

The Thomson Reservoir Triggered Earthquakes

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ABSTRACT:

There are few better documented examples of reservoir triggered earthquakes than those recorded about the Thomson Reservoir, east of Melbourne. In 1977, the Melbourne and Metropolitan Board of Works (MMBW), predecessor to the current Melbourne Water Corporation, commissioned the Seismology Research Centre to install a network of seismographs to monitor seismicity around the Thomson Dam area during the initial filling cycle of the reservoir.

About three years following the commencement of filling in 1983, shallow earthquakes began occurring immediately under the reservoir, with magnitudes up to ML 3.0, at rates of up to 5 events per week. These events were almost certainly reservoir-induced and coincided with steadily increasing water levels.

The reservoir reached, and was consistently near capacity during the period from 1990 to 1996. During this time, the majority of seismic activity near the Thomson Reservoir had migrated to greater depths and away from the reservoir, with decreasing activity levels.

On the 25th September 1996, a magnitude ML 5.0 earthquake occurred at a depth of 12 km adjacent to the reservoir. The mechanism of this event showed southeast to northwest compression, consistent with it occurring on the nearby Yallourn Fault. This was followed by a period of intense seismicity with approximately 200 aftershocks recorded over more than a year.

Recent records indicate that the area seems to be approaching the end of the period when triggered earthquakes are likely with activity levels now similar to those existing prior to commencement of filling. The decreasing earthquake activity rate since 1996 however, coincides with steadily decreasing water levels at the reservoir.

1. RESERVOIR-TRIGGERED SEISMICITY

Since Carder (1945) first reported on the apparent increase in seismicity at Lake Mead in the United States, the number of cited cases of reservoir-triggered earthquakes has steadily increased worldwide.

Reservoir-triggered earthquakes are triggered by several mechanisms: (1) elastic stress increase following the filling of the reservoir, (2) an increase in pore water pressure in saturated rocks due to the decrease in pore volume caused by compaction in response to the surface water load, and (3) an increase in pore fluid pressure due to diffusion of water (Bell and Nur, 1978; Gupta, 1992).

Given the deepest reservoirs only generate surface loads of approximately 2 MPa, it seems that direct activation from the water load is unlikely (Bell and Nur, 1978).

2. THE THOMSON RESERVOIR

Background: The Thomson reservoir is located on the Thomson River, east of Melbourne, and north of the Latrobe Valley. The reservoir is bounded to the west by the Baw Baw Plateau and to the east by a narrow ridge separating the Thomson River from the parallel flowing Aberfeldy River (MMBW, 1975).

In 1973, the Victorian State Government in association with the MMBW announced the approval of the Third Stage in the Thomson River Development. Construction of the 165 m high embankment dam, one kilometre south of the Talbot Creek inlet commenced in 1976, and was completed by 1983. The dam now creates a reservoir extending 23 km upstream, with a capacity of approximately 1.1 million megalitres, and inundates approximately 2,200 hectares (MMBW, 1975).

Geology: The Thomson Reservoir region possesses two main formations of Paleozoic rocks – the Upper Devonian Baw Baw Granite, and a conformable folded sequence of Silurian and Lower Devonian sedimentary rocks which are intruded by the granite. The eastern margin of the granite lies west of and sub-parallel to the Thomson River and dips approximately 70° east under the reservoir (MMBW, 1975). The sedimentary rocks possess numerous folds with north to south striking axial planes, but tend to curve around the granite mass. Faults in the region are commonly associated with these axial fold plains (MMBW, 1975).

The dominant structural feature of the area is the Yallourn Fault which trends southwest to northeast, outcropping about 25 km southeast of the Thomson Dam. The fault dips northwest approximately 12 to 14 km under the reservoir and its fault scarp is readily apparent north of the Latrobe Valley, with cumulative vertical movement of hundreds of metres. In Australia, reverse faults often dip about 30° to 40° under the up-thrown block (Gibson and Wesson, 1979).

3. THOMSON RESERVOIR SEISMOGRAPH NETWORK

In 1977, the MMBW commissioned the Seismology Research Centre (SRC) to install a network of seismographs to monitor the seismicity around the Thomson Dam area. The aim of the project was to locate the earthquake occurrences before, during, and after the initial filling of the reservoir. Other aims of the project were to: (1) study the spatial distribution of earthquakes, (2) determine earthquake magnitudes, (3) investigate reservoir-triggered seismicity, (4) obtain an indication of earthquake focal mechanisms, (5) monitor the response of the dam and outlet towers to vibratory motion from these earthquakes and (6) if possible, predict future patterns of earthquake occurrence (Gibson, 1976).

The initial installation of the Thomson Dam seismograph network consisted of five digital seismographs, installed between May 1977 and February 1978 (Gibson, 1978).

4. HISTORY OF SEISMICITY

The Thomson Reservoir and surrounding region is relatively seismically active by Australian standards. Figure 1 shows the entire catalogue of earthquake activity about the Thomson Reservoir since 1976. The seismicity in the region has been divided into several time periods to demonstrate the spatial and temporal migration of earthquake activity. Figure 2 shows the epicentral distribution of the earthquakes over the designated time periods.

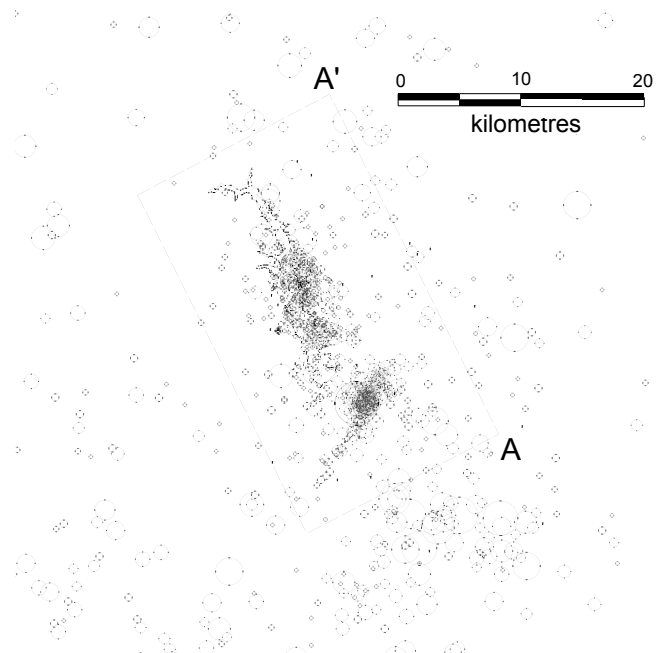


Fig. 1. Total earthquake activity about the Thomson Reservoir since 1976 with respect to the reservoir.

Pre 1976: Few accurate earthquake locations in the area were known before reasonable seismograph coverage in Victoria commenced in 1960, although many reports of earthquakes being felt in the Walhalla, Erica and Moondarra areas were made prior to the advent of this network. In the period from 1891 to 1907, several strong ground motions were felt in the Walhalla-Moondarra areas. One event in 1901 is reported to have destroyed several buildings and was estimated to have a maximum epicentral intensity of 7 on the Modified Mercalli scale (Gibson, 1977). A long period of quiescence ensued during which there was no significant seismological reporting. No major earthquakes occurred in the area from 1960 to 1976, however the new seismographs operated by the Bureau of Mineral Resources and Australian National

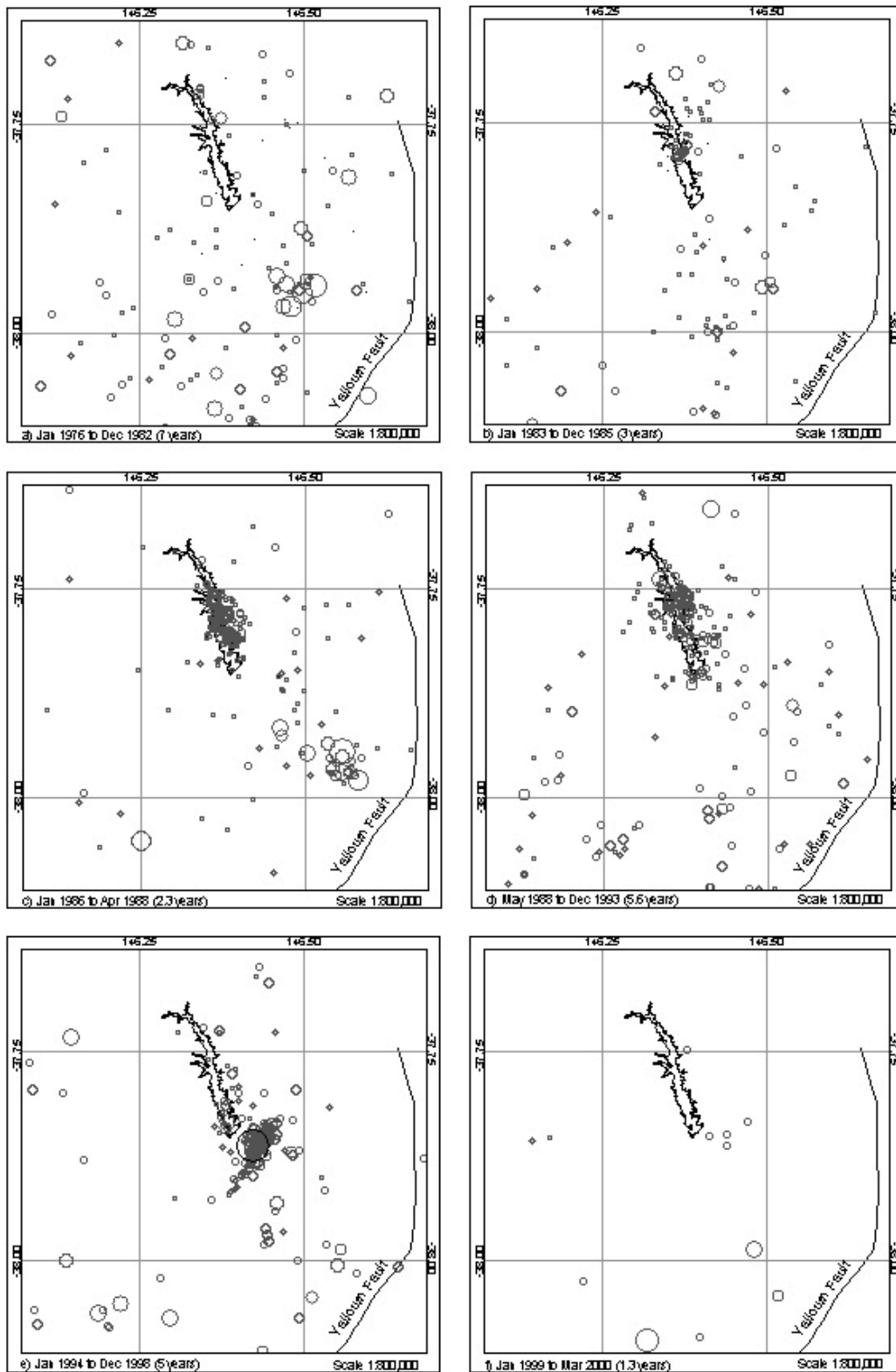


Fig. 2. Seismicity about the Thomson Reservoir since 1976. Circles indicate earthquake location with respect to the reservoir (diameter in mm is equivalent to local magnitude ML).

University respectively, did permit the location of smaller events recorded instrumentally. Five earthquakes with Richter magnitudes of around 3.5 were documented during this period.

January 1976 to December 1982: (Figure 2a) Since the beginning of 1976, the SRC has operated and maintained a number of microearthquake seismographs throughout Victoria, permitting the location of even smaller events. In 1976, this allowed the location of three earthquakes with Richter magnitudes greater than 2 in the Moondarra area (Gibson, 1977). With the completion of the Thomson Reservoir network in 1978, it became clear that the Gippsland area possessed a higher level of background seismicity than average for Victoria (Gibson, 1978).

January 1983 to December 1985: (Figure 2b) In 1983, Stage Three of the Thomson River Development was complete, and filling of the reservoir commenced that year. In November of 1983, a swarm of 37 earthquakes occurred in a small volume about 6 km northwest of the Thomson Dam at a depth of about 11 km. They were all very small events, the largest magnitude being about ML 1.5. The occurrence of the swarm so soon after the commencement of filling suggests that there may be some relationship. However, the 11 km depth of these events is much greater than would normally be expected for reservoir-triggered seismicity caused by increased pore fluid pressure. Similarly, a modification of the regional stress field appears to be an unlikely mechanism given the large depth and the small magnitude of the events. In addition, the reservoir was only at 3 per cent of its capacity at that time (Gibson and Wesson, 1983). Hence it follows that the location of the swarm may just have been coincidental. Apart from the cluster, few events occurred in the three years subsequent to commencement of filling, although seismicity was marginally higher than that of pre-filling with an activity rate of a little over one event per week (Gibson and Wesson, 1986). The reservoir level at the end of this period had increased regularly to approximately 40 m below capacity.

January 1986 to April 1988: (Figure 2c) From 1986, shallow earthquakes within 3 km of the surface began occurring immediately under the reservoir, with magnitudes to ML 3, at rates of up to 5 events per week. These events were almost certainly reservoir-triggered, resulting from water diffusion increasing pore fluid pressure beneath the reservoir.

Earthquakes located within the rectangular polygon (see Figure 1) were employed to quantitatively examine earthquake focus migration with depth and are illustrated in cross-sections along the line A to A' (Figure 3). Figure 3a shows earthquake migration with respect to depth for the period of January 1986 to April 1988.

May 1988 to December 1993: (Figure 2d) During the period from 1988 until December 1993, the seismicity near the Thomson Reservoir area migrated to greater depths, down to about 12 km, and away from the reservoir, with decreasing activity levels (Figure 3b). This behavior is typical of reservoirs in their first ten to twenty years, and can be explained by the increasing pore water pressure in the system migrating to greater depths at a relatively slow rate (depending on rock permeability), until arriving at a state of equilibrium.

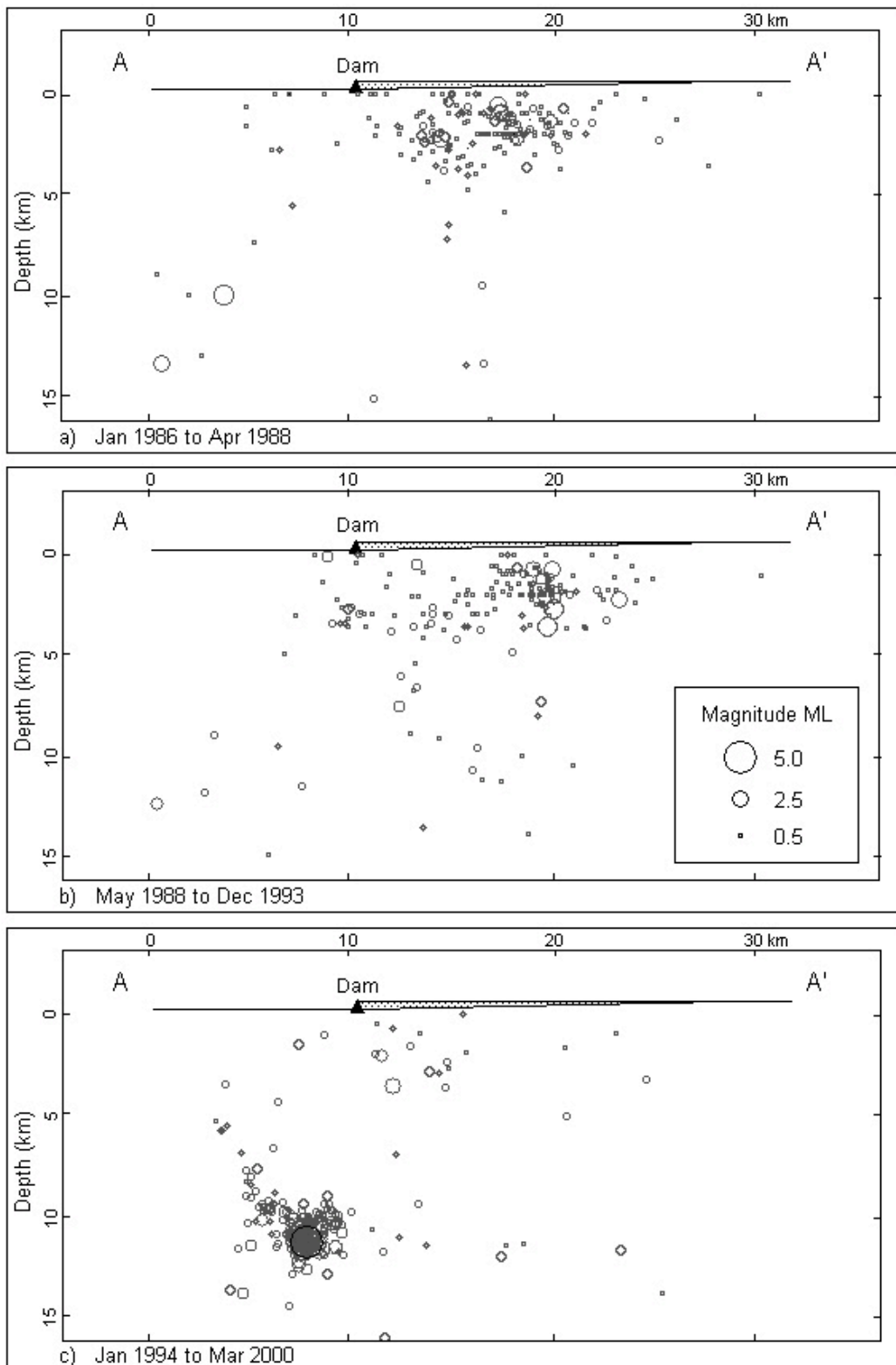


Fig. 3. Earthquake migration beneath the Thomson Reservoir with respect to time. The dam wall and reservoir level have been exaggerated.

January 1994 to December 1998: (Figure 2e) From 1994, earthquake activity at the Thomson Reservoir was consistently at depths between 9 and 12 km with further decreasing activity levels.

On 25th September 1996 at 05:49 pm EST, an ML 5.0 earthquake occurred at a depth of 12 km adjacent to the reservoir. The earthquake was felt strongly in the Thomson area, and as far away as Melbourne. Several strong motion accelerograms were recorded. The earthquake was preceded at 02:53 pm the same day by a foreshock of magnitude ML 3.3 at the same location. Many aftershocks followed for several months. In the first quarter (1 October to 31 December 1996) following the main shock, 99 aftershocks were recorded. Several of these exceeded magnitude ML 2.0. During the next quarter 21 aftershocks were recorded. The number of aftershocks continued to decrease each quarter for two years until no events were recorded at the reservoir for the quarter ending December 1998.

The location of the cluster suggests that the earthquakes occurred on the Yallourn Fault at depths between 9 to 12 km adjacent to the reservoir (Figure 3c). These earthquakes can be explained by an increase in water pore pressure in a highly prestressed environment.

It should also be noted that from 1990 until late 1996, the reservoir reached and was consistently near capacity.

Since 1998: (Figure 2f) Relatively few earthquakes have been recorded at the Thomson Reservoir since the abatement of aftershocks. Coincidentally, water levels at the reservoir have also decreased significantly since 1996 to a capacity similar to that of the first cycle of filling in 1986.

5. THE 1996 THOMSON EARTHQUAKE

The location of the ML 5.0 Thomson earthquake suggests it was most likely on the Yallourn Fault. Plotting the first motions of the direct seismic waveforms on a lower hemispherical projection, the mechanism for the earthquake was observed to possess southeast to northwest compression, consistent with reverse faulting of the Yallourn Fault (Figure 4).

Determinations of the mechanisms for the aftershocks were attempted via moment tensor inversion, but limitations in the software prevented the successful computation of focal mechanism solutions. The moment tensor is an important parameter in earthquake seismology as it describes the seismic source in three dimensions and gives

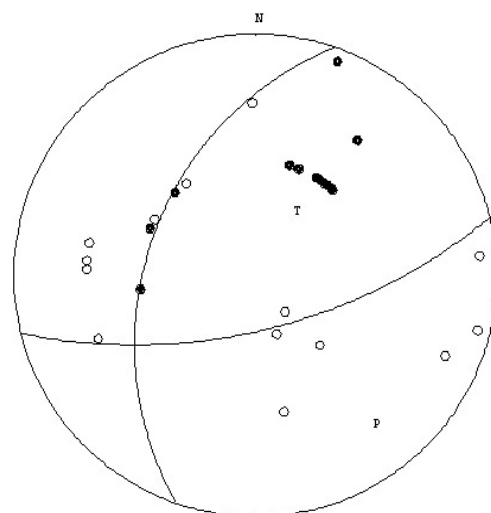


Fig. 4. Focal mechanism for the ML 5.0 Thomson Earthquake plotted on a lower hemispherical projection. The open and filled circles represent dilatational and compressive first motions respectively, illustrating southeast to northwest compression.

an indication of the local stress regime. The deficiency of the inversion techniques however may result from the presence of the Baw Baw Granite affecting the take-off angles of the elastic seismic waves. Therefore, in order to achieve a successful inversion, a 3-dimensional velocity model must be developed.

6. CONCLUSION

There is little doubt that the earthquakes occurring about Thomson Reservoir following commencement of filling in 1983 were reservoir-triggered. Records acquired for the Melbourne Water Corporation by the Seismology Research Centre provide one of the best documented examples of triggered seismicity in the world, and demonstrate the importance of water pore pressure, permeability and diffusion in this process.

On the 25th September 1996, the magnitude ML 5.0 earthquake occurred at a depth of 12 km near the reservoir. The focal mechanism of the main shock showed northwest to southeast compression, consistent with the reverse faulting expected for the Yallourn Fault. The mechanisms of the aftershocks are more complicated. However, their locations correspond to also having occurred on the Yallourn Fault. In order to explain the apparent complex nature of the focal mechanisms of the aftershocks, a comprehensive 3-dimensional velocity model for the area should be developed.

The area now appears to be approaching the end of the period when triggered earthquakes are likely, and the earthquake activity is trending towards pre-filling levels. This assumes that increased pore pressure is the driving mechanism. However, given water level information from the reservoir, it could be argued that the mechanism for earthquakes occurring between 1990 and 1996 was an effect of a stress increase due to the surface water load rather than an increase in pore water pressure. Consequently, how the reservoir responds to refilling is unknown and will be of great interest.

7. REFERENCES

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