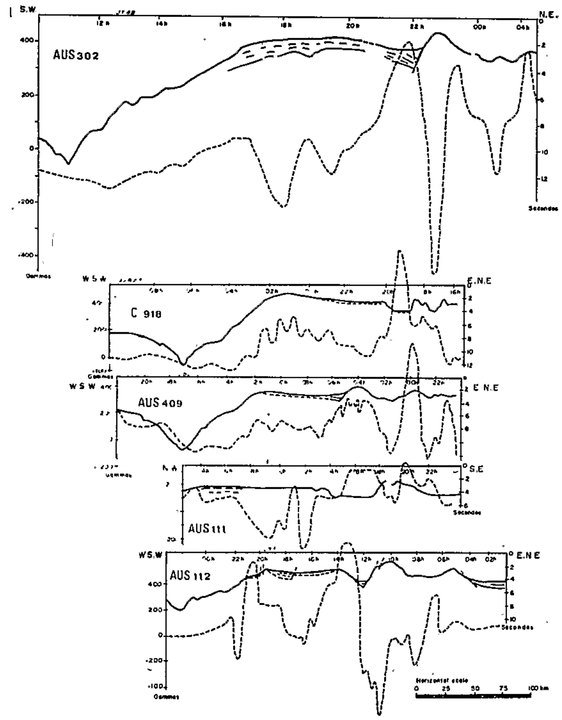
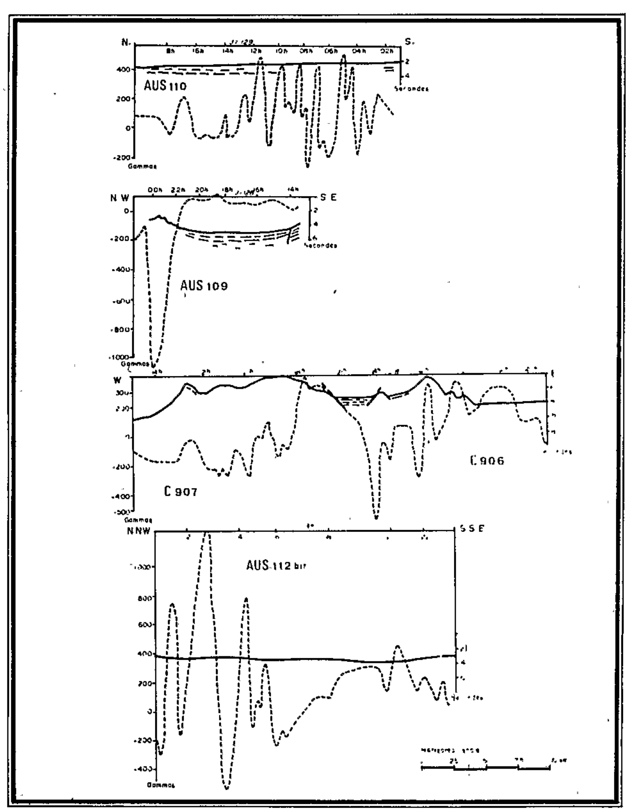


Fig. 3 A - Bathymetric, Magnetic and Seismic reflexion profiles across the New Hebrides arc.



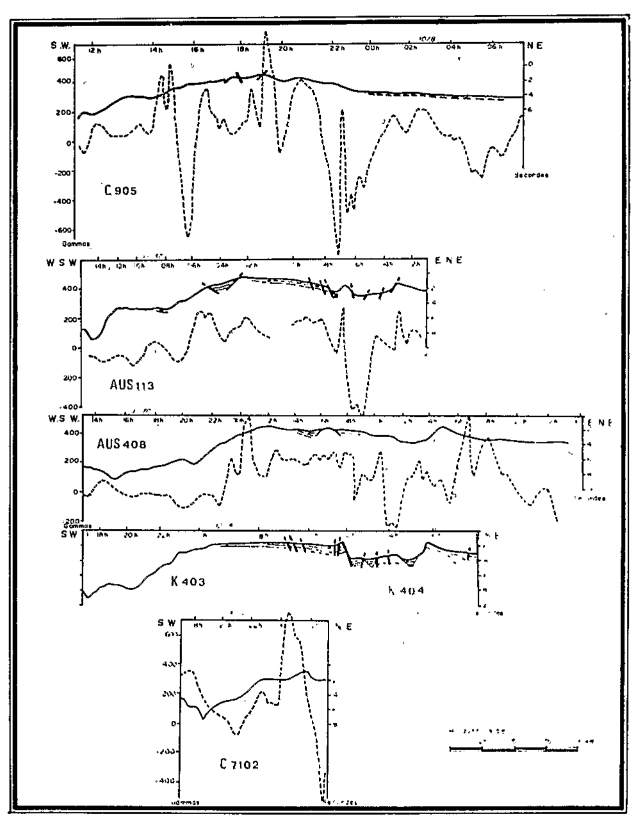


Fig. 3 B - Bathymetric, Magnetic and Seismic reflexion pro-
and 3 C files crossing the New Hebrides arc.

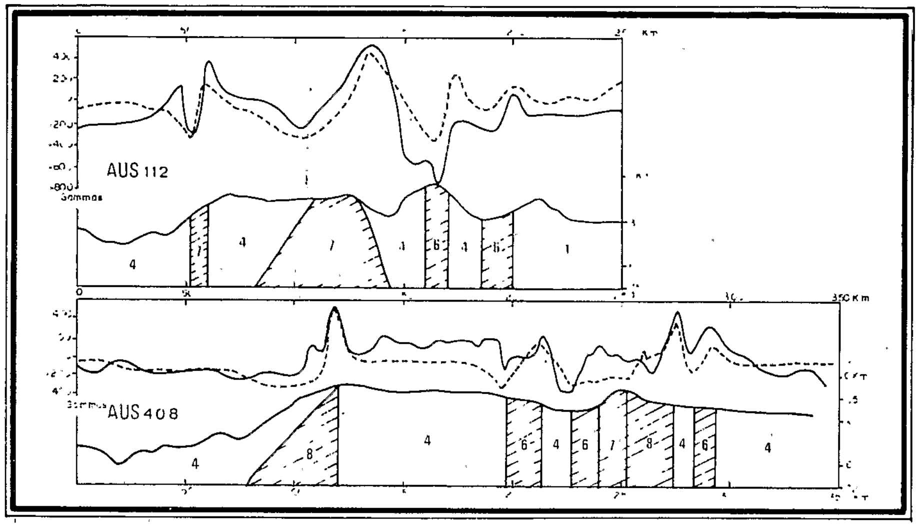


Fig. 4 - Models of magnetic susceptibility (in 10^{-3} e.m.u.) from profiles with experimental (solid line) and computed (dashed line) anomalies curves.

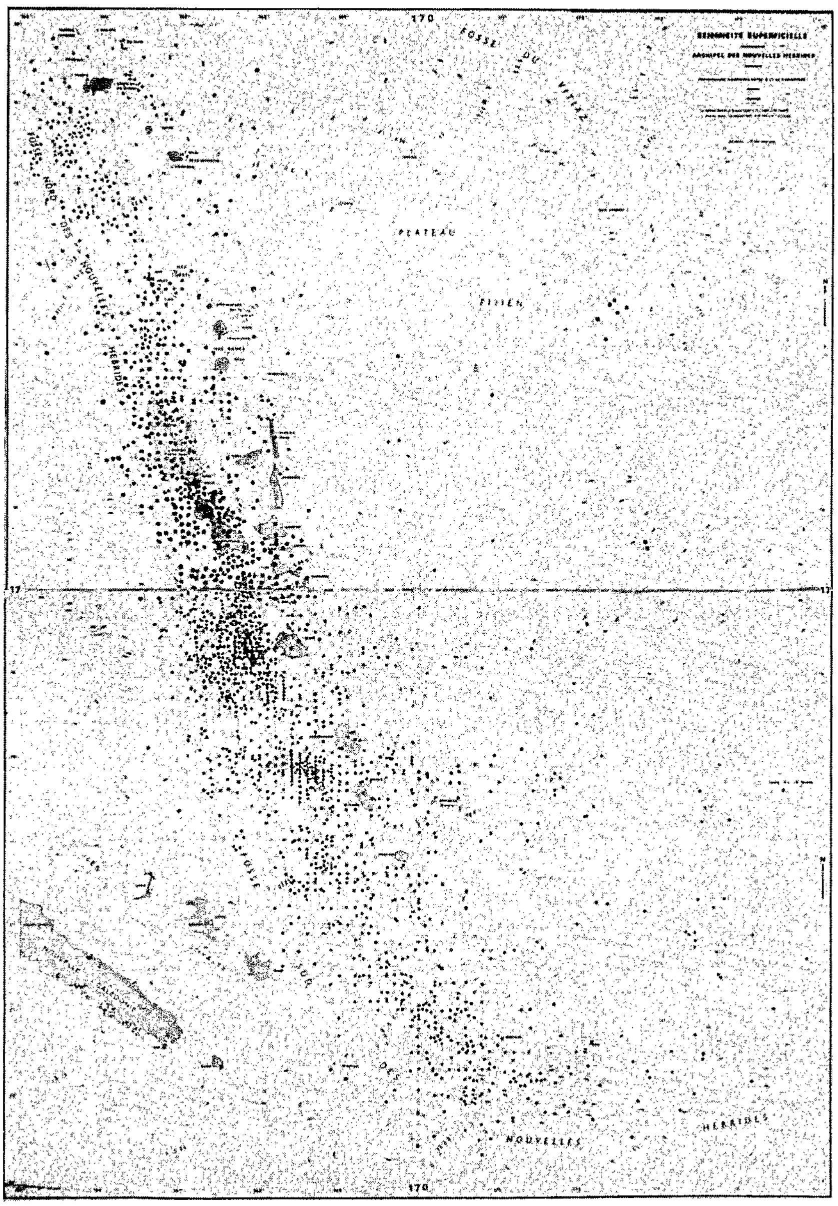


Fig. 5 - Shallow seismicity (0 - 50 km depth) over the New Hebrides.

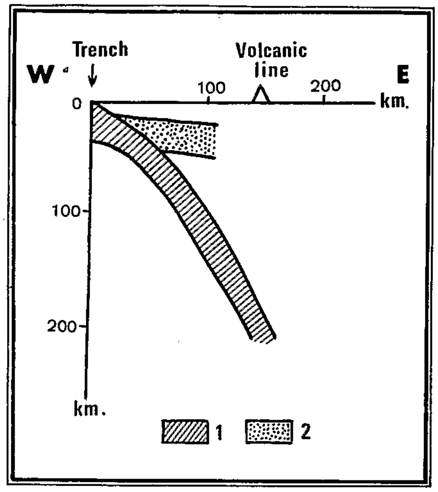


Fig. 6 - Cross section of earthquake distribution in the New Hebrides - 1 : Benioff zone, 2 : tectonic zone.

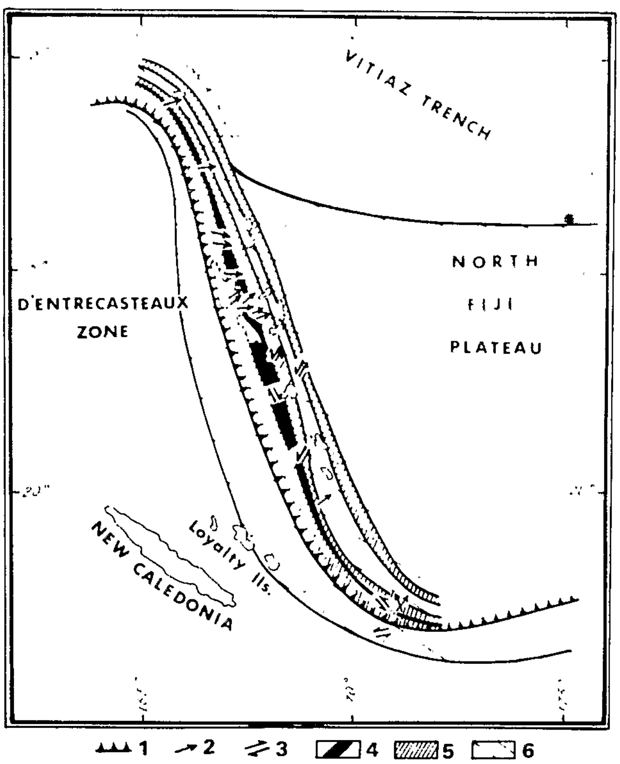


Fig. 7 - Geographical distribution of shallow earthquakes and trends of motion from focal mechanisms. - 1 : subduction, 2 : overlapping mechanisms, 3 : shearing mechanisms, 4 : high energetic zone, 5 : mean energetic zone, 6 : low energetic zone

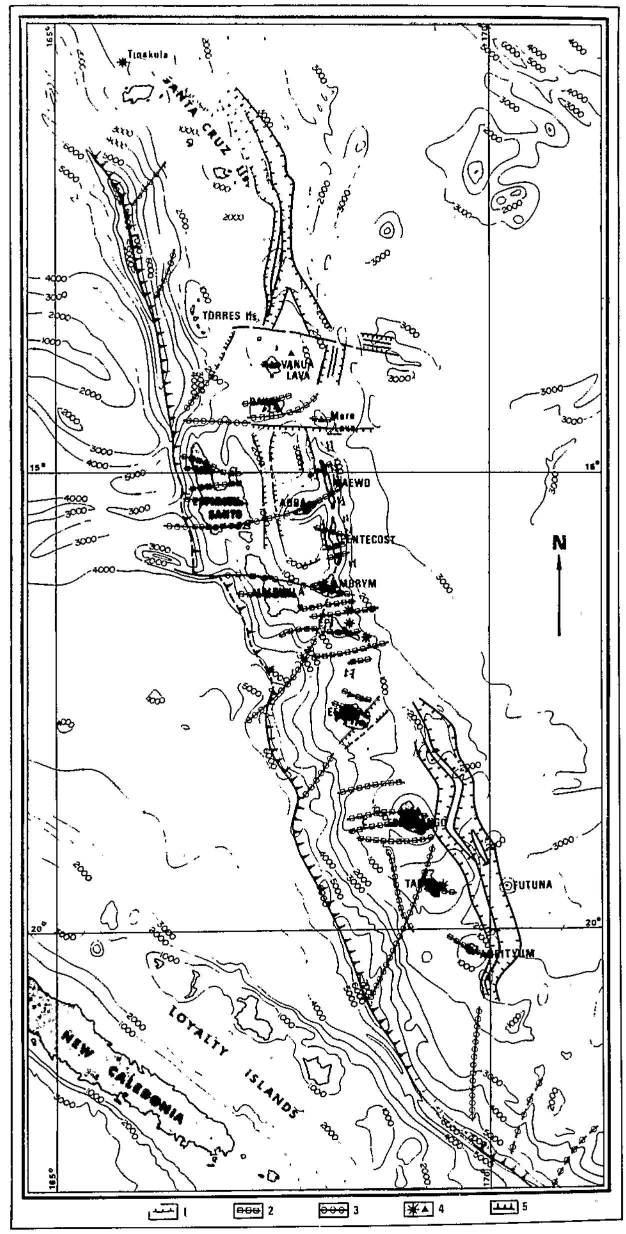


Fig. 8 - Tectonic map on Scripps O.I. Bathymetric map. - 1 : Recent geological faulting, 2 : Main magnetic stretching partly from Malahoff (1970), 3 : Main seismic stretching inferred from shallow seismicity, 4 : Active or extinct volcanoes, 5 : Subduction.

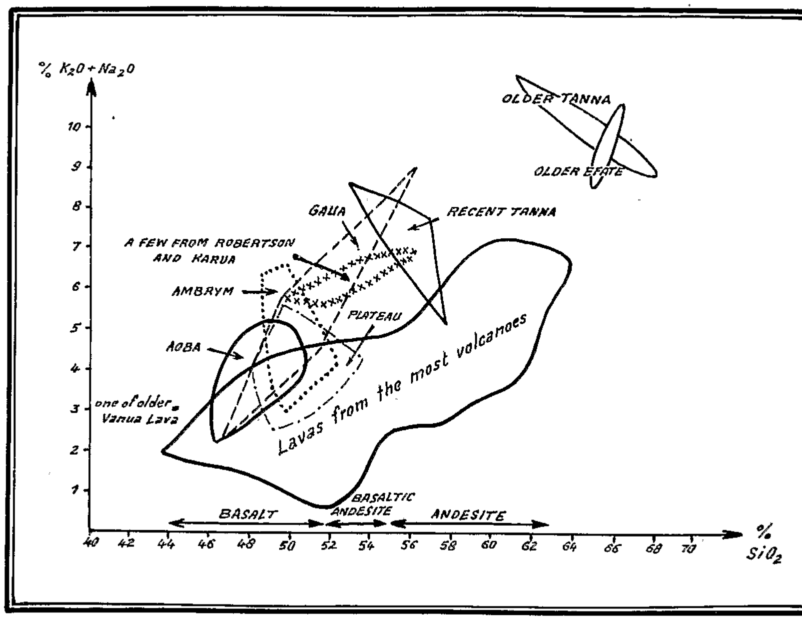


Fig. 9 - $SiO_2/K_2O + Na_2O$ diagram of lavas from New Hebrides volcanoes (after all published analyses).

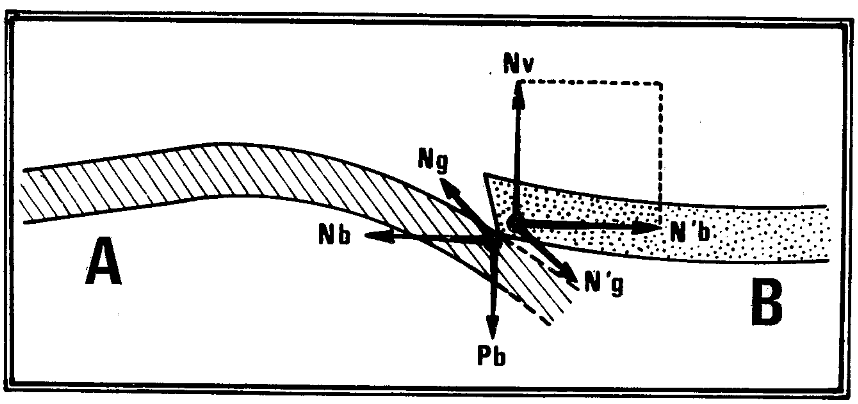


Fig. 10 - Stresses on the edge of two plates in a subduction zone.

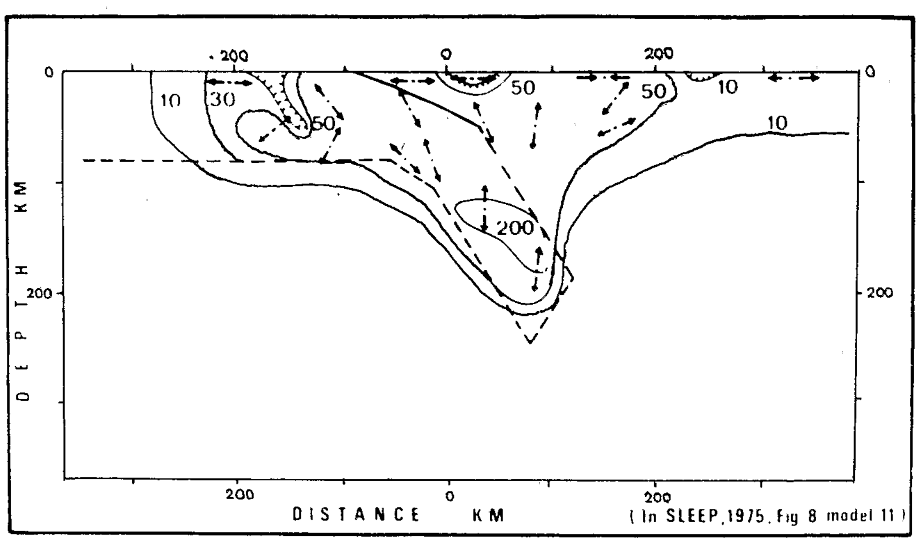


Fig. 11 - Shear stress and flow beneath an island arc with value in kilobars after Sleep (1975 fig. 8 model 11).

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