Data supplement to

Associations between volcanic eruptions from Okataina volcanic center and surface rupture of nearby active faults, Taupo rift, New Zealand: Insights into the nature of volcano-tectonic interactions

Villamor, P., Berryman, K.R., Nairn, I.A., Wilson, K., Litchfield, N., Ries, W.,
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Here we present two examples of detailed restorations of the deformation of recent volcanic deposits displaced by faults in the Taupo rift. This is the type of analysis that has been undertaken to assess time associations between fault rupture and volcanic eruptions around Okataina volcanic center. We first describe restoration of deformation found in the southwest wall of a paleoseismic trench across the Manawahe fault. The second example is the restoration of deformation associated with the Opawhero fault, exposed in a road cut.

A. Restoration of deformation in McDowell trench, Manawahe fault.

The Manawahe fault

The Manawahe fault (Figs. 2 in main text and A1) is the western boundary fault of the Whakatane fault domain north of Okataina volcanic center. It consists of several ENE-trending, mostly SSE-dipping, normal fault traces, forming a right-stepping, en-echelon pattern. The Manawahe fault zone merges with the North Rotoma fault at its eastern end, and they together extend to the Matata fault zone to the north (Fig. 1). To the south the fault terminates close to Lake Rotoma at the northern end of the Haroharo volcanic vent zone.

The fault displaces the geomorphic surface created by the ~ 64 ka old Rotoiti Ignimbrite (Nairn, 2002) and the Holocene valleys incised into that surface (Fig. A2). The McDowell trench was excavated across one of the Manawahe fault traces (Fig. A1, A2 and 4 in main text), at a fault scarp on a Holocene valley floor. The trench was up to 12 m wide, 38 m long and 7 m deep, with walls battered for safety reasons.

The stratigraphy in the trench consists primarily of tephras and their capping paleosols. In some cases reworked tephra (labeled as alluvium in Figs. 4 in main text and A3) has accumulated between fall units and their associated paleosols. The tephras identified in the trench and in auger holes at the bottom of the trench come from the following eruptions, from top to bottom: 1886 Tarawera, Kaharoa, Whakatane, Mamaku, Rotoma, Waiohau and Rotorua (see Table 1 in main text for ages). Primary and derived deposits associated with an eruptive episode are labeled with the same number but different letters (Fig. A3). Most of the primary deposits consist of lapilli and coarse ash with minor fine ash horizons. Parallel fall bedding is common. The alluvium derived from those deposits has similar grain size and are planar to cross-bedded. The basal part of Rotoma Formation, and older tephras were not exposed in the hanging wall end of the trench wall, or in the auger holes excavated from the lowest level of the trench. A GPR line across the fault trace has identified the base of Rotoma Formation at about 6 m below the trench floor.

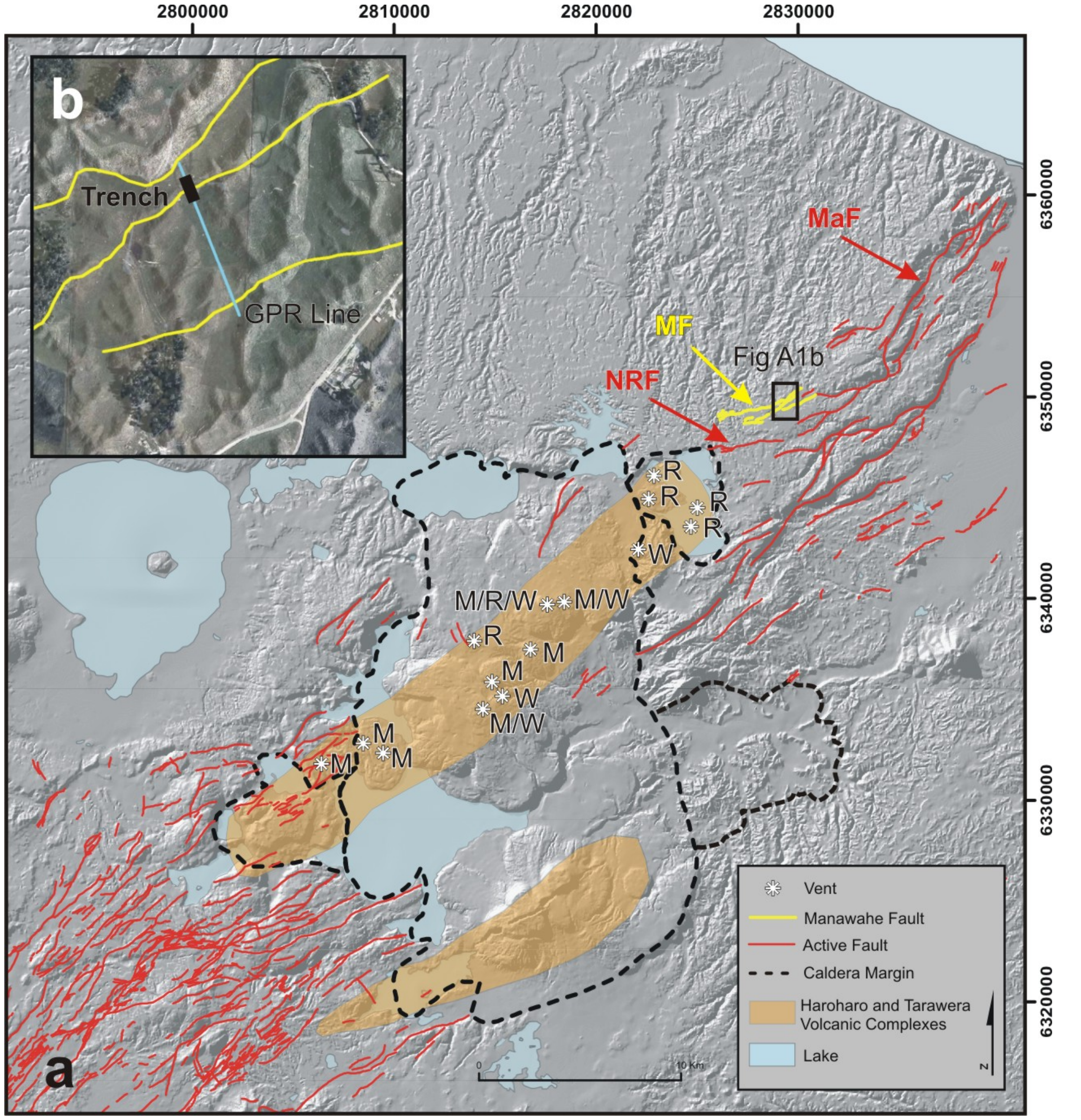


Figure A1. A. Location of the Manawahe fault with respect to other Taupo rift faults and to the Haroharo and Tarawera volcanic complexes. B. Aerial photograph of the section of the fault where the McDowell trench and a GPR survey were located.

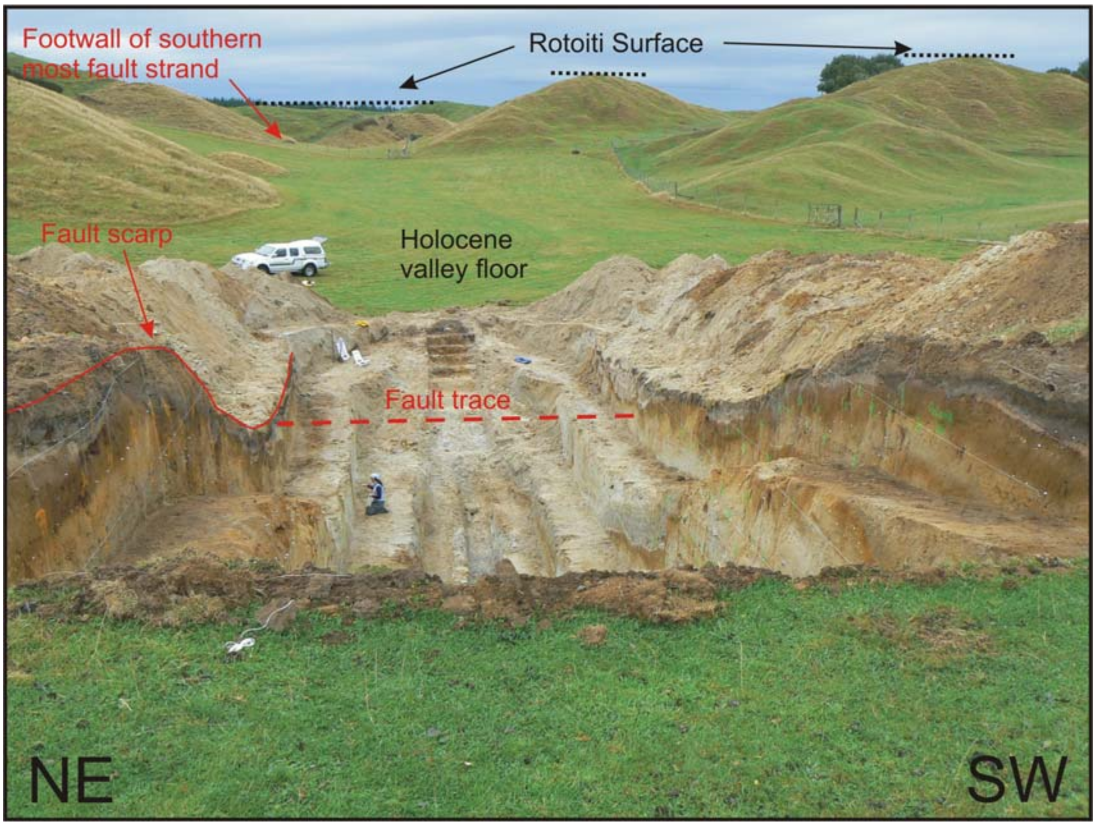


Figure A2. Photograph of the McDowell trench and geomorphic surfaces displaced by the Manawahe fault.

Deformation features in the trench include faulting, drag folding (including meter scale rotations) and minor fissuring. Faulting occurs at three main fault planes, that we label F1, F2 and F3 (Fig. A3). The three fault planes merge with depth. Displacement on F2 and F3 show normal sense of separation while F1 and some upper branches of F2 have reverse separation. The reverse separation is a result of rotation of normal fault planes (in particular secondary fault branching out of the main fault plane) because of the lack of confining pressure on the hanging wall in steep fault scarps (Villamor et al., 2006) that have undergone large displacements.

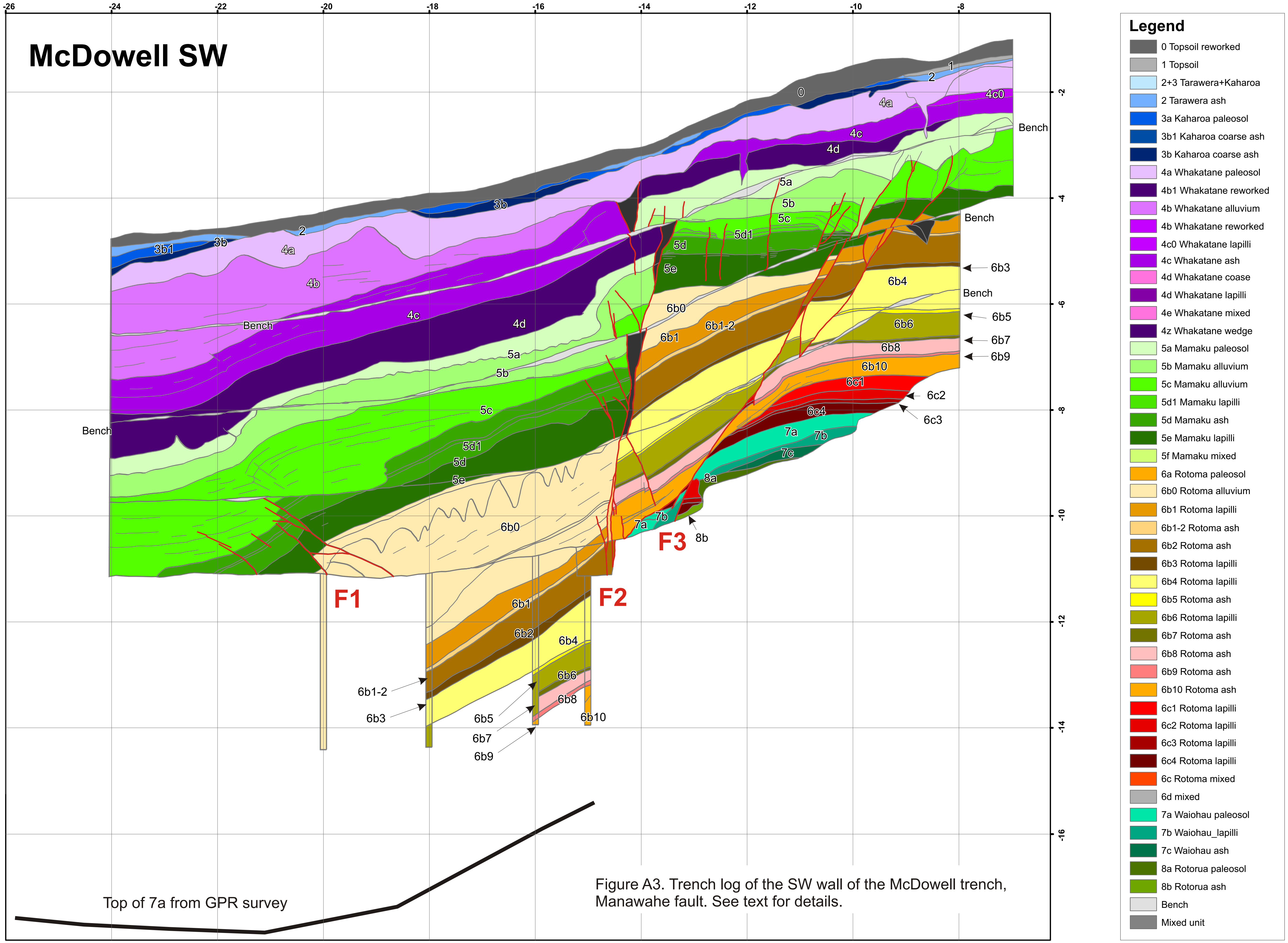


Figure A3. Trench log of the SW wall of the McDowell trench, Manawahe fault. See text for details.

Restoration of deformation

Multiple displacement events on fault planes are identified in the trenches as progressively larger displacement of older units. The progressive deformation can most clearly be evaluated by successively restoring older paleosols as past ground surfaces, and identifying which stratigraphic units that restoration brings into alignment. On some occasions, we have also restored the displacements on other layers when the paleosol was not well preserved, or when there was evidence for multiple faulting events between paleosol pairs. The progressive restoration of older units brackets the age of movement (generally between the ages of known tephras), and amounts of dip-slip displacement in successive surface fault rupture events can be estimated. In many instances, restoring one ground surface brings several lower tephra and paleosol pairs into alignment, showing that there has been no recognizable fault rupture within that interval. In many instances, displacements as small as 0.1 m can be confidently identified, although in general we expect that displacement measurements from restoration often have an uncertainty of ± 0.1 m.

Figure A4a represents the relationships found in the trench as it was logged in the field. Figures A4b to A4g present the steps needed to restore successive stratigraphic units. Sequential figures show the fault-strata configuration just prior to the rupture, that is, at the event horizon. For example, displacement in event 1 occurs as the difference between Figures A4b and A4a, and Figure A4b illustrates the stratigraphic units present at the event horizon. In the restoration we have kept the footwall fixed and move the hanging-wall to account for the successive faulting events. We have added grey polygons to features such as fissures that have closed, units that have been eroded, and spaces that have been created when restoring a layer. Spaces arise as a consequence of: matching layers that are originally exposed in different batters; ductile deformation (drag folding) of soft layers that change the original shape of a block; or (occasionally) extension fissures. When we were able to approximate the original shape we have kept the original pattern to the layer polygons (rather than coloring them in grey) and distortions are reported in the text.

We have noted that when restorations involve crossing different batters, the measurements of single event displacement could be less accurate than restorations within a single batter. An example of the geometric complexity that arises because of the batter slopes is the “step-out” of unit 5a above the bench at about meter 14 in Figure A4a.

For each restoration step, i.e., for each figure, we describe the actions performed to restore the deformation in that single event. We also record: the number of the event restored; the faults on which the deformation occurred; the amount of deformation associated with event restored; and the timing of the event.

Figure A4. Restoration of the SW wall of the the McDOwell trench across the Manawahe fault. a = current exposure. b to g = successive steps in the restoration corresponding to snapshots prior to successive events. For example, Figure A4b represents the geometry of the layers prior to event 1.

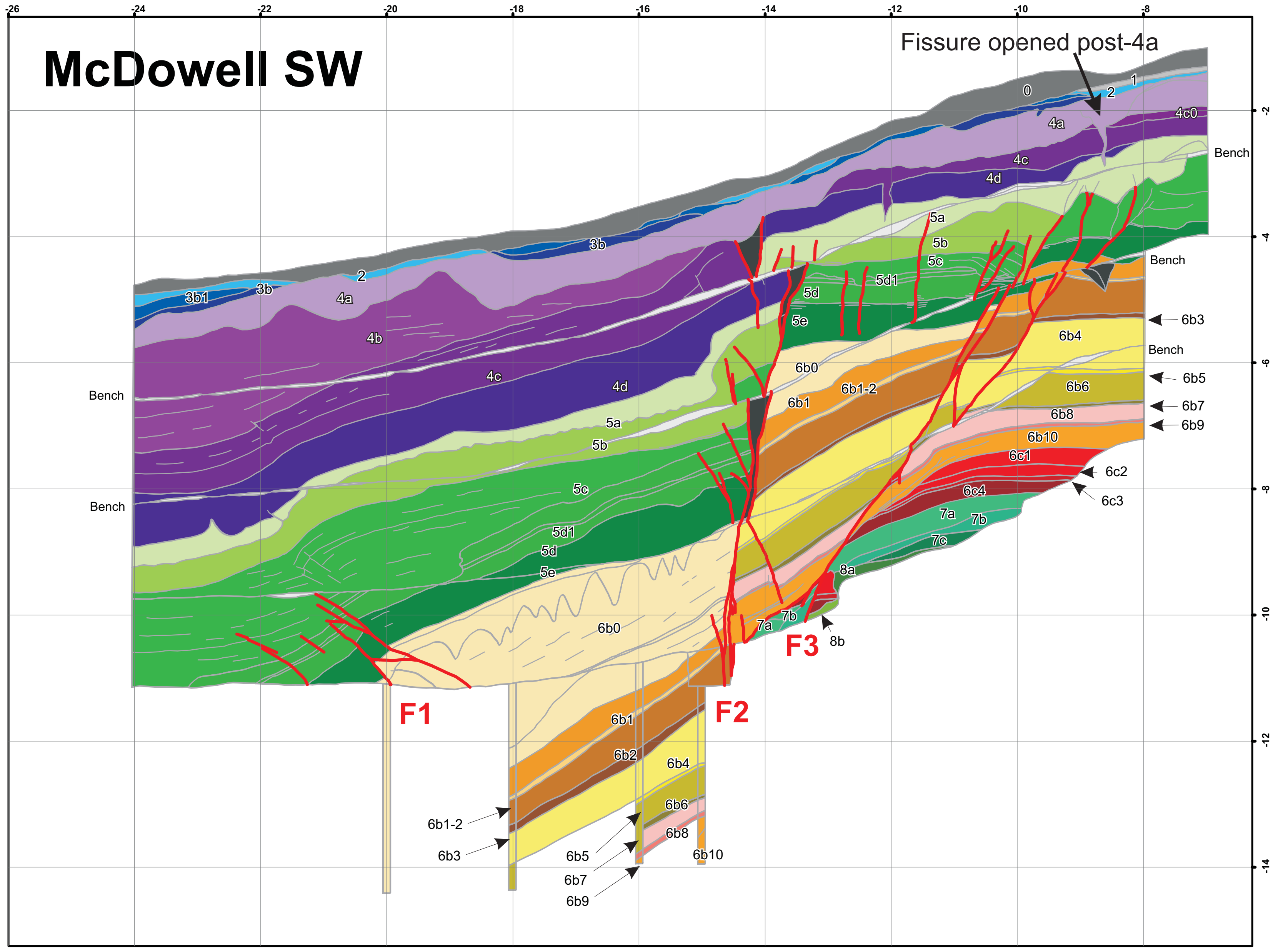
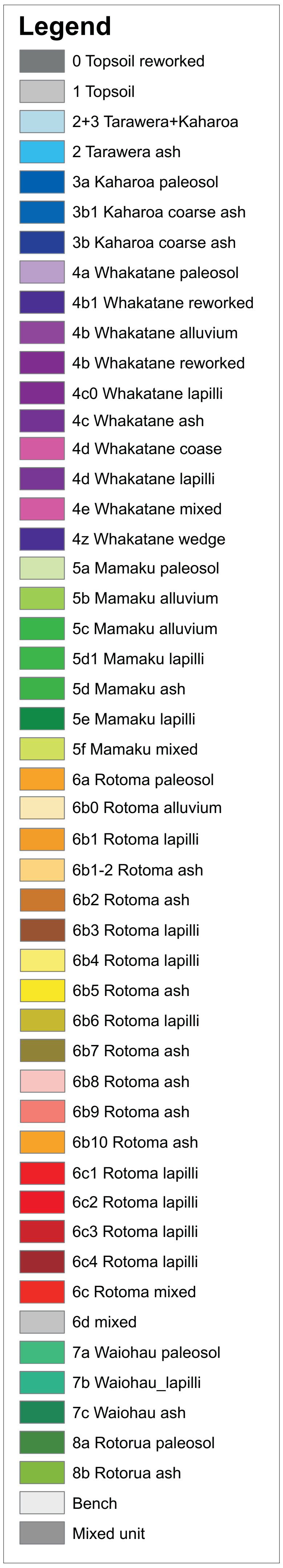


Figure A4a. Trench log of the McDowell trench across the Manawahe fault. See text for details.



1-Restore base of 4c-Whakatane ash

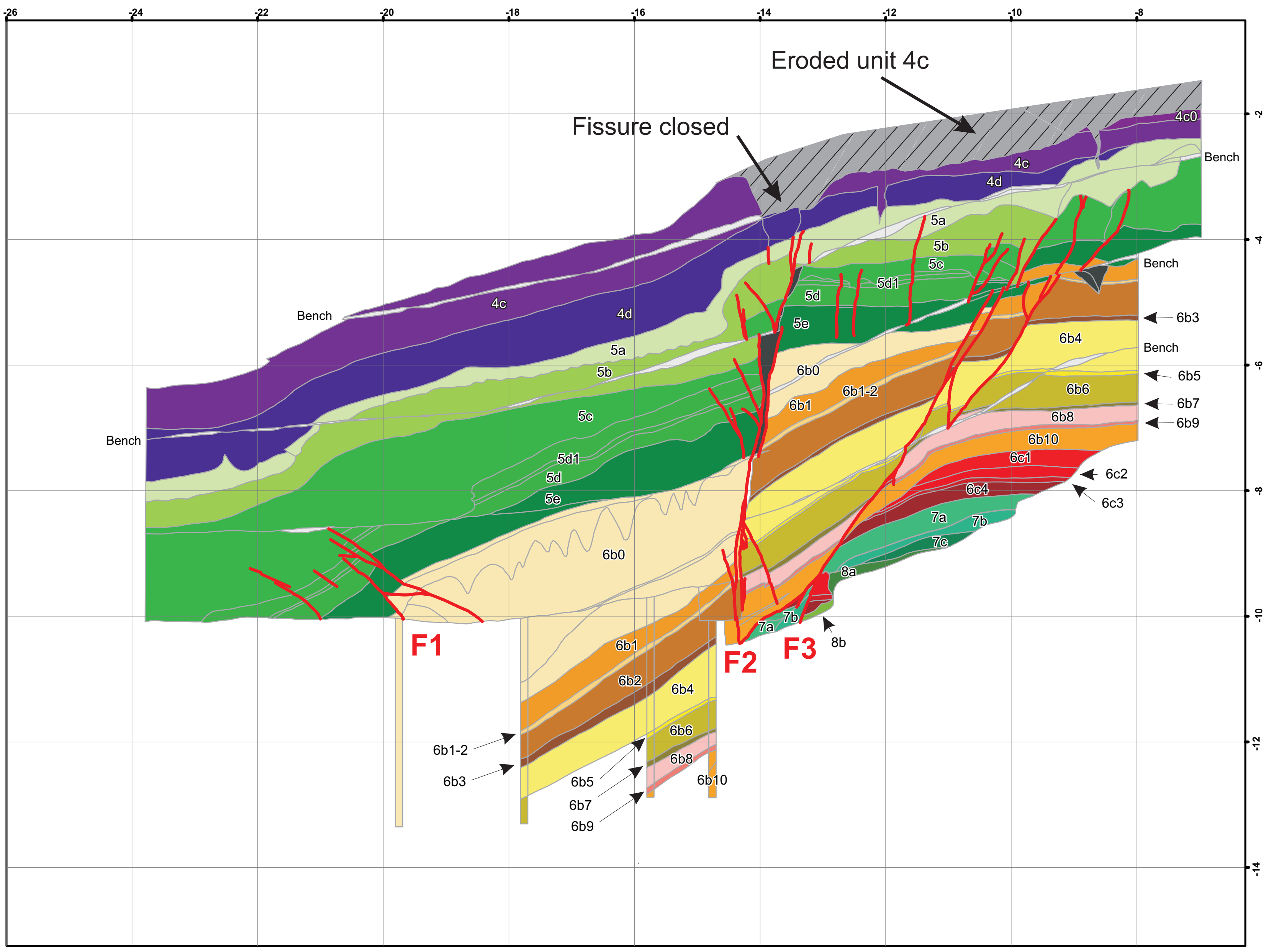


Figure A4b. Restoration 1 of the trench log of the McDowell trench across the Manawahe fault. See text for details.

McDowell SW 2-Restore base of 5a-Mamaku paleosol

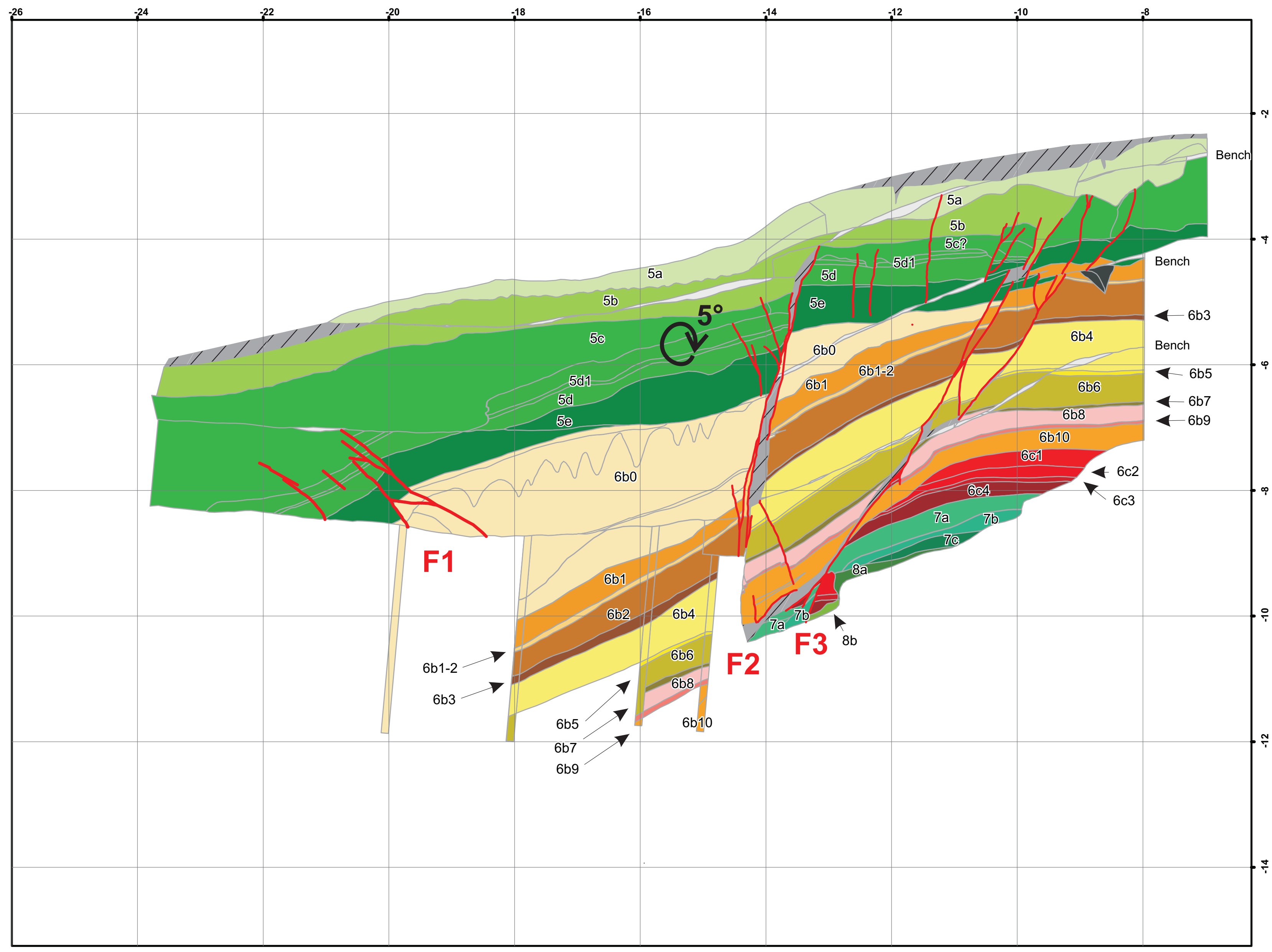
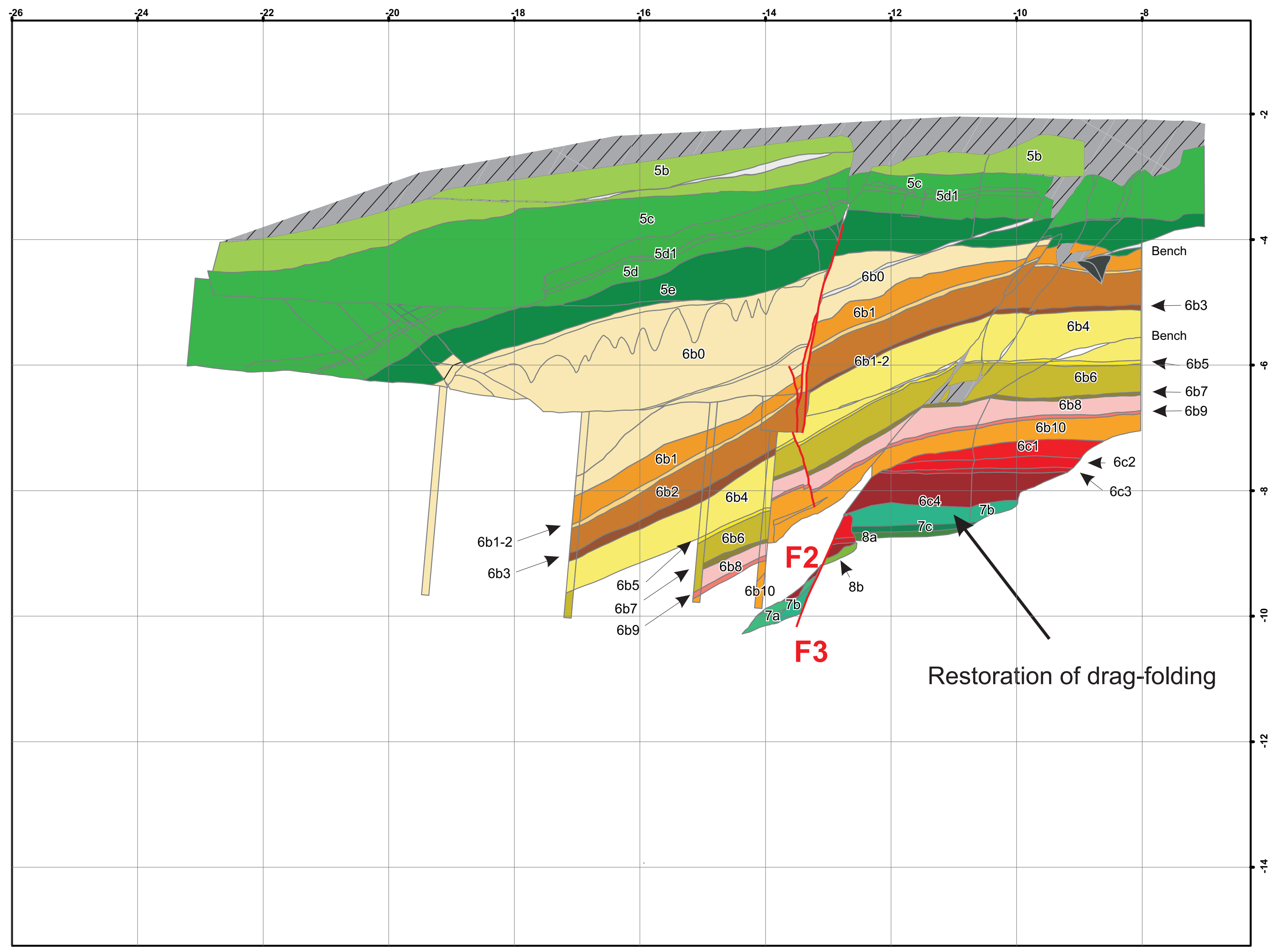


Figure A4c. Restoration 2 of the trench log of the McDowell trench across the Manawahe fault. See text for details.

McDowell SW 3-Restore 5b-Mamaku alluvium



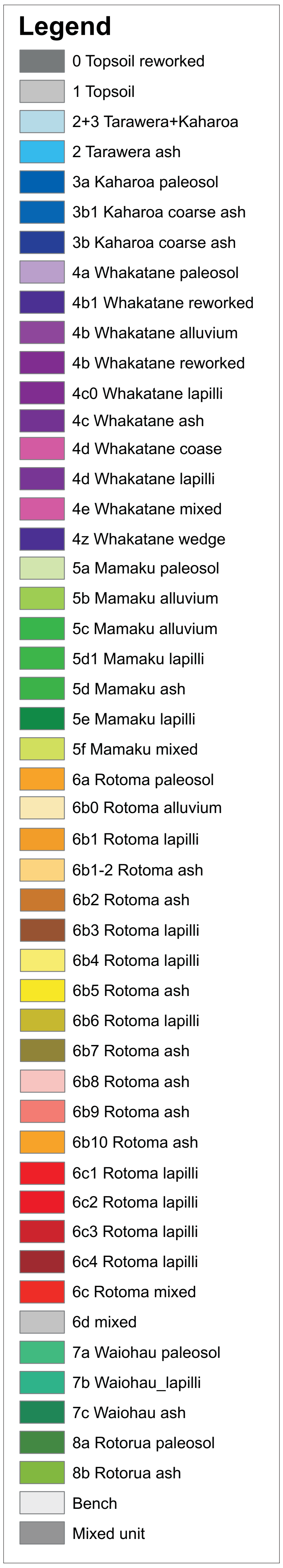


Figure A4d. Restoration 3 of the trench log of the McDowell trench across the Manawahe fault. See text for details.

McDowell SW 4-Restore 5d-Mamaku lapilli

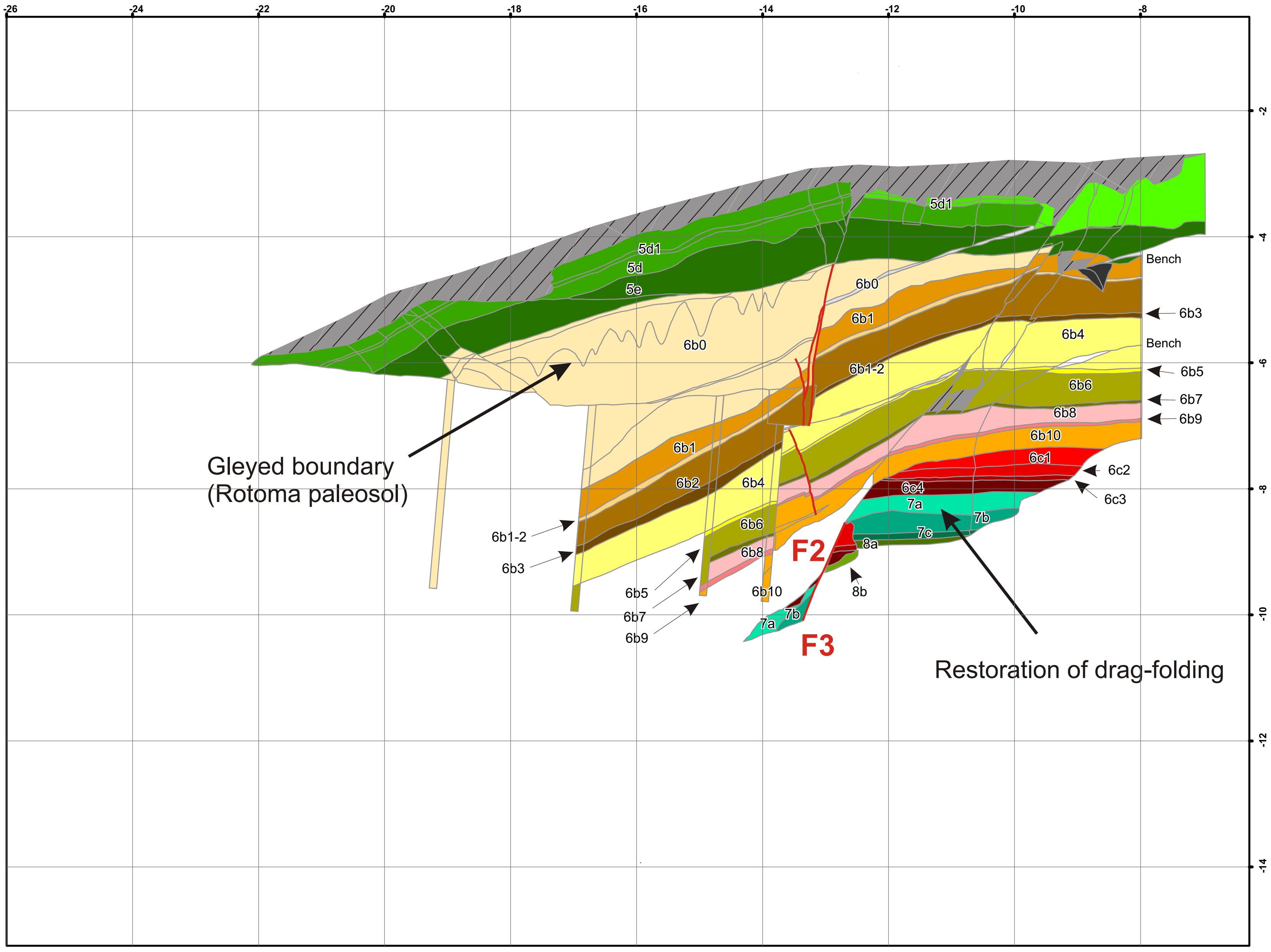
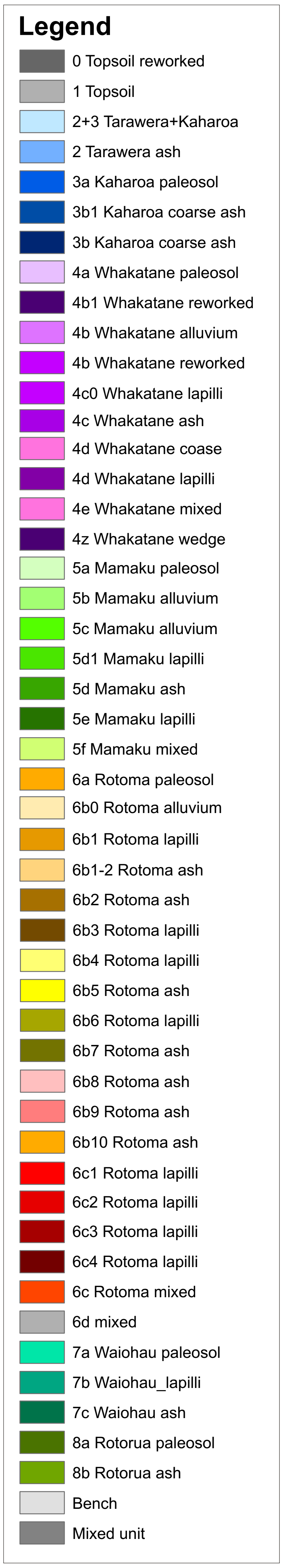


Figure A4e. Restoration 4 of the trench log of the McDowell trench across the Manawahe fault. See text for details.



McDowell SW 5-Restore base of 6b0-Rotoma alluvium

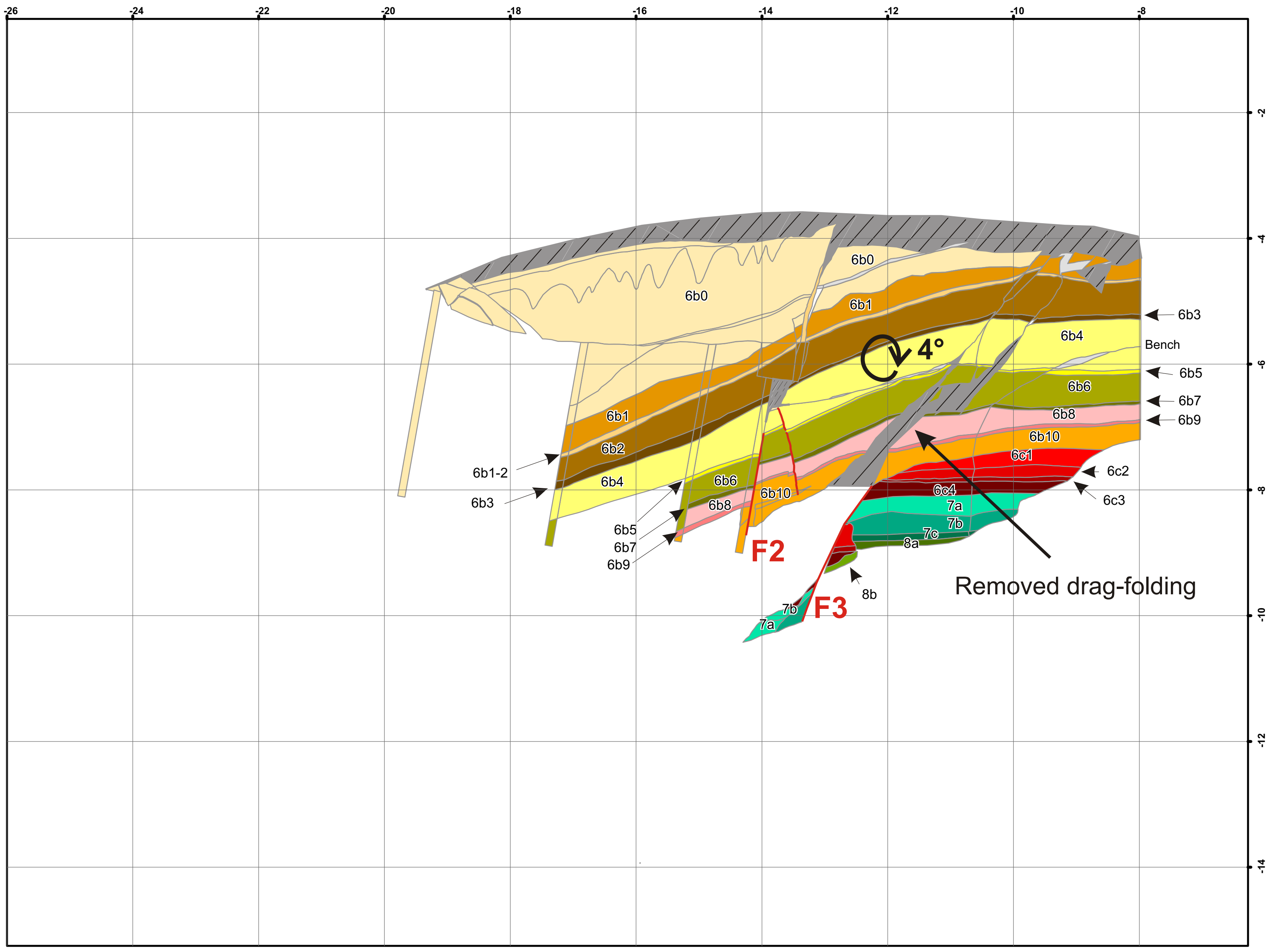


Figure A4f. Restoration 4 of the trench log of the McDowell trench across the Manawahe fault. See text for details.

McDowell SW 6-Restore base of 6b4 Rotoma lapilli

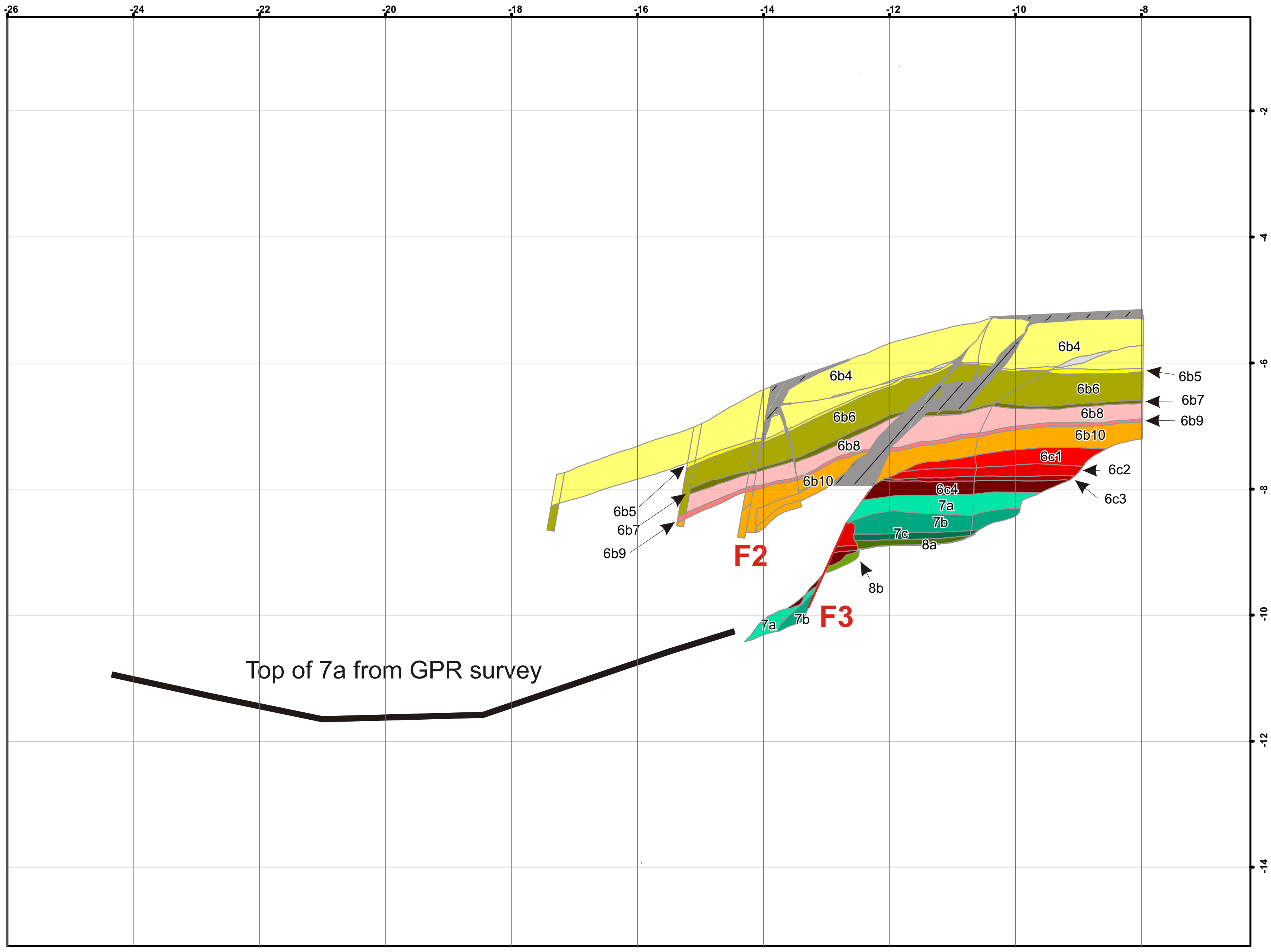
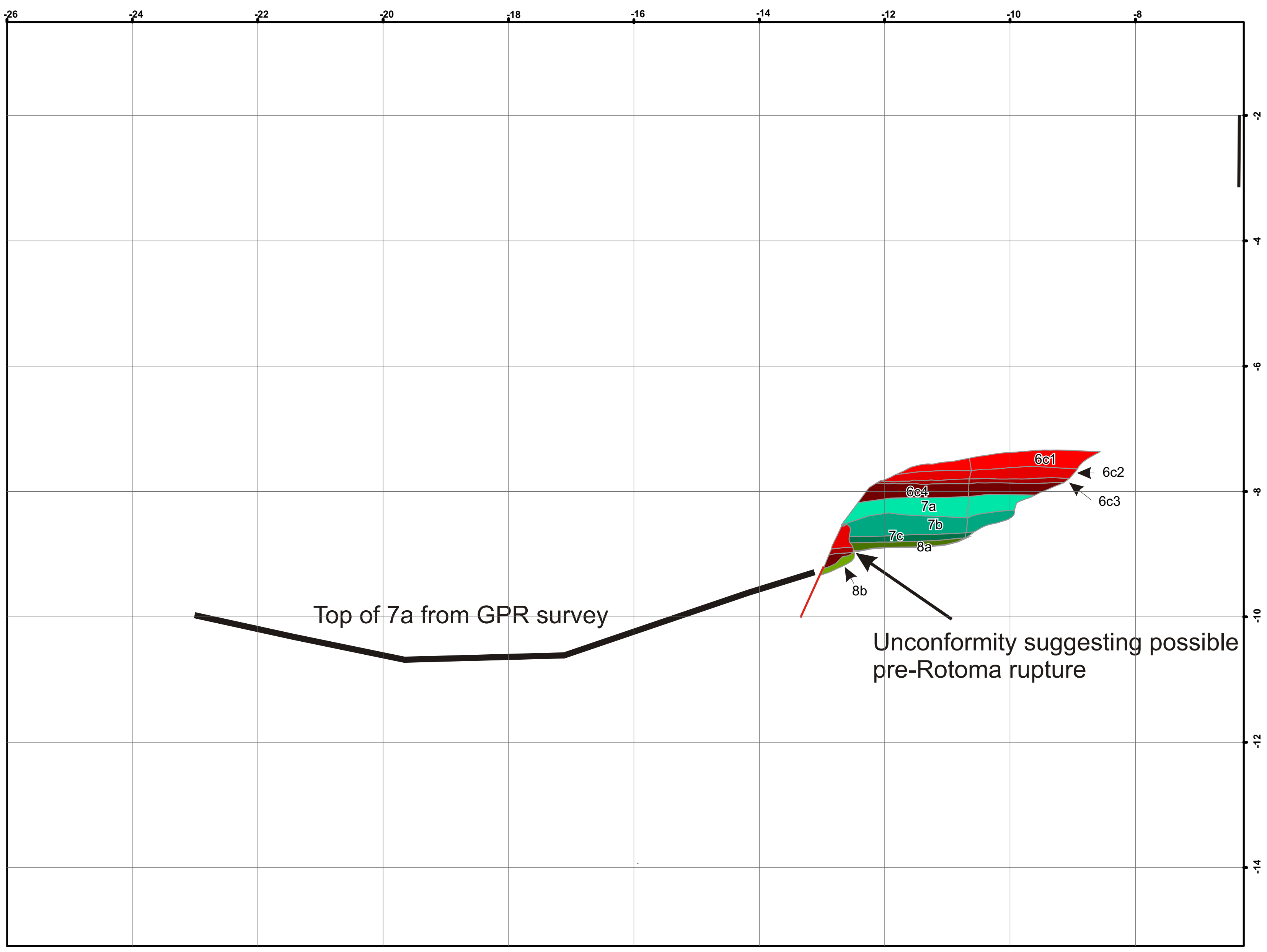


Figure A4g. Restoration 5 of the trench log of the McDowell trench across the Manawahe fault. See text for details.

McDowell SW 7-Restore base of 6c4-Rotoma Lapilli



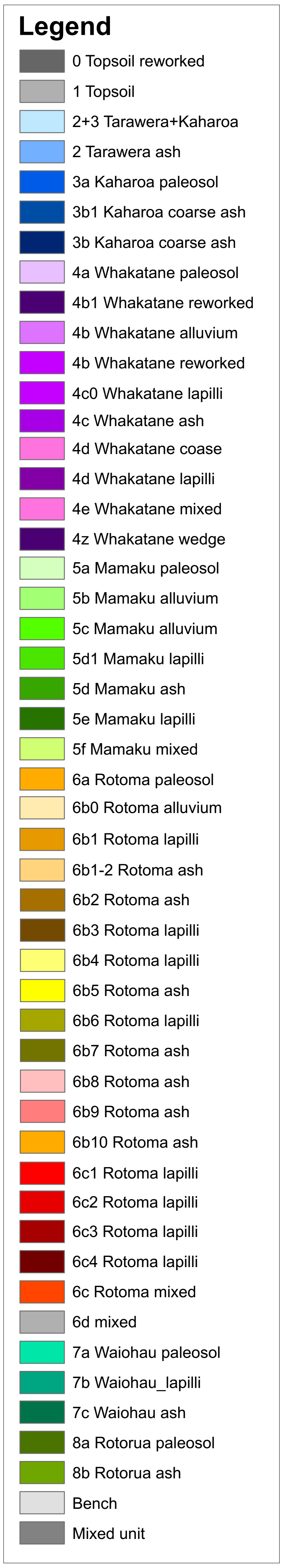


Figure A4h. Restoration 6 of the trench log of the McDowell trench across the Manawahe fault. See text for details.

A) Current exposure (Fig. A4a)

Figure A4a shows the trench log as it was mapped in the field. Fissuring (at vertical line 9 m) occurred after unit 4a (Whakatane paleosol) had formed and before the Kaharoa and Tarawera units were deposited (they are not involved in the fissuring). Unit 4a (Whakatane paleosol) is not displaced across the fault (Fig. A4a). Therefore, fissuring could have been related to ground shaking related to a nearby fault or volcanic eruption, during the formation of unit 4a, but was not related to primary rupture of this fault.

B) Restoring base of unit 4c - Whakatane ash (Fig. A4b)

The youngest layer that is displaced is 4c (Whakatane ash) (Fig. A4a), so we restore this layer to establish how much displacement occurred in this most-recent event. Ideally, we would restore to top of the layer but in this case the top has been eroded from the footwall so we have restored the base. Restoration comprised removal of displacement across F2 and closing fissures. It does not fully restore the base of unit 5a (Mamaku paleosol). The base of Unit 5a remains offset across F3 and F1 and intensely folded at F1 and F2. Unit 4c (Whakatane ash) and unit 4b (Whakatane alluvium) have been completely eroded from the footwall at the fault plane and, thus we can not assess if faulting occurred during the Whakatane eruption.

Event 1 is represented by the difference between Figures A4b and A4a. Figure A4b represents the geometry of the layers before they were deformed by event 1, and the top of unit 4c is the event horizon.
Restoration is across: different batters.
Fault planes active: F2.
SED (single event dip-slip displacement): 1.1 m.
Timing of event: Pre unit 4a (Whakatane paleosol) (pre Kahaora) and post unit 4c (Whakatane ash), 0.7 ka < Event 1 < 5.6 ka.

C) Restoring base of unit 5a (Mamaku paleosol) (Fig. A4c)

The youngest layer that remains displaced after the first restoration is the base of unit 5a (Mamaku paleosol) (Fig. A4b). Restoration of the base of unit 5a does not fully restore base of unit 5b (Mamaku alluvium).

The amount of displacement required to unfold deformation at F2 is uncertain and thus the displacement we assigned to this event is a minimum. We have interpreted that unfolding at F2 in this event can not fully restore the base of unit 5b (Mamaku alluvium) because: (1) unit 5b appears to be faulted against unit 5c (Mamaku alluvium) at F3 after restoration 2; (2) there is intensive faulting and fracturing (between F2 and F1) through unit 5c (Mamaku alluvium) and unit 5b (Mamaku alluvium), which does not appear to extend thought the whole of unit 5b, indicating that the event horizon must be above the basal part of unit 5b. Restoration also required 5° of rotation of units in the hanging wall of F2 to avoid spatial overlap of fault blocks across the fault at the base of the exposure. Folding at F3 is constrained by deeper faulting of unit 5d (Mamaku ash) and unit 5e (Mamaku lapilli units). We have removed some folding on F1, because tilting of units 5a and 5b is less than tilting of unit 5c.

Event 2 is represented by the difference between Figures A4c and A4b. Figure A4c represents the geometry of the layers before they were deformed by event 2 (i.e., event 2 horizon). Figure A4b represents the geometry of the layers, after event 2 occurred and subsequent deposition of Whakatane Formation.

Restoration is across: same batter at F3, and different batters at F1 and F2
Fault planes active: F1, F2 & F3
SED: 1.35 m
Timing of event: immediately pre unit 4c (Whakatane lapilli) and post unit 5a (Mamaku paleosol). This rupture occurred immediately prior to the Whakatane eruption because the steep face of the scarp at F2 and F3 is preserved (Fig. A4b), and this could only happen if immediately after fault rupture the tephra covered and preserved the steep scarp angles from erosion, Event 2 ≥ 5.6 ka.

D) Restoring base of unit 5b (Mamaku alluvium) (Fig. A4d)
The youngest layer that remains displaced after event 2 restoration is unit 5b (Mamaku alluvium) (Fig. A4c). Restoration of unit 5b (Mamaku alluvium) requires removal of displacements across all faults, closure of fissures at F3, removal of drag folding at F2 and removal of the remainder of folding at F1. This restoration restores the base of unit 5c (Mamaku alluvium) across all faults but F2.

The base of unit 5c (Mamaku alluvium) is reasonably well aligned across the faults and, therefore, we consider this boundary restored. The base of unit 5e (Mamaku lapilli) at F2 is not restored but is reasonably well aligned across the other two faults.

At F3, all layers down to unit 6b9 (Rotoma ash) are restored. Therefore, we have also restored the drag folding of layers 8a to 6b9 on the footwall of F3 to match the layers across the faults. We have reshaped the layers to a geometry similar to the scarp profile as exhibited by layers 6b1 to 6b8.

Event 3 is represented by the difference between Figures A4d and A4c. Figure A4d represents the geometry of the layers before they were deformed by event 3, and the top of unit 5b is the event horizon. Figure A4c represents the geometry of the layers after event 3 occurred, including subsequent development of Mamaku paleosol (unit 5a).

Restoration is across: batters at F2 and F3
Fault planes active: F1 , F2 & F3.
SED: 1.75 m.
Timing of event: Post unit 5b (Mamaku alluvium) and pre unit 5a (Mamaku paleosol), 5.6 ka <Event 3< 8.1 ka.

E) Restoring base of unit 5d1 (Mamaku lapilli) (Fig. A4e)

The youngest layer that remains displaced after the event 3 restoration is the base of unit 5d1 (Mamaku lapilli) (Fig. A4d). We have removed faulting at F2. This restores units down to 5e (Mamaku lapilli).

Event 4 is represented by the difference between Figures A4e and A4d. Figure A4e represents the geometry of the layers before they were deformed by event 4, and unit 5d1 is the event horizon. Figure A4d represents the geometry of the layers after event 4 occurred, including subsequent deposition of Mamaku alluvium (units 5b and c)

This is a small event possibly associated with Mamaku eruption. It occurred after deposition of unit 5d, and before the alluvium was deposited. The lack of soil development between 5d and 5c, in areas with no erosion, implies that a short period of time elapsed between the end of deposition of 5d and beginning of 5c. The fault rupture must have happened shortly after, or during the end, of deposition of Mamaku deposits.

Restoration is across: across batters at F2.
Fault planes active: F2.
SED: 0.4 m.
Timing of event: Post unit 5d1 (Mamaku Lapilli) and pre unit 5c (Mamaku alluvium), Event 4, ~ 8.1 ka.

F) Restoring base of unit 6b0 (Rotoma alluvium) (Fig. A4f)

The youngest layer that remains displaced after the event 4 restoration is the base of unit 6b0 (Rotoma alluvium) (Fig. A4e). We removed faulting of unit 6b0 (Rotoma alluvium) across F2 and rotated the hanging wall of F3 by 4° clockwise to bring the alluvium layers to sub-horizontal. This rotation was accompanied by monoclinal deformation at F3. We favor this interpretation because units 6b0 to at least 6b8 appear un-faulted across F3 but are possibly fissured to allow for rotation. We have restored some folding in the footwall of F3. These actions restore Rotoma units down to unit 6b3 (Rotoma lapilli), but unit 6b4 (Rotoma lapilli) is displaced by a small fault that is in turn displaced by F2.

Event 5 is represented by the difference between Figures A4f and A4e. Figure A4f represents the geometry of the layers before they were deformed by event 5, and unit 6b0 is the event horizon. Figure A4e represents the geometry of the layers after event 4 occurred and the subsequent deposition of Mamaku Formation.

Restoration is across: same batters at F2.
Fault planes active: F2.
SED: 1.12 m.
Timing of event: Post unit 6b0 (Rotoma alluvium) and pre unit 5e (Mamaku lapilli), 8.1 ka <Event 5 < 9.5 ka.

G) Restoring base of unit 6b4 (Rotoma lapilli) (Fig. A4g)

The youngest layer that is still displaced after the prior restoration is the base of unit 6b4 (Rotoma lapilli) (Fig. A4f). Restoration of this layer comprises removal of displacement across F2. It is unclear whether this event is accompanied by rotation or not, and thus estimated displacement is a minimum. These actions align units down to unit 6b9 (Rotoma ash) across F2. It is possible that it also restores 6b10 (see discussion below).

Event 6 is represented by the difference between Figures A4g and A4f. Figure A4g represents the geometry of the layers before they were deformed by event 6, and unit 6b4 is the event horizon. Figure A4f represents the geometry of the layers after event 5 occurred and with subsequent deposition of Rotoma units (6b3-6b1) and Rotoma alluvium (unit 6b0).

Restoration is across: interpretation juxtaposes data from auger holes on the hanging wall and exposed layers of bottom batter on the footwall.
Fault planes active: F2.
SED: ≥ 0.23 m.
Timing of event: Intra Rotoma Formation (pre unit 6b3 and post unit 6b4), Event 6 = 9.5 ka.

H) Restoring the base of 6c4 (Rotoma Lapilli) (Fig. A4h)

The youngest layer that clearly remains displaced after the prior restoration is unit 6c4. It is possible that units 6c3 to 6c1 are also displaced but they have been eroded on the footwall and the relationship with the faulting is unclear, However, they are conformable with 6c4 and unconformable with 6b10. Therefore we approximate the event horizon as the top of unit 6c4 and possibly the top of 6c1 (Rotoma Lapilli). We restore the base of 6c4 because we lack information on the other units. The boundary between unit 6c4 (Rotoma lapilli) and unit 7a (Waiohau paleosol) is interpreted from a GPR line. Juxtaposition this boundary across the fault is achieved by removing displacement along F3.

Timing of this event is constrained by the unconformity at the base of unit 6b10 (Rotoma ash) in the footwall. The presence of the unconformity implies that units 6c1 to 6c4 (Rotoma lapillis) were eroded prior deposition of unit 6b10 (Rotoma ash). The erosion on the hanging wall of the faults is likely to be a consequence of faulting and subsequent erosion of the free face, after fault rupture.

Event 7 is represented by the difference between Figures A4h and A4g. Figure A4h shows the geometry of the layers before they were deformed by event 7. Figure A4g represents the geometry of the layers after event 7 occurred and subsequent deposition of units 6b10 to 6b4 (Rotoma ash and lapilli).

Restoration across batters: juxtaposing the interpretation from GPR data on hanging wall and exposed layers of the bottom batter on the footwall.
Fault planes active: F3.
SED: 1.15 m.
Timing of event: Intra Rotoma Formation (pre unit 6b10 and post unit 6c1), Event 7= 9.5 ka.

I) Event 8

Waiohau paleosol is still displaced. In Figure A4h the steep unconformable contact at vertical line 13 with primary fall deposits from the first stages of the Rotoma eruption (units 6c4 to 6c2) buttressed against it maybe the remnants of a free face scarp. This could be indicative of an event “just pre-Rotoma deposition”. Because we lack detail information of the hanging wall, this tentative event has not been incorporated in our compilation of fault rupture-volcanic eruption associations in the main text. We restore the top of Waiohau paleosol (exposed on the footwall and delineated with the GPR line on the hanging wall). Juxtaposition this boundary across the fault is achieved by removing displacement along F3.

Fault planes active: F3
SED: 1.52 m
Timing of event: Just pre Rotoma Formation deposition?: Event 8 ≥ 9.5 ka

Summary of the earthquake history of the Manwahe fault

Results from the restoration of the disrupted trench stratigraphy suggests that, since deposition of the Rotoma Formation at 9.5 cal ka BP., the Manawahe fault has ruptured at least 7 times with a possible 8th event just before, or during, the beginning of the Rotoma episode. Single event displacements range between 0.2 to 1.75 m. Two events (Events 4 and 5) are purely tectonic since they occurred between OVC eruptions. For Event 1, there is not enough information (because of erosion of units at the free face of the footwall) to assess whether it was related to the Whakatane eruption (Table 1). Four events (2, 3, 6 and 7) are clearly associated with deposition of tephra. Event 2 occurred immediately before deposition of the Whakatane Formation. Event 3 occurred possibly at the end of, or just after, deposition of Mamaku Formation. Events 6 and 7 occurred during deposition of Rotoma Formation. It is possible that an earlier event 8 occurred immediately prior to deposition of Rotoma Formation or during its very early stages.

B) Restoration of Opawhero fault exposure, Tarawera Road.

The Opawhero fault

The Opawhero fault is exposed in a road-cut located along Tarawera Road (SSE of Rotorua) at 2799868E 6332361N (NZMG coordinates) (Figs. B1 and B2). This 5 km long, generally ENE trending, SW dipping fault is arcuate, and parallel to one of the nested caldera rims on the western side of the Okataina volcanic centre. The fault is located 2 km outside the caldera rim.

The fault plane exposed on Tarawera Road displaces the following volcanic deposits, from old to young:

1) Te Wairoa Pyroclastics (<220 ka, probably >65 ka old) of unknown source (Nairn, 2002)
2) Pumice fall beds of the ~15.7 ka Rotorua Formation erupted from vents located about 5 km to the SE. The four vents of the Rotorua eruptive episode have a NW alignment over a distance of 1 km, between Lakes Tikitapu and Tarawera (Nairn, 1980) (Fig. B1B).
3) Younger than 15.7 ka undifferentiated pyroclastic largely sourced from different vents along the Tarawera and Haroharo volcanic centres and their paleosols (Nairn, 2002)

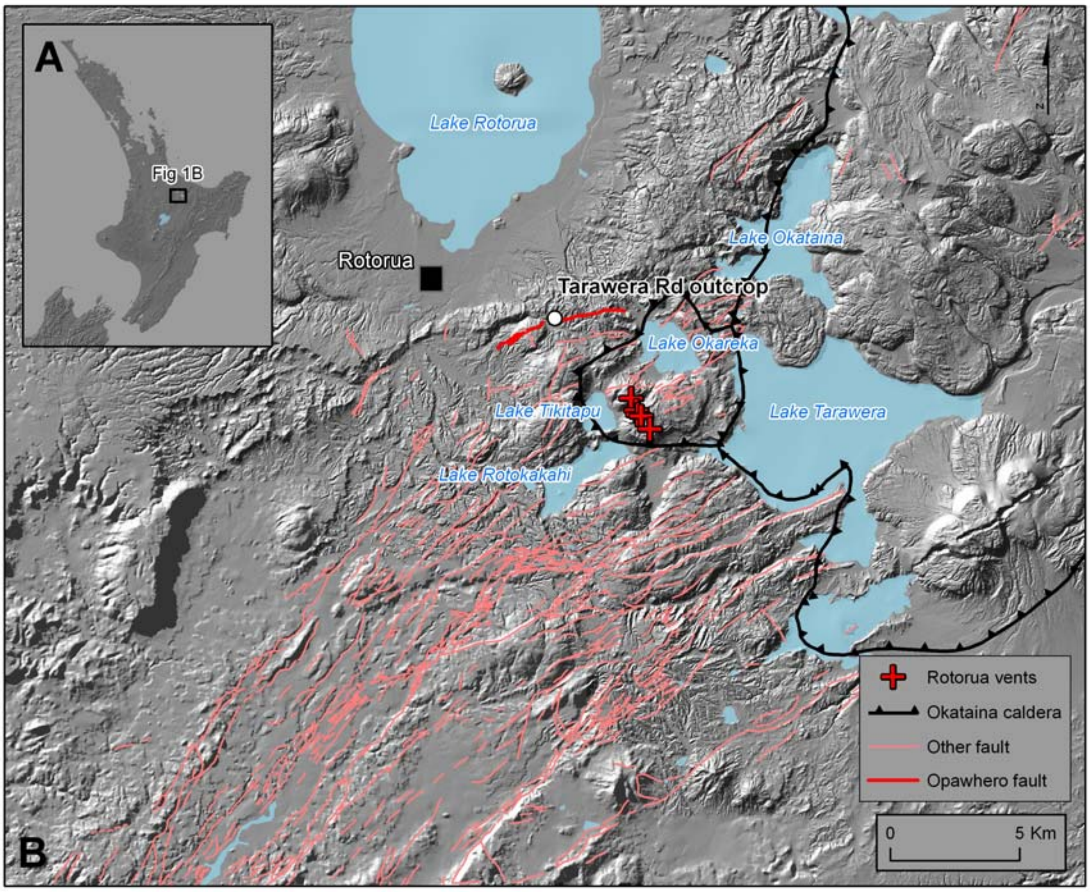


Figure B1. A) North Island of New Zealand showing the location of the study site. B) Location of the Tarawera Road outcrop, Opawhero fault and vents associated with the Rotorua eruption. The vents have a NW alignment ~ 5 km to the SE of the outcrop.

On the fault footwall exposed in the road outcrop, >10 m thick (base not exposed) weakly cross-bedded Te Wairoa Pyroclastics flow units are overlain by locally reworked deposits and loess with a distinctive bleached soil upper contact. On the footwall, this contact is overlain by a ~5 m thick sequence of early plinian coarse pumice beds of the Rotorua Formation (Fig. B2).

The uppermost part of the sequence is about 3 m thick and comprises a series of Holocene tephras. On the hanging wall, the stratigraphic sequence is similar to the footwall, except that the Te Wairoa deposits are downfaulted below the road exposure level, and the plinian Rotorua Formation deposits are >10 m thick (base not exposed) (Fig. B2). The road-cut outcrop has a slope of ~20 degrees from vertical and also follows the curve of Tarawera Road as it bends to the east. The fault plane thus crosses this outcrop at an oblique angle.

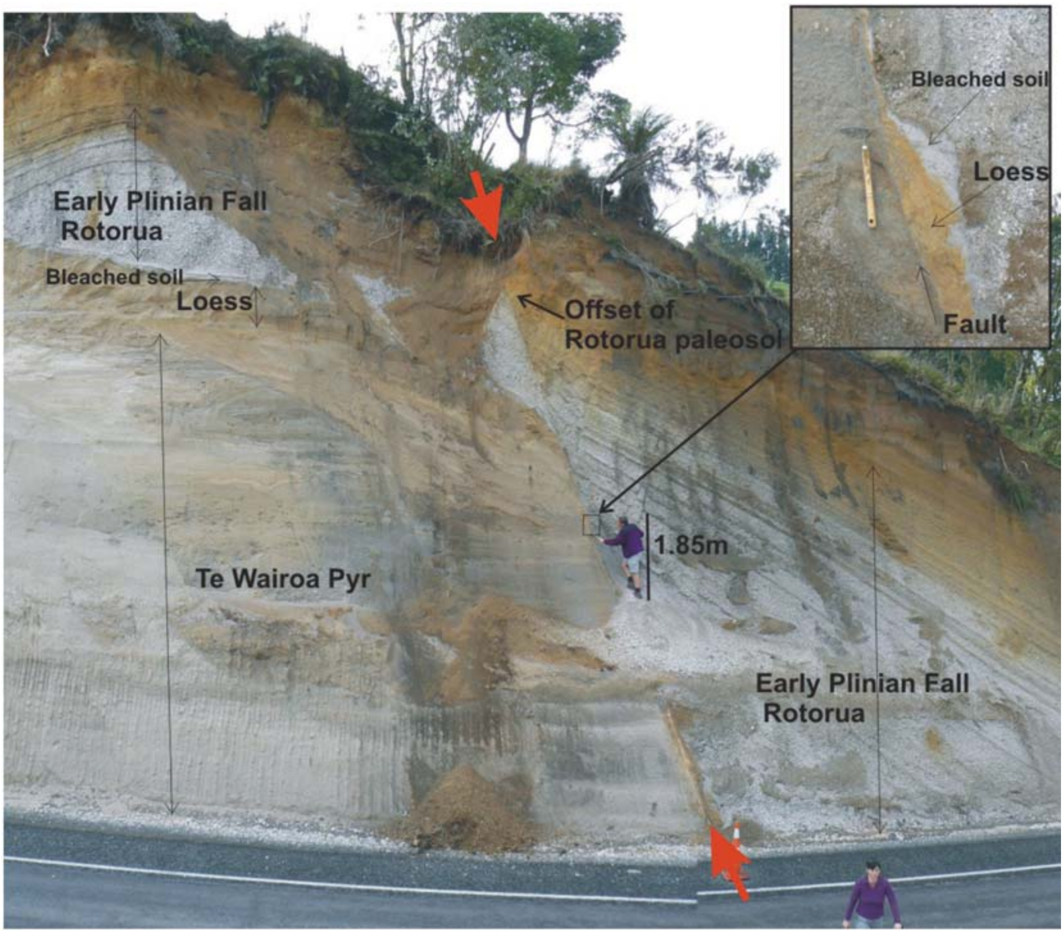


Figure 2. Exposure of the Opawhero fault at Tarawera Road. The fault shows a large displacement of Rotorua Formation. Te Wairoa deposits are downfaulted below road level on the hanging wall

Restoration of deformation

A *RIEGL* LMS-Z420i 3D terrestrial laser scanner was used to capture the 3D geometry of the road-cut. A calibrated Nikon D200 digital camera equipped with a Nikkor 85 mm lens was mounted on top of the scanner and used to provide the digital imagery for the survey. 3D scan data and imagery were captured from three scan positions. Using the RiSCAN pro software these data were processed and registered to known tie-points to provide a photorealistic 3D model of the road cut that could be visualised and measured.

Geometric surfaces of the fault plane and Rotorua Formation beds were created from the survey data. The fault plane was created using multiple clearly defined points along the fault zone. These 3D points allow accurate calculation of dip and strike of the fault. Where possible these bedding surfaces were calculated using three points on each surface to provide information on changes of dip between bedded layers (bold lines on Fig. B3). Where data was insufficient (i.e., where there was not enough difference in depth along the plane) the surfaces have been calculated by assuming they dip in the same direction as the surface represented with bold lines and by projecting of the surveyed points on a vertical plane perpendicular to the bold line surfaces. All bedding surfaces and the fault plane were projected to a plane perpendicular to the fault plane (Fig. B3).

The bounding contacts of the Rotorua Formation and multiple layers within the Rotorua Formation were identified in the data model, and dip and strike values calculated from sections closest to the fault plane. The bed strikes and dips can vary spatially because the tephra mantles the pre-existing topography. Only surfaces close to the fault plane on both sides will be expected to have similar attitudes and thus projection of these to the fault plane have produced more realistic displacement measurements.

The image was then retro-deformed along the fault plane to calculate deformation of tephra layers (Fig. B4). Restoration was achieved by juxtaposing the well constrained yellow bold line (Fig. B3) across the fault. This restoration required ~ 2.5 m of dip-slip displacment along the fault plane, and resulted in matching the top of the Rotorua Formation as well. Rotorua Formation layers below the bold yellow line (dashed yellow line, Fig. B4) are still displaced after 2.5 m of restoration. The bottom of the Rotorua Formation (visible on the footwall but not visible on the hanging wall) is still offset by at least 4.9 m. This suggests the likelihood of additional fault displacement during the deposition of the Rotorua Formation.

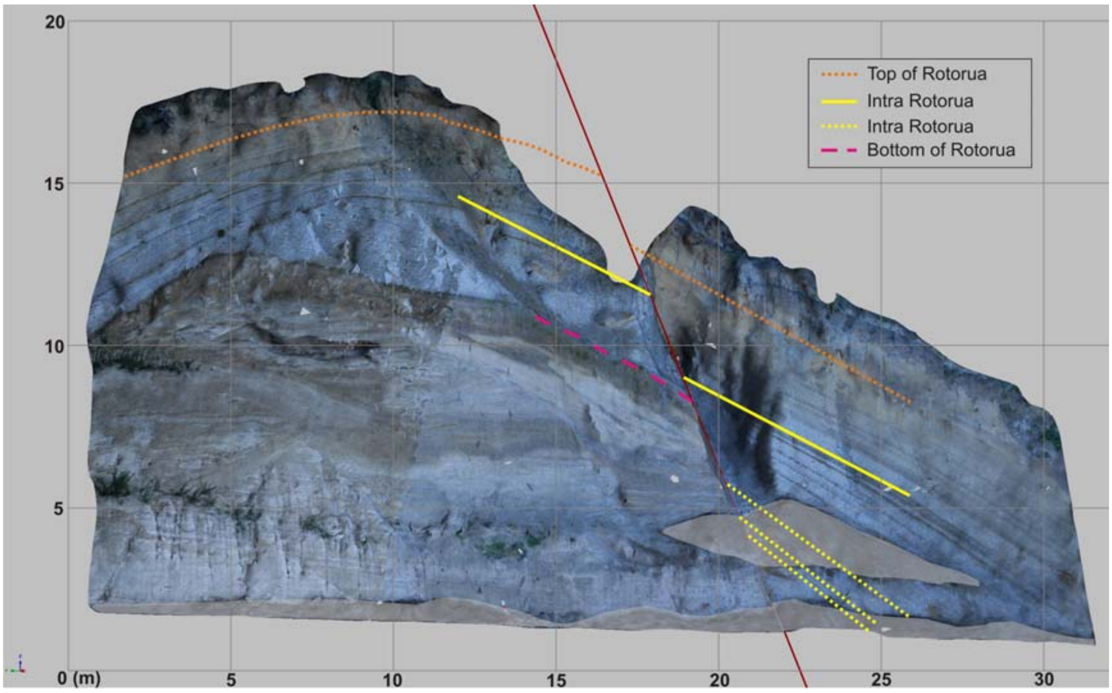


Figure B3. View of the 3D model perpendicular to the fault plane with layers identified from the Rotorua eruption. Orange dashed line is the top of the Rotorua Formation. Yellow lines represent layers deposited during the Rotorua eruption. Yellow bold lines represent surfaces calculated with three or more points on the 3D survey. Yellow dashed lines represent surfaces with not enough information to produce 3 point surfaces. These latter surfaces have been calculated by assuming they dip in the same direction as the surface represented with bold lines and by projecting of the surveyed points on a vertical plane perpendicular to the bold line surfaces.

Displacement during deposition of Rotorua Formation is also suggested by:

1) The variable thickness of tephra on both sides of the fault, with larger thickness on the hanging wall (5 m on the footwall and >10 m on the hanging wall) indicating that fault displacement created accommodation space on the downthrow side of the scarp.
2) The steeper dips on Rotorua Formation beds that are still displaced after restoration compared to the dip of beds that have been restored, indicating more deformation of older deeper layers.

The 2.5 m displacement of post-Rotorua Formation probably occurred in one or more rupturing events judging by typical single event displacements observed elsewhere in the Taupo rift (see next section). The fault displacement record for the upper units cannot be assessed at this exposure because of the great height of the exposure and the erosion on the upper part of the fault plane. The intra Rotorua Formation displacement occurred during the early stages of the Rotorua eruption.The general sequence of the Rotorua episode is: (1) early plinian falls dominated by vesicular, clinopyroxene-bearing pumice; (2) late-stage fall units comprising dense, biotite-bearing pumices and ash; (3) extrusion of biotite-bearing Middle Coulee and Middle Dome lavas; (4) block-and-ash flows interbedded with dense biotite-bearing fall units (Kilgour, 2002; Smith et al., 2004). Units 1 and 2 make a majority of this volume and are the exposed units in the road cut.

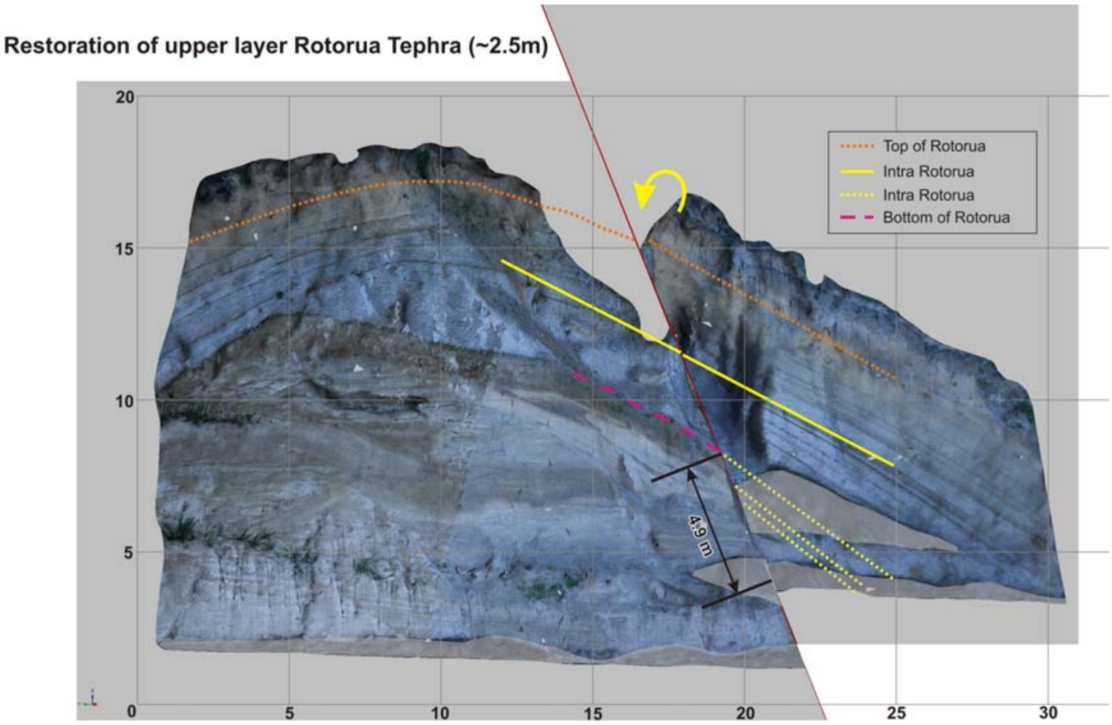


Figure B4. Restoration of the upper layer of Rotorua Formation. Restoration was achieved by juxtaposing the well constrained (see text and Fig. B3) yellow bold line across the fault. This movement of ~2.5 m along the fault plane also restores clearly defined layers below the upper layer of Rotorua Formation (bold yellow line). The base of Rotorua Formation (not visible on the hanging wall) would still require at least 4.9 m of movement to be restored. The yellow arrow represents the direction that surface layers close to the fault need to be rotated to restore original bedding.

Evaluating the type of fault rupture – volcanic eruption association

The Opawhero fault lies ~ 5 km to northwest of the closest Rotorua eruptive vent (Fig. B1). The proximity of the Opawhero fault to the source of the Rotorua eruption suggests two possible types of fault-volcano interactions that could explain the time associations found in the fault exposure:

1) Tectonic faulting could have been triggered by large stresses caused by magma inflation prior and during the Rotorua eruption.
2) Partial evacuation of the magma chamber after the first phases of the eruption could have produced partial collapse of the surrounding crustal volume at locations with weakness planes (e.g., faults). This would imply that the fault plane at depth lies in close proximity to the magma chamber and associated caldera ring fault.

If the ruptures were tectonic, the expected displacement per event for a 5 to 8 km long fault trace would be about 0.5-0.7 m (associated earthquake Mw 5.9-6.1) using scaling relationships for the Taupo rift (Villamor et al 2007b;

for scaling relationships used see Villamor et al 2007a). This would imply that the >4.5 m of intra Rotorua Formation displacements had to be achieved in many increments and many moderate magnitude earthquakes. Evidence for incremental faulting may be present in the form of small discrete blocks of loess deposits, bleached soil and Rotorua deposits dragged along the fault scarp. This detail observed on the fault plane could suggest possible multiple discrete offsets during the eruption (insert Fig. B2).

Alternatively, fault separation could be a consequence of collapse following the accompanying evacuation of the magma chamber. This latter explanation would require that the fault plane intersects or is close to the magma chamber margin at depth. The magma source for the Rotorua eruption has been estimated to reside at 5-7 km depth (Smith et al., 2004). If we assume that the magma chamber resided beneath the vents, the Opawhero fault plane could intersect the chamber. Fault dips at depth in the Taupo rift are uncertain but have been inferred to range between 45 and 60° (Villamor and Berryman 2001; Lamarche et al 2006). For this fault dip range, the deep part of the fault would reach the location of the closest Rotorua vent at 5-8 km depth, a similar depth to the location of the chamber.

At this stage, we are not able to discriminate which one of these mechanisms is responsible for the time associations between faulting and tephra deposition found in the road cut. Numerical modelling of crustal stress changes during eruptions, together with a paleoseismic trench to document the more recent deformation, could provide further insight.