Secondary alpine hazards induced by the 1995-1996 eruption of Ruapehu Volcano, New Zealand

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ABSTRACT

Hazards due to the 1995-1996 eruption included lahars, ballistic blocks and ashfall, and a wide variety of secondary hazards induced by them, including slab and wet snow avalanches (up to class 3), point releases and secondary lahars. Secondary events (n=120) were noted over a 15 month period. Most started within 3 km of the crater, although two avalanches occurred 11 km away.

Secondary lahars were most hazardous but travelled down predictable paths. Ash thicknesses as thin as 5 cm created hazardous secondary lahars that were associated with heavy rain during the spring-autumn of 1995/96. More such events, and wet snow avalanches, seem likely during the 1996 spring or 1996/97 summer.

INTRODUCTION

Mt Ruapehu (2797m, Figure 1) is the highest mountain in the North Island and New Zealand's most visited alpine area. More than 10,000 people will be skiing on its three skifields within 5 km of the active crater on the busier days of the late June-November ski season. Climbers and other visitors frequently visit the summit area with its glaciers and a 10^7 m^3 lake that normally occupies the vent.

Ruapehu is a mostly andesitic composite volcano which is very active by world standards, even for andesite volcanoes (Houghton et al., 1987). There have been 11 significant eruptions this century including the 1995-1996 eruption. Eruptions permanently ejecting more than 10^6 m^3 of lake water create significant hazards in the skifield areas and occur on average every 20-50 years while smaller but still potentially hazardous eruptions occur more frequently (Hancox et al., 1995; Otway et al., 1995). However only two ski seasons (1995 and 1996) have been disrupted significantly by volcanic activity in 42 years of commercial skiing on the mountain although ashfalls during the 1945 eruption interferred with non-commercial skiing.

The combination of a popular mountain and a very accessible, frequently active crater lake surrounded by permanent snow and ice is unique in the world. Managing this part of Tongariro National Park World Heritage Area requires a good understanding of the effects of volcanic activity on the mountain. These include secondary hazards which are produced, or induced, by volcanic hazards and are the subject of this paper.

RUAPEHU CLIMATE

Ruapehu (39°17'S, 175°34'E) is an exposed massif with prevailing west to southwest winds. It is 85 km from the coast and has a temperate, maritime climate. At Whakapapa Village (1119 m) the mean annual air temperature is +7.2°C with mean daily temperatures of 2.4-8.1°C in the July-November ski season (NZ Meteorological Service 1983). At the village mean annual rainfall is 2838 mm. Snowline is down to about 1600 m from April until September-November with measured total snow depths up to 4 m at 2000 m. The snowpack is equitemperature for most of the season (Irwin, 1991) with numerous ice layers.

THE PHASES AND VOLCANIC HAZARDS OF THE 1995-96 ERUPTION

For the purposes of this paper the eruption so far can be divided into six phases. The first and fifth were noneruptive. Table 1 summarises the five which caused secondary events and Figure 1 shows the extent of main life-threatening volcanic hazards.

The fourth phase (Period D on Table 1) deposited a sequence of ash layers on the mountain up to >1500 cm thick (Figure 2). The sixth phase ejected ballistic rocks up to 1.4 km, deposited a further sequence of ash and produced audible airwaves.

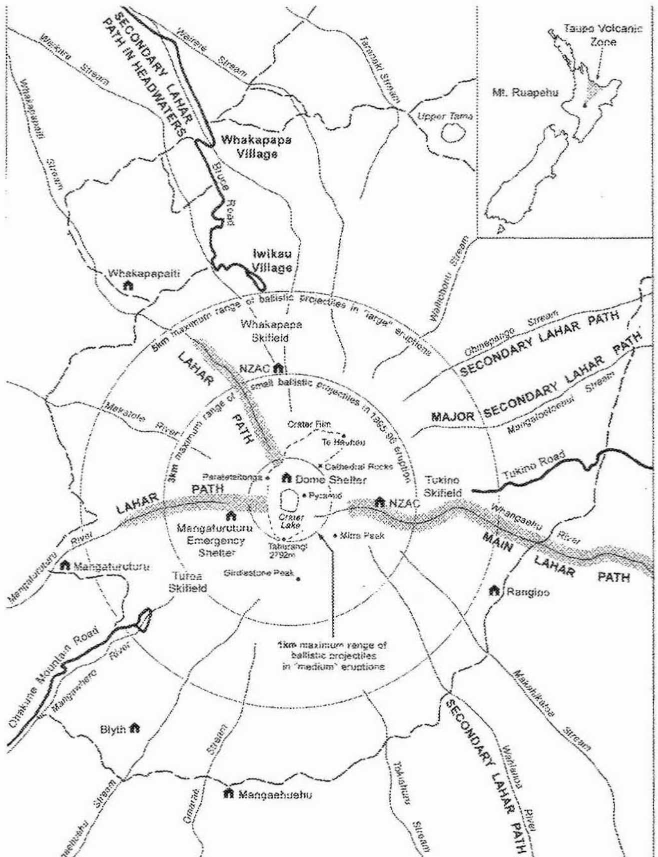

Fig. 1. Map of Mt Ruapehu showing maximum ballistic ranges in "large" and "medium" sized eruption scenarios (Houghton et al., 1987), maximum range downwind of golfball sized ejecta in 1995-96, and 1995 lahar paths.

	Period B	Period C	Period D	Period E	Period F	Totals
	29 June-22 Sep	23-10 Oct	11-31 Oct 95	1 Nov 95-16 June 96	17 June-1 Sep 96	
period length (days)	86	18	21	229	77	431
season(s)	winter, spring	spring	spring	spring-autumn	winter	
days with significant eruption events	4	10	10	0	23	47
volcanic hazards leading to 2∞ events	ashfall, lahar	ashfall,lahar,blocks	ashfall	ashfall	blocks, ashfall	
eruption days producing most 2∞ events	2	3	2	0	7	14
days with 2∞ events	3	at least 8	11	at least 34	at least 11	>67
immediate secondary events or groups of events						
slab avalanches	**1**	**1**	**0**	**0**	**8**	**10**
point releases or sluffs (grouped)	**0**	**1**	**0**	**0**	**9**	**10**
secondary lahars	**0**	**0**	**0**	**0**	**1**	**1**
ash slides or sluffs (grouped)	**0**	**0**	**probable**	**0**	**1**	**1**
subtotal for immediate events	**1**	**2**	**0**	**0**	**19**	**22**
delayed secondary events or groups of events						
slab avalanches	**0**	**0**	**0**	**0**	**10**	**10**
point releases or sluffs (grouped)	**2**	**0**	**1**	**1**	**8**	**12**
wet snow avalanches	**0**	**2**	**0**	**0**	**0**	**2**
secondary lahars and debris flows	**0**	**5**	**15**	**40**	**7**	**67**
ash slides or sluffs (grouped)	**0**	**0**	**0**	**0**	**2**	**2**
other	**1**	**1**	**2**	**1**	**0**	**5**
subtotal for delayed events	**3**	**8**	**18**	**42**	**27**	**98**
total secondary events	**4**	**10**	**18**	**42**	**46**	**120**

Table 1. Summary of secondary (2°) events detected and estimated number of days involved, to 1 September 1996. Events are grouped and/or counted according to type, significance, temporal separation (eg each slab avalanche is recorded separately but point releases and sluffs are groups) and eruption phase.

SECONDARY HAZARD TYPES, NUMBERS AND LOCATIONS

Many secondary events or sets of events have been documented to date (n=120, Table 1). They have included: slab avalanches due to ballistic block impacts, lahars, airwaves, ashfall and weaknesses due to ash layers; point releases due to impacts and ash layers; wet snow avalanches due to ash-induced melting; ice block fall due to undercutting by lahars and warm waves; a range of types of secondary lahars (mud and debris flows); and ash sluffs.

Almost all (116) of these events were on Mt Ruapehu and all except one slab avalanche on Whakapapa Skifield started above 2000 m and within 3 km of the centre of the crater. Two events were noted on each of the neighbouring volcanoes Ngauruhoe and Tongariro 11-14 km north-northeast of the crater. On Ruapehu the start zones of only 9 events were below 2500 m and all these were on north to east facing slopes. The two events recorded on Ngauruhoe (2287 m) both started above 2000 m. The two very small events on Tongariro (1967 m) were at 1700m and many small events probably went undetected at these altitudes.

Events have been classified into six types and two categories - immediate or delayed (Table 1). Immediate events were produced directly and immediately by eruption products such as a ballistic block impacting the snow, whereas delayed events occurred days to months after individual eruptions. About 18 percent of the events were triggered directly, but most (82%) were delayed.

The events discussed in this paper are only a sample of all that would have occurred. But all seasons, aspects and altitudes were able to be examined as the eruption and secondary processes extended for over 15 months and a wide range of topography.

TYPES AND TRIGGERS OF IMMEDIATE SECONDARY HAZARDS

The largest and potentially most hazardous of the immediate events were hard slab avalanches triggered by ballistic blocks and lava bombs (up to 5 m in diameter). Impacts of such material erupted during 17-18 June 1996 set off at least six such avalanches including a class 3+ in Crater Basin below Tahurangi. Immediate slope failure occurred on most aspects except south although projectiles were ejected in all directions. Similar ballistic impacts during other eruptions in spring 1995 and July 1996 produced numerous point releases and small sluffs rather than hard slab avalanches. A weak facetted layer was found in the snowpack at Turoa on 19 June 1996 (M. Brown, personal communication) so the snowpack must have been more unstable in the colder early winter conditions. Two hard slab avalanches were triggered by lahars (3 July, 23 September 1995) again in colder situations and aspects.

Only on one occasion (17-18 June) did hot ballistics appear to create sufficiently intense melting to produce what were interpreted as very small, non-hazardous secondary lahars. The more intense and turbulent pyroclastic

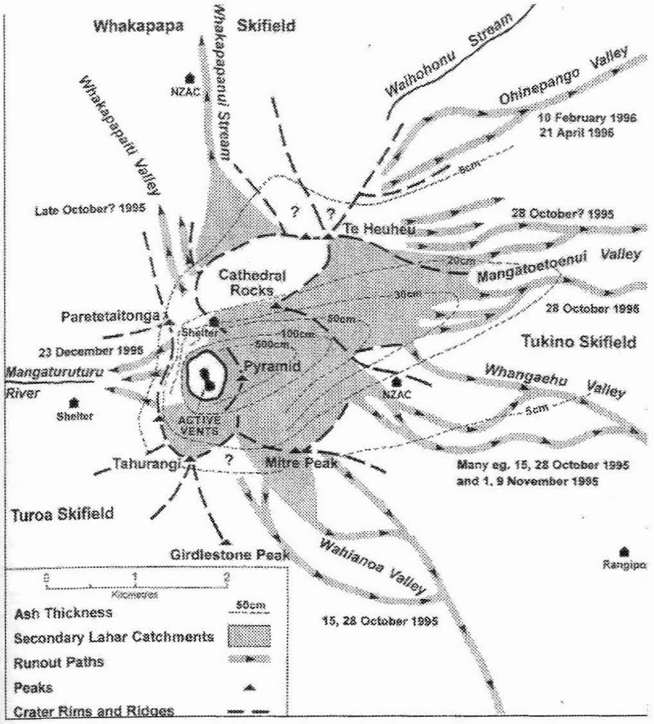

Fig. 2. Preliminary ash thickness isopachs from the 1995 eruption (mainly 11-12 October) courtesy of T Thordarson (Institute of Geological and Nuclear Sciences), and the pattern of various secondary lahars and debris flows which resulted.

hazards of the kind which create hazardous lahars elsewhere (Major and Newall, 1989) did not occur.

Airwaves or ground motion produced by explosions appeared to be the trigger for at least one immediate slab avalanche event and possibly a series of point releases. On 26 July 1996 an eruption ejected blocks up to 300 m from the centre of the crater with no sign of smaller material on fresh snow further out. Hard slabs up to 2 m thick were released from below the crater rim on the crater-facing side (80° aspect) 600 m from crater centre. The slabs slid on an ash layer and a more recent snow or ice layer.

SECONDARY LAHARS AND DEBRIS FLOWS

Secondary lahars have been the most numerous type of delayed event. Most (68%) delayed events (56% of all events) detected have involved some form of mass movement (remobilisation) of erupted material mixed with water, including debris flows entirely or partly composed of 1995 ash and scoria, ash-rich snow slush flows, and hyperconcentrated (stream) flows. Some were detected 57 km downstream.

Field evidence suggests these events start in a variety of ways including:

- dewatering of lahar and ash deposits;
- saturation by rain or snow melt and subsequent flowage of saturated ash or debris;
- failure in weak layers (different grain sizes or textures) within ash deposits;
- slumping, with sliding occuring on new or old material, snowpack or glacier ice;
- gully erosion and undercutting at toes of slopes;
- water storage and release (eg dam building and breaking); and
- coalescing of smaller flows to create large ones.

Generally the initiation of the larger events was associated with recorded heavy rain. Rainfall equivalent to about 20mm per day at rain gauge sites was enough to produce large events soon after the largest ashfall on 11-12 October. Thereafter, larger amounts of rain appeared to produce smaller events although this has not yet been quantified. Heavy rain led to hazardous-sized lahars from ash layers as thin as about 5 cm but the largest events were derived from airfall deposits 0.4 to >15 metres thick (Figure 2). Two lahars in the Whangaehu Valley had peak flows larger than the 23 September eruption lahar (Ruapehu Surveillance Group, 1996). A coinciding event in the Mangatoetoenui Valley was travelling at an estimated 22 m/s when it overtopped a 25 m high spur near Tukino. Further downstream it destroyed a walking bridge.

Snow melt has also been implicated in generally smaller events. Low albedos in thin layers of ash or lahar deposits accelerate melting on sunny days so small debris flows from such deposits are very common. However debris flows (and secondary lahars) appear to be less associated with northerly aspects than are ash-induced avalanches. This suggests that solar radiation and snow melt are less important than rain. In addition, turbidity measured on rivers draining Ruapehu ash deposits during the period 8-15 December (N Edgar, Environment Waikato) was invariably much higher after heavy rain than during or after sunny days.

ASH-INDUCED SNOW AVALANCHES AND THEIR CAUSES

Ash-induced avalanches are the most complex form of secondary hazard. They are affected by interrelationships between eruption timing, nature of the ash, stability and other characteristics of the underlying or overlying snow, aspect and meteorological conditions, many of which vary in time and space. Several possible avalanche mechanisms have been examined using information compiled from 30 snow pits and weather and aspect comparisons. Twenty-two examples of ash-induced point release and slab avalanches were noted, mostly during the 1996 eruption sequence (Period E, Table 1).

The event with the lowest altitude start zone recorded on Ruapehu (1850 m, Third Waterfall, Whakapapa Skifield) was one of six delayed slab avalanches that released during a two day period following the start of the 17 June eruption. The 30-40 cm fracture wall of that event had a wet layer below freshly deposited ash on the snow surface and a 10-15 cm thick layer of rounded snow grains saturated with water sitting on an ice lens which was the slide surface (J. Brockbank, personal communication). Water poured out from above this lens when the wall was trimmed back. As well as providing extra gravitational loading, the dark, salt-containing ash (Table 2) had accelerated melting and lubrication.

Many of the avalanches failed in, on or just above ash layers buried in the pack. Many column and Rutchblock tests gave very easy or easy shears associated with these layers (Figure 3) indicating they can form severe weaknesses in a snowpack.

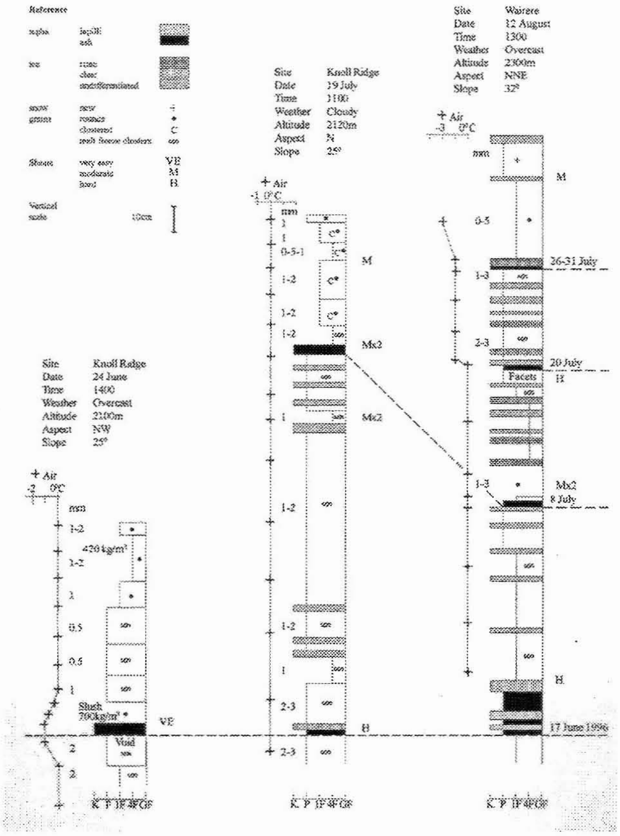

Fig. 3. A sequence of three snow pits on northern slopes of Ruapehu during the 1996 eruption period, showing some influences of ash layers and time on the snow pack.

Such weaknesses may occur in various ways, some of which are related:

- different particles of tephra, and tephra and snow grains may not bond well to each other because of differences in particle size and shape;
- thin dark ash layers or ash particles on the snow surface absorb solar radiation and enhance melting (Major and Newall, 1989);
- ash layers on the snow surface may also cool radiatively and freeze solid while exposed there, perhaps influencing subsequent energy and moisture transfer;
- penetrating solar radiation might be absorbed by buried ash layers and cause melting but temperature measurements did not provide consistent evidence of this (Figure 3);
- soluble chloride and other salt material in the ash depress the freezing point causing melting at temperatures below 0°C (Table 2) and probably alter moisture transfer by affecting vapour pressure and/or thin films between snow grains;
- lateral spreading of melt (or brackish) water occurs within low density snow or at stratigraphic boundaries (Conway and Raymond, 1993) such as between snow and underlying fine-grained and/or frozen ash layers. This weakens bonds between grains. Figure 3 illustrates the presence of a weak, saturated layer of round grains on top of the 17 June ash layer;
- weak layers with facetted snow crystals or thin void spaces develop beneath some ash layers (Figure 3) due to temperature gradient metamorphism, and possibly due to snow melting or settling beneath them;
- fine grained ash particles migrate downwards from their original layer into previously clean snow. Snow pit and spring observations suggest this migration occurs faster on more northerly aspects and with rain-soaked snow, so meltwater and/or capillary action may be involved;

Some of these processes may soften or weaken snow by snow grain metamorphism and disruption or weakening of bonds between snow grains or by altering grain size, shape or texture (Conway and Raymond, 1993).

Depression of freezing points down to -0.5±0.1°C has been measured for some ashes (Table 2) and down to -1.3±0.5°C in one saturated very weak snow layer (Figure 3). The largest depression measured was for a 1:1 (weight for weight) made-up slurry of the 17 June 1996 ash but the dilution factor is important. The -1.3±0.5°C temperature could be explained by meltwater in contact with the ash dissolving more salt as it spread down the sloping upper surface of the impervious ash layer. The freezing point depression varied between layers because the amount of salt present in the ash deposits varies according to whether the Crater Lake was present when the ash was erupted and ash grain size (S. Cronin and W. Giggenbach, personal communications).

STABILISATION OF ASH-INDUCED WEAKNESSES IN SNOWPACK

Changes in the snowpack after the June 1996 eruption, including formation of ice layers and snow melt, helped to stabilise ash-induced weaknesses. A clear (congelation) ice layer formed in place of the slush over the 17 June ash and bonded it strongly into the snowpack (Figure 3). Clear layers were observed forming around ash layers as a result of ash-induced meltwater freezing (e.g. 8-9 July ash layer, Figure 3). Rime formed thick layers on some other ash deposits before they were buried by snow. Early snow melt during warm northerly rain allowed rock anchors to re-emerge below about 2000 m.

MANAGEMENT

Immediate and potential volcanic and secondary hazards were managed by a sequence of volcano and slope monitoring, information dissemination including public warnings and signage, and closure of vulnerable parts of skifields. Skifield evacuation and road closures ensured few people were able to access the higher risk zones around the crater (Figure 1). Existing scientific information on volcanic hazards (Figure 1), and management by consensus between the department, ski operators, police and civil defence were effective tools.

Management of secondary hazards was subsumed by the eruption management at first because existing information on secondary hazards was almost nonexistant in 1995. Sufficient information was able to be developed during 1996 for warnings to be issued. Explosives were used to remove weaknesses above some ash layers and test snowpack strength associated with them (Table 3).

ashfall or snow sample	sample location	ash/water ratio	f.p depression °C	conductivity uS/m
27 Sep 1995 ash	Tukino	1	-0.3	ND
7 Oct 1995 ash	Knoll Ridge	1	-0.3	ND
17 June1996 ash	Top o' Bruce	1	-0.5	ND
17 June 1996 ash & ice	Mangaturuturu pit	in situ, ND	-0.3 (see footnote)	9390
8 July 1996 ash	Top o' Bruce	2	-0.3	ND
8 July 1996 ash	Top o' Bruce	1	-0.2	ND
8 July 1996 ash	Top o' Bruce	0.1	0	ND
8 July 1996 ash & ice	Mangaturuturu pit	in situ, ND	-0.1 (see footnote)	3310
ice on 17 June ash	Wairere pit	0	0	30.9
clean snow below 8 July ash	Wairere pit	0	0	29.2
dirty snow below 8 July ash	Wairere pit	trace	0	22
dirty snow below 20 July ash	Delta pit	trace	0	34.3
fresh snow	Wairere, Delta pits	0	0	9.8-39.0

Footnote:

Temperatures in situ in this pit (23 Aug) were -1±0.5 °C in the 17 June layer and -0.2±0 °C in the 8 July layer

Table 2. Freezing point depression and conductivity due to ash, and background levels. Freezing points in made-up slurries measured by W. Giggenbach. Analytical precision is ±0.1°C and ±10% uS/m. ND=not determined.

CONCLUSIONS

Most secondary hazards due to the 1995-1996 eruption started within the zone of high risk from volcanic hazards within 3 km of the active crater. But several ran well beyond 3 km and two hazardous events occurred up to 11 km away following ashfall on another mountain nearby. Secondary events occurred on at least 67 days, seconds to months after the eruptions which led to them. Those eruptions occurred on far fewer days (Table 1). Therefore, secondary events extended the hazard both spatially and temporally. Most events occurred in spring and winter as a consequence of the timing of eruptions and other processes.

Hard slab avalanches produced by ballistic projectiles, lahars and airwaves or ground motion were the largest snow avalanches up to the end of the 1996 winter. Other slab avalanches large enough to be dangerous occurred at least 10 days after eruptions due to ash layers creating weaknesses in the snowpack. Weakening occurred in a variety of ways, including freezing point depression by salts in the ash and the effects of solar radiation and melting on northwest through east facing slopes. Hazardous wet snow avalanches could occur in the spring or summer of 1996/97.

date	location	charge (1)	result	slide surface(s)
1-Jul	Valley Windroll	Amfo 25kg	class 2 slab (2)	slush on 17 June ash
3-Jul	Valley Windroll	Amfo 14 kg	class 2+ slab	congelation ice layer
3-Jul	Valley Headwall	Amfo 14 kg	class 3 slab	congelation ice layer
3-Jul	Third Waterfall	Powergel 2.5kg	class 2 slab	facetted layer (3)
18-Jul	Valley Notch	Powergel 2.5kg	class 1 slab	new snow layer
18-Jul	Delta Ridge	Powergel 2.5kg	class 1 slab	wet new snow layer
19-Jul	Valley Windroll	Amfo 14 kg	sluff (4)	new snow layer

Footnotes:

1.Amfo charges include 2x1.25 kg sticks of Powergel

2. Also 200m long crack. Partly slid on ash-covered ground

3. Layer was 20cm above congelation ice

4. Weakness (moderate shear) on 8 July ash did not release

Table 3. Results from explosives used at Whakapapa during July (data from Jeremy Brockbank and Mark Woods, Ruapehu Alpine Lifts Ltd) loading.

Secondary lahars were the largest secondary events but travelled down predictable paths. Ash thicknesses as thin as 5 cm created hazardous secondary lahars associated with heavy rain in the spring-autumn of 1995/96. The 1996 eruption deposited more than 5 cm of ash in the upper parts of the Whangaehu, Wairere, Whakapapanui, Mangaturuturu and probably Mangatoetoenui valleys. This ash is lying towards the base of the snow pack rather than at or near the top of it as in spring 1995. This difference may affect the initiation processes and the role of snowmelt, as might textural and grainsize characteristics of the ash layers, and rain intensity and quantity. But hazardous events seem likely in these valleys during the 1996/97 spring/summer.

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