



Experiences Developing and Applying an Anuga Dune Erosion Operator to Assess Risk from Loss of Dune Protection During a Tsunami

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In 2009, Geoscience Australia undertook modelling of tsunami impacts on the south-east coastline of Tasmania using the 2D hydrodynamic model ANUGA. At that time both bathymetric and topographic data were limited and the modelling was focussed on quantification of inundation extents in specific coastal villages considered at risk from a range of possible tsunamis. In 2016, Mineral Resources Tasmania (MRT) was requested to update this earlier work using currently available data and to additionally consider the impact of a worst-case tsunami on Hobart airport and on shipping and maritime safety in the Derwent estuary. In developing and running these updated models, it became clear that some low-lying areas of the coast were being protected from inundation by elevated frontal sand dunes. This raised questions as to the possibility of these dunes eroding during a tsunami, increasing the extent of inundation and risk in these otherwise protected rear dune areas. An ANUGA 'Operator' was therefore developed to allow dune erosion to be included in the model, so that a recommendation could be made as to the need to incorporate dune erosion in future modelling of these areas. This Operator in turn permitted any significant change in risk in these otherwise protected areas, to be assessed. This paper describes the development of this Operator, its incorporation into the ANUGA based tsunami model, and the results obtained from the erosion enabled model. ANUGA and the dune erosion Operator are both free and open source software.

1. INTRODUCTION

Modelling performed by Geoscience Australia in 2009 suggested that parts of the southeast Tasmanian coast could be significantly affected by a tsunami generated from a rupture of the Puysegur subduction zone, off New Zealand's southwest coast (van Putten et al., 2009). Since these results were published, emergency managers in Tasmania have sought greater detail regarding the impacts of such an event on key infrastructure and communities.

In 2015, a project to further quantify the likely impact of a major tsunami on coastal villages was commissioned by the State Emergency Services in Tasmania, and funded by a grant from the Natural Disaster Resilience Grants Program (Australian Government and Tasmanian Government), with the further support of Mineral Resources Tasmania.

A new Southeast Tasmanian (SETAS) tsunami model was created for this purpose, based on the advanced functionality available in ANUGA 2016. This project aimed to specifically address the danger to maritime activities in the Derwent estuary and to Hobart airport, as well as to populated areas and key transport routes close to the coast. The study area extended from West Cape to Bicheno (Figure 2) and covered an area of approximately 17,000 km².

The agreed modelling strategy comprised five scenarios, of which scenario 5 (SC5) involved consideration of the impact of dune erosion on coastal inundation limits and risk at Hobart airport.

SC1: Comparison of GA 2009 results with those from MRT's new model using the 2009 data

SC2: Comparison of GA 2009 results with those from MRT's new model using more recent data

SC3: Simulation of maritime hazards in the Derwent Estuary (13 hours simulation)

SC4: Simulation of coastal inundation and hazard at selected coastal sites (4 hours simulation)

SC5: Simulation of inundation and hazard at Hobart Airport (4 hours simulation)

MRT acquired and processed the required input data and provided reporting on the results obtained. Rienco Consulting was engaged as technical advisor to the project and to develop the new tsunami modelling scripts. Consultants Entura were engaged to execute the scripts for scenarios 1 to 4 and Rienco Consulting to execute the scripts for scenario 5.

In undertaking these simulations, it became clear that there were several locations within the modelled area where sand dunes could be providing some level of protection for property or assets behind the dune line. Hobart airport is one such location. To better understand and quantify the protection provided by these dunes, a new model was needed that could include consideration of erosion of the dunes, during the simulation process. At the time the study commenced, ANUGA had no such functionality but it did include tools, in the form of 'Operators', that could be developed for this purpose. This paper describes the development and incorporation of such an Operator into the South-East Tasmanian tsunami modelling scripts and its application to identify areas where more detailed modelling, incorporating dune erosion, might be needed to properly quantify risk.

2. THE DUNE EROSION OPERATOR

2.1. The Anuga Environment

ANUGA was developed by Dr Stephen Roberts of the Australian National University, together with Ole Nielsen, Duncan Gray and Jane Sexton from Geoscience Australia. It is currently being developed and maintained by Dr Stephen Roberts and Gareth Davies from Geoscience Australia. ANUGA is a free and open source software package, available and distributed under the terms of the GNU General Public Licence.

ANUGA is a hydrodynamic modelling library that allows users to construct models that realistically simulate complex depth averaged, two dimensional (2D) horizontal flow behavior. It was initially developed in 2005 to simulate near and on shore propagation of a tsunami, but in recent years has also found use as a general purpose flood model.

To run a simulation, a model specific set of Python scripts must be created by the user from the ANUGA library. Model inputs to these scripts include a variable mesh of triangular cells that fill the model domain, the domain topography and bathymetry, frictional resistance, initial values for water level (called stage within ANUGA), boundary conditions and ANUGA Operators such as rainfall, stream flows, wind-stress and pressure gradients.

When the Python scripts are run, ANUGA tracks the evolution of water depth and horizontal momentum within each cell over time, by solving the shallow water wave equation using a finite-volume approach. Most ANUGA library components are written in the object-oriented programming language Python.

Computationally intensive components of the library are written for efficiency in C, working directly with Python numpy structures.

An Operator class was added to the ANUGA library shortly after its initial release, to facilitate user control of the solution process at each computational time step. Operators permitted users to include spatially and temporally variable rainfall in their model scripts in a simple manner and to incorporate specialised structures such as culverts. As an Operator has direct access to the centroid values of a cell (stage, xmomentum, ymomentum, bed_elevation) during each computational step, it can provide a means of modifying the bed elevation at each computational step, to simulate dune erosion in user defined areas. The development and application of such a 'Dune Erosion Operator' is described in the following sections.

2.2. Development of The Dune Erosion Operator

2.2.1. Reviewing the Erosion Processes To Simulate

In preparing to code this Operator, it was necessary to decide whether it should include full erosion/transport/deposition functionality. Linked to this consideration was the further question as to whether a clear water or sediment laden approach would need to be simulated. As the prime objective of the dune erosion Operator was to quantify the potential increase in risk, from a tsunami scouring out a protective dune line, the focus was on the erosion process rather than the subsequent transport and deposition processes. With the specific intent of this modelling in mind, it was resolved to proceed with a simple, erosion only, Operator. While the approaching wave would likely include some sand in suspension, it was not considered quantifiable or high enough in level to warrant the use of non-clear water scour functionality in the Operator.

In general, three processes are involved in the removal of sand when water overtops the dune line.

- The detachment of sand by water flowing over the surface of the sand.
- The collapse of sand faces that have been steepened beyond the point of collapse by the erosion process.
- The fluidisation of sand in the rear face of the dune due to an elevated phreatic surface.

Of these three processes, detachment occurs first, closely followed by collapse of any faces steepened beyond their stable slope by the detachment process. These first two processes occur relatively instantaneously in response to the water flow and therefore require simulation to create a realistic response by the Operator.

The third process takes significantly longer, requiring penetration of water from the ocean side into and through the sand mass during the rising limb of the incoming wave (reversed as the wave recedes). Given the significantly longer time scale of this process, it was not deemed necessary to include it in this Operator.

2.2.2. Quantifying the Incorporated Erosion Processes

On the basis of the above, the erosion mechanism adopted assumed a clear water scour with no significant sediment entrained in the approaching wave that could impact detachment rates. It also assumed an environment where the detached sediment remained well within the transport capacity of the water column in the eroding area (viz. no deposition - only erosion within the target area).

The erosional relationships and parameters adopted in this application of the Operator are from the work by Dr David Froelich (2002) in which he investigated erosional rates associated with water flowing at different depths and velocities over different soils. While other relationships have been developed by other researchers, the relationships developed by Dr. Froelich are simple to apply and were considered more than adequate to establish whether or not dune erosion is a factor affecting inundation risk at some locations in the study area. Erosional parameters used in development of this Operator are;

$$\text{Bed shear stress; } \tau_{\text{bed}} = \frac{Wd * G * n^2 * m^2}{d^{2.333}} \text{ Pa} \quad (1)$$

Where:

Wd is water mass density. (1000 kg/m³)
 G is acceleration due to gravity. (9.8 m/sec/sec)
 n is Manning's n. (sand n = 0.025)
 m is absolute momentum. ((mx²+my²)^{0.5})
 d is water depth. (ANUGA stage-elevation m)

Dr Froelich's work demonstrated that erosion occurs when the bed shear stress (Eq 1) is greater than the critical (detachment) bed shear stress (Tau_crit = 2.1 Pa for sand) and the detachment rate associated with this process when Tau_bed exceeds Tau_crit is (Eq 2);

$$\text{Detachment Rate;} \quad S_k = \frac{Kd * (\tau_{bed} - \tau_{crit})}{Sd} \quad \text{m}^3/\text{sec}/\text{m}^2 \quad (2)$$

Where:

Kd is the detachment rate. (0.0250 Kg/sec/m²/Pa)
 Sd is sediment mass density. (1800 kg/m³)

It should be noted that while Dr Froelich's work provides erosional properties for other soils, this dune erosion Operator only uses parameters for, and is specific to, the erosion of sand.

The second process simulated by this Operator is the collapse, fluidisation and removal of sand from the dune system as a consequence of the erosion process creating face slopes that would be steeper than their angle of repose. This is applied in the Operator after the erosion computations for a particular timestep have been completed to compute a new stable surface. Each triangle within the specified erosion zone is checked to see if the elevation of the Center of Gravity (CG) of any neighbouring triangle lies above the angle of repose line from the lowest neighbour's CG. If so, then the neighbouring triangles CG elevation that is above the repose angle is adjusted to lie at the angle of repose relative to the lowest neighbour's CG. This adjustment is also made to the current triangle's CG, if it is also above the repose angle relative to the lowest neighbour's CG. A check is performed to prevent any reduction in elevation that would lower a triangle's CG below the specified no-scour base level. While this algorithm allows each triangle's elevation to be reviewed and adjusted up to three times in each timestep, it cannot guarantee all triangles will be fully adjusted back to a stable face. Given the multiple iterations at each time step and small size of each time step, the above was however considered adequate for the purposes of this study.

2.2.3. Coding the Dune Erosion Operator

The dune erosion Operator is coded in Python (2.7) and makes direct use of the Operator class defined in ANUGA. The Operator is spatially restricted to areas of interest by individual erosion zone polygons (shapefiles) created by the user. These polygons also set the level below which simulated scour cannot occur in each polygon. The erosion parameters are directly coded into the Operator as discussed in the preceding section. Coding is structured such that an alternative relationship for scour or collapse can be incorporated, if desired.

2.2.4. Testing the Dune Erosion Operator

A simplistic model was constructed for testing purposes, incorporating a notched dune 1.4 m high with 1:1 face slopes, followed by a level dune 1.0 m high, also with 1:1 face slopes. The notched dune no-scour base was set at 1.0 m with the level dune no-scour base at 0.3 m. The stable face slope was set at 34 degrees. While undertaken without field data to validate this simulation, the notched dune crest deepened and widened, maintaining the appropriate angle of repose and the level dune uniformly eroded in both a downward and rearward manner, all as properly expected. Manual spot checks on erosion rates confirmed that erosion was progressing in accord with the rates specified in the Operator. Images of the erosion part way into the simulation are reproduced in Figures 1a to 1c. Figure 1a shows the notched dune face scoured down to the no-scour base and the basin between the notched and level dunes starting to fill. Figure 1b shows the notched dune face further scoured and the interbasin water level rising. Figure 1c shows the interbasin area filled, the downstream level dune overtopped and uniformly scoured on the downstream face, to its no-scour base. Each graphic is reproduced with a 5:1 vertical exaggeration to more clearly show the scour geometry as time passes.

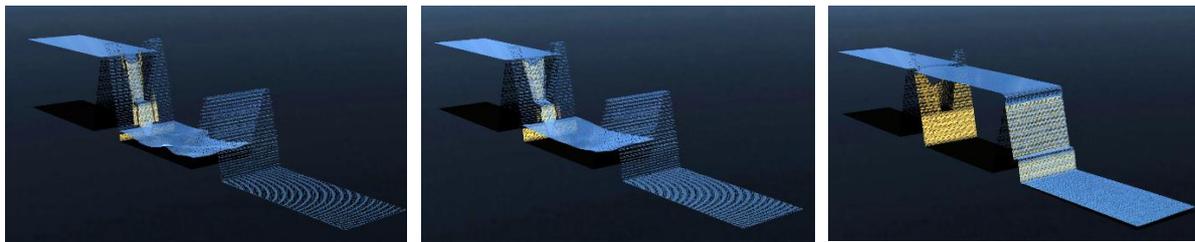


Figure 1a – t= 60 secs

Figure 1b – t=120 secs

Figure 1c – t= 360 secs

Figure 1 – Test of Dune Model Erosion Operator

The test model highlights the significant vertical components of flow that will occur in flow down a relatively steep surface such as those in the test model. The basic assumption that vertical components of flow in a 2D model will be minimal is clearly violated in such circumstances. Steep surfaces also present difficulties for erosion simulation in that shear forces no longer apply to a horizontally aligned surface and the true area of each surface element is significantly more than that of its horizontal projection. Notwithstanding these limitations, no solution to these limitations could be found without moving to a 3D model. Given the realistic response of the test model and the well correlated blind testing undertaken by Dr Froelich in 2002 of the underlying relationships used in this Operator, the 2D based dune erosion Operator was considered adequate for the purposes of this particular study, and adopted, recognising these limitations.

2.3. Integrating the Operator into the Tsunami Modelling Scripts

As several other scenarios had previously been modelled in the SETAS domain, a model was in place that could be extended to incorporate consideration of dune erosion. Integration of the Operator involved reading the erosion polygons with their no-scour base level into the model using a third party shapes.py library and adding code to call the Operator.

In adding the Operator to the SETAS tsunami model, a line of code was added for each of the 12 erosion zones in the model, as each erosion zone is independently managed by its own Operator. This line is required prior to the ANUGA evolve (simulation) loop to activate the Operator during the evolve loop. The call format is as follows.

```
# op6 – Dune Erosion Operator 6 (Dolphin Sands)
op6 = sanddune_erosion_operator( domainbase = nsbase_elev_c,
                                polygon=model_data.erosion_polygons[6][0],
                                verbose=model_ini.model_verbose)
```

As previously noted, each Operator references the associated erosion zone polygon and the no scour base level associated with that polygon. While an outwardly straightforward process, this integration step did not proceed smoothly due to the need to accommodate computation in a partitioned domain, but with some initial assignments in the global domain. At this point, Dr Roberts (one of the ANUGA developers) was consulted and an appropriate coding sequence established that overcame these difficulties.

In developing this additional model code, all dune erosion code was made conditional to facilitate switching between erosional and non-erosional simulations of otherwise identical models. This then permitted the relative impacts of dune erosion on inundation extents, depths and velocities to be easily quantified.

3. APPLICATION OF THE EROSION ENABLED MODEL

The modelled domain and locations of the 12 sites initially selected for review of the impact of dune erosion on risk during a major tsunami are shown in Figures 2 and 3. As in scenarios 1 to 4 (SC1 to

SC4), the modelled event was associated with hypothetical movements in the Puysegur trench, located to the immediate south of New Zealand, with an AEP of about 1:13000 (Geoscience Australia, 2009). Temporal wave data resulting from this hypothetical event, at about 100 m depth off the SE Tasmanian coast, was supplied by Geoscience Australia. The model domain is shown in red in Figure 2, with the stations at which temporal wave data were provided, as black dots. The inset in Figure 2 extracted from Hayes and Furlong (2010), shows the spatial relationship between the trench and the southeast coast of Tasmania, together with tsunami travel time contours from the Puysegur trench. As indicated in this graphic, travel time from the Puysegur trench to the south-east coast of Tasmania is a relatively short two hours.

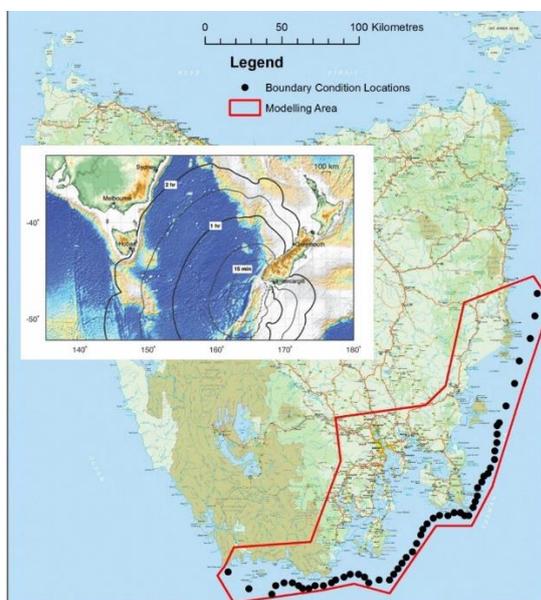


Figure 2 – The SETAS Model Domain



Figure 3 – The Dune Erosion Zones

As the focus of Scenario 5 was initially in regard to the potential inundation of Hobart airport, this area was modelled at a relatively fine resolution (10 m triangles). Eleven other areas were modelled at the same resolution as the coastal strip (50 m triangles) as the purpose was only to establish if further, more detailed, modelling would be required in these areas, to quantify increased inundation levels from erosion of their protective dunes. Depending on location, a base no-scour elevation of 1 to 3 m AHD was set in these areas.

At the airport site, the dune erosion simulation indicated that peak wave height and dune height were comparable (as in previous scenarios), resulting in only minor erosion of the dune line at the western end of the beach, well away from the airport. In the immediate vicinity of the airport, this simulation showed that the existing dune line would remain intact.

Of the 11 other sites included in this simulation, the dunes at Dolphin Sands, Cremorne Lagoon and South Arm remained intact. All other sites suffered significant erosional dune loss during the simulated tsunami. While the consequences of loss of this protection varies, depending on the extent of property or infrastructure put at risk by this increased exposure, it is strongly recommended that all of the remaining 8 sites be modelled at increased resolution with locally specific erosion parameters, to quantify the impact of dune erosion, on risk at these sites.

The coastal holiday village of Doo Town fronts Pirates Bay on the east coast of the Tasman Peninsula. This is one of the sites at which the likely impact of dune erosion on inundation during a tsunami was investigated and provides a qualitative view of the consequences of loss of dune protection at that site.

Figure 4 shows the penetration of the tsunami at this site just after the first wave has peaked, together with the stage time series in the bay at the location indicated. Figure 5 shows the erosion rate of the protective dunes at the circled location, with most loss in two episodes, one at $t = 0.5$ hrs and the other at $t = 1.7$ hrs, some 72 minutes apart. The elevation time series of Figure 6 shows these two periods of

greatest erosion occurred with the arrival of the first and sixth wave in the series, both waves having the greatest peak elevations in the series.

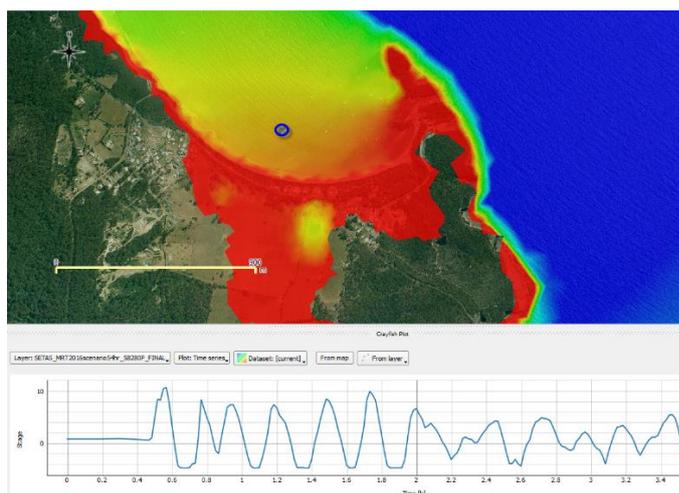


Figure 4 – Doo Town Inundation

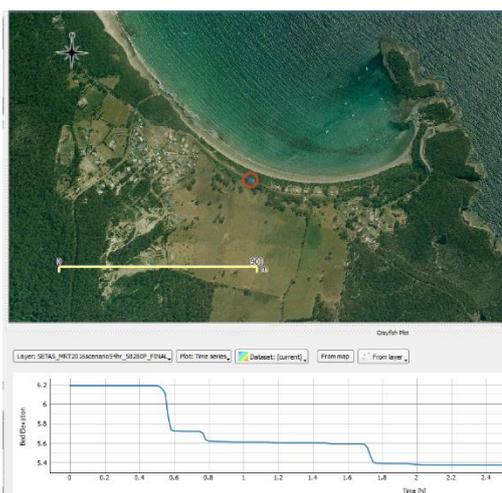


Figure 5 – Doo Town Dune Erosion

Figure 6 shows the erosional depth contours of the dunes after four hours of exposure to the tsunami. As expected, the greatest erosion depths are in and adjacent to the locations where the dunes are lowest. Approximately 240,000 m³ of sand was removed from this dune line during this simulation.

Figure 7 shows the increased inundation levels in the rear dune area as a consequence of partial loss of the protective dune line. The maximum reduction in water surface elevation is on the ocean side of the area of greatest dune erosion and the maximum increase in elevation on the land side of that same location.

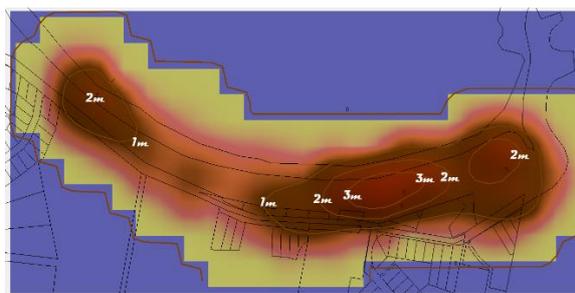


Figure 6 – Doo Town Dune Erosion Depths

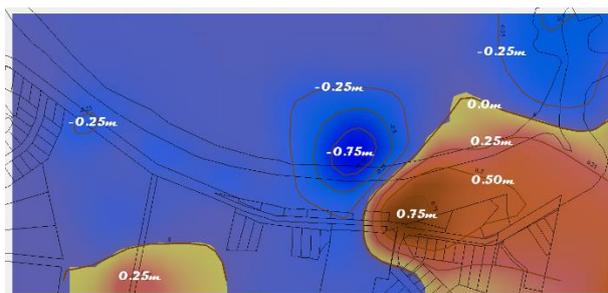


Figure 7 – Doo Town Inundation Impacts

While the results for this site appear sensible, it should be noted that they are from a model with a relatively coarse mesh in the area of interest (50 m triangles) and are based on the average erosional parameters adopted for all sites.

It is also noted that while the erosional parameters used in this modelling were developed from large scale testing by Dr Froelich, they do not distinguish between sand that is relatively bare, from sand that is well stabilised with grasses, shrubs and trees. It is therefore unclear as to what extent well stabilised dunes would, at least initially, lose material relative to the rates used in this modelling. Further investigation in this area is highly desirable before adopting any results in these potentially protected areas. Given the scale of topographic change in the dune field at all 8 sites and significant local differences in dune cover, it is recommended that the present element size be decreased to 20m or less in these areas and the model re-run with locally appropriate dune erosion parameters, to establish inundation extents suitable for input to the mapping process. Prior to undertaking this more detailed modelling, it would also be prudent to undertake more deliberate testing of the Operator and to consider possible alternatives to the relationships proposed by Dr Froelich in the Operator.

4. CONCLUSIONS

1. Where partial erosion of a protective dune line during a tsunami could increase the level of risk for persons, property or other assets located behind this dune line, it is important to quantify that increased risk, as in some circumstances it can be very significant.
2. When augmented with an appropriate dune erosion Operator, the ANUGA library can be used to construct a hydrodynamic model capable of simulating the hydraulic impact of erosion of a protective dune line on inundation in the rear dune area and to assess any increase in risk this might present.
3. The ANUGA Operator described in this paper is provided as a free and open source tool to facilitate this analysis.
4. Modelling of tsunami impacts on the south-east coast of Tasmania using the ANUGA library with the above dune erosion Operator, has confirmed that the 2016 dune line protecting Hobart airport would not be breached by the simulated 1:13000 AEP tsunami event.
5. This modelling does however confirm that eight of the coastal sites included in the extended study are areas where erosion of their protective dune line could significantly increase the risk from inundation, by a tsunami of the magnitude simulated. It is recommended that the present model Operator be further tested to increase confidence in its use and the erosion enabled model re-run with increased resolution and locally relevant parameters in these potentially protected areas, to:
 - a. more realistically simulate overtopping and erosion of the topographically variable dune line.
 - b. more realistically reflect the impact of dune compositional and cover differences at each site, on detachment rates.
 - c. permit a more realistic assessment of risk in these areas and to support development of appropriate inundation mapping and emergency management plans for these areas.

5. ACKNOWLEDGMENTS

Funding for this project was provided by the Natural Disaster Resilience Grants Programme (NDRGP), in conjunction with Mineral Resources Tasmania. We would like to particularly acknowledge the considerable assistance provided by Dr Stephen Roberts of the Australian National University in this work. Colin Mazengarb and Claire Kain publish with the permission of the Director of Mines, Tasmania.

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