Using airborne gravity data to better define the 3D limestone distribution at the Bwata Gas Field, Papua New Guinea

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SUMMARY

As part of an appraisal program by InterOil of the Bwata gas resource and prior to undertaking further 2D seismic surveying, a 3D geology model of the project was rapidly built using the 3D GeoModeller software.

The software implements a methodology developed in the BRGM to jointly interpolate geological contact data and dips of geology formations. The method uses the chrono-stratigraphic order of geological formations, and their rock-relationships. The model is calculated using an implicit 3D potential function as the interpolator for each component part of the geological history. The order and relationships recorded in the stratigraphic column are used to automatically resolve the intersections between component parts, and produce volume reconstructions. The methodology allows the geologist to focus on geological issues and consider alternative interpretations.

The 3D structural geology model was built using a single 2D seismic line, well data from the Bwata-1 and Triceratops-1 wells, surface geological data and airborne gravity data. Eight cross sections across the Bwata Anticline were created from surface geology, seismic and well data in 2D Move. These sections were imported into 3D GeoModeller. A 3D model was then created and the forward gravity response computed. Density variations from general background of 2.24 t/m^3 are provided by the Cretaceous Ieru Formation at 2.40 ± 0.05 t/m^3 and the Puri and Mendi Limestones at 2.70 ± 0.05 t/m^3. The *computed* response was compared to *observed* data derived from an airborne gravity survey. On the basis of such comparisons several iterations of geologic revision were proposed to improve the fit between the computed and observed data.

The outcome of this study was the prediction of the geological setting and the extent and thickness of the limestone beds. The model incorporated c. 30 degree dipping thrusts and a steeper backthrust and introduced two NE/SW near vertical faults which exhibit a sinistral strike slip and east-side-up displacement. A substantial increase in the size of the field was interpreted at its western end. Using the 3D model will enable InterOil to design a follow-up 2D seismic survey with greater confidence that the survey will meet program objectives.

Key words: 3D geology model, gravity forward modelling.

INTRODUCTION

The Bwata Gas Field is located in PPL 237 in the Eastern Papua Basin, Papua New Guinea (Figure 1). As part of an appraisal program of the gas reservoir and prior to undertaking further 2D seismic surveying, a realistic 3D geology model was constructed. Using the model, and known density values for the modelled formations, the forward gravity response was computed and compared to observed gravity data derived from an airborne survey.

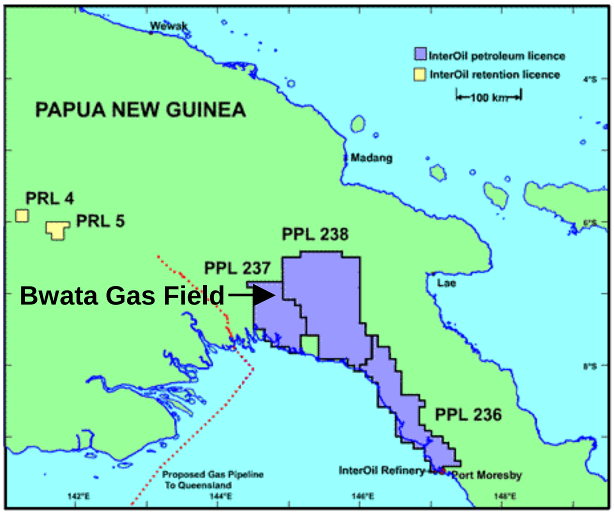

Figure 1. Location of the Bwata Gas Field in PPL 237, Papua New Guinea.

To perform forward modelling of the gravity and/or magnetic signatures of a project area using a realistic 3D model of the project geology requires the following four elements:

- An initial, realistic 3D geology model – (often constructed from quite sparse data due to sparse sampling of the geology as a consequence of cover, or the expense of acquiring data at depth);
- Knowledge of the physical properties of the component geology formations;
- An established procedure to use this 3D distribution of physical properties and compute the geophysical responses of the model, and to compare those *computed* signatures with *observed* field data from the project area;
- A methodology to rapidly revise the 3D geology model in order to propose geologically and structurally plausible amendments, and so attempt to improve the fit between computed and observed geophysical responses.

It is this latter point – an ability to rapidly revise the 3D model - that is fundamental to the approach presented here. Depending on how a model has been constructed, it can be an onerous task to make changes. The solution is to automate the task, and compute a model directly from data (the geologic observations). A revision, then, implies (1) adding the new data (or editing data), and (2) re-computing the model from the modified database. This approach has been implemented in a new 3D geology modelling software package - 3D GeoModeller (http://www.geomodeller.com).

In this paper, the 3D methodology is discussed in the context of the modelling project completed at the Bwata Gas Field. The validity of the model was then tested by computing the expected gravity signature of the model and comparing that with the observed gravity data. On the basis of such comparisons several iterations of geologic revision were proposed, a revised 3D model rapidly re-computed and the model gravity response recomputed. The final outcome from this forward modelling work was an improved 3D geologic model that honoured the original geologic constraints, and that had a modelled gravity response which was in good agreement with the observed field data.

3D GEOLOGY MODELLING METHODOLOGY

The usefulness of 3D geometric modelling to better understand geology is well established (Wijns *et al*., 2003, Wu *et al*., 2005). Modelling requires the ability to reliably infer a representation of the geologic reality by interpolation away from geology observations into regions where no data are available. This representation can be the final goal of modelling or the geological model can be used for further computations, such as geophysical modelling or simulating physical processes (e.g. fluid flow, heat flow, etc.) In both cases, knowing the geological formation at any point in 3D space is fundamental.

Available tools for 3D modelling are mainly designed for data-rich environments, such as in the petroleum industry with 3D seismic data, or extensively drilled mine projects. Many geology projects, however, are limited to only sparse data or poorly distributed data, with some over-sampled locations such as the surface outcrop or bore-holes, and often little or nothing known between those locations. Furthermore, the interpolation methods used model separate horizons but not intrinsic 3D volumes. Where geology is layered, 2D methods are sufficient to construct horizons honouring cross-sections (Galera *et al*., 2003) but such an approach is restrictive.

New methods have been developed in the BRGM for improved modelling of geological bodies known only from sparse or irregularly located data. These tools allow the geologist to use the geometric knowledge from the geological map, cross-sections and bore-holes to test their geological interpretations by building a 3D model. Taking into account both contact locations and orientation data, coherent 3D models are constructed using an implicit scalar method (Lajaunie *et al*., 1997, Chiles *et al*., 2004) to interpolate the data for a geological formation. Multiple interpolators must be used to model the different shapes of successive onlapping, erosional and intrusive formations. The chrono-stratigraphic order of geological formations, and their rock-relationships are recorded in the stratigraphic column, and these in turn automatically determine the geometric relationships between multiple interpolators used to model multiple formations. A feature of this approach is that models are easily refined and updated.

This approach, briefly reviewed here, has successfully been applied to orogenic, basin and mining domains (Courrioux *et al*., 2001, Martelet *et al*., 2004, Maxelon and Mancktelow, 2005, McInerney *et al*., 2005).

Interpolation method using implicit 3D potential field

The major feature of this original interpolation method is that the 3D geological space is described through a potential field formulation in which geological boundaries are iso-potential surfaces and their dips are represented by the gradients of the potential (Figure 2). A unique solution for the 3D geometry of the interfaces between formations is obtained by assuming that:

- Contact data for each interface lie on a potential field surface (an iso-potential).
- Orientation vectors are orthogonal to a local tangential plane to the potential field.

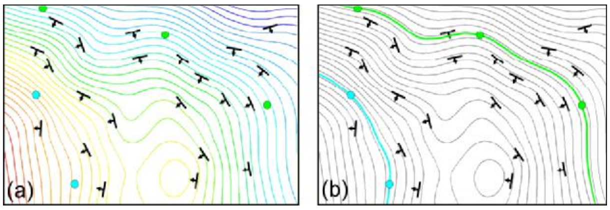

Figure 2. Principle of the geostatistical interpolation using the potential field method. In (a) the contours show the potential field (interpolator) derived from the geology contacts (spots) and geology orientation (strike and dip) data. In (b) two isopotentials of the field are plotted to represent the modelled geology contacts.

On this basis, the field increment (i.e. the change in potential) between any two points belonging to the same geologic interface is null. Orientation data represent the gradient or derivative of the field. The scalar field is then interpolated by universal cokriging of the (null) increment data and their derivatives (Chiles *et al*., *op. cit.*). Interfaces (i.e. geologic contacts) are drawn as iso-values of the interpolated scalar field; iso-lines in 2D (Figure 2) or iso-surfaces in 3D.

When the potential field is calculated, the potential value is known for every point at 3D space, with the result that the method is effective for predicting the structure of geology across the broad gaps that exist between sparse data. Furthermore the method can model the sub-parallel geological interfaces of simple, layered geology. A generalisation of this method is required to model more complex geometry.

Modeling more complex geology with multiple potentials

For the case where the geological history is more complex, and geologic horizons are not sub-parallel, separate potential interpolators must be used - one for each series of strata. For this case it is necessary to define the stratigraphic column, which records the chronological order of the strata, and also the series relationships (either *onlap* or *erode*). Where two geologic surfaces represented by different potential interpolators intersect, an *erode* surface cuts across a stratigraphically older horizon, whereas an *onlap* surface would stop against the older surface (Figure 3). This coded information in the stratigraphic column is sufficient to ensure that a unique geological model is constructed from several overlapping potentials. Note that, from a topological viewpoint, the cross-cutting relationship of an eroded contact is no different from the cross-cutting nature of an intrusive contact; thus the *erode* case is also used to model an intrusive.

The basic inputs to the method include field geology observations and data derived from maps, cross-sections, boreholes, etc. The software allows the geologist to test and refine their interpretations and finally to construct their 3D models. Import/export facilities allow the import of field geology and drillhole data, and the export of 3D model shapes for post-processes.

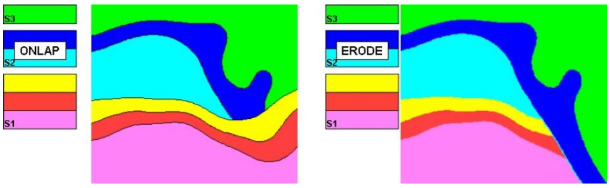

Figure 3. A 2D view of a geologic map or section consisting of three different series of geologic formations. Three interpolators (one for each series) can produce a unique geologic model only with reference to the model's stratigraphic column, which records the chronological order of formations and series, and the relationships between the series. On the left, series S2 *onlaps*, and stops against the older S1 series. For the *erode* case (right) the series S2 cuts across stratigraphically older formations.

BWATA GAS FIELD 3D GEOLOGY MODEL

The Bwata Gas Field is a structural high of fractured Miocene Puri Limestone. Bwata-1, a gas condensate discovery well drilled in 1959-1960, encountered 157 meters of gas pay in the Puri Limestone.

Previous estimates of the total in place gas resource of the Bwata field have ranged from 139 BCF (PNG Department of Petroleum and Energy, 2005) to 306.5 BCF (Keneko, 1997). These estimates were based on structural models generated from the surface geology and limited structural information from the Bwata-1 well.

In 2005 InterOil acquired airborne gravity and magnetic data, which was followed by the acquisition of a 12 kilometre long 2D seismic dip line T1IOL05. These data revealed that the limestone reservoir within the Bwata Anticline was significantly broader that previously modelled and that a considerable attic existed up-dip of the Bwata-1 well. Interpretation of these data also defined an additional fault separated closure (the Triceratops prospect) which lies 3.5 kilometres north of Bwata-1. The Triceratops-1 well (144° 48' 52" E; 006° 57' 29" S) was drilled in 2005 to test this target.

In 2007 InterOil upwardly revised the estimated in place resource to 762 BCF based on incorporation of available surface geological data, new airborne potential field data, new seismic and data from the nearby Triceratops-1 well. This increase is based on initial interpretive work by InterOil geologist David Holland (pers. comm.) who generated a series of eight 2D cross sections using the 2D Move software.

These interpretive cross sections were geo-located in the 3D GeoModeller project, and used to produce the central part of an initial 3D geology model. Additional interpretive work using a broad geological understanding derived from regional mapping, wells and 2D seismic lines resulted in a realistic 3D geology model (41km x 40km x 10km) of the project area centred on the Bwata Anticline (Figure 4).

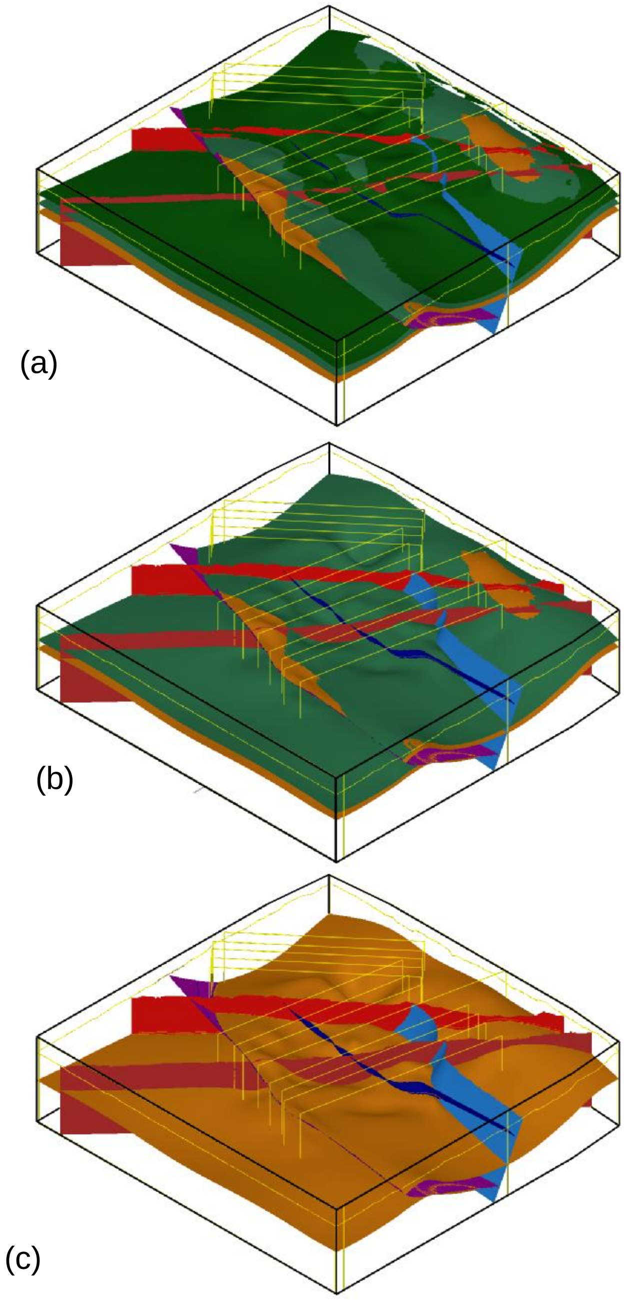

Figure 4. Perspective views, looking north-west, of the final 3D geology model. The dark green horizon in (a) is the base of Era Beds. This is removed in (b), revealing the base of the underlying Orubadi Formation (and thus the top of the dense limestone unit). The base of Orubadi is removed from (c), revealing the modelled base of the Puri and Mendi Limestones. The faults are also shown. Project dimensions are 41km x 40km x 10km.

The model was primarily a study of the targeted reservoir rocks - the fractured Miocene Puri Limestone and the Oligocene to Eocene Mendi Limestone. The overlying Orubadi Formation and Era Beds were included in the model. All of the geology units below the limestone were grouped together into a composite Cretaceous geology unit.

The limestones (2.70 ± 0.05 t/m^3) are anomalously dense relative to the overlying Orubadi Formation (2.30 t/m^3) and Era Beds (2.25 t/m^3). The local gravity anomaly observed in the area of the Bwata Anticline is due to a structural culmination of the dense limestone units which have been ramped up on c. 30 degree dipping thrust faults. With overthrusting, there is some repetition of the dense limestone units, which has also contributed to the observed positive gravity anomaly.

Computation of the Model Gravity Response

Having developed a 3D model of the geology formations and the interpreted thrust faults based on the known geology data, the gravity response of the model was computed. The model was discretised to a set of equi-sized voxels (500m x 500m x 200m high), and the geology formation at the centroid position of each voxel determined from the 3D geology model. On the basis of this voxel geology, density values were assigned to each voxel. The G_{dd} component of the gravity gradient tensor was computed, and compared to the grid of the first vertical derivative of the fully terrain-corrected Bouguer gravity from the airborne gravity survey (Figure 5).

Iterative Adjustment of the 3D Geology Model

On the basis of such comparisons, revisions were made to the 3D geology model. As well as subtle to moderate modifications to the geometry of the limestone reservoir, significant modifications to the preliminary geological model were introduced. These were: the addition of two NE striking steeply dipping faults with a sinistral strike slip and east-side-up displacement; and the introduction of a large structural closure at the western end of the field which significantly increases the size of the field. These adjustments to the model were designed to introduce geological features that might improve the fit between the computed and observed gravity signatures. Several iterations of such adjustments to the 3D geology model, and re-computation of the gravity response (Figure 6) were completed. With each iteration the computed and observed gravity signatures were compared to assess whether the fit between the two had improved, and to postulate further revision of the geology model.

Application of the 3D Model to Exploration Planning

This modelling approach, which takes account of multiple geoscience data sources, successfully integrates geological and geophysical models, resulting in increased confidence in the reliability of the resultant model. In this example, well data, geophysical data (both seismic and gravity) and surface geological data were all used as inputs to constrain the final model. Despite a sparsity of actual geology observations, the final model (or range of models) is more likely to represent an accurate depiction of the geology subsurface than a model derived from any single data source.

The 3D model provides a key input with which to perform (follow-up) seismic Survey, Evaluation and Design (SED). The SED process seeks to ensure a successful seismic survey outcome by using predicted 3D geological structure to optimise survey planning in terms of acquisition parameters, survey line orientations and lengths. Use of a more reliable input 3D model maximises the likelihood of achieving an optimal survey design.

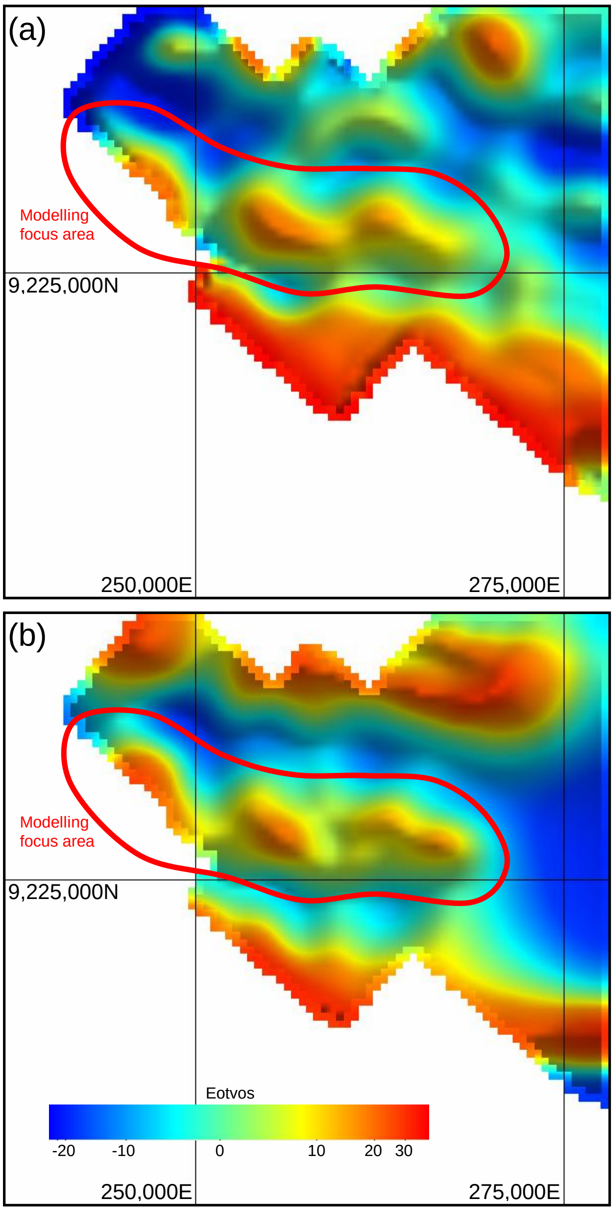

Figure 5. Bwata Gas Field observed vs. modelled vertical gravity gradient signatures, showing the gravity high associated with the Bwata Anticline. Image (a) is the first vertical derivative of the fully terrain-corrected Bouguer gravity anomaly data from the airborne gravity survey. The modelled gravity response (b) is the G_{dd} component of the gravity gradient tensor (equivalent to 1VD). The two images are displayed using the same colour stretch. Map dimensions are 41 x 40km.

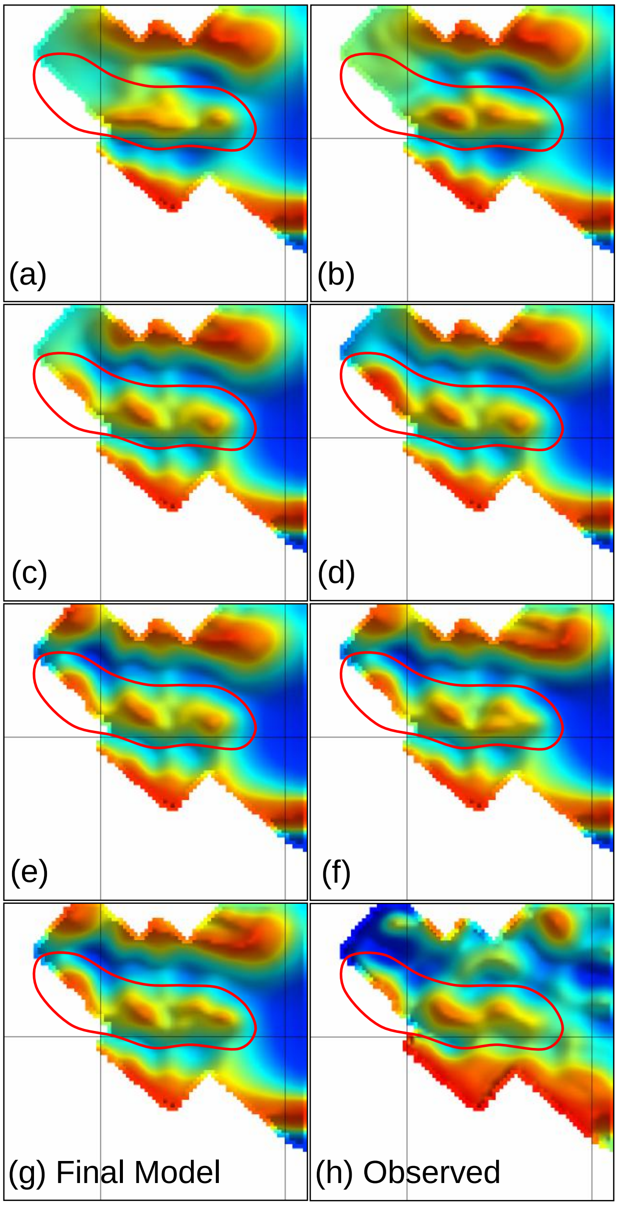

Figure 6. Comparison of computed vertical gravity gradient responses. Images (a) to (g) show the G_{dd} response computed from a subset of the evolving 3D geology models developed during the study. Image (g) is computed from the final model. Image (h) is the 1VD of the observed gravity. All images are displayed using the same colour stretch as in Figure 5. Map dimensions are 41 x 40km.

CONCLUSIONS

Two critical factors which enabled this iterative revision and ultimate improvement of the 3D geology model were (1) the ability to rapidly build a revised 3D geology model using the implicit function interpolator, and (2) the rapid re-computation of the geophysical response of the revised geology model. This interpretive revision of the model would not have been practical if the model-building process had required laborious, manual adjustment of the model. Instead, the use of an automated rapid model construction method allowed the interpreter to remain focused on the practical, geological interpretive considerations of the project.

The result was an improved 3D geology model which honoured the available geology constraints from outcrop, drilling and seismic data, but which now had a modelled gravity response (Figure 5b) that was in better agreement with the observed gravity data (Figure 5a). The regional outcome was the prediction of the geological setting and the extent and thickness of the limestone beds. It is interpreted that two NE/SW near vertical faults connect with a network of low dip faults through the limestone. Also some overthrusting of the limestone is proposed to explain the density anomalies associated with the gas field. The extent and thickness of the limestone were constrained using the vertical derivative of the gravity.

Importantly the revised 3D model introduced a large culmination on the western end of the field. This culmination lies in an area obscured by the apron of the Mt Duau and Favenc volcanoes. This significantly increases the resource potential of the Bwata Gas Field and presents additional data to allow InterOil to design a 2D seismic program targeting previously unrecognised structures.

ACKNOWLEDGMENTS

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