SUPPLEMENTARY INFORMATION FOR *'Recurrent liquefaction in Christchurch, New Zealand during the Canterbury earthquake sequence'* by M.C. Quigley et al.

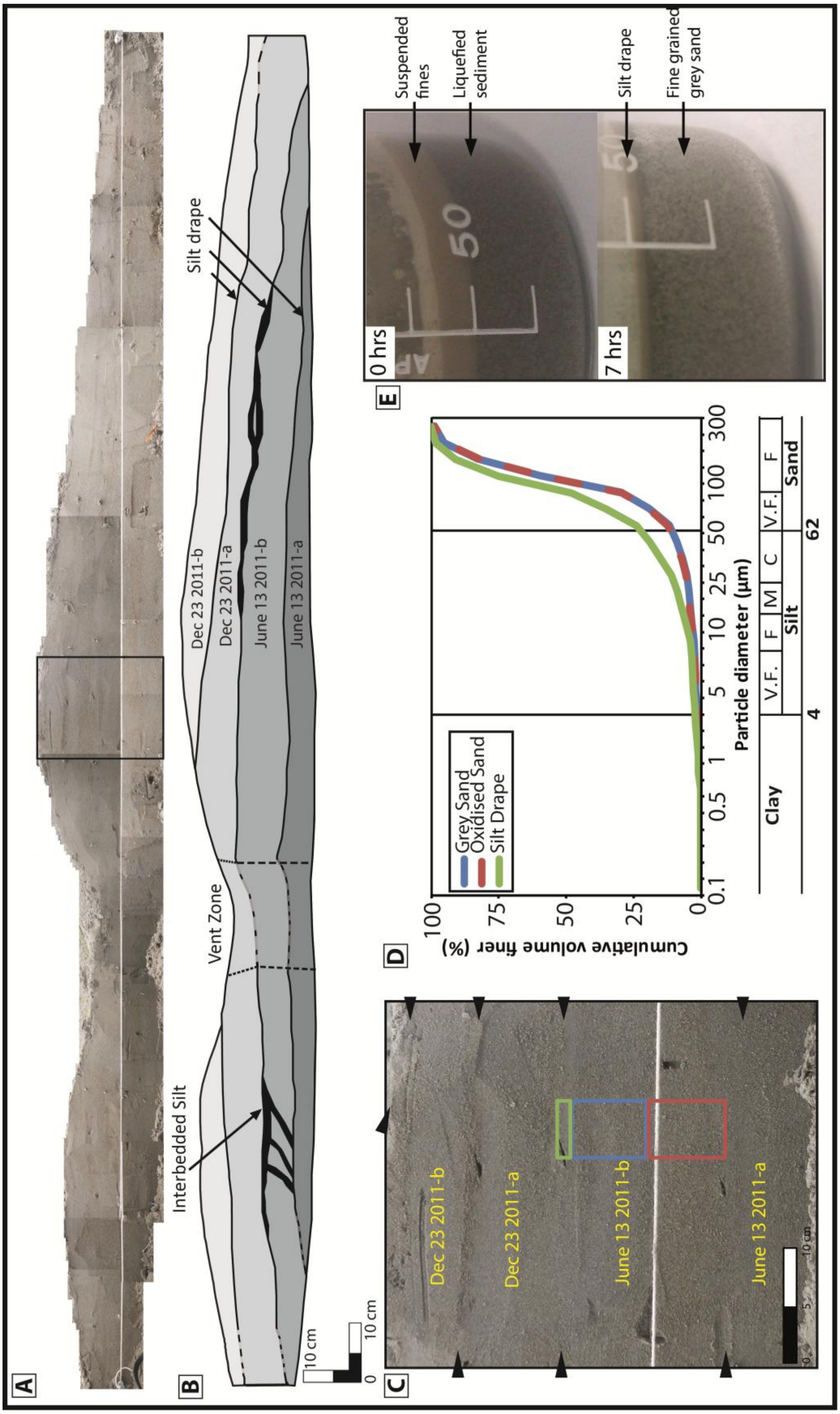
Christchurch liquefaction mapping and seismologic data

The following Figures DR1-DR6, Table DR1, and Video DR1 provide supplementary information relevant to the text of Quigley et al., *'Recurrent liquefaction in Christchurch, New Zealand during the Canterbury earthquake sequence'*.

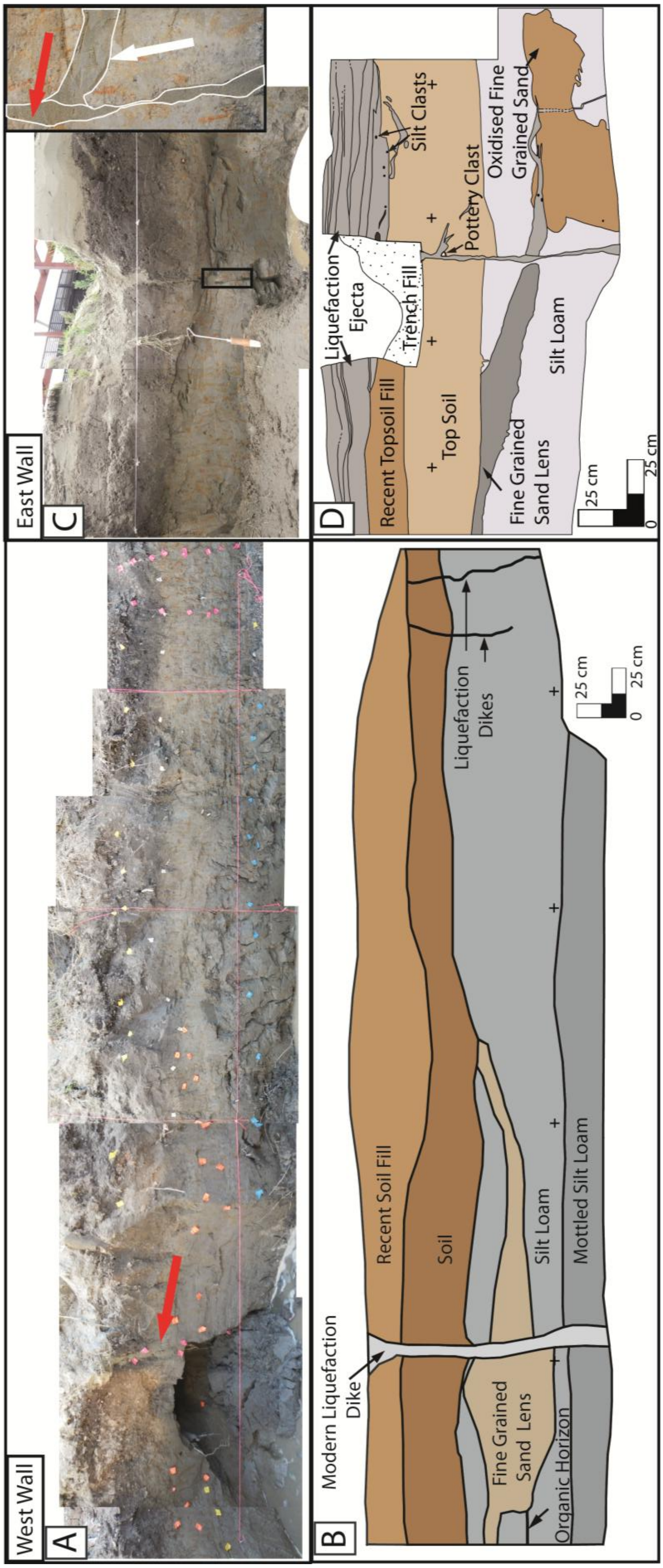
FIGURE DR1: (a) Photo log of a small (~25 cm deep) trench exposing cross-section of successive sand blow units from June 13, 2011 (2 events) and Dec. 23, 2011 (2 events) earthquakes. Box in 'A' corresponds to photograph in 'C'. The location of the trench is shown in Fig. 3 in Quigley et al. (2013)(b) Detailed interpreted log of the above trench through successive liquefaction events, with the packages of liquefaction and dividing silt drapes indicated. Cross-bedding of silt within the sand deposit is also indicated. (c) Close-up annotated photograph indicating the four liquefaction packages within the trench and the location of the overlying 'silt drapes' comprised of coarse-grained silt to very fine-grained sand. The gradational contact from oxidised sand to grey sand is visible. (d) Cumulative grain size plots for the oxidised sand, grey sand and silt drape identified within each package of surface ejecta. (e) Results of lab experiment in attempt to recreate sand blow stratigraphy from a sample of mixed ejecta. We added 20ml of distilled water to beaker then shook the beaker until sediment was in a liquefied state, then placed the sample in oven at 40^{o}C for 7 hrs to speed up the drying of the sample. Photographs were taken of the initial liquefied state, then at the 7 hr mark once the sample had dried. Fines were suspended at 0 hrs, and then settled out by 7 hrs. The compositional layering observed in the liquefaction ejecta, of the oxidised sand grading into gray sand, was not re-created, suggesting that the observed colour differences may reflect different provenance of source material during the liquefaction process and/or post-depositional alteration of similar grain-size / density layers. However, we cannot discount differential settling given the simplicity of this experiment, and more experiments will be conducted.

FIGURE DR2: Field photographs and trench logs for the east and west walls of a 1.2m deep trench through sand blows perpendicular to axis of sand blow vent alignments (location shown in Fig. 3 in Quigley et al., 2013). Blow-ups of feeder dikes (insets) show the absence of clearly recognizable multiple dike sets, with only one, texturally uniform feeder dike recognizable on the west wall (and two smaller feeder dikes also texturally uniform visible in northern part of the trench) that could be interpreted as only one liquefaction episode in the geologic record, despite the occurrence of at least 8 events that used this feeder system. Two different sand intrusions are recognizable on the east wall; a subhorizontal sand sill (white arrow) that is cross-cut by a sub-vertical feeder dike (red arrow). Despite at least 8 liquefaction episodes, only two episodes would be confidently inferred from this geologic relationship at this location. The liquefaction dike on the east wall is truncated by a small trench cut perpendicular to the dike that was dug after the liquefaction causing events. This area is labelled 'trench fill'.

FIGURE DR1



A
B
C
D
E
Interbedded Silt
Vent Zone
Silt drape
Dec 23 2011-b
Dec 23 2011-a
June 13 2011-b
June 13 2011-a
10 cm
0
10 cm
Cumulative volume finer (%)
Particle diameter (µm)
Grey Sand
Oxidised Sand
Silt Drape
Clay
Silt
Sand
V.F.
F
M
C
4
62
0 hrs
7 hrs
Suspended fines
Liquefied sediment
Silt drape
Fine grained grey sand



West Wall
A
B
Modern Liquefaction Dike
Recent Soil Fill
Soil
Silt Loam
Mottled Silt Loam
Fine Grained Sand Lens
Organic Horizon
Liquefaction Dikes
25 cm
0
25 cm
East Wall
C
D
Recent Topsoil Fill
Top Soil
Liquefaction Ejecta
Trench Fill
Pottery Clast
Silt Clasts
Oxidised Fine Grained Sand
Fine Grained Sand Lens
Silt Loam
25 cm
0
25 cm

FIGURE DR2

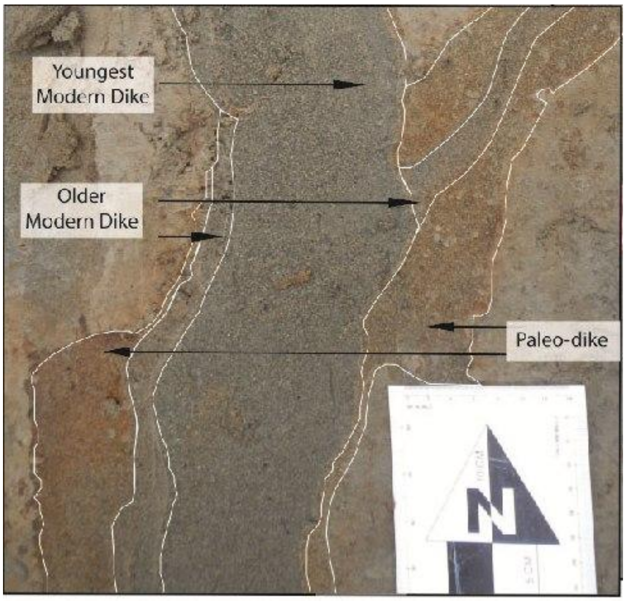


FIGURE DR3: Field photograph taken at Sullivan Park, Avonside (172°40'9''E, 43°30'58''S) indicating multiple feeder dike reactivation, with three distinguishable events. The oxidised and bioturbated nature of the outermost dike indicates this is a paleo-liquefaction feature formed in a pre-CES earthquake. This feature was also traced up the wall where it was truncated by a flood deposit in the subsurface further supporting a pre-CES age (Bastin et al., 2012).

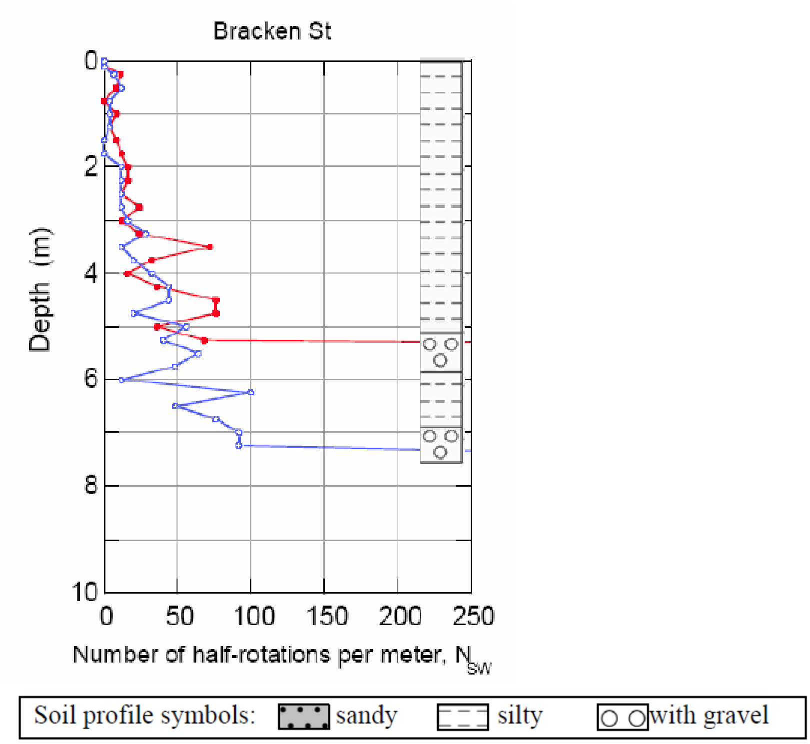


FIGURE DR4: Penetration resistance at the study site in Quigley et al. (2013) measured in Swedish Weight Sounding tests expressed in terms of the number of half-rotations per metre, N_{SW}. The tests were conducted ten days after the Darfield earthquake. The liquefiable layer extends to a depth of ≥5 m. Figure from Cubrinovski et al. (2010).

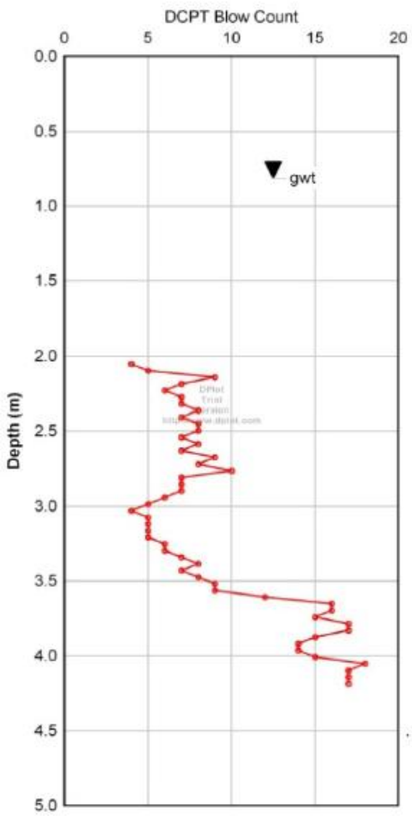


FIGURE DR5: Dynamic Cone Penetration Test (DCPT) data from the study site. The DCPT blow count is the number of drops of the weight required to drive the cone ~4.5 cm. The ground water table at this location was at ~0.8m, and the top of the liquefiable layer was at a depth of ~2 m. The strata overlying the liquefiable layer were clayey. Penetration resistance sharply increases at a depth of ~3.5 m. Figure from Cubrinovski et al. (2010).

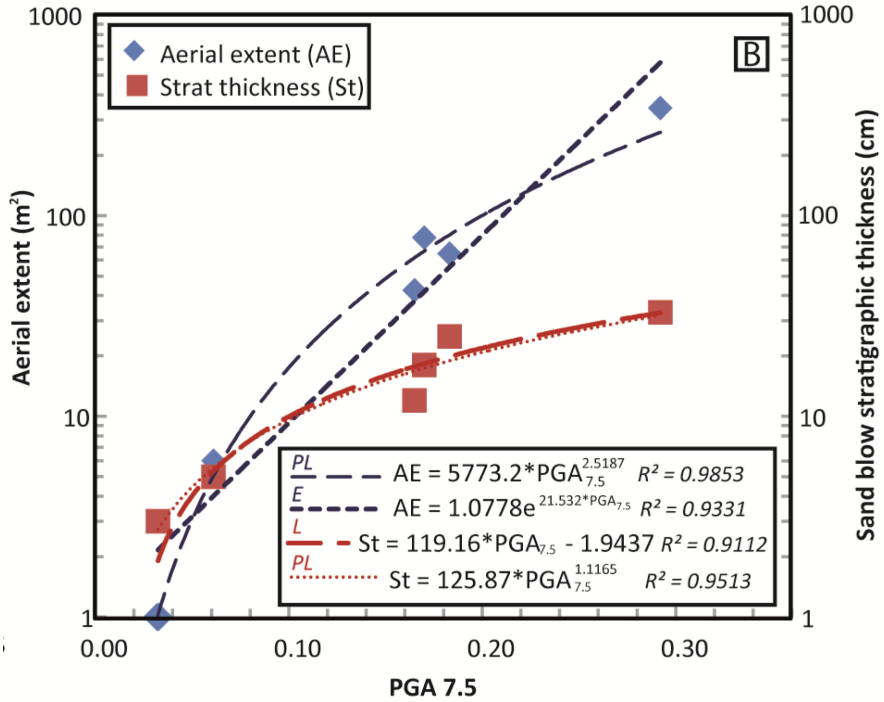


FIGURE DR6: Cumulative (for clustered earthquakes) or individual PGA$_{7.5}$ vs. (individual or cumulative) mapped aerial extent (*AE*) and maximum stratigraphic thickness (*ST*) for sand blows produced in liquefaction-inducing earthquakes. Modelled best fit relations include PL=Power Law, E = Exponential, and L=Linear best fit functions and corresponding R_2 values.

VIDEO DR1: Liquefaction at the study site approximately 3-5 minutes after the June 13, 2011-b earthquake, showing largest water discharge from source in NW corner of the property, and abundance of suspended sediment that eventually forms silt drapes as water drains.

TABLE DR1: Seismologic and liquefaction data for the Canterbury earthquake sequence

						Recorded PGA values (g)						Inferred PGA values				liquefaction (1=yes; 0=no;-1=inferred)	Cumm PGA7.5 for sequence	% increase over largest individual event	Cumm mapped aerial liq extent (m2)	% of study area covered	Normalized area to max coverage	Max Strat thickness (cm)	Nomalized T to max T
Event						PRPC		CCCC		SHLC		11 Bracken St											
CUSP_ID	Date	Latitude	Longitude	ML	Mw	H1	H2	H1	H2	H1	H2	Repi (km)	PGA geo (g)	MSF	PGA7.5 (g)								
3366146	20100903163500	-43.5382	172.1635	7.1	7.2	0.198	0.231	0.228	0.220	0.176	0.175	40.4	0.203	1.110	0.183	1	0.1830879		65	12.0	0.188	25	0.758
3366230	20100903195600	-43.6048	172.4042	5.1	4.8	0.034	0.046	0.036	0.028	-	-	22.9	0.036	3.133	0.012	0							
3366933	20100905010400	-43.6309	172.382	4.9	4.5	-	-	0.033	0.015	0.013	0.010	25.8	0.016	3.696	0.004	0							
3367742	20100906112400	-43.5699	172.3878	5.1	4.8	0.021	0.027	0.027	0.028	0.019	0.036	22.9	0.026	3.133	0.008	0							
3367749	20100906114000	-43.5885	171.8914	5.4	5	-	-	0.047	0.026	0.033	0.028	62.7	0.032	2.823	0.012	0							
3368445	20100907194900	-43.574	172.69	5	4.7	0.198	0.221	0.250	0.129	0.137	0.191	6.3	0.185	3.307	0.056	0							
3382676	20101004092100	-43.5627	172.4031	5.2	4.8	-	-	0.029	0.023	0.018	0.025	21.5	0.023	3.133	0.007	0							
3391440	20101018223200	-43.6256	172.5636	5.1	4.8	0.052	0.056	0.173	0.084	0.112	0.049	14.2	0.079	3.133	0.025	0							
3437105	20101225213000	-43.5544	172.6615	4.9	4.7	0.082	0.086	0.220	0.217	0.194	0.127	3.7	0.145	3.307	0.044	0							
3450113	20110119170300	-43.6153	172.5497	5.1	4.8	-	-	0.052	0.034	0.025	0.020	14.0	0.031	3.133	0.010	0							
3468575	20110221235100	-43.566	172.6909	6.3	6.2	0.647	0.609	0.490	0.376	0.297	0.375	5.5	0.472	1.627	0.290	1							
3468581	20110222000400	-43.5892	172.6605	5.8	5.5	0.123	0.198	0.156	0.134	0.096	0.084	7.6	0.130	2.211	0.059	-1							
3468635	20110222015000	-43.5904	172.6336	5.9	5.6	0.092	0.079	0.072	0.142	0.139	0.223	8.1	0.121	2.112	0.057	-1	0.292	1%	344	63.6	1.000	33	1.000
3468672	20110222030400	-43.5652	172.647	5	4.5	-	-	0.030	0.027	0.040	0.043	5.1	0.036	3.696	0.010	0							
3474093	20110305063400	-43.5686	172.7337	5	4.6	0.248	0.128	-	-	-	-	7.7	0.178	3.494	0.051	0							
3481489	20110320084700	-43.522	172.6974	4.9	4.5	0.094	0.166	-	-			2.7	0.125	3.696	0.034	0							
3497857	20110416054900	-43.6134	172.7886	5.3	5	0.192	0.259	-	-	0.111	0.122	14.4	0.172	2.823	0.061	1	0.0610651		6	1.1	0.017	5	0.152
3509905	20110509150400	-43.5994	172.4068	5.2	4.9	0.042	0.054	-	-	0.058	0.087	22.5	0.059	2.972	0.020	0							
3525264	20110605210900	-43.6051	172.4125	5.5	5.1	0.038	0.055	-	-	-	-	22.3	0.046	2.683	0.017	0							
3528810	20110613010100	-43.5684	172.7531	5.6	5.3	0.339	0.264	-	-	0.301	0.198	8.9	0.273	2.431	0.112	1							
3528839	20110613022000	-43.5638	172.7431	6.4	6	0.291	0.399	-	-	0.211	0.163	8.0	0.267	1.770	0.151	1	0.17	11%	78	14.4	0.226	18	0.545
3529702	20110614182700	-43.6461	172.8382	5	4.8	0.053	0.050	-	-	0.024	0.022	19.8	0.038	3.133	0.012	0							
3529858	20110615010300	-43.6546	172.8547	4.7	4.6	0.035	0.035	-	-	0.020	0.029	21.4	0.030	3.494	0.009	0							
3533107	20110621103400	-43.5988	172.5249	5.4	5.2	0.086	0.092	-	-	0.076	0.075	14.2	0.083	2.553	0.032	1	0.0323403		1	0.2	0.003	3	0.091
3572067	20110901152900	-43.5711	172.8137	5	4.6	0.174	0.074	-	-	0.036	0.060	13.3	0.082	3.494	0.023	0							
3591448	20111008031700	-43.696	172.8486	4.8	4.6	0.039	0.041	-	-	0.014	0.016	24.5	0.028	3.494	0.008	0							
3591999	20111009073400	-43.5799	172.7899	5.5	4.9	0.171	0.103	-	-	0.057	0.070	12.1	0.100	2.972	0.033	0							
3631359	20111223005800	-43.4862	172.7957	5.9	5.8	0.316	0.283	0.140	0.137	0.253	0.244	11.3	0.239	1.930	0.124	-1							
3631363	20111223010600	-43.4729	172.8406	5.3	5.4	0.068	0.075	0.067	0.057	-	-	15.2	0.067	2.318	0.029	0							
3631380	20111223021800	-43.53	172.7428	6	5.9	-	-	0.165	0.196	0.242	0.282	6.4	0.226	1.848	0.122	1	0.165	25%	42	7.9	0.124	12	0.364
3631432	20111223035000	-43.4955	172.7734	5.1	4.7	-	-	0.045	0.040	0.033	0.043	9.3	0.040	3.307	0.012	0							
3631755	20111223173700	-43.6638	172.8397	5.1	4.9	0.070	0.041	0.032	0.048	0.027	0.039	21.3	0.042	2.972	0.014	0							
3635309	20111231004400	-43.5173	172.7754	4.8	4.5	0.065	0.058	0.048	0.032	0.028	0.033	9.0	0.045	3.696	0.012	0							
3636018	20120101122700	-43.4695	172.8519	5.1	4.8	0.068	0.068	0.048	0.036	0.058	0.022	16.2	0.050	3.133	0.016	0							
3636397	20120102055900	-43.4679	172.8752	4.8	4.6	0.076	0.058	0.040	0.032	0.046	0.037	18.0	0.050	3.494	0.014	0							
3638237	20120106012000	-43.4791	172.801	5	4.5	0.024	0.032	0.017	0.020	0.021	0.018	12.0	0.022	3.696	0.006	0							
3638451	20120106122100	-43.51	172.8219	5.3	4.8	0.171	0.118	0.080	0.053	0.060	0.039	12.8	0.089	3.133	0.028	0							
3642657	20120114134700	-43.5376	172.7654	5.1	4.6	0.117	0.115	0.048	0.042	0.047	0.062	8.4	0.075	3.494	0.022	0							
3711648	20120525024400	-43.4867	172.8007	5.2	5	0.000	0.000	0.041	0.047	0.044	0.045	11.7	0.044	2.823	0.016	0							

Date: yyyymmddhhmm00; ML: local magnitude; Mw: moment magnitude;
H1,H2 = peak horizontal accelerations
PGA geo = geometrically corrected peak ground acceleration at study site
MSF = Magnitude scaling factor (Youd et al. 2001)
PGA7.5 = PGA*1/MSF = equivalent PGA for a Mw7.5 event
Cummulative PGA7.5 computed for clustered sequences
Mapped aerial extent derived from Arc GIS
T=max strat thickness

REFERENCES:

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