The stratigraphy and sedimentology of the Waindalithi Conglomerate of northeast Viti Levu, Fiji: hyperconcentrated flows and Pliocene environmental history

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Exposures of the Early Pliocene Waindalithi Conglomerate are confined to no more than a dozen scattered outcrops in the northeast part of Viti Levu, the main island of the Fijian archipelago. The Waindalithi Conglomerate is waterlain, but its sedimentology is unlike that expected either in debris flow deposits or in sediments entrained by conventional fluvial processes. Instead, the unit is likely to represent deposition from hyperconcentrated flows. Deposits of this sort have probably been under-identified in the rock record. In part, this is because no single characteristic is diagnostic of hyperconcentrated flow deposition. A combination of gravel lithology, sedimentary fabric, particle-size distribution and the sedimentology of individual beds proved valuable for the recognition of these deposits in this work. The deposition of the Waindalithi Conglomerate appears to have been immediately predated by a significant episode of volcanicity along the Nakauvadra and Nakorotubu ranges to the north of the region. Several eruptive centres may be recognised in the ranges, including the 25 km-diameter Rakiraki Volcano and the newly identified Nadelanadro, Namara, Tova and Naimasi volcanoes. Fan-like masses of volcanic conglomerate drape the southern flanks of the ranges. Southerly drainage down these fans was diverted east along the gutter developed where the fans abutted the ridge-and-vale topography of the Wainibuka and Matailombau hills. Downstream, the drainage resumed its southerly course via the topographic outlet of the Wainibuka gap and onto the coastal lowlands of the Early Pliocene sea. The Waindalithi Conglomerate forms a fan-like sediment body at the southern end of the gap. While the basal components of the Waindalithi Conglomerate may have been laid down under terrestrial conditions, the upper elements may have been deposited in shallow marine conditions, with the environment of deposition changing over time as local sea-levels rose.

KEYWORDS: Fiji, Pliocene, hyperconcentrated flows, debris flows, volcano, particle-size analysis, gravel lithology, sedimentary fabric, drainage patterns, geomorphology.

INTRODUCTION

The islands of the Fijian archipelago (Figure 1a) have their origin in volcanic activity associated with the interaction of the Pacific and Indo-Australian plates. Viti Levu, the largest of the islands, began to form around 40 million years (Ma) ago. The island represents an intricate melange of submarine and terrestrial volcanic and volcanioclastic rocks. It preserves evidence of island subsidence and uplift, intrusion within the volcanic pile and episodes of denudation, while the imprint of relative changes in sea-level is recorded in a complex suite of marine sediments. Our understanding of the geological and geomorphological history of the Fijian Islands remains provisional, however; stratigraphy is generally poorly understood, and the detailed description and interpretation of individual rock units remain rare.

The purpose of this work is to re-assess the sedimentology and stratigraphy of the Waindalithi Conglomerate1 of northeast Viti Levu. We aim to establish the environmental context in which it was deposited, to clarify the poorly understood geological and geomorphological history of

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1Most Fijian stratigraphic names were established in the middle years of the 20th century when the long (‘phonetic’) system of Fijian spelling was employed on maps and in those texts intended mainly for overseas readers. Since that time, the spelling of Fijian words on formal documents and maps has officially reverted to the system of orthography devised by Cargill in the 1830s. In this text, we have followed the convention of the International Commission on Stratigraphy that, once established, the spelling of the geographical component of a stratigraphic name should not be changed (Murphy & Salvador 1999). We have therefore retained the original spellings of geographical names in stratigraphic units, although we have used modern spellings for all other geographical names. In 1984, however, Rodda proposed that the spelling of stratigraphic names should follow the original Fijian system of orthography, and he adopted this principle in the second edition of the Lexicon of Stratigraphy of Fiji (Rodda in press). In order to ensure that the two naming systems are intercomprehensible, we have included an appendix listing the alternative spellings of the geological features referred to in this paper.

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northeast Viti Levu and add to our understanding of the post-eruptive history of oceanic volcanoes.

The known exposures of the Waindalithi Conglomerate are confined to no more than a dozen scattered outcrops in the central eastern part of Viti Levu. The formation was formally described and named by Hirst (1965), who recorded 150 m of conglomerates resting unconformably on a suite of rocks of probable Miocene age. Hirst noted that the conglomerates became finer towards the top of the succession, with sandstones becoming increasingly important. He described the formation as grading vertically (and, to the south, laterally) into the overlying Nathua Sandstone, in which he identified occasional thin and lens-like interbeds of conglomerate. The lithology of the gravel component of the Waindalithi Conglomerate varies widely and Hirst identified distinctive lithologies in individual exposures and systematic changes in gravel lithology across the largest of the outcrops. Hirst did not speculate either on the nature of the sedimentary environment within which deposition took place or on the broader environmental conditions under which the Waindalithi Conglomerate was laid down. In the introduction to the regional memoir, however, there is a bald reference to the marine origin of the conglomerates and the overlying sandstones (Hirst 1965).

The Waindalithi Conglomerate has been variously regarded as of later Pliocene to Pleistocene age (Hirst 1965), as no older than Early Pliocene (Rodda 1982a) and as having been deposited in the interval 8.6–5.5 Ma (Rodda 1977, in press; Nathan & Leckie 2003) or 4.5–4.0 Ma (Stratford & Rodda 2000).

GEOLOGY AND GEOMORPHOLOGY OF NORTHEAST VITI LEHU

Much of the regional stratigraphy described here follows that of the existing map sheets and Geological Survey of Fiji memoirs (Hirst 1965, 1966a, b, 1967a–c), taking account of the stratigraphic re-assessments of Rodda & Band (1987) and Rodda (in press).

The geology of northeast Viti Levu is dominated to the north by rocks of the Mba Volcanic Group and to the south by deposits of the Verata Sedimentary Group. These abut and are separated by the folded basement rocks and east–west aligned ridge-and-vale topography of the Wainibuka and Mataibau hills (Figure 1b). Both the Mba Volcanic Group and the Verata Sedimentary Group unconformably overlie rocks of the Wainimala Group and the Mendrausuthu Group.

Quantitatively, the most important unit of the Mba Volcanic Group is the Nakorotumbu Basalt. This consists mainly of volcanic conglomerates interbedded with lavas. The Basalt crops out along the northern fringes of the study area, where it forms the Nakauvadra and Nakorotubu ranges, separated by the topographic trough of Viti Levu Bay (Figures 1b, 2). The formation reaches a maximum thickness of about 900 m in the central part of the Nakorotubu Range, becoming progressively thinner with distance south (Hirst 1965).

Gradationally overlying the Nakorotumbu Basalt and locally forming the highest unit of the Mba Volcanic Group is the Tova Andesite (Figure 2). This crops out along the central crest and the southeast flanks of the Nakorotubu Range, and is largely made up of volcanic conglomerates, tuffs and lavas (Hirst 1965).

The Nakauvadra Range is made up of the eroded remnants of the 25 km-diameter Rakiraki Volcano (Rodda 1976; Ollier & Terry 1999). By contrast, little is known of the geomorphology of the Nakorotubu Range (Stratford & Rodda 2000). Ollier & Terry (1999) interpreted the Range as ‘…a simple slab of volcanics sloping seawards’, concluding that its origin is unknown and that its drainage pattern reveals nothing of its volcanic origin. Yet the occurrence of a stock of hornblende andesite (Rodda in press) (here informally named the Naimasi Andesite) is strongly suggestive of a discrete eruptive centre at the southeast end of the Nakorotubu Range (Figure 2). This andesite lies at the focus of a radial configuration of drainage, indicative of the pattern of streams formed on a volcanic cone developed around a single centre of eruption. Further north, the disposition of the lavas of the Tova Andesite, the radial pattern of drainage across the outcrop and the presence of a large dyke located at the focus of the drainage lines close to Tova peak.
Figure 2: Geomorphology of northeast Viti Levu, Fiji. The mapped units represent the volcanic rocks of the Nakorotubu Basalt and the Tova Andesite and the intrusion of the Naimasi Andesite (informal name) (Hirst 1966a, 1967a–c). These make up the northwest–southeast aligned Nakorotubu Range. The Nakauvadra Range lies to the northwest, separated from the Nakorotubu Range by the topographic trough of Viti Levu Bay. The drainage on the volcanic rocks represents second-order and greater stream lines (based on Strahler’s 1952, 1957 stream-order classification) derived from the 1:50 000 geological map sheets (Hirst 1966a, 1967a–c). The radial pattern of drainage is indicative of a series of individual eruptive centres: the Nadelanadro, Namarai, Tova and Naimasi volcanoes.

(Figure 2) may tell a similar story. Similar drainage arrays occur at the northwest end of the range, again indicative of radial drainage around a discrete volcanic centre. We suggest that these features provide evidence for the existence of at least four volcanoes along the range. From northwest to southeast, these are the Nadelanadro, Namarai, Tova and Naimasi volcanoes (Figure 2).

Volcanic activity seems to have taken place concurrently along the Nakauvadra Range and Nakorotubu Range within the period 5.2–3.7 Ma (Table 1). The initial volcanic activity appears to have been submarine, becoming terrestrial over time (Hirst 1965; Stratford & Rodda 2000). This interpretation conforms with the geomorphological evidence, which suggests that the final stages of volcanic development were subaerial, allowing the development of radial drainage around the eruptive centres along the ranges.

Table 1: K/Ar geochronology of rocks of the Rakiraki, Tova and Naimasi volcanoes of northeast Viti Levu, Fiji.

| Volcano          | Date (Ma) | Dated material | Reference                          |
|------------------|-----------|----------------|------------------------------------|
| Rakiraki Volcano | 3.7 ± 0.2 | Basalt         | Malahoff et al. (1982, pp. 405, 407) |
| Rakiraki Volcano | 3.7 ± 1.0 | Basalt dyke    | Malahoff et al. (1982, pp. 405, 407) |
| Rakiraki Volcano | 3.71 ± 0.01 | Basalt       | Whelan et al. (1985, p. 416)         |
| Rakiraki Volcano | 3.8 ± 0.2 | Trachy-basalt  | Malahoff et al. (1982, pp. 405, 407) |
| Tova Volcano     | 3.96 ± 0.09 | Basalt        | Whelan et al. (1985, pp. 416, 436)   |
| Rakiraki Volcano | 4.51 ± 0.06 | Basalt       | Whelan et al. (1985, p. 416)         |
| Naimasi Volcano  | 4.6 ± 0.5  | Andesite      | Rodda & Kroenke (1984, pp. 93, 102)  |
| Rakiraki Volcano | 5.15 ± 0.4 | Quartz gabbro stock | Snelling & Chan (1971); Rodda (1982b) |
| Rakiraki Volcano | 5.2 ± 0.1  | Olivine basalt | Malahoff et al. (1982, pp. 405, 407) |
units contain basaltic lavas, with pillow basalt in the Vatukoro Greywacke suggestive of submarine conditions. The units reach a maximum thickness at the foot of the Nakauvadra Range, with the Rokavukavu Basalt thinning rapidly to the east and west (Hirst 1965).

The disposition of the Mba Volcanic Group rocks is thus indicative of a series of volcanic cones composed of lavas and volcanic conglomerates. These form the high ground along the northern margin of the study area. Fan-like masses of volcanic conglomerate, presumably reworked from the volcanoes along the ranges, drape the southern flanks of the ranges, becoming thinner to the south and west (Figure 1b).

The drainage across the Rokavukavu Basalt and the Vatukoro Greywacke is to the south. However, the trunk stream of the Wainibuka River, to which these flowlines are tributary, is aligned west–east (Figure 1b). It is likely that the Wainibuka River flows in the gutter formed where the southern edge of the volcanic rocks butted up against the ridge-and-vale topography of the Wainibuka and Matailobau hills. Drainage was thus diverted east, capturing flow off the volcanic conglomerates en route. Downstream, the Wainibuka River appears to have resumed its southerly path, following the lowest topographic outlet across the Wainibuka Hills (Figure 1b). In this, it may have been assisted by the development to the east of the volcanic pile of the Naimasi Volcano (Figure 2). Alternatively, the southerly drainage of the Wainibuka River (which the river still follows in its upper reaches) may have been diverted by post-Mba Volcanic Group upfaulting along the Navuthu Fault (Hirst 1965, 1967a), cutting off the route to the south and forcing the flow to the east (Figure 1b).

The basalts and conglomerates of the Rokavukavu Basalt and the Vatukoro Greywacke are separated from the depositional basin of the Verata Sedimentary Group by a 10–15 km-wide, east–west aligned tract of basement rocks (Figure 1b). To the south, the Waindalithi Conglomerate forms the basal component of the Verata sediments. The Waindalithi Conglomerate is scattered among a handful of small outcrops that lie unconformably on the basement units (Hirst 1965). The Waindalithi Conglomerate is overlain to the south by the Nathua and Korovou sandstones, although the tapering edge of the main outcrop of the conglomerate overlies the Nathua Sandstone, indicating that the two units interfinger along the northern edge of the basin. The age-diagnostic marine foraminifera in the Nathua and Korovou sandstones have been assigned to planktonic foraminiferin zone N19 (5.54–4.08 Ma; Nathan & Leckie 2003) (Rodda 1982a).

FIELD DESCRIPTION OF THE WAINDALITHI CONGLOMERATE

Since the initial description of the Waindalithi Conglomerate by Hirst (1965) in the early 1960s, over a kilometre of new exposures, reaching heights in excess of 20 m, has been cut through the formation (Figure 3). Our field description of the unit thus differs in several ways from that of Hirst.

The Waindalithi Conglomerate consists of subangular to rounded gravels supported within a matrix of sands and granules and interbedded with rare beds of sandstone. The sediments form a series of sheets, 10⁻² to 10⁰ m thick, dipping southwards at angles of around 5°. The frequency and size of the gravels vary from bed to bed, with the gravels ranging from pebbles to a maximum observed diameter of 620 mm. The base of individual beds is commonly marked by a layer of coarse gravels, typically a single clast thick. The gravels are largely composed of basalt, but clast lithology varies both laterally and vertically within the unit.

The Waindalithi Conglomerate has a maximum observed thickness of 119 m. At Natokalau village (17°46'08"S, 178°24'29"E), the Waindalithi Conglomerate appears to overlie Miocene limestones of the Wainimala Group, although the contact at this point is obscured by colluvium. At Navatudua Creek (17°50'48"S, 178°23'51"E) and the Waimaro River (17°46'58"S, 178°27'07"E), the feather edge of the Waindalithi Conglomerate overlies Early Pliocene Nathua Sandstone. Elsewhere, the conglomerate is likely to unconformably overlie Miocene plutonic rocks, the Miocene Wainimbuka Trachyte and the Miocene Wainindia Sandstone.
At the top of the sequence, the formation is overlain by the Nathua and Korovou sandstones. At Nava- tudua Creek and the Waimaro River, the contact appears to be conformable. Elsewhere, the contact is sharp, with a local relief of up to 10 m and occasional steep-walled features trenched into the top of the Waindalithi Conglomerate. Across the whole unit, the relief of the contact amounts to several tens of metres. Where the Nathua Sandstone has been observed to overlie the Waindalithi Conglomerate, the basal sandstone commonly contains rounded pebbles, cobbles and occasional boulders. These appear to have been reworked from the underlying unit, probably contemporaneously with the entrenchment of the top of the Waindalithi Conglomerate and the deposition of the basal component of the sandstone. Fossils are uncommon in the Waindalithi Conglomerate. In the northernmost part of the unit, sediments from Site WC9 (Figure 4; Table 2), 24 m above the base of the unit, contain rare marine shells and rare plant stems; while sediments from Site WC7 (17°46’08”S, 178°24’15”E), 17 m above the base of the unit and Site WC2 (Figure 4, Table 2), about 40 m above the base of the unit, contain fragments of wood. Close to the easternmost part of the outcrop and at the top of the sequence, the sediments contain marine shells, rare angular cobbles of limestone and coral fragments.

![Figure 4](image.png)

**Figure 4** Geology of central eastern Viti Levu, Fiji, showing the location of the study sites and the directions of the flows that deposited the Waindalithi Conglomerate. The geology is based on the surveys of Hirst (1966b, 1967c), taking account of the stratigraphic re-assessments of Rodda (in press).

| Site  | Latitude (°S) | Longitude (°E) | Gravel fabric | Gravel lithology | Vertical particle-size profile | Particle-size distribution |
|-------|---------------|----------------|---------------|------------------|-----------------------------|--------------------------|
| WC1a  | 17.76889      | 178.40417      | WC1a          | WC1a             |                             |                          |
| WC1b  | 17.76801      | 178.40417      | WC1b          |                  |                             |                          |
| WC2   | 17.80913      | 178.41424      | WC2a, WC2b    | WC2              |                             | WC2                      |
| WC3a  | 17.91788      | 178.45968      | WC3a          | WC3a             |                             |                          |
| WC3b  | 17.92593      | 178.46221      | WC3b          |                  |                             |                          |
| WC9   | 17.79590      | 178.44483      |                | WC9              |                             |                          |
| WC10  | 17.71231      | 178.31706      | WC10          |                  |                             |                          |
| NC1   | 17.96730      | 178.52546      | NC1           |                  |                             |                          |
METHODS

Our investigations were focussed on the main outcrop of the Waindalithi Conglomerate. This lies between 178°21.50'E and 178°27.25'E and north of 17°47.45'S. This outcrop accommodates the thickest part of the sequence, with excellent exposures through almost the entire depth of the formation. In addition, over a dozen other outcrops of the Waindalithi Conglomerate and related units were studied. Six sites were selected for detailed investigation (Figure 4; Table 2).

Bulk samples of the Waindalithi Conglomerate were taken from Sites WC1 and WC2 for clast lithological analysis. At Site WC1, two samples were collected from locations 12.7 m apart. Sample WC1b lay stratigraphically about a metre below sample WC1a. The samples were obtained by collecting the entire volume of material within an area not exceeding 0.33 m². Given the coarse nature of the sediments, strenuous efforts were made to collect sufficient material to ensure representative sampling of their coarsest fractions (Gale & Hoare 1992, 1994). Size fractions were obtained using square aperture sieves. The lithology of the >-4.0 mm fraction of samples WC1a and WC1b and the >-8.0 mm fraction of sample WC2 was determined. Lithological analysis was also undertaken at Site WC3a. The lithified nature of the rock at this location precluded bulk sampling, and clast lithology was determined here by recording the lithology of every clast of >-4 mm within an area of 1.0 m × 1.0 m.

Particle-size distribution was determined on bulk samples from Sites WC1a and WC9. Samples were collected from an area not exceeding 0.33 m² following the procedures described above for gravel lithological analysis. Square-aperture sieves were employed at quarter phi-unit intervals for those fractions >-4.0 mm, at half phi-unit intervals for those fractions between 4.0 and 2.0 mm, and at one phi-unit intervals for the <2.0 mm fraction (Gale & Hoare 2011). Particle-size distributions were determined using square aperture sieves. Textural terms are those proposed by Folk (1954).

Gravel fabrics were determined by recording the inclination and declination of the axis of dip (whether a or b) of all clasts of a-axis >-20 mm within a limited area of the exposure. Twenty-five gravels were measured at Sites WC2a, WC2b and WC10, 40 gravels at Site WC3a, 26 gravels at Site WC3b and 35 gravels at Site NC1.

The variation in maximum apparent particle diameter with depth through the Waindalithi Conglomerate was determined at Site WC2. All clasts of diameter >-20 mm in the sequence were measured.

RESULTS

Gravel lithology

The gravel fractions of samples WC1a, WC1b, WC2 and WC3a are dominated by basalts of the Mba Volcanic Group, basalts of the Wainimala Group and dacite tuffs of the Lawalevu Sandstone (Figure 5). Outcrops of the Mba basalts and Lawalevu Sandstone occur only to the north of the Waindalithi Conglomerate. The Wainimala Group is more widely distributed, but significant exposures also occur to the north of the Waindalithi outcrop.

Particle-size distribution

The sediments from Sites WC1a and WC9 consist of bimodally distributed sandy gravels, with peaks in the medium pebble and very coarse sand fractions (Figure 6). The deposits are generally sorted, platy/kurtic and of varying skewness (Table 3). It should be stressed, however, that these characteristics are, at least in part, statistical artefacts resulting from the application of measures devised for use with unimodal data sets to bimodal distributions.

Gravel fabric

The fabrics of the gravels are dominated by a-axis dips (Figure 7). Sites WC2a, WC2b and WC3b possess an unambiguous north–south alignment; Sites WC3a, NC1 and WC10 display a broad northwest–southeast alignment. The inclinations are generally gentle.

Vertical particle-size profile

The deposits at Site WC2 display normal grading, with a series of upward-fining sequences within successive units (Figure 8). No evidence of inverse grading was observed, either here or elsewhere in the sequence.

DISCUSSION

Age of the Waindalithi Conglomerate

The Waindalithi Conglomerate contains gravels reworked from the Mba Volcanic Group. Since the Mba Group appears to have formed in the period 5.2–3.7 Ma, the Waindalithi Conglomerate can be no older than this. The Waindalithi Conglomerate is overlain by the Korovou Sandstone, and interfingers with and is overlain by the Nathua Sandstone. The sandstones contain a planktonic foraminiferal fauna diagnostic of zone N19 (5.54–4.08 Ma). The deposition of the Waindalithi Conglomerate is thus tightly bracketed between 5.2 and 4.1 Ma. The deposits are therefore likely to be of Early Pliocene age.

Environment of deposition

Marine conditions are likely to have existed at this time to the south and east of the site, with terrestrial environments to the north and west (Stratford & Rodda 2000). According to Hirst (1965), the deposition of the Waindalithi Conglomerate took place in a marine environment, but he offered no evidence in support of that claim and, given our current understanding of the contemporary paleogeography, the possibility of terrestrial sedimentation should not be overlooked.

The bimodal and very poorly sorted particle-size characteristics of the sediments are typical of material transported by sediment-rich, high-viscosity flows (Gale & Hoare 2011). Bull (1964) used various measures of sediment sorting to distinguish between these sorts of deposits, classifying them into waterlain, mudflow and intermediate types. His waterlain sediments are the products of clearwater flows characterised by low suspended sediment loads (Bull 1964). Sediment is supported by fluid turbulence, transport is traction-
dominated and sedimentation occurs by particle-by-particle accumulation. The water and the sediment it transports exist as two distinct phases, although as sediment loads increase the fluid may begin to possess low shear strengths (Costa 1988).

With increasing sediment concentration, fluid density and viscosity may increase, and the settling velocity of particles through the flow may begin to fall. Flows with sediment-transport characteristics that are intermediate between normal stream flow and mudflows were termed ‘hyperconcentrated’ by Beverage & Culbertson (1964). These are initiated once suspended sediment concentrations exceed 20% by mass (Beverage & Culbertson 1964). Although the solids and the fluid remain as separate components of the flow, such flows possess a small but measurable shear strength (Costa 1988). The capacity of these flows to support particles is enhanced by grain interaction and increases in the apparent

Figure 5 Lithological types as a function of particle size, Waindalithi Conglomerate, Viti Levu, Fiji. (a) Site WC1a, (b) Site WC1b, (c) Site WC2 and (d) Site WC3a.

Figure 6 Particle-size distributions of samples from Sites WC1a and WC9, Waindalithi Conglomerate, Viti Levu, Fiji.
viscosity and apparent density of the suspension. Neverthe-
less, the velocity profiles of hyperconcentrated flows
remain logarithmic, and coarser particles are deposited
first as flow velocities fall (Costa1988).

Mudflows are synonymous with debris flows, the dif-
ference depending on whether the gravel content is
greater than or less than 50% (Varnes1978). In either
case, the volume concentration of suspended grains is so
high that the yield strength of the suspension is suffi-
cient to support gravel-sized particles, although other
mechanisms of particle support such as dispersive pres-
sure (Bagnold1954) and grain contact (Pierson1981)m a y
also operate. Solids and fluid move together as a single
unit, the shear strength of the flow is high, and as
flow velocities fall, only the very coarsest particles are
deposited.

We have taken Bull’s database, greatly increasing its
size to include samples from environments ranging from
humid tropical to glacial, and encompassing fluvial,
hyperconcentrated flow and debris flow deposits (Figure 9).
Irrespective of climatic environment, the 160 samples plotted lie within discrete envelopes that reflect
the sedimentary setting of the deposits. With one excep-
tion, the small number of anomalous samples is better
sorted than might be expected given the sedimentary
environment in which they formed. This is likely to
reflect source control on the particle-size distribution.

Plotting the Waindalithi Conglomerate on Figure 9 sug-
ests that the material is transitional between a true flu-
vial deposit and one deposited by hyperconcentrated flow.

Additional clues to the environment of deposition
come from the domination of the gravel fabrics by $a$-axis

### Table 3

Summary particle-size distribution statistics (calculated following the procedures of Folk & Ward 1957), verbal descriptions (following the terminology of Folk 1954) and textural classification (following the definitions of Folk 1954) of samples from Sites WC1a and WC9, Waindalithi Conglomerate, Viti Levu, Fiji.

| Sample | Sample size (g) | Texture      | Graphic mean (phi-units) | Inclusive graphic standard deviation (phi-units) | Inclusive graphic skewness (phi-units) | Graphic kurtosis (phi-units) |
|--------|----------------|--------------|---------------------------|-------------------------------------------------|--------------------------------------|-----------------------------|
| WC1a   | 25 944         | Sandy gravel | -2.58                     | 2.39                                            | 0.27                                 | 0.73                        |
| Verbal description |            | Very poorly sorted |                          | Positive (fine)-skewed                          | Platykurtic                         |
| WC9    | 14 906         | Sandy gravel | -1.66                     | 2.58                                            | -0.22                               | 0.82                        |
| Verbal description |            | Very poorly sorted |                          | Negative (coarse)-skewed                        | Platykurtic                         |

Figure 7 Orientation of gravels of $a$-axis $>$20 mm, Waindalithi Conglomerate, Viti Levu, Fiji: stereographic equal-angle projection. Closed circles represent $a$-axis dips; open circles represent $b$-axis dips. (a) Site WC2a, (b) Site WC2b, (c) Site WC3a, (d) Site WC3b, (e) Site NC1 and (f) Site WC10.
alignments (Figure 7). These are strongly suggestive of transport of the coarse fraction of the sediment in suspension (Johansson 1965; Rees 1968; Allen 1982) and are quite unlike the bedload-transported b-axis fabrics characteristic of conventional waterlain sediments (Rust 1972; Harms et al. 1982). The flows that laid down the Waindalithi Conglomerate are therefore likely to have been capable of maintaining the coarse fraction of the deposits in suspension in the fluid.

This interpretation is reinforced by the matrix-supported nature of the gravels, indicating that the coarse fraction of the deposit must have been transported within a suspension of fine material. Some process capable of keeping large particles in suspension in fluid flow must therefore have been at work. Possible mechanisms include conventional fluid turbulence, dispersive pressure (Bagnold 1954), grain contact (Pierson 1981), Bernouillian lift (Fisher & Mattinson 1968; Mattinson & Fisher 1970), boundary lift (Rubinow & Keller 1961; Saffman 1965) and buoyancy enhancement in high-density suspensions (Rodine & Johnson 1976; Hampton 1979; Pierson 1981).

Flow-parallel σ-axis fabrics are common (although not ubiquitous) in debris flows (e.g. Lindsay 1968; Houmark-Nielsen 1983). However, the internally graded character of individual beds of the conglomerate is not usual in debris flows, which are typically uniform or even inversely graded (Smith 1986), a product of deposition en masse as shear stress falls below the yield strength of the flow. In addition, the presence of single-clast layers of coarse gravels (Figure 3) is suggestive of winnowing processes that leave lag gravels at the bed of the channel, processes incompatible with a debris flow origin for the sediments.

On the other hand, the variation in the relative proportions of the lithologies contributing to the gravel assemblages of the samples is quite unlike that anticipated under fluvial conditions. The most extreme example of this comes from samples WC1a and WC1b. The sampling sites were separated laterally by only 12.7 m, with the beds stratigraphically only a metre apart. Yet the relative contribution of petrographic types in each sample is entirely different (Figure 5a, b). River deposits tend to integrate the contribution of the various rock types in the upstream catchment. Gravel lithology thus varies little over time at a particular point in the drainage system (e.g. McGregor & Green 1983) (assuming, of course, no major changes in catchment size and neither the introduction nor removal of sediment sources; Gale & Hoare 2011). By contrast, the deposits here appear to represent the products of transport along individual flow paths, in which particular combinations of rocks are available for entrainment. This may arise where deposition takes place from a series of discrete flows, each following different paths into the depositional basin. There is copious evidence that, whereas rivers tend to respond to floods that activate the entire drainage network (in small- to medium-sized catchments, at least), debris flows and lahars tend to be the products of individual events that mobilise material along separate flow lines. The result is a distal sequence of sedimentary units, each of distinct provenance (e.g. Vallance 1999). The lithological evidence is therefore strongly indicative of an alternative waterlain origin for the sediments.

Thus, while the deposits possess certain of the characteristics of debris flows (gravel lithology and perhaps fabric), the sediment sorting and the sedimentology of individual beds are quite unlike those expected in debris flow deposits. Meanwhile, the compelling evidence for the transport of coarse gravels in suspension excludes the possibility of traction-dominated fluvial-type sedimentation. Instead, the assemblage of properties is likely to represent deposition from hyperconcentrated flows. We envisage a series of very high suspension-load flows along individual flow paths, each capable of supporting clasts in suspension, able to winnow the channel bed and accumulating by rapid particle-by-particle aggradation to produce poorly developed normal grading.

We should note that several attempts have been made to establish criteria for the recognition of hyperconcentrated flow deposits (Pierson & Scott 1985; Smith 1986; MacFadyen 1989; Benvenuti & Martini 2002). These have come to contradictory conclusions. In part, this may be because few researchers have observed the processes of hyperconcentrated flow directly, and inferences about flow conditions have largely been made indirectly after the event. In other cases, inferences have been drawn even less directly from the geological record. Additionally, it is likely that the complexities of the products of hyperconcentrated flows are still not fully understood.
Although hyperconcentrated flows have been widely reported as occurring under terrestrial conditions, they have occasionally also been recognised in submarine settings (Sohn et al. 2002). In the context of the Waindalithi Conglomerate, clues to the nature of the depositional environment may come from the presence of reworked organic materials within the sediments. Wood fragments are found in the north and towards the base of the unit. By contrast, with the exception of some rare examples of marine shells at the base of the sequence, marine fossils are largely absent through the entire thickness of the unit. They appear only towards the top of the succession where angular cobbles of limestone and rare marine shells may be found. Neither the limestone nor the shells can have been transported far, and it appears that terrestrial sedimentation may have been succeeded by near-shore deposition as relative sea-levels rose and as the depositional environment changed into one in which the succeeding Nathua Sandstone was able to accumulate.

Provenance and flow direction

The gravel assemblages of WC1a, WC1b, WC2 and WC3a (Figure 5) are dominated by rocks from the north of the region: the Mba Volcanic Group and the Lawalevu Sandstone. The flows that laid down the Waindalithi Conglomerate are therefore likely to have been from the north. The other major component of the gravels, rocks of the Wainimala Group, crops out more widely across the region, but plenty of exposures may be found to the north of the sample sites. The remaining lithologies (sandstones, andesites and diorites) generally occur only rarely in the samples, but outcrops of all these rock types may be found to the north of the sites, and their presence offers no grounds for challenging our conclusions about the provenance of the unit.

WC1b, the sole sample in which limestone is recorded (Supplementary Papers Table 2), comes from a few metres above the base of the sequence, at which point the Waindalithi Conglomerate almost certainly overlies limestones of the Wainimala Group. Limestone clasts were also observed less than a metre above the base of the unit at Site NC1. Apart from a single rounded pebble observed (but not recorded as part of the sample) at Site WC3a, there is no evidence of Wainimala Group limestone in any stratigraphically higher sample. The lowest deposits of the Waindalithi Conglomerate are thus likely to have buried the Wainimala Group limestones, quarantining them from further erosion.

The fabrics of the Waindalithi Conglomerate gravels are dominated by \(\alpha\)-axis dips and north–south or northwest–southeast alignments (Figure 7). Gravels carried in suspension in fluids characteristically possess \(\alpha\)-axis fabrics parallel to the direction of flow, usually (but not always) with an upstream inclination (Johansson 1965; Rees 1968; Allen 1982). Aligned (bimodal) data may be characterised by the first eigenvector of the \(\alpha\)-axes at each site (Table 4). The resultant directions may be constrained by the clast lithological data, which are strongly indicative of flow from the north. The fabrics may thus be interpreted as representative of local flow directions that lie in the quadrant between east-southeast and south-southwest (Table 4).

The Wainibuka gap provides the only topographic link between the deposits of the Waindalithi Conglomerate and their source rocks. The gap must therefore have existed from at least Early Pliocene times, and the Wainibuka River is likely to have followed that path for at least the last four million years. The Waindalithi Conglomerate forms a fan-like sediment body at the southern end of the gap, but there is no obvious geomorphological reason why deposition should have taken place here and not elsewhere along the length of the river. Along Navatudua Creek and the Waimaro River; however, the basal deposits of the Waindalithi Conglomerate to the north interfinger with the marine Nathua Sandstone to the south. It would appear that, early in the deposition of the Waindalithi Conglomerate, the area formed a narrow coastal belt, fringing the ridge-and-vale topography of the Wainibuka and Matailobau hills, and bordered by rising seas to the south. Deposition is thus likely to have taken place in a coastal and near-shore setting where the Wainibuka River reached the sea.

CONCLUSIONS

1. The Waindalithi Conglomerate is of Early Pliocene age, with deposition occurring in the period 5.2–4.1 Ma.
2. The sedimentology of the Waindalithi Conglomerate is quite unlike that expected either in debris flow deposits or in sediments entrained by conventional fluvial processes. Instead, the unit is likely to represent deposition from hyperconcentrated flows. Deposits of this sort have probably been under-identified in the rock record. In part, this may be because hyperconcentrated flows are poorly understood and poorly reported in the literature. Of equal importance is that, with the possible exception of particle-size distribution, there is no single sedimentological characteristic that is diagnostic of hyperconcentrated flow deposition. A combination of gravel lithology, sedimentary fabric, particle-size distribution and the sedimentology of individual beds proved valuable for the recognition of these deposits in this work.
3. Evidence of gravel lithology and sedimentary fabric indicates that the flows that laid down the Waindalithi Conglomerate came from the north. The conglomerate forms a fan-like sediment body at the southern end of the Wainibuka gap, a feature that must have existed since at least Early Pliocene times. Deposition appears to have occurred on a narrow coastal belt, fringing the ridge-and-vale topography of the Wainibuka and Matailobau hills, and bordered by rising seas to the south.
4. The deposition of the Waindalithi Conglomerate appears to have been immediately predated in the

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**Table 4** Alignment of the first eigenvector of the \(\alpha\)-axes of the gravel fabric at Sites WC2a, WC2b, WC3a, WC3b, NC1 and WC10, Waindalithi Conglomerate, Viti Levu, Fiji, calculated using the algorithm of Allmendinger et al. (2013).

| Gravel fabric site | Alignment of first eigenvector (°) |
|-------------------|----------------------------------|
| WC2a              | 168–348                          |
| WC2b              | 017–197                          |
| WC3a              | 160–340                          |
| WC3b              | 013–193                          |
| NC1               | 125–305                          |
| WC10              | 109–289                          |
northern part of the region by the formation by a series of volcanoes. Several eruptive centres may be recognised, including the 25 km-diameter Raikiraki Volcano and the newly identified Nadelanadro, Namarai, Tova and Naimasi volcanoes. Fan-like masses of volcanic conglomerate drape the southern flanks of the volcanoes. Southerly drainage down these fans was diverted east along the gutter developed where the fans abutted the ridge-and-valle topography of the Wainibuka and Mataiambau hills and south across the lowest topographic outlet of the Wainibuka hills onto the coastal lowlands of the Early Pliocene sea.

5. While the basal components of the Waindalithi Conglomerate may have been laid down under terrestrial conditions, it is likely that the upper elements were deposited in shallow marine conditions, with the environment of deposition changing over time as local sea-levels rose.

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SUPPLEMENTARY PAPERS

| Table 1 | Waindalithi Conglomerate Site WC1a: percentage by number of lithological types as a function of particle size. |
| Table 2 | Waindalithi Conglomerate Site WC1b: percentage by number of lithological types as a function of particle size. |
| Table 3 | Waindalithi Conglomerate Site WC2: percentage by number of lithological types as a function of particle size. |
| Table 4 | Waindalithi Conglomerate Site WC3a: percentage by number of lithological types as a function of particle size. |

Supplementary papers are available with the online version of the article, at http://dx.doi.org/10.1080/08120099.2015.1127857

REFERENCES

Allen J. R. L. 1982. Sedimentary Structures Their Character and Physical Basis Volume 1. Elsevier, Amsterdam, 593 pp.
Allmendinger R. W., Cardozo N. & Fisher D. M. 2013. Structural Geology Algorithms: Vectors and Tensors, Cambridge University Press, Cambridge, 289 pp.
Bagnozzi R. A. 1954. Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. Proceedings of the Royal Society of London Series A. Mathematical and Physical Sciences 225, 49–63.
Bencini M. & Martini I. P. 2002. Analysis of terrestrial hyperconcentrated flows and their deposits. In: Martini I. P., Baker V. R. & Garzon G. eds. Flood and Megaflood Processes and Deposits: Recent and Ancient Examples, pp. 167–193. International Association of Sedimentologists Special Publication 32. Blackwell Science, Oxford.
Beverage J. P. & Culbertson J. K. 1964. Hyperconcentrations of suspended sediment. Proceedings of the American Society of Civil Engineers Journal of the Hydraulics Division 90, 117–128.
In: Prell W. L., Wang P., Blum P., Rea D. K. & Clemens S. C. eds. Proceedings of the Ocean Drilling Program, Scientific Results 184, 43 pp.
Ocean Drilling Program, Houston. doi:10.2973/odp.proc.ir.184.2000

OLLIER C. D. & TAREY J. P. 1999. Volcanic geomorphology of northern Viti Levu, Fiji. Australian Journal of Earth Sciences 46, 515–522.

PIERSON T. C. 1981. Dominant particle support mechanisms in debris flows at Mt Thomas, New Zealand, and implications for flow mobility. Sedimentology 28, 49–60.

PIERSON T. C. & SCOTT K. M. 1985. Downstream dilution of a lahar: transition from debris flow to hyperconcentrated streamflow. Water Resources Research 21, 1511–1529.

PIESK A. I. 1968. The production of preferred orientation in a concentrated dispersion of elongated and flattened grains. The Journal of Geology 76, 457–465.

RODDA P. 1976. Geology of northern and central Viti Levu (an explanation of Viti Levu Sheets 2, 6 and 12). Mineral Resources Division Bulletin 3, 160 pp.

RODDA P. 1977. Lexicon of Fiji Stratigraphy. Mineral Resources Division, Suva, 87 pp.

RODDA P. 1982a. Sedimentation in southeastern Viti Levu from the Late Miocene onwards. Fiji Mineral Resources Department Note BP1/39, 16 pp.

RODDA P. 1982b. Fiji radiometric dates recalculated. Fiji Mineral Resources Department Note BP1/35, 9 pp.

RODDA P. 1984. Stratigraphic names in Fiji – revision of spelling. New Zealand Journal of Geology and Geophysics 27, 97–98.

RODDA P. in press. Lexicon of Stratigraphy of Fiji, Mineral Resources Department, Suva, 2nd ed., 260 pp.

RODDA P. & BAND R. B. 1967. Geology of Viti Levu. New Zealand Journal of Geology and Geophysics 10, 1179–1180.

RODDA P. & KROENKE L. W. 1984. Fiji: a fragmented arc. In: Kroenke L. W. ed. Geomorphic Tectonic Development of the Southwest Pacific, pp. 87–109. United Nations Economic and Social Commission for Asia and the Pacific Committee for Co-ordination of Joint Prospecting for Mineral Resources in South Pacific Offshore Areas (CCOP/SOPAC) Technical Bulletin 6. Mineral Resources Department, Suva.

RODING J. D. & JOHNSON A. M. 1976. The ability of debris, heavily freighted with coarse clastic materials, to flow on gentle slopes. Sedimentology 23, 213–234.

RUBINOW S. I. & KELLER J. B. 1961. The transverse force on a spinning sphere moving in a viscous fluid. Journal of Fluid Mechanics 11, 447–459.

RUST B. R. 1972. Pebble orientation in fluvial sediments. Journal of Sedimentary Petrology 42, 384–388.

APPENDIX

Appendix Table Original spelling of geological features referred to in the text alongside the revised spelling based on the traditional Fijian system of orthography. Most of the revised names are from Rodda (in press).

| Original spelling                  | Revised spelling                  |
|-----------------------------------|-----------------------------------|
| Korovou Sandstone                 | Korovou Sandstone                 |
| Lawalevu Sandstone                | Lawalevu Sandstone                |
| Mba Volcanic Group                | Ba Volcanic Group                 |
| Mendrausuthu Group                | Medrausucu Group                  |
| Naimasi Andesite (informal)       | Naimasi Andesite (informal)       |
| Nakorotubu Basalt                 | Nakorotubu Basalt                 |
| Namosi Andesite                   | Namosi Andesite                   |
| Nasili Metavolcanics              | Nasili Metavolcanics              |
| Nathua Sandstone                  | Nacua Sandstone                   |
| Navuuthu Fault                    | Navucu Fault                      |
| Rokavukavu Basalt                 | Rokavukavu Basalt                 |
| Tova Andesite                     | Tova Andesite                     |
| Vatukoro Greywacke                | Vatukoro Greywacke                |
| Verata Sedimentary Group          | Verata Sedimentary Group          |
| Waindalithi Conglomerate          | Waidalici Conglomerate            |
| Wainimala Sandstone               | Wainimala Group                   |
| Wainimbuka Trachyte               | Wainimbuka Trachyte               |

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SAPMAN P. G. 1965. The lift on a small sphere in a slow shear flow. Journal of Fluid Mechanics 22, 385–400.

SCOTT K. M., VALLANCE J. W. & PENGLE P. T. 1995. Sedimentology, behavior, and hazards of debris flows at Mount Rainier, Washington. U.S. Geological Survey Professional Paper 1547, 56 pp.

SMITH G. A. 1986. Coarse-grained nonmarine volcanioclastic sediment: terminology and depositional process. Geological Society of America Bulletin 97, 1–10.

SNELLING N. J. & CHAN K. P. 1971. K-Ar determinations on samples from Fiji. Institute of Geological Sciences Geochemical Division Isotope Geology Unit Report 71.10. British Geological Survey, Keyworth.

SONG Y. K., CHOE M. Y. & JO H. R. 2002. Transition from debris flow to hyperconcentrated flow in a submarine channel (the Cretaceous Cerro Toro Formation, southern Chile). Terra Nova 14, 405–415.

STRAHLER A. N. 1952. Hypsometric (area-altitude) analysis of erosional topography. Bulletin of the Geological Society of America 63, 1117–1141.

STRAHLER A. N. 1957. Quantitative analysis of watershed geomorphology. Transactions, American Geophysical Union 38, 913–920.

STRATFORD J. M. C. & RODDA P. 2000. Late Miocene to Pliocene palaeogeography of Viti Levu, Fiji Islands. Palaeogeography, Palaeoclimatology, Palaeoecology 162, 137–153.

VALLANCE J. W. 1999. Postglacial lahars and potential hazards in the White Salmon River system on the southwest flank of Mount Adams, Washington. U.S. Geological Survey Bulletin 2161, 49 pp.

VARNE D. J. 1978. Slope movement types and processes. In: Schuster R. L. & Krizek R. J. eds. Landslides, Analysis and Control, pp. 11–33. Transportation Research Board Special Report 176. National Academy of Sciences, Washington, D.C.

WALDSON H. J. 1967. Debris flow and erosion control problems caused by the ash eruptions of Izan Volcano, Costa Rica. U.S. Geological Survey Bulletin 1241–I, 37 pp.

WENTWORTH C. K. 1922. A scale of grade and class terms for clastic sediments. The Journal of Geology 30, 377–392.

WEHLS P. M., GILL J. B., KOLLMAN E., DUNCAN R. A. & DRAKE R. E. 1985. Radiometric dating of magmatic stages in Fiji. In: Scholl D. W. & Vallier T. L. eds. Geology and Offshore Resources of Pacific Island Arcs – Tonga Region, pp. 415–440. Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series 2. AAPG, Houston.