

FRACTURE LINEAMENTS, FAULT MESH FORMATION AND SEISMICITY: TOWARDS A SEISMOTECTONIC MODEL FOR VITI LEVU, FIJI

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SUMMARY

Viti Levu, the main island of Fiji, is located in a seismically active area within the Fiji Platform, a remnant island arc that lies in a diffuse plate boundary zone between the Pacific and Australian tectonic plates in the SW Pacific. The upper crust of Viti Levu is dissected by numerous intersecting fault/lineament zones mapped from remote sensing imagery of the land surface (topography, radar and aerial photos) and basement (magnetic) and have been subject to rigorous statistical tests of reproducibility and verification with field mapped fault data. Lineaments on the various imagery correlate with faults mapped in the field, and show spatial continuity between and beyond mapped faults, thereby providing a fuller coverage of regional structural patterns than previously known. Some fault/lineaments zones extend beyond the coastline to the offshore area from the SE Viti Levu study area. Multibeam bathymetry and seismic reflection data show the fault zones occur along and exert control on the location of a number of submarine canyons on the SE slope of Viti Levu. Evidence for Late Quaternary fault activity is only rarely observed in onshore SE Viti Levu (e.g. by displaced shoreline features), and in seismic reflection profiles from offshore.

The principal fault sets in Viti Levu represent generations of regional tectonic faulting that pervade the Fiji Platform during and after the disruption of the proto Fijian arc in the Middle to Late Miocene (~15Ma). These fault sets combine to form a complex network of interlocking faults creating a fault mesh that divides the upper crust into a number of fault blocks ranging from ~2-30 km wide. It is inferred that the fault mesh evolved throughout the Neogene as a response to the anticlockwise rotation of the Fiji Platform through progressive development of different fault sets and intervening crustal block rotations. Regional tectonic deformation is presently accommodated in a distributed manner through the entire fault mesh. Low magnitude earthquakes (<M4) occur regularly and may represent ruptures along short linking segments of the fault mesh, while infrequent larger earthquakes (>M4) may result from complex rupture propagation through several linking fault segments of the mesh that lie close to optimum stress orientations. The interpreted model of distributed deformation through the fault mesh for the study area in SE Viti Levu is inferred to be characteristic of the style of active deformation that occurs throughout the entire Fiji Platform.

INTRODUCTION

Seismotectonics deals with tectonic plate boundary interactions and the resulting crustal deformation, seismicity and their spatial and temporal evolution. The progressive build up of tectonically induced elastic strain in the crust is released suddenly by earthquakes, primarily along faults. There is, therefore, a direct link between plate tectonic processes, crustal deformation and seismicity. Based on this relationship, earthquakes can provide direct insights into active tectonic processes; while, on the other hand, investigations of tectonic deformation can be used to understand the earthquake generating process and can be utilised in seismic hazard evaluations. Seismotectonic studies permit the identification and quantification of seismic hazards within the framework of regional tectonics.

The development of a seismotectonic model for an area or region allows for the separation of the Earth's crust into seismic source zones that have distinctive geologic, tectonic and seismogenic properties, and exhibiting similar earthquake potential throughout [1].

Present day seismicity within the Fiji Platform provides direct evidence of active tectonic processes operating in this area [2]. However, the origin of this seismicity in the context of Fiji's tectonic setting and structural evolution has remained poorly understood. No detailed previous work has been done on the seismotectonics of the islands, in particular in terms of correlating the observed seismicity with identifiable structural geological features along which tectonic deformation is accommodated. While our study documents compelling, albeit indirect, geomorphic evidence from onshore, and offshore, indicative of Quaternary active faulting, there are only a few faults in SE Viti Levu which provide clear evidence of activity in the Late Quaternary ([3], [4]). A review of Fiji's tectonic history and present tectonic setting indicates a hypothetical relationship between crustal tectonic rotation, internal deformation and present day seismicity of the Fiji Platform. Our research on the structural lineaments, especially in southeast Viti Levu, has allowed further investigations of this hypothesis ([5], [6]).

In this paper we outline an approach for structural and tectonic analysis in a region characterized by paucity of exposures,

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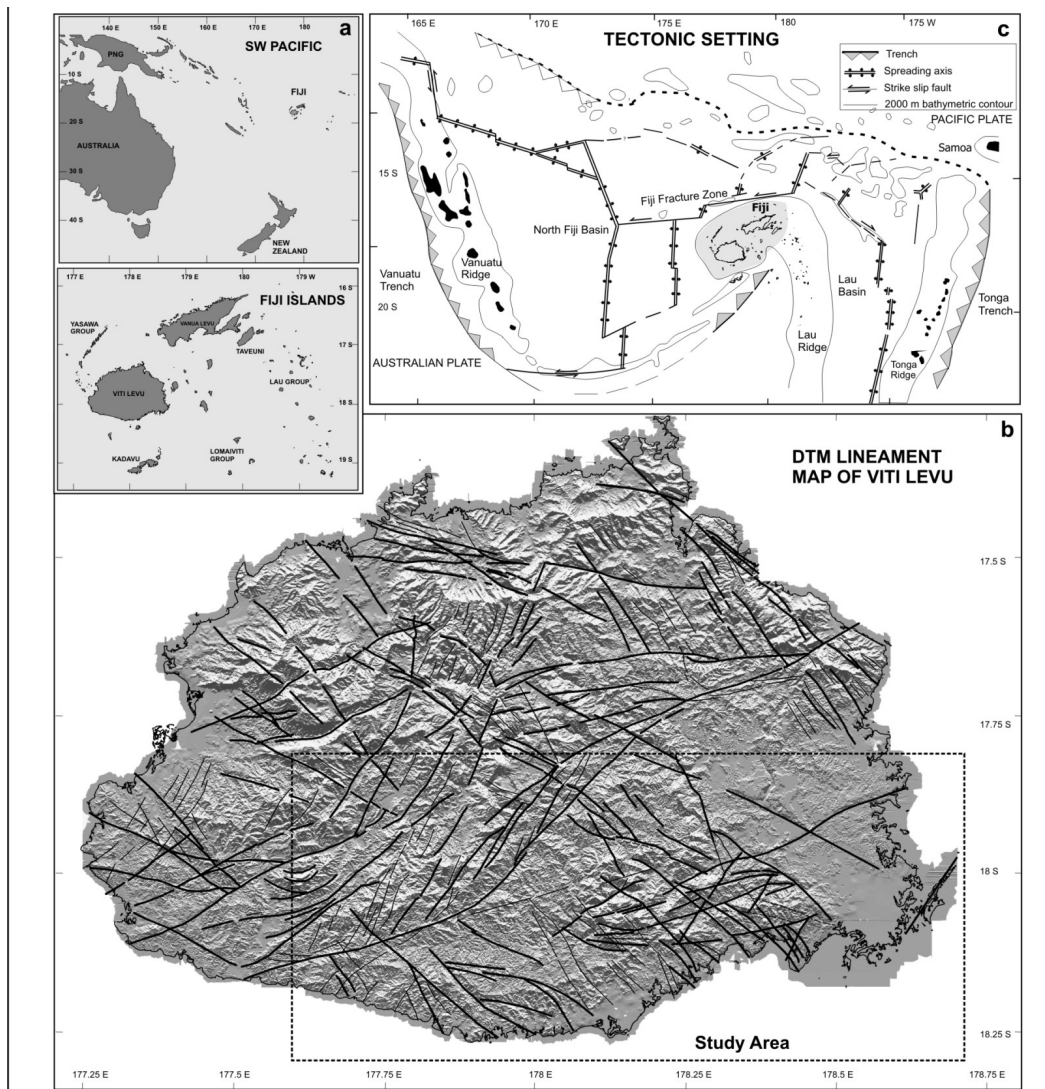


Figure 1: (a) Location on Fiji in the SW Pacific and the main islands of the Fiji archipelago. (b) Synoptic lineament map of Viti Levu based on 20 m resolution digital terrain model, illumination is from the N, 30° from the horizontal. Studied area is outline in the SE. (c) Tectonic setting of Fiji.

through utilising the inference about lineaments (geomorphic and magnetic) identified from remote sensing imagery as two dimensional expressions of crustal structure. Our lineament maps presented here are based on the approach developed for a control area in the SE of Viti Levu using multiple imagery, confirming their validity by demonstrating that the most robust sets of lineaments identified are related to fractures mapped on the ground and are of tectonic origin ([5], [6]). This summary of the detailed investigation of fracture lineament data is used in turn to infer the structural framework for southeast Viti Levu in terms of a complex fault mesh. The development of this fault mesh is related to internal deformation during the rotation of the Fiji Platform in the Neogene and Quaternary. Through the use of accurate seismicity data, it is shown how an active mesh style of faulting may be related to the seismicity in SE Viti Levu and may be used to develop a seismotectonic model for the entire Fiji Platform.

REGIONAL TECTONIC SETTING

The Fiji Islands presently lie in the complex boundary region between the Australian and Pacific plates in the SW Pacific, in between the Tonga and Vanuatu subduction zones (Figure 1a

& c). The plate boundary near Fiji has undergone rapid and repeated re-organizations over the last ~20Ma by various plate boundary related tectonic processes, including normal subduction, seamount collision, arc fragmentation, arc polarity reversal, arc rotation and back-arc spreading [5]. Presently Fiji is situated in the active back-arc region, between the west dipping Tonga arc trench system and the east dipping Vanuatu arc trench system (Figure 1c). The Fiji region occurs in a broad zone of deformation accommodating east-west divergence of the arc-trench systems, and left-lateral wrenching due to relative offset between the westward motion of the Pacific plate and the eastwards motion of the Australian plate.

The main islands of Fiji are located on a broad, shallow submarine plateau, known as the Fiji Platform, circumscribed by water less than 2 km deep at the northern end of the Lau Ridge ([7], [8]). The crustal thickness of the Fiji Platform is 15 to 20 km, typical of island arcs, and shallow earthquake depths are concentrated within the upper 13-16 km of the crust [9]. The state of stress within the Fiji Platform is defined by north-south orientation of the maximum compression and east-west orientation of tension, in which deformation is primarily accommodated by strike-slip faulting along broadly NE and NW trending fault planes.

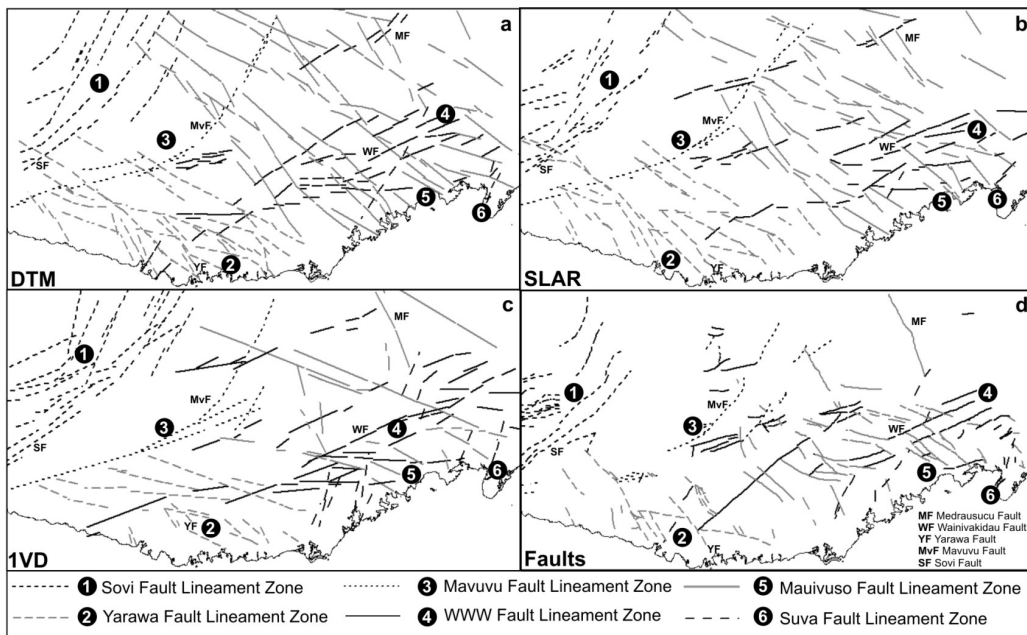


Figure 2: *Spatial comparison of regional lineament set compilation maps of (a) DTM, (b) SLAR, (c) 1VD images and (d) field mapped regional faults. Six spatially coincident fault lineament zones are labelled. Also labelled are individual faults that show excellent correlation between the datasets.*

FAULT AND LINEAMENT MAPPING

Definitive field based studies of geological structure, tectonic deformation and earthquake sources in Fiji, as well as in other tropical environments, are extremely difficult as they suffer from lack of good bedrock exposures due to near continuous vegetation cover, deep weathering, rugged terrain and poor access. Structural and tectonic analysis in such environments can be achieved through an innovative multidisciplinary approach that combines remotely sensed imagery, geographical information systems and field geology for mapping structural lineaments. Lineaments are considered to be naturally occurring, mappable linear topographic features on the Earth's surface, or linear forms at deeper levels of the crust discernible in aeromagnetic imagery, which may be formed by fractures in the Earth's crust that can be joints, faults or shear zones ([10], [11]).

The characteristics of fracture systems contain fundamental information about deformational processes and can provide insights into structural and tectonic evolution of a region (e.g. [12], [13] and [14]) and how ongoing deformation and seismicity may be related to tectonic setting and local structural features (e.g. [15]).

SE Viti Levu Control Study Area

The lineament analysis procedure adopted for this control area was carried out in four main steps that included: 1) the acquisition of lineament data from multiple imagery, 2) their analysis to select those that are significant, 3) their presentation as statistical and spatial plots, and 4) their comparison with fracture data. Each of the steps involved the use of clear definitions and strict statistical rules, which are presented in Rahiman [5] and Rahiman and Pettinga [6], but are not further detailed here.

Within the study area regional lineaments were mapped digitally in a GIS from the 1VD (1st derivative vertical magnetic component), DTM (digital terrain model) and SLAR (side-looking airborne radar) images at 1:150,000 scale (Figure 2). DTM lineaments were mapped by systematic

application of lighting direction from eight azimuths (0, 45, 90, 135, 180, 225, 270, 315) with source at 45° to the horizontal to create various illumination and shadow effects (shaded relief) on the DTM. SLAR lineaments from both the north and south looking SLAR data were mapped, largely based on morphological (textural) grounds, and then combined to produce a single SLAR lineament map. Lineaments on the 1VD image were drawn to show boundaries of areas with contrasting magnetic intensity. Larger-scale (1:50,000) lineaments were delineated from aerial photographic interpretations by plotting linear geomorphic features such as drainage channels and scarps on acetate overlays marked with reference co-ordinates (Figure 2). These lineaments were then also digitised on screen in a GIS after scanning, rectifying and geo-referencing the overlays using control points from 1:50,000 topographic maps.

Spatial correlation between regional lineaments and regional faults

The most continuous and through-going sets of reproducible regional lineaments were selected from the database for each of the images. Extraneous and isolated lineaments were removed. Six prominent lineament sets were identified from each of the images as shown in Figure 2 a, b and c. The through-going lineament sets from the various images were then compared for spatial coincidence in GIS. The geographical extent of every lineament set from one image was found to have an excellent spatial correspondence with lineament sets from the other images over the same area. All images show i) a 10 to 15 km wide NE to NNE lineament set in the NW of the study area, ii) a 20 to 30 km wide NW to WNW set in the SW, iii) a continuous narrow zone of ENE to NE set passing from the SW through to the central north, iv) a broad ENE set in the central SE and a narrow ENE set in the central north, v) a broad continuous NW to WNW set extending from the SE coast to the NW, and vi) a weak NE set confined to the SE region.

The lineament sets were checked for spatial correlation with mapped faults (Figure 2d). It was found that the extent of each of the six lineament sets correlated either fully or in part with

a major fault zone of similar orientation mapped in this part of Viti Levu [6]. Fault zones on Viti Levu represent zones of shearing comprising multiple fault strands rather than a single structure. Careful checking revealed that the trajectories of some individual lineaments, which were fully or partly reproducible on all the images, corresponded with the exact location of a known fault mapped on the ground. This relationship is clearly shown by the corresponding lineaments of five mapped faults; the Wainivakidau Fault (WF), Medrarusucu Fault (MF), Mavuvu Fault (MvF), Yarawa Fault (YF) and the Sovi Fault (SF), and are labelled with abbreviations on all the maps in Figure 2. The close spatial correlation between the lineaments and mapped faults implies that the lineaments largely represent fractures in the bedrock and are of tectonic origin.

The lineaments mapped over a wide area of southeast Viti Levu in a variety of remote sensing imagery, of both the surface and sub-surface, are expressions of fault and fracture zones in the bedrock (Figure 2). The mapping of lineaments has allowed for the identification and corroboration of six new fault zones and has provided a vast coverage of, and comprehensive information on, two dimensional fracturing in southeast Viti Levu, that until now was insufficiently known for a seismotectonic analysis. The system of fractures mapped is fundamentally related to the crustal brittle deformational processes and thus provides insights into the structural and tectonic evolution, as well as allowing for the interpretation of seismicity of the area.

Additionally, based on detailed work done in the offshore and near-shore areas of southeast Viti Levu [16], and along exposed rock shore platforms [6], showing that submarine canyon lineaments represent fault zones that are continuous with the onshore topographically defined fault zones.

Synoptic Lineament Map of Viti Levu

It is generally not possible to trace an individual fault or shear zone for long distances along strike in the field. As shown in the fracture lineament study of the control area in SE Viti Levu, fracture lineaments identified from analysis of remote sensing imagery can be used to infer and/or identify and quantify the extent of fault and shear zones [6]. Significant fault zones are often associated with closely spaced and intense fracturing at the Earth's surface and such fractures are preferentially more prone to erosion than the surrounding unfractured country rock. The lineaments appear as mappable linear topographic features, especially in shaded digital elevation models.

Based on the approach developed in the SE Viti Levu control area, we have compiled a synoptic fault lineament map for Viti Levu in order to identify the major potential earthquake source structures (Figure 1b). All faults in Viti Levu, based on published 1:50,000 scale geological maps of the Geological Survey of Fiji/Mineral Resources Department are included and augmented by data from the lineament analysis. New fault data from field mapping undertaken as part of this study in SE Viti Levu, is also included in this compilation [5]. A DEM for all of Viti Levu was prepared from 20m topographic contours derived from the Department of Lands and Surveys, Fiji, 1:50,000 topographic map series. The lineaments were mapped using a selection of shaded relief images of this DEM using a variety of sun-angles and azimuths at 1:250,000 scale. The main objective of the interpretation was to identify major continuous lineament structures. Figure 1b presents the synoptic fault lineament map of Viti Levu, with previous geologically mapped fault data integrated. Due to limitations of the existing fault map database, the more comprehensive fault/lineament map covering Viti Levu underpins our study. It

integrates published fault data and new fault mapping data with lineament data interpreted from the high resolution Digital Elevation Model (DEM) of Viti Levu.

Bathymetric data for the offshore area of southeast Viti Levu was acquired in 2003 [5], using a Multibeam Echo Sounder system. The data was gridded in Surfer[®] version 8 software using ordinary point kriging method, with linear variogram, search radius at 1500 m with 8 minimum points and grid-size set at 20 m. Figure 3 presents a lineament interpretation of the DEM map for the entire onshore area of eastern Viti Levu, combined with the more limited offshore bathymetric DEM.

STRUCTURAL FAULT MESH OF EAST VITI LEVU

The detailed analyses of lineaments and faults were used to map six prominent and continuous fault lineament zones in southeast Viti Levu. The fault lineament zones are shown to be composed of parallel fracture sets with lengths in the order of a few kilometres to tens of kilometres, which follow the principal orientations of NNW to NW, NNE to NE, WNW and ENE. The structural pattern in the onshore and offshore areas of southeast Viti Levu that emerges when these fracture sets are superimposed is one of a complex fault mesh (Figure 3). Within the fault mesh, fracture sets terminate against, or are offset by each other. High concentrations of fractures occur at the intersection of fracture sets and large areas (blocks), which have very little internal fracturing, are enclosed by intersecting fracture sets of a number of orientations. It appears that the upper crust of southeast Viti Levu is subdivided into numerous upper crustal blocks that typically range from ~2 to 30 km across, by a network of interlocking fault sets that follow the principal orientations defined in this study.

This fault mesh represents the superposition of several generations of fracture sets. It is possible that some of the fracture sets in the fault mesh may have developed as conjugate or orthogonal sets. On large-scale lineament maps [5], the ENE and WNW fractures are discontinuous and have undergone disruption and offset along younger generations of fractures.

The NNW to NW and NNE to NE fractures appear to be younger than the WNW and ENE fractures, as they cut across the fabric of the older ENE and WNW trends (Figures 2 & 3). The fracture sets impart significant control on the geomorphic expression of bays, peninsulas and nearshore islands of the SE Viti Levu coast, disrupting the ENE trend of the coastline [6].

The main orientations of the mapped fractures in the structural fault mesh of southeast Viti Levu are parallel to major structural features elsewhere on the Fiji Platform (Figure 4). The principal fracture sets in SE Viti Levu are considered to represent generations of regional tectonic faults, which have pervaded the Fiji Platform during and after disruption of the proto Fijian arc.

EVOLUTION OF THE STRUCTURAL FAULT MESH

Crustal block rotations about vertical axes between parallel fault sets are widely recognized in regions of strike slip tectonics (e.g. [17], [18]). Rotations of blocks are accommodated by displacements on block bounding faults, which themselves need to rotate. Mechanical consideration of faults require that large rotations (>45°) need to be progressively accommodated by the development and rupturing of new faults across the blocks as older faults move out of optimal positions of slip [19]. The amount of rotation that can be accommodated by only one set of parallel faults, under the same stress field is limited to 25° to 45° [19]. It

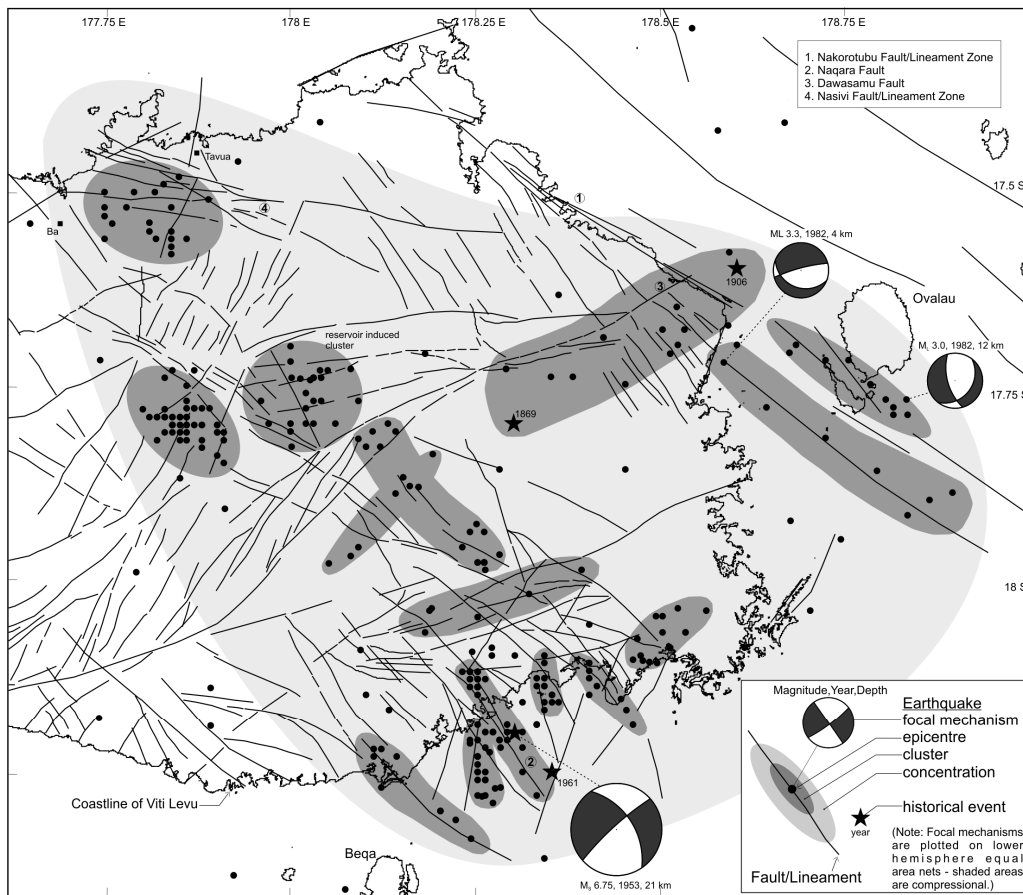


Figure 3: Map of eastern Viti Levu showing the geographical correlation between the location of earthquakes and the structural fault mesh model. The larger shaded area represents the Viti Levu Seismic Zone.

It is proposed that the structural fault mesh of southeast Viti Levu has progressively evolved as the brittle deformational response to the Upper Cenozoic anticlockwise tectonic rotation of the Fiji Platform. Regional paleomagnetic declinations reveal the anticlockwise rotation of the Fiji Platform about a vertical axis, apparently as a coherent mass, since the late Miocene (10 Ma), by amounts ranging as high as 75° to 135° ([20], [21], [22], [23]). The degree of Neogene brittle deformation in southeast Viti Levu, as shown by the fault mesh documented in this study, suggests considerable internal deformation contemporaneous with the period of arc rotation.

A simple model for accommodating block rotations within the Fiji Platform is proposed here, and is consistent with the development of the observed fault mesh pattern. Counterclockwise rotation of the Fiji Platform was initiated about 10 Ma as a result of distributed left lateral wrenching which developed across the zone of overlap between the Tonga and Vanuatu subduction zones, due to the opposing plate motions to the north and south (Figure 5a). Assuming that the regional stress orientations in the Fiji Platform have remained constant after the Middle Miocene (e.g. [24]), an early set of faults, now ENE trending, developed presumably as N to NNE trending dextral riedel faults to accommodate the anticlockwise rotation in response to the distributed left lateral shear (Figure 5a). These early faults caused intense deformation within the Fiji Platform, dividing the terrain into elongated crustal blocks. These faults formed zones of weakness in the crust that would have also imparted structural control on the distribution of arc volcanism and basin evolution.

With the counter-clockwise rotation of these blocks approaching close to 45° , misorientation of these early faults with respect to the regional paleostress field led to the propagation of new faults to accommodate further rotation (Figure 5b). These new generation faults are today represented as the WNW trending faults. As rotation progressed further, successive misorientations of older fault sets, and rupture of new optimally oriented transtensional faults after rotation intervals of 25° to 30° produced NW, NNW, NNE trending faults sets, that now occur as narrow morpho-structural grabens and form the later stages of fault mesh development (Figure 5c,d,e). The total amount of rotation recorded by these successive faults sets amounts to $\sim 120^\circ$ - 135° , in close agreement with the total amount of rotation of the Fiji Platform obtained from the recent paleomagnetic study [23]. The arcuate and fanning nature of some fractures are particularly evident in southwest and southeast Viti Levu, and across the length of the southern coast of Vanua Levu (Figure 4). These may reflect the constant readjustment of the positions of faults as block rotation took place, and fault relays evolved.

It is possible that the formation of block bounding faults may have been more complicated than represented in this simplistic model, such as through the formation of conjugate sets. Nevertheless, as demonstrated by this evolutionary model, during the initial stages of the rotation there would have been fewer fractures on the Fiji Platform. As rotation progressed, more fractures developed on new orientations further building the fault mesh. It is possible that with the increase in the density of fractures, the deformational strain imposed on the Fiji Platform would become more distributed through the fault mesh. With the increase in distributed deformation, rupture of

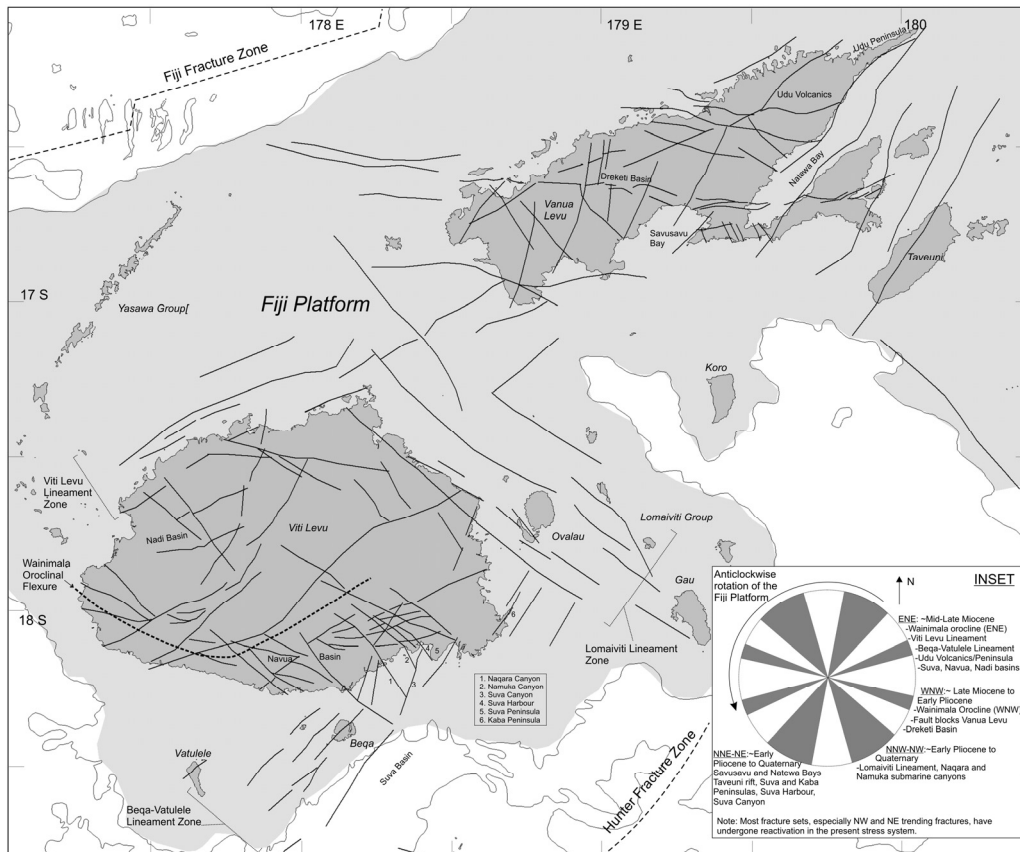


Figure 4: *Synoptic structural lineament map of the Fiji Platform, based largely on interpretation of aeromagnetic data (after Gunn et al. [25]) and DTM lineaments on Viti Levu. Inset: A diagrammatic summary of the present orientations of structural features on the Fiji Platform and their inferred relation to anticlockwise rotation of the Fiji Platform.*

new block bounding faulting would become more complex and as a result the rotation of blocks more inefficient. The overall rotation of the Fiji Platform therefore may have waned through time to the present day. It is also possible that the overall rotation could have decreased with the establishment of the Fiji Fracture Zone and the Hunter Fracture Zone as major left lateral transform faults to the north and south of the platform respectively (Figure 5e). These regional structures presently accommodate a large component of left lateral shear in the Fiji region. A decrease in the rotation rate of the Fiji Platform is implied by some paleomagnetic results (e.g. [21], [26]).

DEFINING FAULT ACTIVITY

Under the fault mesh model of the Fiji Platform presented here, most faults within the Fiji Platform can be defined as neotectonic faults, that is, faults that are accommodating current plate boundary stresses. Certain groups of faults whose orientations are NE or NW trending are favourably oriented to accommodate the regional stress field and are associated with the largest earthquakes. Faults with these orientations on the Fiji Platform can be defined as capable faults. There is generally a lack of sufficient existing data to identify comprehensively the activity of faults in Viti Levu. There are no historical records of coseismic surface fault rupture in Viti Levu. Paleoseismic data concerning average slip rates, surface faulting earthquake recurrence intervals, magnitudes associated with past ruptures and the time of last coseismic surface rupture are not available. All the mapped faults are widely recognised to disrupt Oligocene to Pliocene strata on land. In most cases, overlying younger strata above these

“basement” rocks are hidden by vegetation, covered by deep weathering and colluvial soil profiles, removed by erosion and/or have poor stratigraphic age control. For most faults the most recent activity is not well constrained geologically. It is conceivable that activity of many faults may have continued into the Quaternary. The close association of well located shallow earthquakes (<20 km depth) along the surface traces of some faults indicates renewed (or continued) rupture may be occurring. It is proposed that the main reason for the deficiency in fault activity data is the fact that there have rarely been field investigations in the past that focussed primarily on obtaining such data on faults, and not because the evidence of activity does not exist. Despite the current limitations in field data, Rahiman [5] has attempted to classify fault activity based on a range of indirect observations. The approach used is modified from Cluff et al. [27], and makes use of the geographic association of faults with microseismicity and strong earthquakes, and where available, age limiting geological and geomorphological data. A further criteria applied is the structural relationship between groups of faults based on proximity and orientation [5]. This approach led Rahiman [5] to establish four categories of fault activity, including (a) active fault; (b) potentially active fault; (c) tentatively active fault, and (d) inactive fault. Active faults are defined as those faults that have a history of strong earthquakes and surface rupturing defined by historical data, clear geological/geomorphological data, as well as geodetic indication of movement. Potentially active faults have not ruptured historically, but are known to displace recent (Quaternary) geological deposits and geomorphological features, as well as having an alignment of epicentres along the fault trace. Tentatively active faults either show displacement of Quaternary geological deposits and

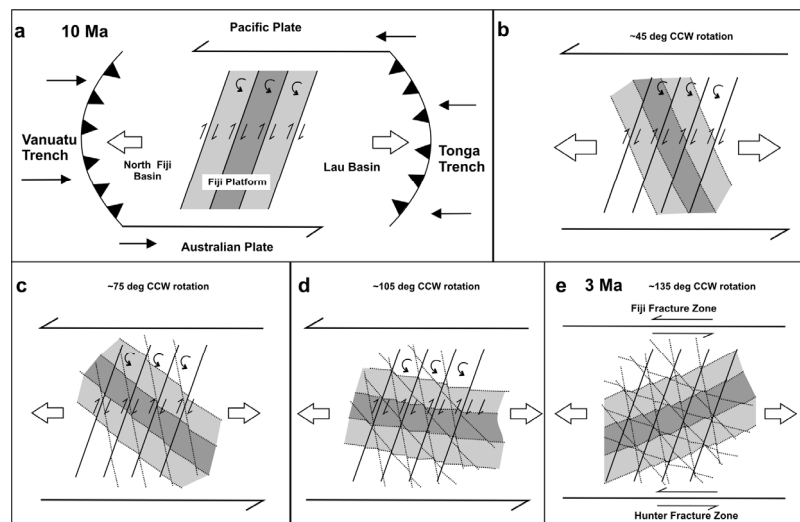


Figure 5: Schematic diagram showing progressive development of a complex fault mesh by fault and block rotations within the Fiji Platform in the Neogene.

geomorphological features, or have alignment of epicentres along the fault trace. Inactive faults have neither geological/geomorphological evidence nor seismological evidence of recent activity. Based on these criteria Rahiman [5] classified no faults as active, while he noted that almost certainly such faults will be identified with further targeted studies. Six priority fault/lineament zones are identified in Viti Levu that comprise potentially active and tentatively active faults.

STRUCTURAL FAULT MESH AND THE ORIGIN OF SEISMICITY

Supporting evidence for distributed tectonic deformation through activity of the structural fault mesh is provided by seismicity data in Viti Levu. Seismicity data was recorded from the closely spaced and well-calibrated telemetered Fiji Seismograph Network between 1979 and 1994 [28]. High-quality recordings of earthquakes on Viti Levu are mostly from the period between 1979 and 1985 [9], when the network comprised up to 12 seismograph stations operating on Viti Levu, Beqa and Ovalau (see Figure 4). The close array of seismographs in Viti Levu (less than 30 km separation) allowed for recordings of reliable epicentral locations to within 1 to 3 km and sensitive recordings of small to micro-earthquakes (M_L 4 to -1) [9]. The accuracy of seismicity data for Viti Levu and the detailed level of work done on the mapping of faults in the onshore and offshore area of southeast Viti Levu [5] permit the evaluation of the relationship between seismicity and present day deformation within the context of the interpreted structural fault mesh.

Seismicity is concentrated in the eastern half of Viti Levu (Viti Levu Seismic Zone), and the pattern of seismicity within this zone, from a regional perspective, appears to be broadly disseminated (Figure 3). Closer examination of the seismicity pattern, however, reveals discrete clusters of earthquake epicentres, most of which can be correlated to fault segments that form the structural fault mesh (Figure 3). This correlation of earthquake clusters suggests that the active structures are short fault segments within the fault mesh. These fault segments follow a range of orientations without showing a preference for a particular trend. The correlation of earthquake clusters to mapped faults is shown in Figure 3 and described as follows:

- In the area between Viti Levu and Ovalau two linear clusters of epicentres occur along the southern continuation of the Nakorotubu Fault/Lineament Zone (part of the Lomaiviti Lineament Zone). Aeromagnetic data over the offshore area shows that these linear clusters of earthquakes occur on well-defined NW trending faults along the southern trajectories of the Nakorotubu Fault/Lineament Zone. An earthquake focal mechanism from within each of the two clusters shows a nodal plane that is NW trending [29], and are comparable with the strike of the mapped fault/lineaments.
- Along the southeast coast of Viti Levu, there are several elongate epicentral clusters that correlate to NE, NNW and NW trending faults that have been mapped spanning the onshore and offshore areas. A prominent linear cluster occurs along the NW trending Naqara Fault. This cluster contains the epicentres of the damaging historical earthquakes of 1953 and 1961 ([30], [31]). The NW trending nodal plane of the 1953 earthquake coincides with the strike of the Naqara Fault.
- Several other epicentral clusters in Viti Levu correlate closely with the mapped traces of fault/lineament zones. A broad, ENE elongated cluster extends from the middle of the island to the eastern coast, north of Ovalau. The strong historical earthquakes of 1869 (M_s ~6.0) and 1906 (M_s ~5.5) can be grouped into this cluster. This cluster occurs along the trace of the ENE trending Dawasamu Fault, the northeastern segment of the prominent Mavuvu Fault Lineament Zone.
- A cluster of epicentres in the northern part of Viti Levu, between Ba and Tavua townships, occurred as a sequence of events between 1999 and 2001, with the largest event recorded measuring M_s 4.2 [32]. This earthquake sequence occurred in an area that was previously considered aseismic. This cluster correlates with the northern end of the WNW trending faults of the Nasivi Fault/Lineament Zone.

There is a cluster of very shallow earthquakes (< 4 km) in central Viti Levu that surrounds the Monasavu Dam. These are not related to tectonic activity of the fault mesh, as they are shown to be reservoir-induced seismic activity associated with water impoundment of the 85 metre high earth and rockfill dam ([33], [34]).

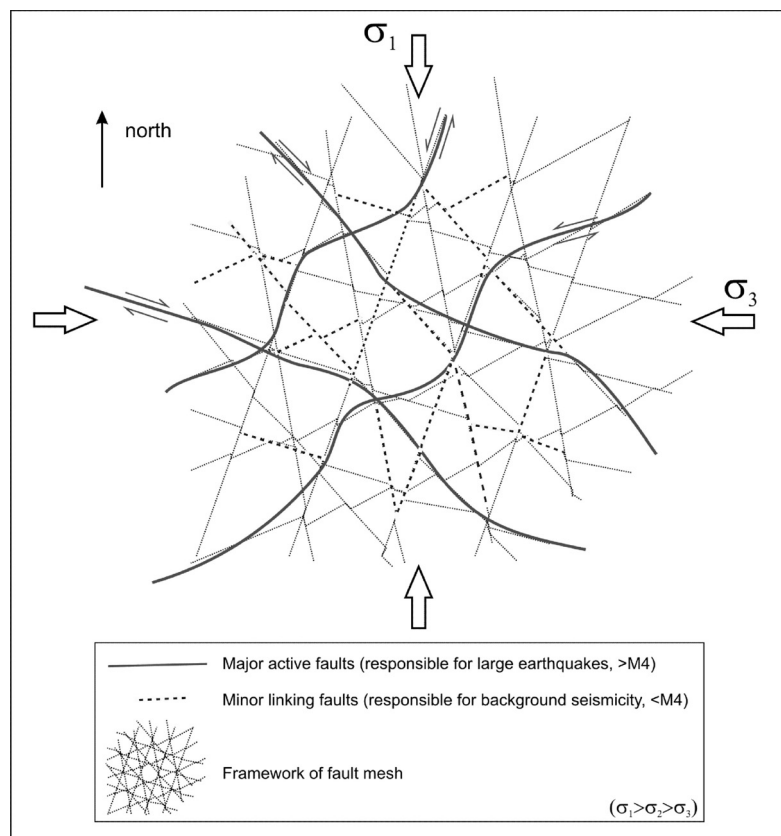


Figure 6: Conceptual diagram showing the relationship between seismicity (both large and small earthquakes), and active linking fault segments and major through-going faults within the structural fault mesh.

Reliable hypocentral depths of earthquakes indicate seismic activity in Viti Levu is generally confined to the top 20 km of the crust, with most activity between 7 and 13 km [9]. The occurrence of linear clusters of earthquakes coincident with the mapped fault/lineament traces is indicative of steeply dipping faults and is in agreement with the steep dips on fault planes measured in outcrop exposures in southeast Viti Levu. The distribution of hypocentres outlines the three dimensional geometry of the crustal fault blocks and provides constraints on the depth limits of fault mesh activity.

The seismicity data indicates the rupturing of fault segments over a range of azimuthal orientations. The activity occurring on multiple fault segments indicates that tectonic strain may be accommodated by the entire structural fault mesh in a distributed manner. The fault mesh presently functions as a network of interlocking and linked faults that accommodate this tectonic deformation. This probably occurs by a process that involves complex mesh style coseismic faulting, whereby ruptures propagate through short linking fault segments that form the fault mesh. These ruptures may occur along reactivated older linking faults, or may occur along newly created faults associated with continued rotation of some crustal blocks. Small earthquakes on linking faults may be the result of ongoing stress-driven instabilities in parts of the fault mesh which are constantly reacting to the regional stress field. It is possible that due to stress build-up in a particular part of the mesh, a set of linking fault segments, which are optimally oriented with respect to the regional stress field, will sometimes combine to rupture as a large earthquake, accommodating a larger fraction of the deformation. The following cycle of stress build-up leading to the next large earthquake may begin at some other location of the fault mesh, following the continued partial release of strain energy through lower magnitude earthquakes on linking faults of the fault mesh.

It has been suggested by Hamburger *et al.* [9] that the Fiji Platform is currently deforming under the same stress field as the neighbouring North Fiji and Lau back-arc basins in which N-S contraction and E-W extension are accommodated by NE and NW strike-slip faults. The focal mechanism of the Suva 1953 event (M_s 6.75) has nodal planes that show these orientations. It is inferred that large earthquakes in Viti Levu are primarily the result of rupturing on either NW and NE trending faults, which lie in the optimum stress field orientation for slip within the fault mesh. Fault rupturing during these large earthquakes, however, may be occurring in a complex manner through the fault mesh, utilising the zones of weakness along older previously locked faults, that now lie close to favourable orientations for slip. This concept is shown diagrammatically in Figure 6. The results of this inferred process are the large through-going faults on the Fiji Platform that overall may show a complex sigmoidal form such as, for example, the Mavuvu Fault/Lineament zone. The complex geometry of these through-going faults may exert a topographic response in releasing and restraining bends and/or step-overs.

The complex mesh style coseismic faulting postulated for southeast Viti Levu is consistent with the historically low occurrence of large earthquakes. Numerous small to moderate magnitude earthquakes (M 3 to >4) have been recorded in this zone over the last 25 years by the Fiji Seismograph Network. However, only one earthquake with magnitude $>M6$ has been reported in the last 150 years within this zone ([29], [33]). Due to the complex interactions between faults, the fault mesh is rarely able to sustain rupture along a single fault of sufficient length to produce large earthquake magnitudes ($>M7$). While there are no clear indications of large, Late Holocene surface ruptures along any of the onshore or offshore faults, there is evidence of displaced shorelines across the projected location of a number of inferred active faults,

and there are a number of faults documenting Quaternary activity in SE Viti Levu (e.g. [3], [4]). These observations are consistent with the prediction of complex spatial and temporal rupture propagation through the fault mesh in which coseismic surface displacements are likely to be limited, due to near surface partitioning of the fault slip through the mesh.

SEISMOTECTONICS OF THE FIJI PLATFORM

The seismotectonic model proposed for southeast Viti Levu is also applicable to the entire Fiji Platform. The principal fracture orientations as seen in southeast Viti Levu are also recognised in other parts of the Fiji Platform especially on Vanua Levu (see Figure 4). The structure of large offshore areas of the Fiji Platform, however, remains unknown. The geometry of regional scale faults mapped in other parts of the Fiji Platform reflect, on a more local scale, internal structural breaks similar to the fault mesh mapped in southeast Viti Levu and may similarly control the seismicity in those areas.

It remains unclear at this stage why earthquakes occur in only two areas of the Fiji Platform, that is, eastern Viti Levu and northeast Vanua Levu. This distribution, however, may be a reflection of the short period of available recordings of instrumental seismicity data. The longer-term seismicity distribution is inferred to be more widespread throughout the Fiji Platform. Large historical events, such as the Koro earthquake of 1932, have occurred well outside these two main areas of concentrated seismicity. A recent series of earthquakes between 1999 and 2002, in northern Viti Levu, occurred in an area of no known previous seismic activity.

It is possible that the two areas of seismicity within the Fiji Platform represent the presently active zones of the fault mesh accommodating deformation within the Fiji Platform. These areas probably represent zones of weakness that may be presently localising deformation within the Fiji Platform fault mesh. Possible changes in the geometry of the active fault mesh, due to continued internal deformation, may lead to a shift in the position of the accommodation zone. It is valid to speculate that the spatial and temporal distribution of seismicity within the Fiji Platform varies as the fault mesh reacts to the tectonic stress field by continually shifting the locus of the deformation zone to other parts of the Fiji Platform. Based on this interpretation, earthquakes are expected to occur anywhere within the Fiji Platform. Eastern Viti Levu and northeast Vanua Levu, however, continue to largely remain the presently active areas.

The seismotectonic model proposed here is an attempt to address the origin and distribution of seismicity within the Fiji Platform. As in other parts of the world, the cause of seismicity in areas distal from well defined tectonic plate boundary zones is a question that cannot be answered unequivocally. The structural fault mesh model and the explanation provided for its control on the characteristics of seismicity within the Fiji Platform are presented here as a hypothesis to be more thoroughly tested as new seismicity data, GPS/geodetic data and structural data on faults within the Fiji Platform become available in the future.

SUMMARY AND CONCLUSIONS

Fault lineaments mapped in the onshore and offshore area of southeast Viti Levu are used to define a structural model of Neogene brittle deformation, the context of which is then used to interpret the seismicity of the area and the seismotectonics of the entire Fiji Platform. The principal sets of fault/lineaments mapped on remotely sensed images, bathymetric and seismic reflection data, and verified with field mapped structures, follow the orientations of NNW-NW, NNE-NE, WNW and ENE. These fracture sets combine to

form a complex fault mesh, dividing the upper crust of SE Viti Levu into a number of crustal blocks ranging from ~2 to 30 km wide.

The structural fault mesh is a composite feature that is the product of the superposition of several generations of faults that pervaded the Fiji Platform during and after disruption of the proto Fijian arc. The ENE and WNW faults correlate to the earliest sets of larger scale structural features on the Fiji Platform, while the NNW-NW and NNE to NE faults are younger fault sets that are associated with more recently formed (Pliocene-Quaternary) structural features that have clearer geomorphic expressions. It is interpreted that the fault mesh formed as a result of progressive tectonic deformation of the Fiji Platform, during the Neogene, by distributed faulting and associated crustal block rotations.

The fault mesh is used to explain the origin of seismicity in southeast Viti Levu, including both higher magnitude earthquakes (e.g. $M > 4$), as well as the more numerous events of $M < 4$. The correlation of seismicity data to short fault segments of the structural fault mesh indicates that regional tectonic deformation is presently being accommodated in a distributed manner within the entire fault mesh. This may be occurring by a process that involves complex coseismic faulting throughout the mesh. Ongoing tectonic deformation is expressed by low magnitude earthquakes, probably following ruptures on short linking faults, and larger earthquakes when several linking faults combine at optimum stress field orientations forming longer ruptures in a complex manner. Low occurrence of large earthquakes and the diffused pattern of seismicity currently observed in southeast Viti Levu reflect a complex mesh-style coseismic faulting. Distributed deformation through the structural fault mesh in southeast Viti Levu is probably characteristic of the type of deformation that occurs within the entire Fiji Platform. The current lack of field evidence for late Quaternary ground rupture is considered to in part reflect the limited opportunity for fault scarps preservation, as well as the long return times inferred for large magnitude events. There is a clear need for future research to focus on establishing a paleoseismic record for the main fault zones defined in the study by Rahiman [5].

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