LIQUEFACTION DURING HISTORIC EARTHQUAKES IN NEW ZEALAND

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SUMMARY

The literature has been searched for accounts of liquefaction during historic earthquakes in New Zealand. About 30 fairly clear cases of liquefaction were found in 10 earthquakes since 1843. The 1848 Marlborough and the 1931 Napier earthquakes appear to have caused the most widespread occurrences. Both were large earthquakes in regions with extensive saturated fine-grained alluvial deposits. Since liquefaction has only recently been recognised as a distinct phenomenon, evidence of its occurrence was not expressly searched for in early investigations, and it is possible that many instances have gone unrecorded. Therefore it is likely that liquefaction has been more pervasive than the 30 clear cases suggest. With the exception of the $M \geqq 6$, 1895 Taupo earthquake which liquefied a pumice soil, all have occurred in earthquakes with magnitudes of at least 6.9. However, some larger earthquakes, most notably the 1929, M = 7.8 Murchison earthquake, have produced no records of liquefaction that we could find. Given the uncertainties of early epicentral locations, the New Zealand cases are consistent with the expression of Kuribayashi and Tatsuoka (1975) for distance to the farthest site of liquefaction, although the number of cases is too small to establish the correctness of the relationship under New Zealand conditions.

INTRODUCTION

Seismic liquefaction of sands has been studied intensively during the past 20 years following the dramatic failures in the Niigata and Alaskan earthquakes of 1964, and it is now recognised that liquefaction is a fairly common seismic effect and one with great potential for destruction. However, while the hazard is recognised and the general mechanism known, the detailed mechanics of liquefaction are not yet understood and predictions of liquefaction potential are far from reliable (Peck, 1979; Davis and Berrill, 1983). Therefore, it is valuable to study past instances of liquefaction, both to obtain a better understanding of the phenomenon, and to accumulate data for the formulation of mechanical and empirical models.

The aim of this article is to catelogue historical cases of liquefaction in New Zealand. It is hoped that the reader will gain a better overall appreciation of the magnitude of liquefaction hazard in this country, that this general study will lead to more detailed examination of particular cases, and that further historical cases might be brought to light. The geological and seismological literature has been searched for descriptions of liquefaction. Since it has been recognised only recently as a distinct phenomenon, early observers did not search expressly for liquefaction effects. Hence the cases found have been inferred from indirect information that is often sparse and incomplete. Only clear cases have been included in the catelogue below; because of the scarcity of observations, it is likely that many occurrences have gone unreported and that liquefaction has been more widespread than the catalogue suggests.

Phenomena which may be used as indicators of liquefaction are as follows:

1. water ejection and sand boils
2. settlement
3. landslides on moderate slopes
4. foundation failures
5. flotation of light structures

Of these, the first is the most common and unambiguous; water ejection and sand boils provide the evidence for most of the historical cases identified in this study. There are many instances of settlement and spreading of embankments during New Zealand earthquakes, and while some of these cases may have been caused by liquefaction it is difficult to distinguish these, especially well after the event. Similarly, some of the many landslides triggered by earthquakes may have been induced by liquefaction. No attempt has been made to analyse instances of settlement and sliding to find whether liquefaction was the cause.

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In the remainder of the article, we report the observations indicating liquefaction. These have resulted from an extensive search within a wide variety of New Zealand sources. Details of the search are presented by Fairless (1984), together with descriptions of the major historic New Zealand earthquakes, and some information about other seismic effects besides liquefaction.

OBSERVED LIQUEFACTION

Reports of earthquake effects starting with the 8 July 1843 Wanganui earthquake were searched for evidence of liquefaction. About 30 instances in which there is fairly clear evidence of liquefaction were found. The sites of liquefaction and the epicentral locations of the 10 associated earthquakes are shown in Figure 1. Details of the effects implying liquefaction, together with other information about the sites and earthquakes are listed in Table 1. Apart from the special case of the 1895 Taupo earthquake, in which pumice (an exceptionally light material) was ejected, all of the cases found occurred in earthquakes with a magnitude of 6.9 or greater. The most widespread occurrences were found in the three large events of 1848, 1855 and 1931 with magnitudes of about 7.1, 8.1 and 7.9 respectively. These occurred in coastal regions with plentiful fine-grained, recent alluvial deposits. By contrast, no reports of liquefaction could be found for the 1929, M = 7.8 Murchison earthquake. This may be attributable partly to sparsity of population in the region, but it is also possible that there was, in fact, little liquefaction in the generally coarser sediments found in this mountainous area.

The evidence for liquefaction is now considered, earthquake by earthquake.

Marlborough 1848 ($M = 7.1$, $I_o = X$)*

The main shock on 16 October was followed by two major aftershocks on 17 and 19 October; the shock of the 19th was particularly severe, demolishing some masonry buildings that had survived - albeit with damage - the first two shocks. Eiby (1980b) has made an exhaustive study of the Marlborough earthquake, examining and quoting from a large number of historical documents. His report is the main source of our information. From contemporary reports, Eiby concludes that the epicentre of the earthquake was in the lower Wairau Valley, and that fresh breakage took place on the Wairau fault.

There is clear evidence of liquefaction in the lower Wairau Valley during the earthquake. Eiby cites the diary of Frederick Weld, who wrote that:

> "In the Wairau the surface crust of dry land has in some places sunk 10 ft, the water spouting up through diminutive craters from the swamp subsoil."

Eiby also quotes from a letter by Thomas Arnold in which he describes conditions in the Wairau Valley after the earthquake:

> ". . . I also saw numerous deep holes, by which a lower stratum of sand and water had burst its way through the overlying ground, and covered everything with sand for some distance."

Both are clearly descriptions of sand boils induced by liquefaction. Other reports quoted by Eiby indicate liquefaction near the site of the present Wairau Pa, about 8 kilometres from the river mouth. Further accounts record that the sediments of the lower Wairau Valley subsided by about 1.5 metres. Eiby concludes that this was due to settlement within the sediment rather than to tectonic movement on the fault. This conclusion is certainly consistent with the observations of widespread water explusion and formation of sand boils. The existence of favourable conditions for liquefaction in the lower Wairau is confirmed by the observation of Wild (1915) that no gravels were found in the Wairau River downstream of the rail bridge; only sands, grading to silts near the coast. The rail bridge is about 10 kilometres upstream from the river mouth.

Liquefaction also occurred well away from the epicentral region of the 1848 earthquake. An account from Wellington (Chapman, 1849) reports cracks in a beach, with shells "thrown up". The Reverend R Taylor's journal of 1847-48, quoted by Eiby, records accounts of water ejection and sand boils at Waikanae and at a beach near Ohau, Manawatu. Taylor (1870) again refers to what are almost certainly sand boils at Ohau when he says:

> "At Ohau gas was ejected from circular openings, surrounded by quicksands."

Taylor also describes the formation of large sand boils near Wanganui. Liquefaction may also have been the cause in Wanganui of ". . . a row of posts near the gun wharf . . . thrust out a full 3 feet" (Eiby, quoting the "New Zealand Spectator", 6 December 1848).

Thus it appears that liquefaction was quite widespread in the lower Wairau Valley during the 1848 earthquake, and that it was also found at various places along the west coast of the North Island as far north as Wanganui, a distance of nearly 200 kilometres from the epicentre.

Wairarapa Earthquake, 1855 ($M = 8.1$, $I_o \geq XI$)

The 1855 earthquake, the strongest since European settlement, also caused much liquefaction in Marlborough and the lower North Island.

Liquefaction occurred in Wellington

* I_o denotes epicentral intensity, in Modified Mercalli units unless marked R-F when the Rossi-Forel scale is used.

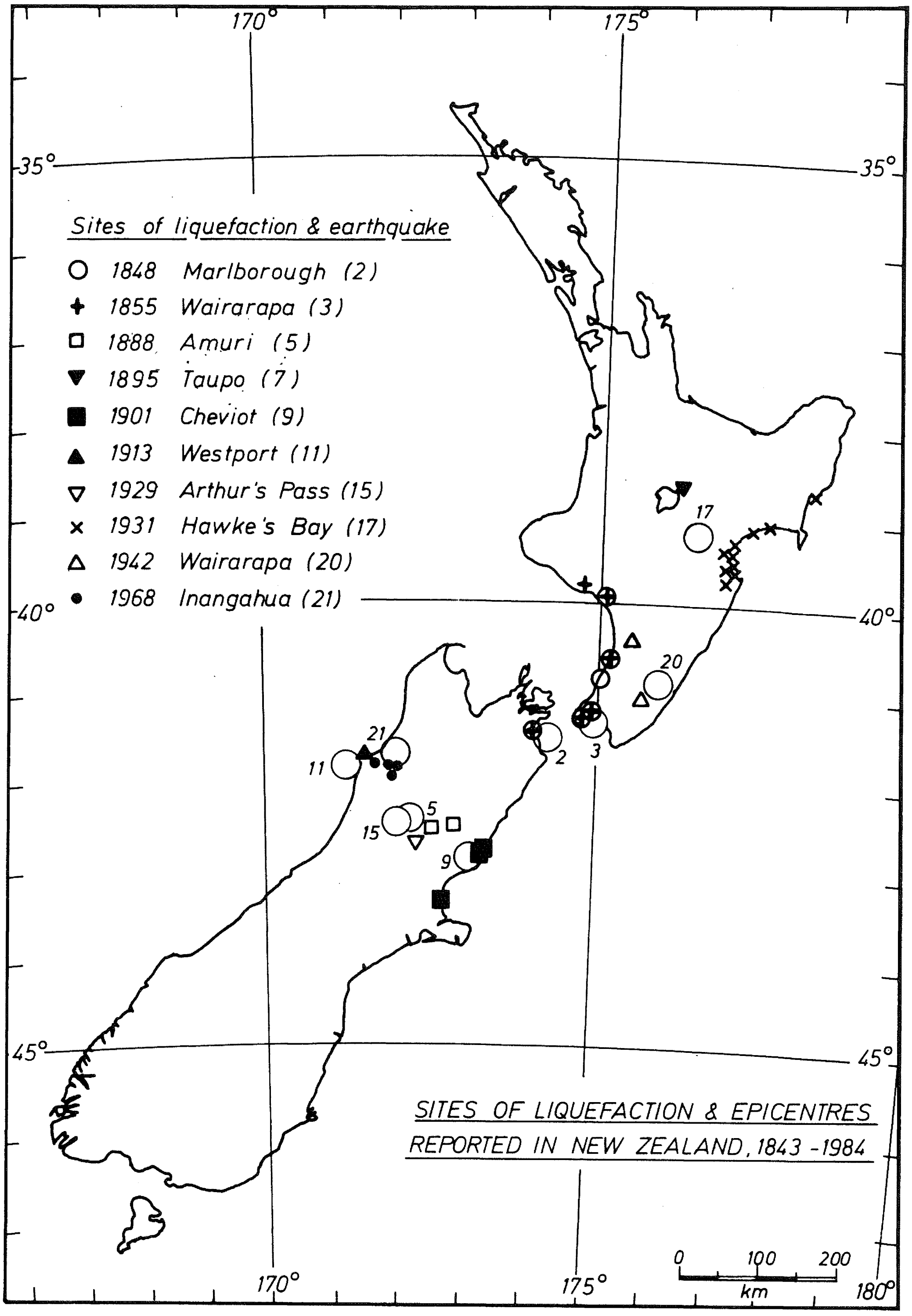
170°
175°
35°
35°
40°
40°
45°
45°
Sites of liquefaction & earthquake
1848 Marlborough (2)
1855 Wairarapa (3)
1888 Amuri (5)
1895 Taupo (7)
1901 Cheviot (9)
1913 Westport (11)
1929 Arthur's Pass (15)
1931 Hawke's Bay (17)
1942 Wairarapa (20)
1968 Inangahua (21)
17
20
21
11
2
3
5
15
9
SITES OF LIQUEFACTION & EPICENTRES
REPORTED IN NEW ZEALAND, 1843 -1984
0
100
200
km
170°
175°
180°

Figure 1.

TABLE 1. Major Historic Earthquakes and Observations of Liquefaction

Earth-quake No.	Date	Epicentral Area	Epicentre	Magnitude and Focal Depth	I_o (MM or R-F)	Liquefaction: Nature of Effects	Liquefaction: Area	Liquefaction: Coordinates	Liquefaction: Epicentral Distance	Other Effects	Reference
1	1843 8 July	Wanganui	Less than 50 km to NE of Wanganui	$7\frac{1}{2}$ or greater	MM IX-X	No reports found				Building damage, large landslides, 2 deaths. Deep fissures in river bed	Eiby, (1968a) (1980a)
2	1848 16 Oct	Lower Wairau Valley, NE Marlborough	About 41.56°S 174.25°E (scaled from Eiby 1967)	Est. 7.1 h ≈ 40 km	MM X	Posts thrust out of ground	Wanganui	39.96°S 175.03°E	193 km	Serious damage to buildings in Wellington 3 deaths in large aftershock on 19 October	Eiby, (1980b) (1968a) (1968b) Taylor (1870)
						Soil cracking and ground water phenomena	Wanganui. A Manawatu Beach, near Ohau	40.65°S 175.16°E	128 km		
						Sand craters	Waikanae.	40.86°S 175.02°E			
						Sand craters, release of ground water, subsidence (up to 10 ft, generally about 5 ft)	Lower Wairau (widespread) near present Wairau Pa	41.48°S 173.99°E	15-33 km 24 km		
						Cracks in beach, cockles "thrown up"	A Wellington beach	41.29°S 174.77°E	54 km		Chapman (1849)
										Little damage in Nelson	Henderson (1937) Grayland (1957)

Table 1. (Continued)

Earth-quake No.	Date	Epicentral Area	Epicentre	Magnitude	I_o (MM or R-F)	Liquefaction: Nature of Effects	Liquefaction: Area	Liquefaction: Coordinates	Liquefaction: Epicentral Distance	Other Effects	Reference
3	1855 23 Jan	SW Wairarapa	41.37°S 174.93°E (scaled from Eiby 1967)	About h ≈ 15 km	MM XI+	Possible expulsion of sand and ground water; also possible subsidence.	Lower Wairau	About 41.5°S 174°E	79 km	Extensive faulting and coastal uplift. Destructive in Wellington, severly damaging in Wanganui. Most severe NZ earthquake known.	Eiby (1968a) (1968b) (1980a) (1980b) Hayes (1953) Carter (1866)
						Sand cones, fissuring of ground, subsidence.	Lower Hutt Valley	41.23°S 174.89°E	17 km		Roberts in Taylor (1855)
						As above, but to a greater degree; ejection of soft mud and slime.	Manawatu Plains, many places		100 km or more		Ongley (1943a)
										Little damage in Nelson	Henderson (1937)
						Gas ejected from circular openings surrounded by quicksands.	Ohau (near Levin)	40.66°S 175.25°E	83 km		Taylor (1870, 2nd ed)
						Ground fissures with gas and water ejection, sand boils.	Wanganui?	39.95°S 175.03°E	160 km		
						Emission of slimy mud	Cnr.Willis and Manners Streets, Wellington	41.29°S 174.77°E	17 km		Grayland (1942)

Table 1. (Continued)

Earthquake No.	Date	Epicentral Area	Epicentre	Magnitude	I_o (MM or R-F)	Liquefaction: Nature of Effects	Liquefaction: Area	Liquefaction: Coordinates	Liquefaction: Epicentral Distance	Other Effects	Reference
3 cont.						Fissuring, sand and water ejection	Waitotara near Wanganui	39.81°S 174.73°E	175 km		Field (1892)
4	1863 23 Feb	Hawkes Bay	Not known	7? or greater	R-F IX	No reports found				Destroyed several houses in Napier and opened fissures in the ground. Felt over most of the country. Little else is known.	Eiby (1980a) Callaghan et al (1933)
5	1888 1 Sept	Amuri, Nth Canterbury	42.52°S 172.22°E	About 7 h ≈ 25 km	MM 8½					Fissures in river beds near Charleston,	Hayes (1953) Henderson (1937)
										at Kelly Creek near Otira,	Hutton (1889)
						Mud ejection	Hanmer Springs	42.53°S 172.83°E	50 km	Hope River, and	MacKay (1888), (1890)
						Subsidence (circular holes)	Glynn Wye Station	42.60°S 172.51°E	25 km	Hopefield Station	Hutton (1889)
6	1893 12 Feb	Nelson	5 or 6 miles SW of Nelson	6½-7 h = 40 km	MM VIII or greater	No reference to fissures etc				Damage in Nelson suggests MM VIII	Hayes (1953) Hogben (1894) Eiby (1968b)

Table 1. (Continued)

Earthquake No.	Date	Epicentral Area	Epicentre	Magnitude	I_o (MM or R-F)	Liquefaction: Nature of Effects	Liquefaction: Area	Liquefaction: Coordinates	Liquefaction: Epicentral Distance	Other Effects	Reference
7	1895 17 Aug	Taupo		Greater than 6	R-F VIII+	Cracks in ground, and fine pumice ejected	Between Wairakei and Opepe	38.70°S 176.13°E		Damage to buildings. Landslides	Hogben (1898) Eiby (1980a)
8	1897 8 Dec	Wanganui Bight		7 h ≈ 25 km	MM 8½	No reports available				Damaging in Wanganui Felt from Auckland to Timaru	Hayes (1953) Eiby (1980a)
9	1901 16 Nov	Cheviot	42.9°S 173.1°E (scaled from Eiby 1967)	7 h ≈ 10 km	MM IX	Water and sand ejection	Kaiapoi Cheviot Estate	43.39°S 172.66°E 42.83°S 173.28°E	69 km 11 km	Damage and landslides in North Canterbury. 1 death	Hayes (1953) Eiby (1980a) MacKay (1902)
						Dry creeks suddenly full	Cheviot area				
						Water and sand ejection	MacFarlanes near Swamp Creek.	42.79°S 173.26°E	13 km		
							Hurunui riverbed below Domett	42.88°S 173.23°E	4 km		
10	1904 9 Aug	Off Cape Turnagain	42.24°S 178.58°E	7½ h ≈ 15 km	MM IX	No reports				Damage at Castlepoint	Hayes (1953) Eiby (1980a) Hogben (1904)

Table 1. (Continued)

Earthquake No.	Date	Epicentral Area	Epicentre	Magnitude	I_o (MM or R-F)	Liquefaction: Nature of Effects	Liquefaction: Area	Liquefaction: Coordinates	Liquefaction: Epicentral Distance	Other Effects	Reference
11	1913 22 Feb	22 miles WSW of Westport	41.52°S 171.12°E		R-F VIII or IX	Cracks in ground. Mud ejection	Cape Foulwind	41.45°S 171.29°E	27 km		Morgan (1913) Hogben (1913) Henderson (1937)
12	1914 7 Oct	Eastern Bay of Plenty		7-7½; h ≃ 25 km	MM IX	No reports				1 death, eastern Bay of Plenty	Hayes (1953) Eiby (1980a)
13	1914 22 Nov	East Cape Peninsula		6½-7; h ≃ 50-60 km	MM VII	No reports				Little damage reported. Widely felt in North Island to Oamaru in South Island	Hayes (1953) Eiby (1980a)
14	1921 29 Jun	Hawke's Bay	39.3°S 176.4°E ±.4°	7; h ≃ 70-100 km	MM 7½	No reports				Minor damage over much of Hawke's Bay	Hayes (1953) Eiby (1980a) Bullen (1937b)
15	1929 9 Mar	Arthur's Pass	42.5°S 172.0°E	6.9; h ≃ 30 km	MM IX	"earthquake craters"	Lake Sumner	42.73°S 172.29°E (Eastern end)	23-36 km Probably 36 km	Felt over whole country except Northland	Hayes (1953) Eiby (1980a) Speight (1933)

Table 1. (Continued)

Earthquake No.	Date	Epicentral Area	Epicentre	Magnitude	I_o (MM or R-F)	Liquefaction: Nature of Effects	Liquefaction: Area	Liquefaction: Coordinates	Liquefaction: Epicentral Distance	Other Effects	Reference
16	1929 17 Jun	Murchison: White Creek fault, 11 km west of Murchison	41.8°S 172.2°E	7.8; h ≃ 20 km	MM XI	No reports				Fissures and subsidence in Westport, Karamea, Greymouth. Destruction in Murchison area: 17 deaths; numerous landslides and faulting.	Hayes (1953) Henderson (1937) Eiby (1968b) Eiby (1973b) Eiby (1980a)
17	1931 3 Feb	Hawke's Bay	39.20°S 176.40°E	7.9; h = 15-20 km	MM XI	Sea discoloured in patches. "Penetrating marshwater" 50% more water in streams Large quantities of water, sand and silt issued from holes in the ground Buildings leaning Settlement and expulsion of sand and mud Spouts of sediment Mud boils	Hawke's Bay. Seems widespread. Mohaka area widespread especially Mohaka Mouth. Tongoio Lagoon, Petane. Taradale, Wairoa. Near mouth of Tutaekuri River (Ahuriri?) and in Heretaunga Plains Esk Valley	39.13°S 177.19°E 39.34°S 176.92°E 39.43°S 176.87°E 39.53°S 176.85°E 39.03°S 177.43°E 39.48°S 176.88°E 39.39°S 176.83°E	About 50 km; 51 km 22 km 19 km 27 km 26 km 15 km	Destructive in Hawke's Bay. Regional uplift, minor faulting. Massive landslides. 256 deaths. Subsidence of embankments. Largest aftershock of M = 7.1, 13 Feb	Hayes (1953) Eiby (1973b) Eiby (1980a) Eiby (1981) Daily Telegraph (1981) Bullen (1938a) Callahan et al (1933)

Table 1. (Continued)

Earthquake No.	Date	Epicentral Area	Epicentre	Magnitude	I_o (MM or R-F)	Liquefaction: Nature of Effects	Liquefaction: Area	Liquefaction: Coordinates	Liquefaction: Epicentral Distance	Other Effects	Reference
17 cont.						Mud boils	Site of Princess Margaret Hospital	39.48°S 176.90°E	26 km		Daily Telegraph 02/02/81
						Mud boils	Through floor boards of Tuckers Woolscour, Clive.	39.60°S 176.90°E	36 km		Conly (1980)
						"Blowhole"	Road near Taradale	39.53°S 176.86°E	28 km		Grayland (1942)
						"Boiling mud pool"	Longlands	39.68°S 176.81°E	40 km		Daily Telegraph 17/02/31 21/02/31 Grayland (1957) Jaggar (1931) Guthrie-Smith (1969)
						"Geysers"	Gisborne Beach	38.69°S 178.04°E	140 km		
						"Blowouts"	Mohaka area				
18	1932 16 Sep	Wairoa	38.9°S 177.55°E	6.8; h< 50 km	MM VIII+	No reports				Damage in Gisborne and Wairoa. Subsidence near river in Wairoa	Hayes (1937a) Hayes (1953) Eiby (1980a) Ongley et al (1937) Bullen (1937a) Bullen (1938b)
19	1934 5 Mar	Pahiatua	40.5°S 175.6°E	7.6; h = 20-40 km	MM 8½	No reports				Damage in southern Hawke's Bay and northern Wairarapa. 1 death	Hayes (1937b) Hayes (1953) Eiby (1980a) Bullen (1938c)
20	1942 24 Jun	Southern Wairarapa	40.9°S 175.9°E	7.0; h = 20-30 km	MM VIII-IX	Craters built up in mud, silt, and shingle along fissures.	Gladstone area?	41.09°S 175.64°E	30 km	Damaging in southern Wairarapa and Wellington	Hayes (1953) Eiby (1980a) Ongley (1943b) Grayland 1942
						Sand and water ejection	Opiki	40.45°S 175.46°E	63 km		

Table 1. (Continued)

Earthquake No.	Date	Epicentral Area	Epicentre	Magnitude	I_o (MM or R-F)	Liquefaction: Nature of Effects	Liquefaction: Area	Liquefaction: Coordinates	Liquefaction: Epicentral Distance	Other Effects	Reference
21	1968 24 May	Inangahua	41.77°S 172.01°E	7.0 h = 13 km	MM X	Sand and water ejection	Lower post Otira glacial terraces at Inangahua, south to Rotokohu, NE to New Creek and west over Walkers Flat to 6 km west of Inangahua. Also, at 25 km west of Inangahua (Te Kuha)	41.86°S 171.96°E; 41.97°S 171.89°E; 41.77°S 172.03°E; 41.86°S 171.86°E; 41.83°S 171.65°E	10.5 km 23.9 km 0.3 km 13.4 km 29.4 km	Large landslides. Serious damage to wooden houses, bridges, railway lines and underground pipes. Fault breakage. 3 deaths	Eiby (1980a) Lensen et al (1968)
						Sand boils	Alluvial river flat, ¼ mile from Inangahua towards Murchison	41.86°S 171.96°E	10.5 km		Shepherd et al (1970) Adams and Lowry (1971)
							Three Channel Flat	41.85°S 171.97°E	9.6 km		
						Earthquake fountains and mud craters	Near Te Kuha, western end of Buller Gorge	41.83°S 171.65°E	29.4 km		Grayland (1978) Adams et al (1968)

city itself. Grayland (1942) refers to a report by a Commander Drury in which it is recorded that near the corner of Manners and Willis Streets

> "a considerable opening on the road emitted slimy mud, and the main street was inundated."

Further, an anonymous author (anon, 1862) states that:

> "large quantities of mud were ejected in parts of the city of Wellington in 1855, more especially opposite the Union Bank in Willis Street..."

Taylor (1855) records accounts of sand boil formation in the Hutt Valley and, less definitely, in the Manawatu in the following passage:

> "In the lower part of the valley of the Hutt, numerous hillocks of sand were thrown up, forming cones, varying from 2 to 4 feet in height, and in many parts of the valley large fissures were formed, with partial subsidences in many places. In the plains of the Manawatu this was the case to a much greater degree."

Again, liquefaction occurred near Wanganui. There is a clear account of sand ejection at Waitotara, near Wanganui, in the following quotation from Field (1892):

> "On an alluvial flat just in front of the house there was a crack fully fifty yards long, through which sand and water had been thrown up from a depth of fifteen feet or twenty feet, and scattered on the surface to a width of about twelve feet, and to a depth of several inches."

Reports from Marlborough were few, though apparently some liquefaction occurred near the mouth of the Wairau River. Eiby (1980b) quotes from the Nelson Examiner of 31 January 1855:

> "From the mouth of the Wairau River . . . we received no accounts . . . although we hear that cracks in the ground had taken place in the neighbourhood of the wood, and that sand and mud had been thrown up in places."

Surprisingly, no clear evidence of liquefaction in the Wairarapa Valley was found.

Amuri Earthquake, 1888 (M = 7, I_o = IX-X)

Although widespread settlement and fissuring of alluvium is reported in the epicentral region, the only reports suggestive of liquefaction come from the Hanmer Springs area. From Hutton (1889) we have:

> "A small opening was made close to the swimming bath, which spouted out mud and gas, with very little water, for the three days that the ground was in continuous motion."

MacKay (1890) also records that the smaller well at Hanmer had thrown out some mud and fine sands.

Taupo Earthquake, 1895 (M > 6, $I_o \geq$ VIII R-F)

Hogben (1898) describes

> "Large cracks in the ground between Wairakei and Opepe, emitting cold water and fine white pumice".

Cheviot Earthquake, 1901 (M = 7, I_o = IX)

In a comprehensive report of the Cheviot earthquake, MacKay (1902) records liquefaction at a number of places in North Canterbury; namely Kaiapoi, the Cheviot Estate, Macfarlanes, and the Hurunui River bed below Domett.

Westport Earthquake, 1913 (I_o = VIII R-F or IX R-F)

Morgan (1913) reports cracks opening in the ground at Cape Foulwind, with mud issuing from one of them.

Arthur's Pass Earthquake, 1929 (M = 6.9, I_o = IX)

Only one report was found for this earthquake, that of Speight (1933), based on observations made in 1933. The only instance of liquefaction referred to in the report was on the shores of Lake Sumner, where sand boils were observed.

Hawke's Bay Earthquake, 1931 (M = 7.9, I_o = XI)

While many investigators state that subsidence and water ejection were widespread during this earthquake, the most damaging in New Zealand to date, few give specific details or pinpoint sites.

The Government geologist, Mr J Henderson, in a 1931 article reprinted in the 1981 facsimile edition of the "Napier Daily Telegraph", states that during and after the earthquake large quantities of water, sand and silt issued from fissures in the ground. He goes on to imply that this occurred in Napier, Hastings and other parts of the Heretaunga Plains, at Wairoa, the Mohaka River mouth, Tongoio Lagoon and at Petane. Grayland (1957) refers to a number of sand boils in the Mohaka area and in Grayland (1942), shows a photograph of a sand boil on a road near Taradale. Jaggar (1931) and Eiby (1981) make general references to sand ejection, the latter specifically mentioning the Heretaunga Plains and the mouth of the Tutaekuri River. Guthrie-Smith (1969), referring to Tutira Station some 40 kilometres north of Napier, states:

> "The fractures in the turf remained dry, from them no muddy liquid was ejected as in other localities of Hawke's Bay."

The "Daily Telegraph" (21 February 1931) reports the appearance of "dozens of small geysers" in the beach between Taumotu Island and Pa Hill, about 1.5 miles east of Gisborne harbour. Another specific report comes from Callaghan (1933) who states that mud pools appeared at Muriwai Beach. Also several spouts of sediment at an area in the Esk Valley were observed by Mr W B Stewart, a teacher at Napier Boys' High School in 1931 (Fraser, personal communication, 1980).

While it appears that the attention of observers was focused on the more dramatic effects of the earthquake and that precise reports of liquefaction phenomena are scarce, it is nevertheless obvious from the several general reports referred to above that the occurrence of liquefaction was widespread in the region from the Heretaunga Plains north to Gisborne.

Wairarapa Earthquake, 24 June 1942 (M = 7.0, I_o = VIII to IX)

Sand boils are reported at Gladstone, east of Masterton, by Ongley (1943b), and at Opiki near Palmerston North by Grayland (1942).

Inangahua Earthquake, 1968 (M = 7.0, I_o = X)

Several instances of liquefaction occurred in alluvial terraces in the Inangahua region within 30 kilometres of the epicentre. These include formation of sand boils:

1. at Three Channel Flat, 3 kilometres east of Inangahua, and on the flats immediately south of Inangahua Junction (Dodd, in Shepherd et al, 1970);

2. at Walker's Flat, 3 kilometres west of Inangahua, where water ejection continued for about five hours (Sutherland, in Shepherd et al, 1970);

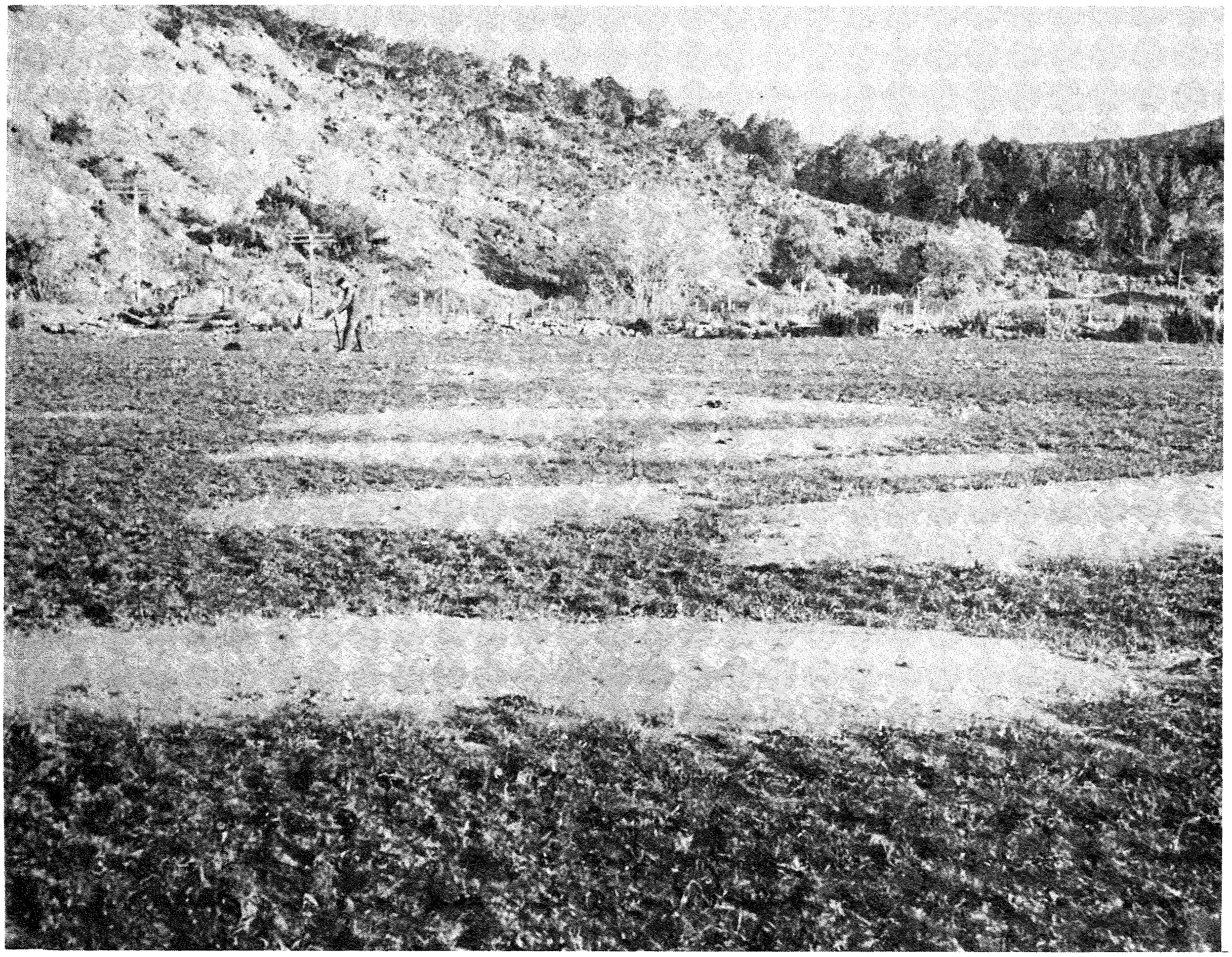

Figure 2. Sand Boils at Three Channel Flat.

3. on various other post-glacial terraces between Inangahua and Rotokohu about 8 kilometres to the south, and between Inangahua and New Creek about 10 kilometres north-east of Inangahua;

4. at Te Kuka, 25 kilometres west of Inangahua at the western end of the Buller Gorge (Lensen et al, 1968). Adams et al (1969) also refer to sand boils at Te Kuha.

The sand boils at Three Channel Flat are shown in Figure 2. Nearby trenching and boring by Dodd showed fine silty sand strata at a depth of 1.8 metres and again between 2.6 metres and 3.5 metres, interbedded with clayey silts. Samples from both sand layers and from the ejecta had quite similar gradings, with a D_{60} of about 0.12 millimetres. Dodd found the watertable at 3 metres, but this is not necessarily the level prevailing during the earthquake, especially since drainage works were in progress at the site at the time of the inspection.

No records were found in the literature of liquefaction outside the areas mentioned above.

MAXIMUM EPICENTRAL DISTANCE FOR LIQUEFACTION

Based on Japanese observations, Kuribayashi and Tatsuoka (1975) have proposed the following relationship between magnitude and R_{max}, the distance (in kilometres) from the epicentre to the farthest site of liquefaction:

$$\log_{10} R_{max} = 0.77M - 3.6$$

The New Zealand data (except for the 1895 Taupo case involving pumice), from Table 1, are plotted in Figure 3 to check whether or not they follow this rule. Clearly there are not enough points to define an envelope and verify the curve over a large range of magnitudes. However, with four exceptions the New Zealand data do obey Kuribayashi and Tatsuoka's rule. The two points that fall well outside the curve are both from the 1848 earthquake, whose magnitude and epicentre were derived from sparse, felt reports. Both may be in error. Further, it was not certain that liquefaction was the cause of one of the cases (posts "thrust out" at Wanganui) and the precise location of the other site, a beach near Ohau, is not known. Similarly, the exact locations of the other two sites just outside the curve (at Kaiapoi in 1901, and Opiki in 1942) are uncertain, and the epicentral distances given may be in error by several kilometres.

CONCLUSIONS

At least 30 fairly definite reports of liquefaction during historic earthquakes since 1843 have been found in the literature. Vague, general statements, especially with respect to the 1848 Marlborough and the 1931 Napier earthquakes, suggest that many specific instances went unrecorded. No reports of liquefaction were found for the relatively quiet period since 1968.

These 30-odd cases occurred in 10 earthquakes which, except for the 1895 Taupo earthquake, had magnitudes of at least 6.9. The Taupo earthquake is exceptional since in it pumice was ejected. Because of the lower density and thus smaller overburden pressures in pumice soils, less seismic energy is required for liquefaction. However, there are eight other historic earthquakes with magnitudes of 7 or greater for which no accounts of liquefaction were found. Most notable among these was the M = 7.8, 1929 Murchison earthquake. The lack of cases from this earthquake may be due to the generally coarse sediments found near Murchison, and possibly to a lack of population in the region.

It may be concluded from this study that liquefaction is likely to be common in New Zealand regions with widespread fine, saturated, recent sediments subject to earthquakes with magnitudes of 7 or greater. Also, the limited number of data are in reasonable agreement with the Kuribayashi and Tatsuoka rule for maximum epicentral distances. This observation in turn gives some confidence in applying the results of other Japanese studies, or those based on Japanese data, to New Zealand.

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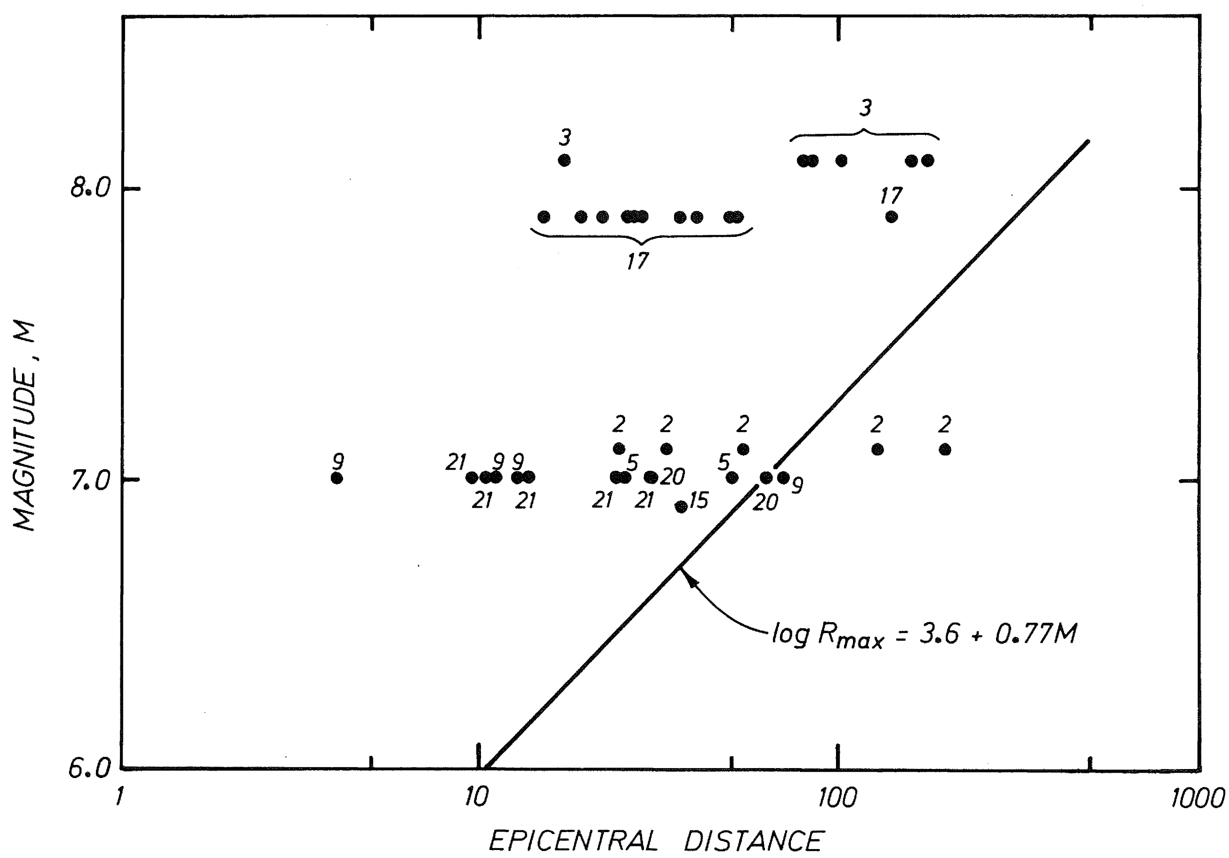

Figure 3. Earthquake Magnitude vs. Epicentral Distance for New Zealand data.