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Integrating rapid 3D structural validation into interpretation: forward modelling of the Katnook Graben, Otway Basin

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ABSTRACT

Structural validation of a prospect is invariably applied after the interpretation is finished, by restoring one or two key lines in 2D or, rarely, by a full 3D restoration that needs finished horizons and a specialist. The authors propose that a simple 3D kinematic forward model, built in minutes using a few explicit structural rules, fully restorable and scaled onto the mapped horizons, is a highly effective way of building structural validation into the early stages of interpretation. The rules are taken from the published literature and built into a software module, referred to herein as the rules module. The rules module is made available together with the crestal collapse graben solution used in this paper. The structural rules are those of the published literature: (1) fault-parallel flow, (2) slip decaying towards the fault tips and (3) syn-rift deposition to a datum. The fourth rule is that any accommodation problem arising when using them in a restorable forward model is flagged to the user. The resolution of the accommodation problem is a decision made by the user as part of the model build. Where the hangingwall of a listric fault cannot be carried over a bend in the fault without strain, that resolution is a crestal collapse graben. How the graben scales with slip is part of scaling the model onto the data, and it may differ between geological provinces. The method is tested here on the Katnook Graben of the Penola Trough, the main gas province of the onshore Otway Basin, which the authors interpreted twenty years ago as bounded by a basement-rooted, thick-skinned fault and its antithetic. The dip of the listric Hungerford Fault and its top basement cutoff are taken from 2D regional sections and the geometry of the graben from 3D interpretation. With these inputs the authors' model fits the mapped thickness of the base Laira to top Crayfish growth interval along dip to within about 120 m, roughly 10% of the 1.2 km by which the interval thickens along dip. It also

reproduces the proportions of the syn-tectonic thickening into the graben. The detachment depth is projected and two parameters are fitted, namely the proportion of the slip pre-dating the base Laira horizon and the keystone throw. No basement fault beneath the graben is needed to account for the mapped geometry. Thus the authors now interpret the Katnook Graben as a crestal collapse graben, detached within the sedimentary fill and formed as a consequence of the large displacement on the listric Hungerford Fault. This has important implications for fault seal integrity risk in the area. The model also implies that the mapped basement, poorly imaged and broken by faults carried down from the reservoir level, can reasonably be re-interpreted as a simpler and less faulted surface. The value of the approach lies in structural validation carried out while the horizons are still being picked. Several structural ideas can be tested against the fault geometry, the growth pattern and the isopachs within hours, and the scenario that survives carries a structural history into trap definition, charge timing and volumetric uncertainty. The method is at an early stage of development. The purpose of this paper is to outline a new method and demonstrate its usefulness at prospect scale for reducing structural risk and the associated risk to fault seal.

Keywords: kinematic forward modelling; listric fault; rollover; crestal collapse graben; structural restoration; prospect evaluation; fault seal; Otway Basin.

1. INTRODUCTION

A structural trap is primarily defined by a map, and a map is an interpretation. Whether the interpreted horizons and faults could have been produced by a plausible deformation history is a question that is asked far less often than it should be, and when it is asked it is asked late. The usual practice is to select one or two regional or key lines through the prospect and to restore them in 2D. The limitations of this practice are well known and generally accepted (Dahlstrom, 1969; Gibbs, 1983; Rowan and Kligfield, 1989; Groshong et al., 2012). A section restored in its own plane cannot represent an arcuate fault, a slip that changes along strike or a structure whose ends lie at different distances from the fault that produced it. The alternative, a full 3D restoration (Rouby et al., 2000; Griffiths et al., 2002; Maerten and Maerten, 2006; Moretti, 2008; Durand-Riard et al., 2010), is demanding in a different way. It requires a complete and consistent set of horizons and fault surfaces, mesh construction, decompaction and boundary conditions, and it requires an experienced practitioner and, in practice, a period of weeks to months. Because its input is the finished interpretation, it is necessarily retrospective, and it can only endorse or reject a map that has already been built.

The authors advocate a different order of work. A simple 3D kinematic forward model does not require finished horizons. It requires a structural style, a fault geometry and a slip magnitude, together with whatever horizons and thickness maps exist at the time, in whatever state they are in. These are things the seismic interpreter holds provisionally from the first days of work on a prospect. A model of this kind can be built in minutes from a small number of explicit rules. It is restorable by construction because it is run forwards from an undeformed state. It can be sliced in the dip and strike directions and compared directly with the 3D seismic. Furthermore, it can be scaled onto the actual horizons and fault surfaces so that the comparison is made at scale rather than by eye. Several models can be tested in an afternoon. Some are dismissed by the fault geometry, the map or the

73 isopach trends. The one that survives carries a structural history into the map, and it does so while the horizons
74 are still being picked.

75 The purpose of such a model is to test whether the interpreted observations are consistent with a structural
76 style that is sensible, restorable and explicit, and to find out what the observations require. A perfect match is
77 not the aim. The deviations are themselves observations, such as a fault cutoff in the wrong place, a fold
78 amplitude that cannot be reached or a growth interval that thickens where the model thins, and these are
79 where the next structural idea starts. Where a model explains the mapped horizons, the fault geometries and
80 the thickness distributions to the standard that the data justify, the interpretation has been validated, in the
81 sense that at prospect stage a defensible kinematic history exists.

82 The structural rules are based on peer-reviewed, published literature and are built into a software module,
83 referred to throughout this paper as the "rules module". This rules module holds four simple rules, as well as the
84 thickness calculation needed to test them and the crestal collapse graben solution used in this paper. The latter
85 two items are kept separate from the rules so that they can be checked or applied independently of any
86 particular model. In this case the graben was added to resolve an accommodation problem flagged by the rules
87 module. The way the model is scaled onto the data is part of the model build and not of the rules. The graben
88 solution is included so that the reader can see how the flagged problem was resolved and check it. Two
89 objectives must be met if such a method is to be credible. Firstly, the rules must be stated and must stand up to
90 scrutiny, so that the model is more than a drawing. The rules used here are set out in structural terms in Section
91 3, together with the geological features they conserve or do not. Secondly, a comparison with the data must be
92 honest about what was taken from the map, which items were fitted and what was tested, so that a good fit
93 cannot be dismissed as an adjusted model. In the test presented here the fault shape, slip, fault trace and
94 graben geometry are all inputs from the published data. Two parameters are fitted, the share of the slip that
95 pre-dates the base Laura horizon and the throw of the keystone faults. This is then tested against a mapped
96 thickness distribution.

97 The work reported here began as an experiment rather than as a study of the Penola Trough in South Australia
98 (Figure 1). The first author set out to build classic structural styles, starting with the listric normal fault and its
99 rollover, not as sections but as complete 3D bodies. The idea was to find out what each style implies once its
100 along-strike behaviour is included. Listric fault deformation and the faulting that goes with it are usually pictured
101 on a section, but their 3D expression is far less explored. Understanding this was the aim of the project. The
102 structural rules of the literature were introduced first, and the model was then given the 3D geometrical
103 character the authors had seen on real data in many settings, an arcuate trace with the slip decaying along
104 strike. What followed was recognition that the maps the models produced resembled maps the authors had
105 interpreted, and one structure, the Katnook Graben, matched, feature for feature, the graben that had been put
106 on the model to accommodate the rollover. Scaling the model onto the Katnook data gave the fits reported
107 here, and the paper followed from that.

108 The test case is the Katnook Graben of the Penola Trough, onshore Otway Basin, South Australia. It hosts the
109 main gas fields of the trough, it is imaged by 3D seismic data, and the authors interpreted it twenty years ago as
110 bounded by a thick-skinned, basement-rooted fault and its antithetic (Lyon et al., 2004, 2005, 2007). It lies in the

hangingwall of the large listric Hungerford Fault, which is imaged only on 2D lines to the south. The principal purpose of the paper is to use this new method and to demonstrate its usefulness at prospect scale for de-risking a structural trap. This paper is not a revisit of the structural interpretation of the trough. It is a demonstration that the method gives new insight into an old structural area. The insight is that the Katnook Graben is best explained as a crestal collapse graben, detached within the sedimentary fill and formed as a direct consequence of movement on the Hungerford Fault. This finding has implications for fault seal in an area where trap risk and fault seal integrity have been studied for exploration and, for the Ladbroke Grove and Katnook fields, as a natural laboratory for the geological storage of carbon dioxide (Watson et al., 2004).

2. THE PENOLA TROUGH AND THE KATNOOK GRABEN

2.1 Setting

The Penola Trough is a northwest-southeast-trending half-graben of the onshore Otway Basin, bounded to the south by the landward-dipping listric Hungerford/Kalangadoo fault system (Figure 1; Finlayson et al., 1993; Lyon et al., 2007), referred to hereafter as the Hungerford Fault. Rifting between Australia and Antarctica began in the Late Jurassic, and the initial rift fill comprises the lacustrine, source-rich Casterton Formation and the fluvio-lacustrine Crayfish Group, which includes the Pretty Hill Formation reservoir, the Laira Formation seal and the Katnook Sandstone (Morton et al., 1995; Boulton et al., 2004). Deep seismic profiling suggests that the major landward-dipping faults of the region sole out at mid-crustal levels into ramp and flat geometries (Finlayson et al., 1996, 1998). On the regional depth section through the Katnook Graben (Figure 2) and on the published section through the deepest part of the trough (Lyon et al., 2007, fig. 4a) the Hungerford Fault dips at about 35 degrees at the level of the top Crayfish Group, flattens progressively to about 20 degrees by 9 to 10 km depth, and is not imaged below that. The syn-rift wedge in its hangingwall is thickest at the fault, where the top of the basement is interpreted at approximately 8 km below the surface, and the top basement rises northward across a rollover limb.

The Katnook Graben sits on that rising limb, about 16 km north of the top Crayfish cutoff on the master fault. It is bounded by the south-dipping Pyrus Fault to the north and the north-dipping Ladbroke Grove Fault to the south, about 5 km apart at reservoir level, and it hosts the Katnook and Redman fields within the graben and the Ladbroke Grove and Pyrus traps on its upthrown flanks (Lyon et al., 2005). The Katnook and Redman hydrocarbon columns are full to structural spill. Ladbroke Grove holds a live column not full to spill. Pyrus holds a palaeocolumn and is breached (Boulton et al., 2004; Lyon et al., 2005, 2007). The Katnook Sandstone occurs at the top of the Crayfish Group and is barely offset by the graben faults. The base Laira Formation horizon (mapped as the top Pretty Hill Formation in Lyon et al., 2007) is a seismic pick that follows the base of the shale-prone Laira facies, rather than the lithostratigraphic top of the Pretty Hill sandstones, and it is named here for what it follows. It records about two-thirds of the deepest mapped throw on the Pyrus Fault. The Laira Formation thickens into the graben, whereas the Casterton Formation shows no discernible thickening across the graben faults (Lyon et al., 2007). Both faults were reactivated in the Late Cretaceous with evidence of inversion in the Miocene. Both show displacement to near surface (Lyon et al., 2005).

2.2 The earlier interpretation

Two published interpretations of the same regional line differ in precisely the respect that matters here. Boulton et al. (2004) and Lyon et al. (2005) carried the Ladbroke Grove Fault down to meet the Pyrus Fault at about 5 km below the surface, the Ladbroke Grove Fault being interpreted as a collapse structure in the footwall of the Pyrus Fault. The Pyrus Fault continued to offset the basement. Lyon et al. (2007) carried both faults as steep planes to 9 to 10 km and described the graben as bounded by an activated east–west basement fault and its associated antithetic fault linked at depth. They used the correlation between basement-cutting faults and breached traps in the trough as an empirical argument that basement faults are prone to recent reactivation and hence to seal breach, with the Pyrus Fault classed as basement-cutting and breached, and the Ladbroke Grove and Katnook faults as not cutting basement and holding live columns. The same paper records that seismic resolution and over-migration effects made interpretation of the basement below about 7 km difficult, and Lyon et al. (2005) note that the section beneath the graben is degraded by out-of-plane effects. The depth to which the graben faults extend, and whether they offset the basement, is therefore the least constrained element of the published interpretation, and it is the element on which the present paper focuses.

In Lyon et al. (2007) the cover faults were described as hard-linked where they cut down into basement and soft-linked where they were detached within the sedimentary cover, and the terms are used in that sense here. This is not the sense in which linkage is used for the physical connection of overlapping fault segments across relays (Peacock and Sanderson, 1991; Fossen and Rotevatn, 2016), which is a separate matter.

2.3 Data

The test uses the first author's Katnook interpretation, four horizons (near top Sherbrook Group, top Crayfish Group, base Laira Formation and top basement) gridded at 50 m over the area of 3D coverage, 18 km east–west by 16 km north–south. The fault polygons are left as gaps in the mapped grids, and the gaps are 'healed' by interpolation for the isopachs. The area is deliberately confined to where the structure is constrained by 3D coverage, because the isopach trends of the field-wide interpretation, constrained by sparse 2D lines, do not increase cleanly towards the master fault and the fault location itself is subjective there. The smaller faults of the interpretation are omitted and only the two graben-bounding faults are used. The regional depth sections (Figure 2; Lyon et al., 2007, fig. 4a) supply the dip of the master fault and the depth of its top basement cutoff. The hangingwall edge of the fault system (Figure 1) supplies the position of the trace at the top Crayfish level. In Figure 2 that edge and the published top Crayfish cutoff on the fault agree to within a few hundred metres. The isopach used as the test is the vertical thickness between the base Laira Formation and the top Crayfish Group horizons (Figure 2), the growth interval that records the later part of the slip. The thicker basement to top Crayfish interval is computed for comparison but is not fitted, because the top basement pick beneath more than 7 km of section is uncertain.

3. THE RULES MODULE

3.1 What is required of the model

The requirements placed on a structural model at prospect stage are stated here, because in the authors' view they do not include a strict material balance. The architects of section balancing (Dahlstrom, 1969; Gibbs, 1983) were clear that a balanced section is admissible rather than correct, and that balancing permits the rejection of

185 an interpretation rather than its acceptance (Groshong et al., 2012). In extensional systems a strict balance is
186 not attainable in any case, because a large part of the extension is taken up on faults below seismic resolution
187 (Walsh et al., 1991), and with most seismic data carrying some degree of artefact and uncertainty it is fair to ask
188 whether a fully balanced 3D restoration is practically achievable in areas where seismic imaging is limited. What
189 is required is (1) that the model be kinematically explicit, so that every element of the geometry follows from a
190 stated rule, (2) that it conserve what a section restoration would conserve, namely the area in the plane of
191 section, (3) that it be restorable, so that the geometry at any earlier stage, in particular at the time of charge, can
192 be inspected rather than assumed, and (4) that it be tested against observations that did not set it up, above all
193 the syn-rift thickness distribution, the most under-used dataset available to the user, whose form the rules must
194 reproduce with at most a parameter or two fitted. The rules below meet these requirements, and where they
195 fall short of a full restoration it is duly stated.

196 **3.2 The rules module and the model build**

197 A distinction is drawn throughout between the structural rules, which are statements of how rock deforms and
198 how sediment records it, and the model build, which is the particular geometry the rules are applied to. There
199 are four rules. (1) The hangingwall deforms by fault-parallel flow, which conserves area in section but not bed
200 length. (2) Slip decays along strike towards the fault tips. (3) Syn-rift horizons are deposited to a datum as slip
201 accumulates. (4) Where the hangingwall cannot be carried over a bend in the fault without strain, the
202 accommodation problem is flagged, requiring a geologically plausible model input to resolve it. In the listric fault
203 case the accommodation problem flagged arises from the lengthening that the flow imposes on a horizon
204 between its cutoff and the hinge, and a geologically reasonable resolution of it is imposed by the user, which is a
205 crestal collapse graben. The rules module defines the geological viability of a model. The resolution of the
206 accommodation problem is not itself a rule. It is a geological decision made by the user and it belongs to the
207 model build. The graben solution used here is included in the module alongside the rules, labelled as the build's
208 resolution rather than a rule, so that it can be checked. The model build is the particular geometry to which the
209 rules are applied, a listric fault with a planar upper segment, a circular bend and a flat detachment, a gently
210 arcuate trace along strike, a slip profile and a graben at a chosen position, introduced by the user as a
211 description of the structural style under test. How the build is scaled onto the mapped data, including how the
212 graben scales with slip, is likewise separate from the rules and may differ between geological provinces. The
213 rules accept any fault geometry. The build is one choice among many, and it is described here so that the test
214 can be understood.

215 **3.3 The workflow**

216 The workflow is a loop (Figure 3). The provisional map inputs, the top pre-rift, top syn-rift and top post-rift depth
217 horizons and the principal faults, are input as spatial xyz data. These are used to specify the simplest model that
218 could reproduce them. A structural style, a fault geometry, a slip magnitude and profile, a transport direction
219 and a depositional datum are stated in words. The model is built in 3D as a self-contained forward model with a
220 slider that runs the deformation forwards and backwards. It can be sectioned along the mapped dip and strike
221 lines, and compared with the interpretation on three criteria: (1) the form of the top pre-rift surface, (2) the
222 trace and geometry of the fault system and (3) the syn-rift thickness distribution. Where model and map

disagree the model can be repeatedly asked by the user, in plain words, to accommodate the misfit, adding only the simplest element that resolves it. The loop ends when the model reproduces the horizons, the fault geometry and the thicknesses to the standard that the data justify. If it cannot, this is itself an informative result. The model is best served by an approximate solution, smoothed and simplified maps on which only the structural elements relevant to the trap are carried, e.g. the upthrown and downthrown blocks rather than every mappable fault. Once a model is reached that explains the map, it is approximately scaled to the actual horizons and faults and compared. Deviations in fault cutoffs, fold amplitude, fault geometry and growth thickness are then the next observations to be explained.

3.4 *The listric fault and its hangingwall*

The master fault of the build is a listric normal fault of the kind described by Bally et al. (1981) and Gibbs (1983): a planar upper segment of stated dip, a circular bend of stated radius tangent to it, and a horizontal detachment tangent to the bend at a stated depth. The hangingwall deforms by fault-parallel flow (Egan et al., 1997; Kane et al., 1997; Ziesch et al., 2014). Each material point is assigned a perpendicular distance from the fault surface and a position along it, and slip advances every point along the curve parallel to the fault by the same distance while holding its perpendicular distance constant. The rollover is a consequence of this rule and not an additional ingredient, because a point carried over the bend must descend as the fault beneath it flattens. Fault-parallel flow conserves area in section, and it was adopted in preference to vertical or inclined simple shear (Verrall's construction as developed by Gibbs, 1983; White et al., 1986; Dula, 1991; Xiao and Suppe, 1992) because the displacement path it imposes follows the fault, so that the hangingwall rotates over the bend rather than being sheared through it. The two constructions differ in the shape they give the limb, not in whether the wedge and the growth pattern are present (Dula, 1991; Withjack et al., 1995). The choice is stated here so that it can be challenged.

Three consequences of the rules matter for what follows, and they can be checked from the rules alone. Firstly, the thickness of the syn-rift wedge at the fault is set by how far down the fault the hangingwall has slipped, so for a given fault shape a given wedge thickness requires a definite slip. On a fault dipping 35 degrees, for example, 8 km of slip produce less than 5 km of throw. Secondly, the rollover limb extends from the fault to a hinge that lies beyond the bend in the fault by the amount of the slip. The width of the limb therefore records the size of the bend plus the slip, and the depth of the detachment is constrained by that width. Thirdly, the rule strains the beds. It holds distance from the fault constant, not bed thickness, so across the rollover the beds thin and lengthen. In the example the uppermost pre-rift bed thins by up to roughly 20% and the top pre-rift horizon lengthens by about 20% between the cutoff and the hinge (Ziesch et al., 2014). All thickness comparisons in this paper are therefore made on vertical thickness, which is what a mapped isopach measures. The strain rule reports non-viable bed strains. Wall-rock strains above a geologically plausible maximum are a recognised test of a fault interpretation, and this information can be used to find missing faults and reject implausible ones (Boult et al., 2009; Freeman et al., 2010). McClay and Ellis (1987) and Withjack et al. (1995) showed that in sandbox rollovers the equivalent extension of the crest is taken up by faulting. The lengthening that rule 4 flags here is therefore to be read as the extension that faults on the limb must account for, which is why it is resolved by a crestal collapse graben rather than absorbed, and Section 3.7 states how much of it the graben takes up.

261 **3.5 Along strike**

262 The trace of the fault in map view is gently arcuate, concave towards the hangingwall, with a bow that is a small
263 fraction of the fault length, based on the authors' observation of listric faults mapped on 3D seismic data. Slip
264 varies along strike. A plateau of full displacement over the central part of the fault decays smoothly towards the
265 tips, and it is not required to fall to zero at the edges of the model. Displacement profiles of this form, with a
266 broad central maximum and tapering ends, are the general observation on normal faults (Walsh and Watterson,
267 1988; Cowie and Scholz, 1992; Dawers et al., 1993). The model is deformed on a series of dip sections, each by
268 fault-parallel flow in its own plane. The sections share the trace and the slip profile, and no material is
269 transported between them. The 3D character of the model results from the deformation generated for every
270 section at once. When inspected as a map, the rollover amplitude, the heave and the syn-rift maximum all decay
271 towards the tips, and any structure on the limb whose position is created by the heave migrates with it. A
272 coupled 3D treatment of hangingwall deformation (Kerr et al., 1993; Egan et al., 1999) is not attempted, and the
273 consequence is stated in Section 8 on limitations.

274 **3.6 Growth**

275 Syn-rift horizons are material lines deposited at a flat depositional datum at successive increments of slip on the
276 fault. In the model each is flowed only by the slip that post-dates it, and pre-rift horizons experience the full slip.
277 This is the standard treatment of growth strata over an extensional fault-bend fold (Shaw et al., 1997), and it is
278 what generates the growth geometry and the syn-rift thickness distribution used in this test. The wedge
279 thickens towards the fault with its maximum at the hangingwall cutoff, and an interval bounded by two syn-rift
280 horizons records the subsidence between their deposition. Within the model, the syn-rift thickness at any point
281 is by construction the structural relief of the top pre-rift horizon below the datum, so that the model's own
282 isopach tests nothing. The test is the thickness of the modelled isopach compared to the thickness mapped from
283 the data.

284 **3.7 The crestal collapse graben**

285 An unbroken hangingwall carried over a concave-upward fault must lengthen along the limb, and the
286 lengthening is greatest where the bend is greatest, at the crest of the rollover. This is the accommodation
287 problem of the rollover, and its natural solution is a keystone graben: a pair of conjugate normal faults
288 converging downwards, one synthetic and one antithetic to the master fault, bounding a keystone that drops as
289 the limb extends. Crestal collapse grabens of this kind were produced in the earliest analogue experiments on
290 rollovers (Cloos, 1968) and are a standard feature of sandbox models of listric extensional systems (McClay and
291 Ellis, 1987; McClay, 1990; Withjack et al., 1995; McClay et al., 2002), and their relationship to the geometry of
292 the master fault has been analysed by Xiao and Suppe (1992). The model build treats the graben as follows. Its
293 existence is an argument made by the user, not a prediction of the rules, and its form is taken from the map and
294 a key section. The way it scales with slip, described next, is part of the build and of the scaling onto the data
295 rather than one of the rules. Its throw grows with slip on the master fault once a stated onset fraction of the slip
296 has been reached, and a syn-rift horizon records only the share of the throw that post-dates its own deposition,
297 so that growth into the graben follows from the same rule as growth against the master fault. Each horizon's
298 cutoffs are solved on the fault planes, and the footwall and hangingwall cutoffs differ because the keystone has

299 dropped. Because the graben's position and throw are dependent on the heave and the slip, and both decay
300 along strike towards the fault tips, the graben's faults deflect towards the master fault where the slip decays and
301 the graben ends where the slip falls below its onset.

302 The throw of the keystone is a parameter taken from the map rather than derived from the lengthening of the
303 limb, and the keystone is not area-balanced against that lengthening. In the scaled model of the Katnook test
304 below, the graben's horizontal extension is about 1 km for a horizon at the top Crayfish level (0.5 km at the base
305 Laira) when compared against a lengthening of about 2.6 km implied by the kinematics for the top pre-rift strata
306 between the cutoff and the hinge, so the graben is the largest single accommodation structure on the limb, but
307 not the only one. The smaller intra-rift faults seen on Figure 2 take up part of the remainder. Where and when a
308 rollover crest fails is not modelled.

309 **3.8 Restorability**

310 Because every horizon has the same rule acting on a different starting height, the model is restored simply by
311 reducing the slip. The graben closes, the wedge thins, the rollover unfolds and the pre-rift returns to a flat,
312 unfaulted state. Figure 4 shows the model at three stages of its slip. Restoration is therefore a property of the
313 model rather than a separate exercise, and a palaeostructure map at any stage, for example at the time of peak
314 charge, is available at once. Footwall uplift, part of the model build rather than the structural rules, is an
315 imposed flexural profile, and the rules treat dip slip only. What the model leaves out, and which gives a real
316 basin a thickness where the modelled syn-rift thins to zero, are compaction, decompaction, isostasy and the
317 regional subsidence beyond the hinge. See Section 8 on limitations. The four structural rules, and the graben
318 solution of this paper, are contained within a standalone Python module, the rules module, which accepts any
319 fault surface as its input. The fault of the build, the scaling onto the data and the fit are not part of it.

320 **4. THE MODEL**

321 The authors' model was built as a generic structural style, not as a model of the Penola Trough, and it is
322 dimensionless and deliberately kept as simple as possible because it describes a structural style and not any one
323 place. In the build used here the fault dips at about 60 degrees at the datum with a radius of curvature about
324 twice the detachment depth, so that the bend begins at the datum. The maximum slip is three-quarters of the
325 detachment depth, and the fault trace and slip profile are as described above. Two iterations are worth
326 recording, shown in Figure 5a and b. The listric fault produced the rollover limb and the wedge of syn-rift
327 thickening towards the fault, with its maximum at the hangingwall cutoff, which is the relationship seen on
328 Figure 2. It also produced the accommodation problem, and it was the fourth rule that found it. As the slip was
329 increased the model reported that the top pre-rift horizon had lengthened, by about 20% between the cutoff
330 and the hinge at full slip, and sandbox modelling shows that no unbroken hangingwall can sustain a stretch of
331 that size without faulting. The choice was either to accept the strain or to break the crest. The crest was broken
332 by imposing a conjugate graben on the limb, the resolution the literature gives for a rollover crest (Cloos, 1968;
333 McClay and Ellis, 1987), and that decision was the user's, made as part of the model build rather than by the
334 rules. That step did three things without further adjustment. (1) It generated growth of the upper syn-rift into
335 the graben and none in the section beneath it. (2) It produced throw on the graben faults that decays as slip

336 decays along strike and, because the graben's position is set by the heave, faults deflect towards the master
337 fault where the slip decays. (3) Its faults lay parallel to the local trend of the master fault.

338 The authors recognised the result as the Katnook Graben: a graben on the rising limb of a large listric fault, with
339 deflections at its ends and a growth interval that thickens into it. In the earlier interpretation those features had
340 been read as the expression of a basement fault beneath the graben. The model offered a simpler scenario, that
341 they are what a rollover produces, and the remainder of the paper tests it.

342 The map views are where the implications of the 3D geometry are best described (Figure 6a and b). On a single
343 section the graben is a step in the limb, whereas on the map it is a structure whose distance from the master
344 fault, throw and along-strike extent are all governed by the slip profile on the master listric fault. The syn-rift
345 isopach shows the wedge, the thickening into the graben and the decay of both towards the fault tips. It is the
346 map that shows the ends of the graben deflecting towards the master fault where the heave decreases, an
347 observation that a section cannot make and that had been made previously by the authors on the Katnook maps
348 without an explanation.

349 **5. THE KATNOOK GRABEN TEST**

350 ***5.1 Inputs, fitted parameters and the test***

351 The model was oriented on the Katnook graben, with the transport direction north–south, perpendicular to the
352 Pyrus and Ladbroke Grove faults and parallel to the Early Cretaceous extension direction of Lyon et al. (2007), so
353 that the line A–A' of Figure 1 is a dip line of the model (Figure 7), and the top Crayfish Group is the depositional
354 datum. The inputs are taken from the data. The trace of the master fault at the datum is the hangingwall edge of
355 the fault system drawn on Figure 1, 16 km south of the graben axis on A–A'. The fault dips at 34 degrees at the
356 datum and its shape to 9 km depth follows the published section (Lyon et al., 2007, fig. 4a). The detachment
357 depth, which the seismic data do not reach, is projected. The slip is set by the depth of the top basement cutoff
358 on the regional sections, 6.5 km below the top Crayfish cutoff, which requires 13 km of slip. With the footwall
359 about 1 km above the datum, this gives a vertical separation of the top basement across the fault of 7 to 8 km, as
360 on the published sections.

361 The 5 km-wide test graben, measured at the datum, is positioned along the axis of the mapped graben. The
362 mapped Pyrus and Ladbroke Grove traces are 5 km apart at the base Laira level (Figure 1), with their faults
363 converging within the cover at 3.7 km below the datum (approximately 5.5 km below the surface). This
364 convergence is close to the depth of about 5 km at which the cross-sections show the Ladbroke Grove Fault
365 joining the Pyrus Fault (Figure 2; Boulton et al., 2004; Lyon et al., 2005).

366 The test graben is assumed to initiate at two-thirds of the total slip. This is based on the minimal offset of the top
367 Crayfish horizon and the observation that the base Laira horizon records approximately two-thirds of the
368 deepest mapped throw.

369 Two parameters are fitted to the mapped thickness of the growth interval along section A–A': the proportion of
370 total slip that occurred before deposition of the base Laira horizon, and the keystone throw. The model is

371 evaluated by how well it reproduces the observed growth-interval thickness along A–A' and then along other
372 sections across the study area.

373 **5.2 Result**

374 The results are shown in Figure 7. With the detachment modelled at 9.5 km below the top Crayfish Group, the
375 growth interval thickness along A–A' is reproduced by the model with a root mean square misfit of 116 m,
376 roughly 10% of the 1.2 km by which the interval thickens along the line. The interval thickens southward
377 towards the master fault on the map and in the model alike, from about 0.4 km at the northern edge of the area
378 to about 1.5 km at the southern edge, and the step of about 0.4 km into the graben, the fingerprint of the
379 keystone, is reproduced in the same proportion. The southward thickening of the growth interval constrains the
380 rollover hinge to about 40 km north of the fault trace and provides a constraint on detachment depth. Along A–
381 A' the best-fitting detachment lies 9.5 km below the datum. Detachments between 9.5 and 10.5 km fit almost as
382 well, their misfit being no more than about 10% larger than the best, so the depth is constrained to within about
383 a kilometre. Shallower detachments produce a limb that is too short, whereas deeper detachments produce
384 one that is too long. The model also indicates that the base Laira horizon was deposited after approximately 80%
385 of the total slip had occurred. Consequently, the growth interval records the final 2.6 km of slip.

386 The modelled fault geometry, with its bend matched to the published section, follows the published fault to
387 within 0.3 km over the 9 km interval for which it is imaged. The model also satisfies an independent check. In the
388 southern part of the study area, the mapped top-basement horizon follows the modelled fault surface,
389 consistent with the published cross-section. This agreement was not imposed as a constraint during model
390 construction.

391 Section A–A' is representative rather than selectively chosen. Repeating the fit along eight north–south sections
392 across the study area, using the mapped fault trace, graben axis and graben width at each location, yields root
393 mean square misfits of 85 to 145 m. All eight sections favour detachment depths of 9 to 10 km. The fitted
394 keystone throw decreases to zero at the westernmost section, where the mapped graben terminates.

395 For the map-view model (Figure 7b), the slip profile is prescribed so that slip decreases to the onset value at the
396 western end of the mapped graben. This illustrates the behaviour of the model under an assumed slip profile. It
397 is not an independent fit to the mapped graben termination. Under this profile, the modelled graben terminates
398 at the same location as the mapped graben. As slip decreases westward, the graben faults deflect towards the
399 master fault, and the growth wedge thins along strike accordingly.

400 The mapped throws on the Pyrus Fault along the graben are about 0.1 to 0.2 km at the top Crayfish and 0.6 to
401 0.8 km at the base Laira. The model reproduces the pattern at these levels. The fitted keystone throw is 810 m
402 for a horizon at the top Crayfish level which has recorded the whole of the post-onset slip. Throw decreases with
403 depth to zero where the faults converge, the base Laira horizon drops 350 m, and the top Crayfish, deposited at
404 the end of the slip, is not offset. The model carries no post-rift deformation, so the offset of the top Crayfish, and
405 an equivalent part of the offset beneath it, is the Late Cretaceous reactivation and the Miocene inversion that
406 Lyon et al. (2005) documented. With it, the base Laira throw is about 0.5 km against 0.6 to 0.8 km measured

407 across polygons 0.7 to 1.1 km wide that include the drag into the fault. The mapped basement throw is
408 discussed below, because it is the observation that bears most on the interpretation.

409 The basement to top Crayfish interval thickness was not fitted and is shown faintly in Figure 7c and d. The
410 modelled wedge reaches the mapped thickness at the fault, but north of the graben the mapped top basement
411 flattens within about 20 km of the trace, whereas the modelled limb continues to the hinge. Thus the model
412 carries about 1.5 km more syn-rift than the map at the northern edge of the area. There are several reasons for
413 this: (1) the model has no regional syn-rift thickness beyond the hinge, (2) the top basement pick is uncertain
414 beneath more than 7 km of section (Lyon et al., 2007), and (3) the fault may be steeper below its imaged depth
415 than the bend assumed here. A shorter limb for the basement than for the growth interval would suggest that
416 the fault shape, or the locus of slip, changed with time, a possibility discussed below. Figure 7c and d also show
417 something simpler. The mapped top basement is offset on the graben faults and on other large faults carried
418 down to it from the base Laira level, whereas the modelled top pre-rift beneath the graben is a smooth,
419 unbroken limb. If those faults, like the graben faults, are detached within the cover, the offsets carried from
420 them into the basement are not required, and the basement beneath them is simpler and less faulted than has
421 been mapped previously. The authors' reading of the comparison is that a simpler basement structure can
422 reasonably be imposed on the area and that the basement interpretation should be re-evaluated on that basis.
423 The modelled limb is a guide to its form, though not to its depth north of the graben, where the model carries
424 too much section, and given the poorer imaging at this depth a less faulted surface is more befitting to what the
425 model implies.

426 **6. A REVISED INTERPRETATION OF THE KATNOOK GRABEN**

427 The interpretation now preferred by the authors is that the Katnook Graben is a crestal collapse graben. Its
428 bounding faults, the Pyrus and Ladbroke Grove faults, are soft-linked in the sense of Lyon et al. (2007). They are
429 detached within the sedimentary fill above the master fault, and they formed as a conjugate pair as a
430 consequence of the large displacement on the Hungerford Fault rather than by the reactivation of a basement
431 fault beneath the graben. This is a revision of Lyon et al. (2005, 2007), and it was arrived at through the
432 modelling described here rather than through new data. It rests on the following.

433 Firstly, the model requires no basement fault beneath the graben. A graben of the observed position, width,
434 growth expression and along-strike behaviour, parallel to the local trend of the master fault and deflecting
435 towards it at its ends, is a sufficient consequence of rollover above the listric Hungerford Fault. Where two
436 interpretations explain the same observations above the basement the authors prefer the one that requires the
437 fewer structures. Secondly, and most importantly, the timing is consistent. Growth of the Laira Formation into
438 the graben faults with none in the Casterton Formation places the formation of the graben during accumulation
439 of the upper syn-rift, and the onset placed from the mapped throws at about two-thirds of the slip on the master
440 fault is late enough for the limb to have been carried well over the bend, which is when a rollover crest should
441 fail. Thirdly, the geometry is consistent. The sections carry the Ladbroke Grove Fault into the Pyrus Fault at
442 about 5 km (Figure 2; Boulton et al., 2004; Lyon et al., 2005), a junction that lies well above the master fault
443 beneath the graben. A keystone whose faults converge within the cover is the form a crestal collapse graben
444 takes in the build, as in the analogue models, and the planar continuation of both faults to 9 to 10 km drawn by

445 Lyon et al. (2007) lies in the part of the section that the same paper describes as poorly imaged. Fourthly, the
446 obliquity of the graben to the master fault, taken in 2007 as evidence of basement control, is an obliquity to the
447 regional northwest–southeast trend of a system that is arcuate. Against the local trend of its hangingwall edge
448 south of the graben, the graben is close to parallel, which is the relationship a crestal collapse graben should
449 show. The regional trend itself rests largely on 2D lines and on the margins of the 3D survey, where faults were
450 mapped on every tenth line at most, and the shallow northwest–southeast trend may have been carried too
451 deep into poorly imaged data, including the Hungerford Fault. This aligns better with the gravity and magnetic
452 interpretations, which are suggestive of a northwest–southeast structural grain (Lyon et al., 2007).

453 One observation bears against the revision and is stated here. The mapped top basement pick is offset by up to
454 about 1 km across the Pyrus Fault on the 3D data, and the published sections carry that fault through the top
455 basement pick. A keystone graben whose faults converge within the cover cannot produce an offset at or below
456 the level at which its faults meet, and the top basement beneath the graben lies at about that level. The
457 interpretation therefore makes a definite and testable prediction. The throw on the graben faults decreases
458 downwards through the Pretty Hill and Casterton formations and dies out above the master fault, which the
459 graben faults do not cut, and the mapped basement offset is an interpretation carried down from shallower
460 levels through a poorly imaged interval. The same reasoning may extend beyond the graben. Where other large
461 faults mapped at the base Laira level can be explained as soft-linked within the cover, the basement beneath
462 them is a candidate for re-interpretation as a less faulted and simpler structure, which the poorer imaging at
463 that depth makes reasonable. That is a suggestion for the interpreter rather than a result of the modelling,
464 which carries only the two graben faults. The earlier reading of a hard-linked graben, bounded by an east–west
465 basement fault that controlled the orientation of the cover faults, was, in the authors' present view, probably
466 wrong. The graben is more neatly and more convincingly explained with no basement involvement. The section
467 beneath the graben is degraded by out-of-plane effects (Lyon et al., 2005) and the basement is poorly imaged
468 below about 7 km (Lyon et al., 2007), and a reprocessed depth-migrated volume would settle it.

469 The revision changes the reading of the fault seal integrity story in one respect and leaves it intact in another.
470 The breach of the Pyrus trap was explained by Lyon et al. (2005) by a sand-on-sand juxtaposition window at the
471 crest of the trap and by reactivation of a fault that is critically oriented in the present-day stress field, and
472 neither of those arguments depends on the fault reaching basement. The empirical observation of Lyon et al.
473 (2007), that the traps bound by basement-cutting faults in the trough are breached or partially breached
474 whereas those bound by cover faults hold live columns, was made on a population of eleven traps. If the Pyrus
475 Fault is a cover fault, it becomes the one exception, breached by juxtaposition and reactivation rather than by
476 basement linkage, and the correlation for the remaining traps stands as it was made, although the same
477 question, whether a fault classed as basement-cutting is in fact detached within the cover, now arises for each of
478 them. What matters for containment, at Katnook or at any trap on a crestal collapse graben, is then the
479 reactivation potential of the graben faults in the present stress field and their juxtaposition, not their depth of
480 origin.

481 One further idea arose from the exercise and is described without being argued. The published section shows a
482 splay in the hangingwall of the master fault that back-steps landward into the trough, and the mapped top
483 basement has a shorter limb than the growth interval. A listric fault that back-stepped landward, so that

484 displacement transferred with time to a younger surface farther into the hangingwall, would account for both. It
485 lies in the part of the section that is least constrained, it is not required by anything in this paper, and it is left for
486 separate examination. It raises interesting geometrical implications for the graben itself and for future
487 prospectivity of the area northward of it.

488 7. DISCUSSION

489 *7.1 What the method delivers at prospect stage*

490 The practical value of the authors' approach is that structural validation is carried out during interpretation
491 rather than after it. A geometry that cannot be produced kinematically is identified while the horizons are still
492 open on the workstation, at the point where the time cost of changing them is small, and the structural
493 understanding is built into the map rather than applied to it. In the conventional sequence the interpretation is
494 built, delivered, tested and, where necessary, rebuilt, and in practical terms the effort already invested in the
495 map can become an argument for retaining it. Where the test is applied continuously no such time investment
496 accumulates, and in the authors' experience a different map is delivered, because the structural choices that
497 would otherwise have been carried into it without examination, how a fault is picked, whether it is listric or
498 planar, how a horizon is tracked across it, were tested at the point where they were made. Several structural
499 styles can be tested against the same data within hours, whittled down to the most likely, and more than one
500 valid model can be carried where the data do not discriminate, which is itself a statement of structural risk. In
501 the authors' experience the effect on the user is as marked as the effect on the map. The model challenges the
502 assumptions that have been carried into the interpretation, invites several tests rather than one, and lets the
503 work proceed with the best fit rather than the first idea.

504 More importantly, structural assumptions made early in an interpretation can be tested against the maps in 3D
505 and validated before they are committed to and carried into the interpretation. The resulting structural model is
506 much more certain and much better constrained by the data in 3D. A solid structural story must itself converge
507 on the data, so that no glaring inconsistency remains, for example an isopach that does not thicken in the same
508 proportions, pre-rift fault traces that run in a different direction or displacement profiles that do not agree.

509 The model answers questions that a map alone cannot. It explains why and how the trap formed, which is
510 integral to prospect risk. It gives the palaeostructure at any stage, so that the trap at the time of peak charge is
511 inspected rather than assumed. In the Penola Trough the principal charge post-dated the initial rifting (Boult et
512 al., 2004; Lyon et al., 2005), so that the end state of the rift model approximates the structure at the time of
513 charge, and where a trap has grown substantially after charge the restoration constitutes a risk statement that
514 the map cannot make. It turns closure into a sensitivity rather than a single value, because the range of
515 geometries consistent with the mapped data can be generated explicitly and carried into the estimate of gross
516 rock volume. And it makes crestal collapse a risk that can be assessed, since the graben segments the structure
517 and introduces across-fault juxtapositions on the flank closures.

518 The method is intended to be used by one person. Most small companies do not employ a structural geologist,
519 and the structural questions on a prospect are often not recognised as such until late. A model that can be built
520 in minutes, sliced in the dip and strike directions, adjusted and restored during a discussion puts the structural

reasoning in the hands of the user, who contributes what the data will and will not support while the rules module reports what the kinematics will and will not permit. Where a structural specialist is involved, the model gives both a single object to work on at the same time. The model communicates a structural history to a partner, a reviewer or a data room in a way that a section and a map do not.

7.2 The Katnook Graben as a 3D problem

The features that define the Katnook Graben, a graben on the limb of an arcuate master fault, a slip that decays along strike, ends that deflect towards the fault, growth into the graben and a section that could not be balanced in its own plane without breaking the crest, are consequences of the along-strike behaviour of the system, and a 2D restoration cannot do justice to them. A fully balanced 3D restoration is inappropriate for a different reason. The graben cannot be considered apart from the master fault that produced it, and only the graben is imaged in 3D. The simple kinematic model occupies the ground in between. It represents the poorly imaged part of the system by a structural style whose shape is taken from the published section, and it lets the well-imaged hangingwall constrain that style. The growth interval fixes the hinge of the rollover and, through it, the depth of the detachment, and the mapped top basement in the south of the area lies along the modelled fault. This is the practical form of the argument that the well-imaged part of a system constrains the poorly imaged part, and it is available to any prospect in which a subsidiary structure is better imaged than the fault that produced it, which is the case for most structural prospects.

7.3 What validated means here

What the fit establishes should be stated. A well-established structural style was translated at scale onto the mapped horizons and fault, with two parameters fitted, the share of the slip that pre-dates the base Laira horizon and the keystone throw. The fault shape, slip, trace and graben geometry were taken from the published data. The model reproduced, to about 120 m, a mapped thickness distribution that thickens by some 1.2 km along the line A-A', including its step into the graben. The mapped top basement in the south of the area lies along the modelled fault, and the model reproduces the pattern of the mapped throws at the two upper levels. That is what has been validated here. A sensible, explicit and restorable history exists that explains the observations to the standard that the data justify, and it has been tested quantitatively, on nine dip lines across the area, rather than by eye on one section. The model is not unique, since the slip and the fault shape below 9 km trade off against one another, and the basement wedge north of the graben is not reproduced. Those are where the next iteration begins, with a regional syn-rift thickness in the model and, for the basement, the re-evaluation of the interpretation towards a simpler and less faulted surface that the cover-detached reading of the faults implies. An additional model, scaling the back-stepped listric fault hypothesis that arose during this work and testing its implications for the syn-rift thickness, might give a better fit in the north.

7.4 Why the models were built this way

Kinematic forward modelling of listric fault systems is not a new capability, and commercial software exists to perform it. The distinction drawn here is one of time cost and of what the method demands as input. In a conventional package surfaces are imported and repaired, parameters are entered and rebuilding the model after a structural change takes appreciably longer than describing it, with the practical consequence that only

the one or two variants the user already favoured are ever tested. The models in this study were specified in natural language, working conversationally with a large language model, and returned as self-contained, parameterised forward models that run in a browser. A structural revision required a further sentence, six or eight variants were tested in an afternoon, including variants expected to fail, and the scaled comparison of Figure 7 was set up within a few hours. Language models are beginning to be applied to 2D and 3D geological model construction in this way (Anikiev et al., 2026; Guo et al., 2026).

The language model contributed no geological knowledge and its role was purely as a process tool. It rapidly constructed the model geometry and applied the rules, which flagged when the hangingwall could not be carried over the bend without stretching the beds and so exposed the accommodation problem. It also scaled the geometry to the Katnook data, tested numerous parameter combinations and projected the detachment depth. Throughout this process, the authors determined which parameters were constrained by the data and which were fitted, namely the share of the slip pre-dating the base Laira horizon and the keystone fault throw, refining the comparison until the result shown in Figure 7 was obtained. All judgements about geological plausibility and all interpretations were made by the authors. The defensibility of the result rests on the rules, not on the tool used to apply them. The rules are contained within the rules module, and they can be examined and tested independently of any particular implementation.

7.5 Stage of development

The method is at an early stage. The rules used here have been applied to one structural style, the listric normal fault with a hangingwall rollover and a crestal collapse graben, because that is the style the Katnook Graben required. Further structural styles should be tested, and the rules, the tests applied to them and the way a model is scaled onto mapped horizons should be refined as more prospects are worked. What is demonstrated here is the principle and one worked case at prospect scale. In this case a simple, explicit and restorable 3D model, built during interpretation, tests a structural interpretation against the observations that matter to a drilling or containment decision, and does so quickly enough to be used on every prospect. More importantly, a restorable 3D model of this kind, continuously refined as the interpretation is built, generates new structural ideas in old areas, ideas that can be compared explicitly and semi-quantitatively with the seismic data. It also gets the user thinking not only about the movement on the prospect-bounding fault as the control on risk but about the kinematic evolution of the sub-regional structure as a whole and how its elements relate to one another in a coherent and structurally valid way. An understanding of the structure and the trap sometimes comes from the bigger picture, from sub-regional faults outside the scale of, in this case, the crestal graben itself. The method also teaches structural geology to the user, such that eventually the disciplines of geophysicist, interpreter and structural geologist are combined in one operator.

7.6 The user's perspective

In the authors' view, current approaches to interpretation are limited by the lack of any practical means of forming a structural idea and testing it through maps and fault geometries as the interpretation is built. The attempt to create a simple model of listric fault deformation and to impose sensible structural rules on it inadvertently created the Katnook Graben, and that was the moment of recognition. In creating structural styles in this way, extrapolated into the third dimension with observations made on successive maps, the user starts to

recall the maps and data previously interpreted. When testing maps against such models there is a compelling case for a way of assessing the robustness of a structural model quickly and semi-quantitatively as the interpretation is being built. The method makes the user challenge assumptions, run several tests and proceed with the best fit. Not only will this affect how faults and structure are interpreted, the process itself will have a marked effect in reducing the structural risk of a trap in the first instance, and indirectly the risk to charge and seal. This happens through a better appreciation of how the structure formed, when it formed and whether a trap works.

8. LIMITATIONS

The models are kinematic rather than mechanical. They impose a deformation rather than compute one. The crestal graben in this study is a kinematic solution imposed at a position taken from the map, with its throw fitted rather than derived from the lengthening of the limb. Each dip section is deformed independently, so that the along-strike behaviour follows from the trace and the slip profile rather than from a model of out-of-plane flow, and the rules treat dip slip only. Fault-parallel flow does not preserve bed length or true bed thickness across the rollover. Compaction, decompaction, isostasy and regional subsidence are not treated, and the growth interval is capped by the top Crayfish Group unconformity, so that the mapped magnitude is partly erosional and only the comparison of pattern is the test. Solutions are not unique. The slip and the shape of the fault below its imaged depth trade off against one another, and the detachment depth is constrained only through the width of the limb. The rules module has been applied to one structural style, and the application here is retrospective, to a completed and published interpretation, so that the benefit of validation during interpretation is inferred from this result and from the authors' experience rather than demonstrated in a controlled comparison.

9. CONCLUSIONS

- Rapid, restorable 3D kinematic forward models, built from a few explicit structural rules and scaled onto the mapped horizons, can and should be built alongside a prospect interpretation rather than after it. They test whether the interpreted observations are consistent with a sensible and restorable structural style, from very early stages of interpretation. They allow several styles to be tested within hours and the one that survives carries a structural history into trap definition, charge timing and volumetric uncertainty.
- The structural rules are those of the published literature, being (1) hangingwall deformation by fault-parallel flow, which conserves area in section but not bed length or true thickness, (2) slip decays along strike towards the fault tips, (3) syn-rift deposition to a datum proceeds as slip accumulates, and (4) where the hangingwall cannot be carried over a bend in the fault without strain, the accommodation problem is flagged and a geologically reasonable resolution suggested. In this case a crestal collapse graben whose faults converge within the cover and whose throw grows with slip after onset is the most appropriate. The rules are separate from the model build to which they are applied. What they conserve and what they do not is reported back to the user.

- 632 ● A structural trap interpreted in this way carries with it the continuous validation of the geological

633 observations from the maps and isopachs as the interpretation is built. Many styles can be examined to

634 arrive at the simplest model that explains the maps, the user is led to challenge assumptions, to run

635 several tests and to proceed with the best fit, and this has a direct effect in reducing the trap risk of

636 fault-bound structural prospects. In particular, the syn-rift isopach thickness magnitudes hold the key

637 to 3D structural validation.
- 638 ● The listric fault with a hangingwall rollover modelled here cannot carry its hangingwall unbroken over

639 the bend. In the generic build the top pre-rift lengthens by about 20% between the cutoff and the hinge.

640 Breaking the crest with a conjugate graben provides the accommodation in the model and generates,

641 without further adjustment, growth into the graben, throw that decays along strike with the slip and a

642 graben whose ends deflect towards the master fault. This structure was recognised as the Katnook

643 Graben.
- 644 ● Scaled with the fault dip and the top basement cutoff from the regional sections and the graben

645 geometry from the 3D interpretation, the model reproduces the mapped thickness of the base Laira to

646 top Crayfish growth interval along dip to within about 120 m, roughly 10% of the 1.2 km by which the

647 interval thickens along the dip line. This also reproduces the proportions of its thickening into the

648 graben, taking into account the projected detachment depth and the two fitted parameters, namely

649 the proportion of the slip pre-dating the base Laira horizon and the keystone throw. The detachment

650 lies about 9.5 km below the top Crayfish Group (9 to 10.5 km across the nine lines), the slip set by the

651 top basement cutoff is about 13 km, the base Laira horizon was deposited after about 80% of the slip,

652 and the graben initiated after about two-thirds of it.
- 653 ● The Katnook Graben is best explained as a crestal collapse graben, detached within the sedimentary fill

654 above the Hungerford Fault and formed as a consequence of the large displacement on it. Its bounding

655 faults meet within the cover, well above the master fault, which they do not cut. No basement fault

656 beneath the graben is required and the earlier interpretation of a hard-linked graben controlled by a

657 basement fault was probably wrong. On this interpretation the throw on the graben faults dies out

658 downwards above the master fault, as interpreted by Boulton et al. (2004) and Lyon et al. (2005).
- 659 ● The comparison of the mapped and modelled basement implies that a simpler basement structure can

660 reasonably be imposed on the area. Some of the large faults mapped at the base Laira level can be

661 explained as soft-linked within the cover, so the offsets carried from them into the basement are not

662 required, and the basement interpretation should be re-evaluated into a less faulted and simpler

663 structure, which is reasonable given the poorer imaging at that depth.
- 664 ● For fault seal, the breach of the Pyrus trap is explained by juxtaposition and reactivation, as Lyon et al.

665 (2005) argued, rather than by basement linkage. The empirical correlation of Lyon et al. (2007) between

666 basement-cutting faults and breached traps stands for the remaining traps, and what matters for

667 containment on a crestal collapse graben is the reactivation potential and juxtaposition of its faults in

668 the present stress field.

- The problem is a 3D one, and this simple kinematic model translates it into a form that a section restoration cannot and a full 3D restoration cannot yet. It represents the poorly imaged master fault by a structural style taken from the published section and lets the well-imaged hangingwall constrain it. The authors consider that a model of this kind should be a standard product of structural work in exploration and storage prospects.
- The method is at an early stage of development. The rules have been applied to one structural style and further styles should be tested and the rules further refined. The purpose of this paper is to set out the method and to demonstrate its usefulness at prospect scale for de-risking a structural trap.

DATA AND CODE AVAILABILITY

The four structural rules are defined in a standalone Python module, the "rules module". It contains (1) fault-parallel flow along any fault surface supplied as a polyline, (2) the along-strike slip profile, (3) the syn-rift growth rule and (4) the accommodation flag, the lengthening of a horizon between its cutoff and the hinge, together with the vertical thickness calculation that a mapped isopach measures. The rules module also contains, but kept separate from the rules and labelled as the model build's resolution of the flagged problem, the crestal collapse graben solution used in this paper: two planar faults converging within the cover and a keystone whose throw grows with the slip after onset, each horizon recording the share of slip that post-dates its deposition. Run directly, the module reports its own behaviour on an example fault: (1) what the flow rule conserves and what it does not, (2) the lengthening that flags the accommodation problem, (3) the position of the syn-rift maximum, (4) the decay of slip along strike and (5) the keystone drop growing with slip after onset and dying out where the graben faults converge. When handed the fault of the scaled model as a polyline, with the slip, the share of the slip pre-dating the base Laira horizon and the graben parameters stated in this paper, it reproduces the modelled isopachs of Figure 7c. The geometrical build of the models, the scaling onto the data, the fit, the gridded interpretation and the interactive models are not part of the module, because they carry the intricacies of the method rather than its rules, and the scaling may differ between geological provinces. What is important is that a user can see the structural concepts applied and check them, and that the approach goes beyond a drawing tool. Figures 1 and 7 are drawn from the first author's interpretation. Figure 2 is redrafted from the original interpretations of the seismic lines. Figures 4 and 5 are rendered from the 3D model, and Figure 6 is computed by the rules module.

The rules module (relaylab_rules_v1_2.py) is available at <https://doi.org/10.5281/zenodo.23600941> and by request from relaygeoscience.com.

The seismic data on which the Penola Trough interpretation was made were originally provided by Origin Energy and its joint venture partners. Otway Basin petroleum exploration data are released open-file by the South Australian Department for Energy and Mining.

DECLARATION ON THE USE OF ARTIFICIAL INTELLIGENCE

The forward models were specified by the authors in natural language and returned by a large language model (Claude, Anthropic) as parameterised, self-contained code; this use is part of the method described above. A

705 language model was also used as a drafting aid for the manuscript and the figure scripts. The structural rules, the
706 model design, the scaling onto the Katnook data, all interpretations and all judgements of geological plausibility
707 are the authors' own, as is the manuscript, for which they take full responsibility. Figures derived from a model
708 are deterministic renders or computations from that code, not generative images.

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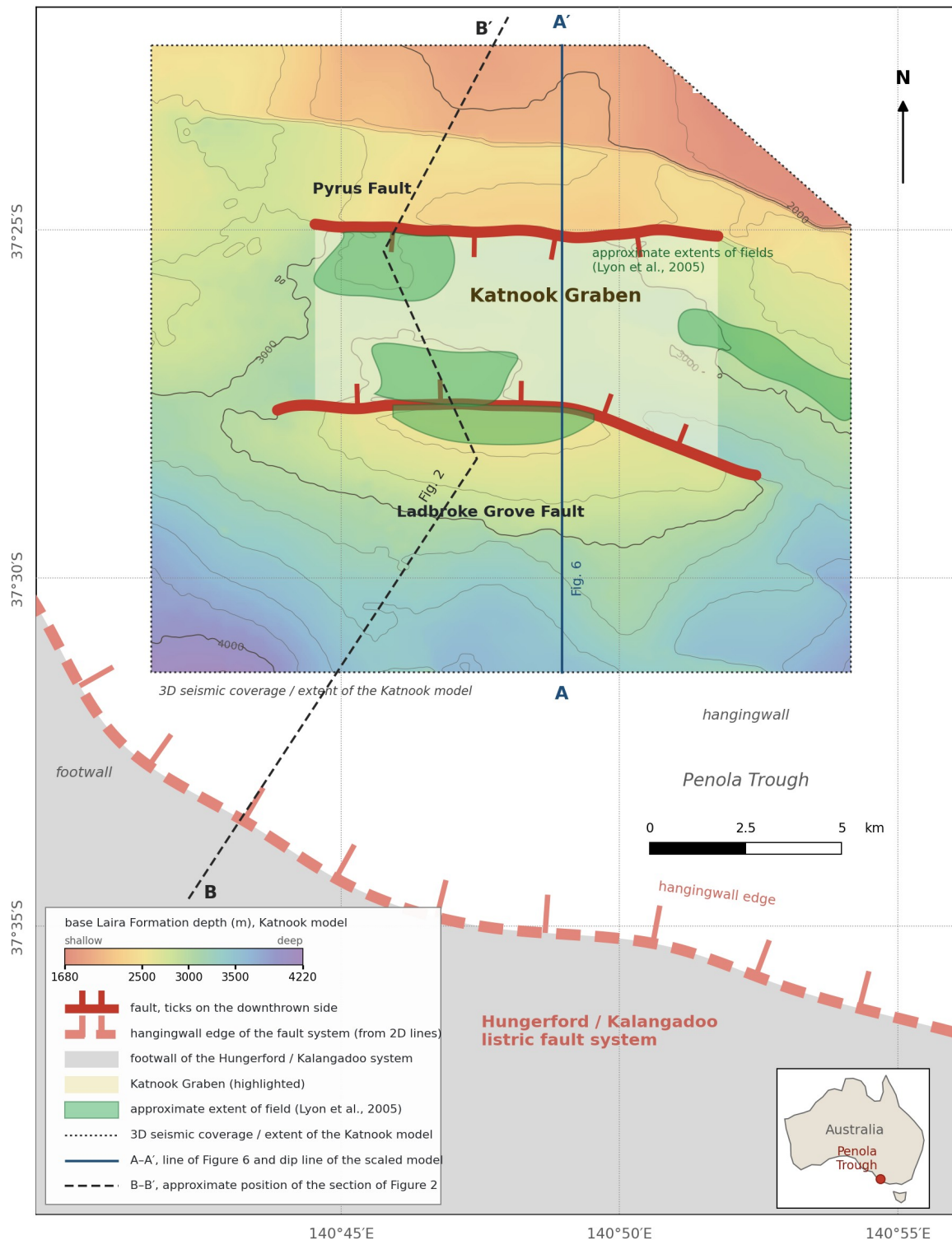
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810 **FIGURES**



811
 812 **Figure 1.** The Katnook Graben and the Hungerford/Kalangadoo listric fault system, Penola Trough. Backdrop:
 813 base Laira Formation depth structure over an area of 3D coverage. The hangingwall edge of the fault system is
 814 the first author's interpretation from sparse 2D lines. The Pyrus and Ladbrooke Grove faults are constructed along
 815 their mapped polygons at the base Laira level. The green polygons are the approximate extents of the fields
 816 (Lyon et al., 2005). A-A' is the dip line of the scaled model (Figure 7). B-B' is the approximate position of the
 817 section of Figure 2.

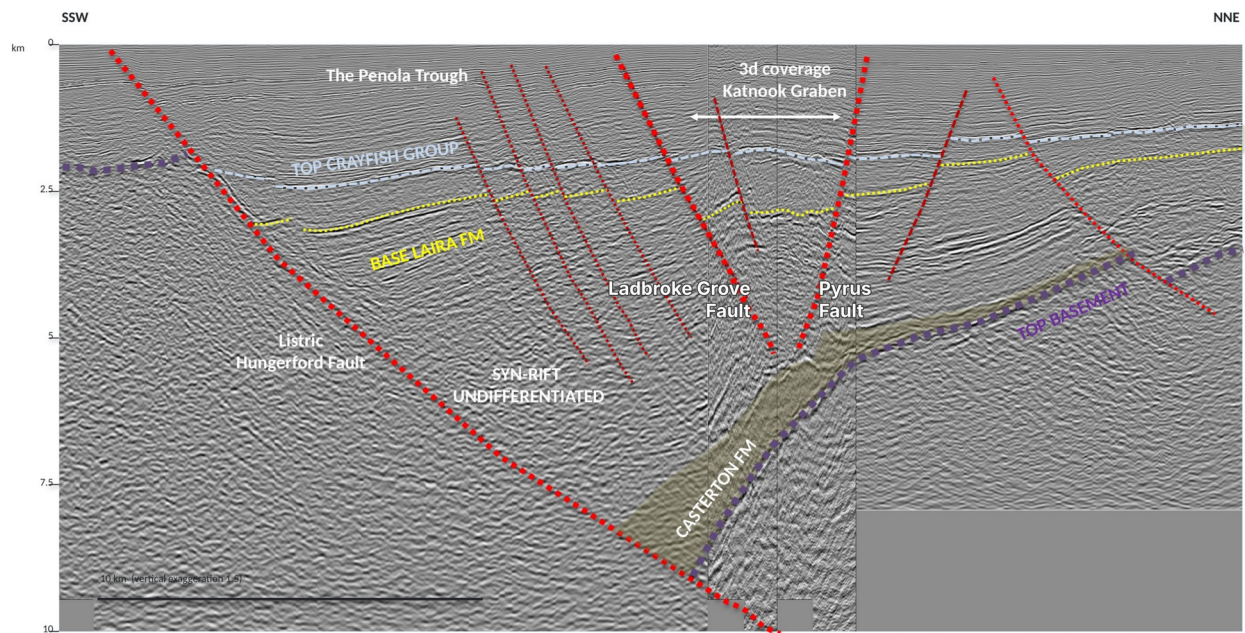


Figure 2. Regional depth-stretched seismic section through the Penola Trough and the Katnook Graben, south-south-west to north-north-east (B-B' on Figure 1, approximate position), redrafted by the first author from the original interpretations of the seismic lines. The listric Hungerford Fault (the Hungerford segment of the Hungerford/Kalangadoo system), the top Crayfish Group and the base Laira Formation horizons bound the growth interval, which thickens into the graben and southward towards the master fault and is the interval tested in Figure 7. The top of the basement, the Casterton Formation wedge against the master fault and the smaller intra-rift faults of the hangingwall are shown. The Katnook Graben is bounded by the Ladbrooke Grove Fault to the south and the Pyrus Fault to the north (heavy dotted lines, labelled), which converge within the sedimentary cover at about 5 km, well above the master fault, as in Boulton et al. (2004) and Lyon et al. (2005); compare Lyon et al. (2007, fig. 6a), where the same two faults were carried into basement. The thinner dashed faults within and beside the graben are smaller intra-rift faults. Fault positions are approximate and the horizontal scale is inferred from the published figure. The graben geometry used in the model is taken from the 3D interpretation (Figure 1). Vertical exaggeration is about 1.5.

Model build, test and revise

From provisional map inputs to a scaled, restorable three-dimensional model within hours to a day or two

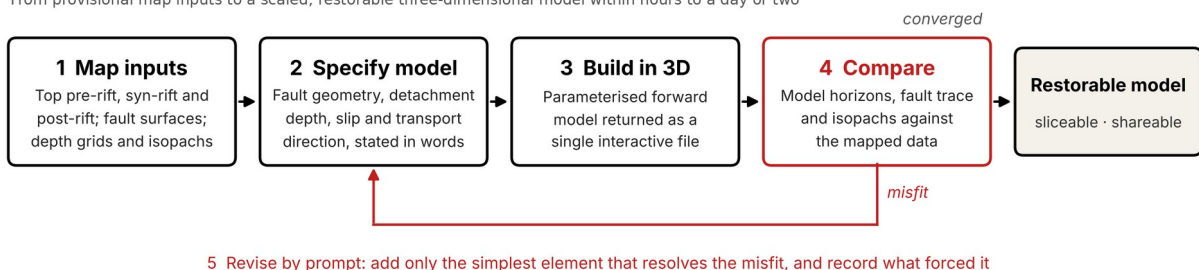


Figure 3. The model build, test and revise workflow loop. Provisional map inputs are used to specify a model. The model is built in 3D, compared with the mapped horizons, fault geometry and thickness maps, and revised by adding only the simplest element that resolves the misfit, until the misfit is resolved or shown to be irreducible.

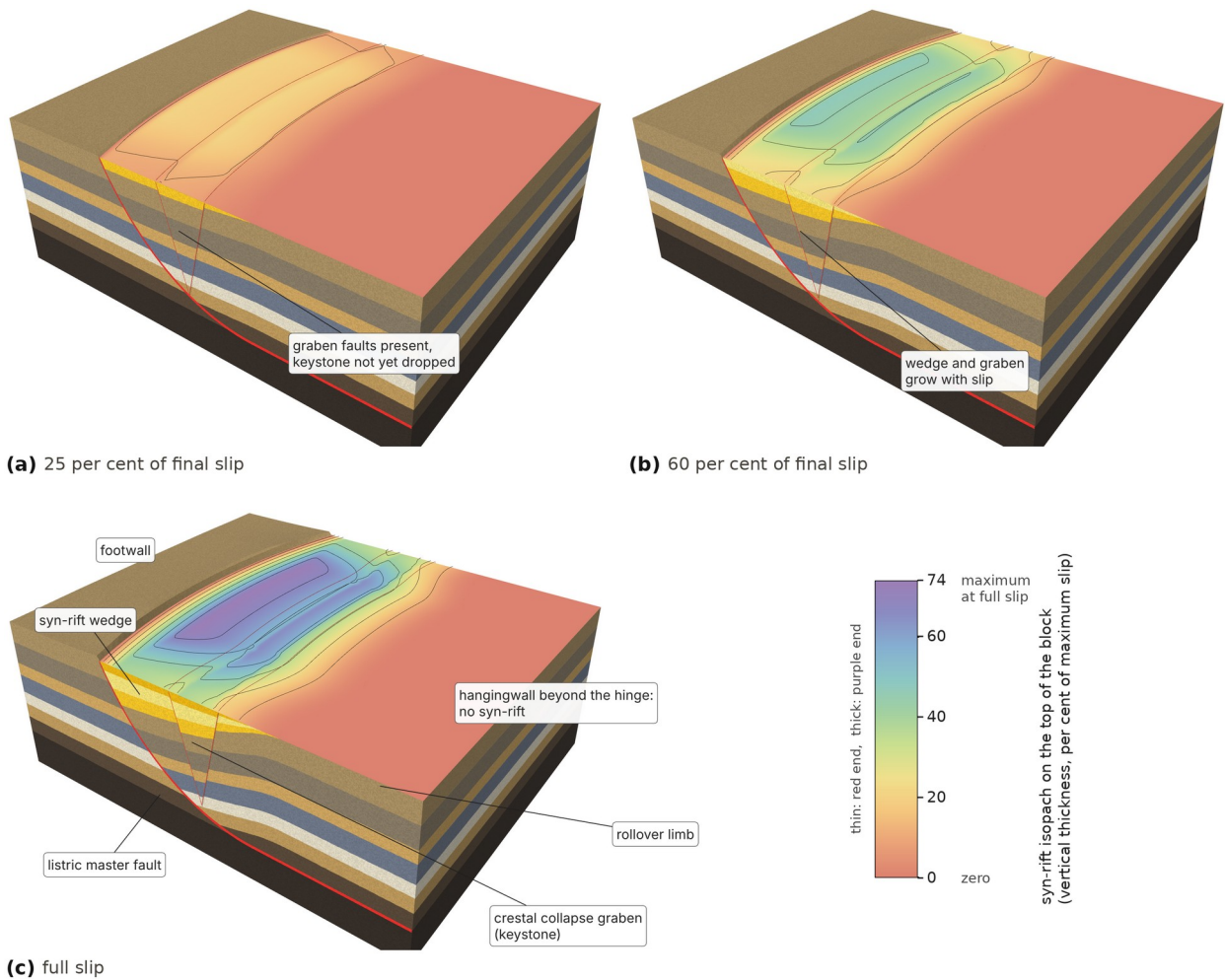
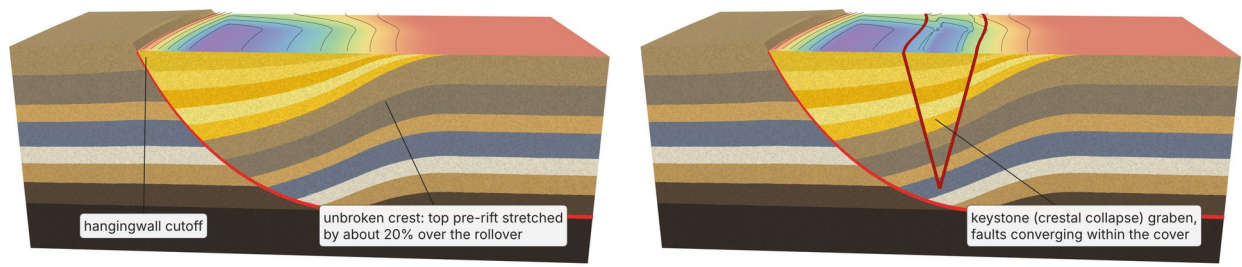
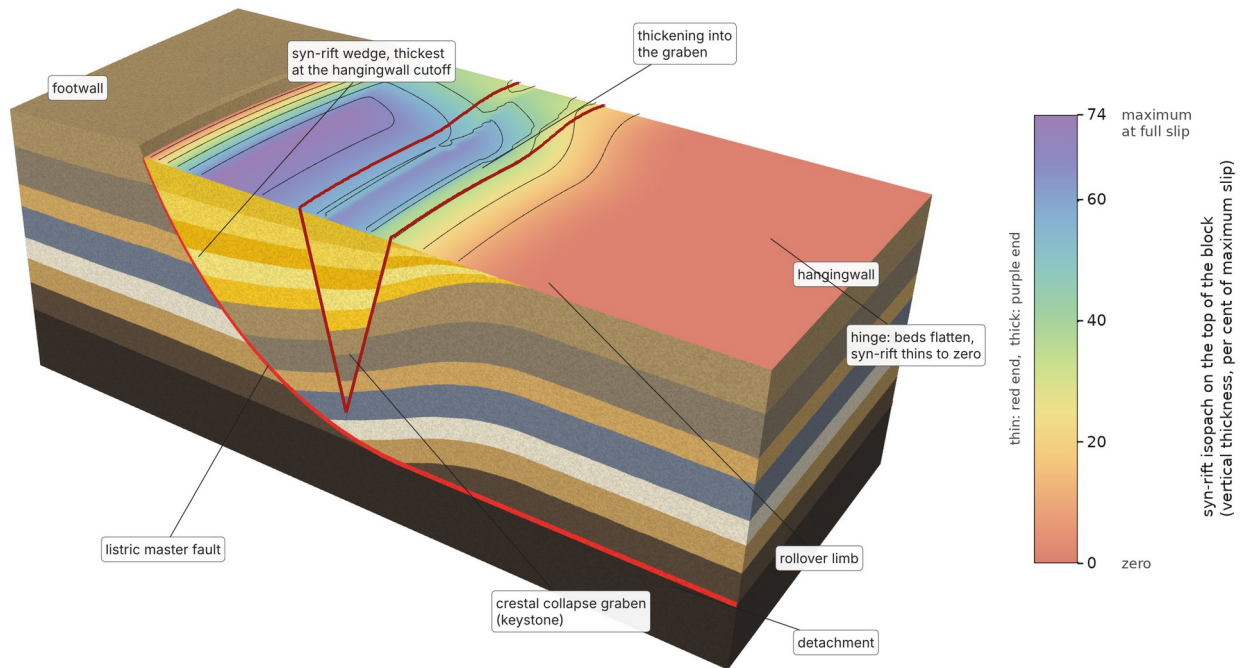


Figure 4. The model run back to (a) 25%, (b) 60% and (c) 100% of final slip, with the syn-rift isopach on one colour scale fixed to the maximum at full slip. The wedge thickens and the graben lengthens and deepens as the slip accumulates, and the geometry at any stage of the rift history is inspected directly rather than assumed.



(a) listric fault, crest unbroken

(b) listric fault with crestal graben



(c) the same model in three dimensions, isopach of the syn-rift on top

Figure 5. The model at full slip. (a) Dip section with the crest unbroken. The rollover limb and the syn-rift wedge are produced, but the limb has lengthened by about 20% and the unbroken hangingwall provides no accommodation for it. (b) The same section with a crestal collapse graben imposed on the limb, which resolves the accommodation problem and generates growth of the syn-rift into the graben. (c) The same model in 3D, cut away along strike. The top of each block carries the syn-rift isopach, thin at the red end and thick at the purple end of the colour bar, with its maximum at the hangingwall cutoff and its thickening into the keystone. Vertical exaggeration 1.35 for display.

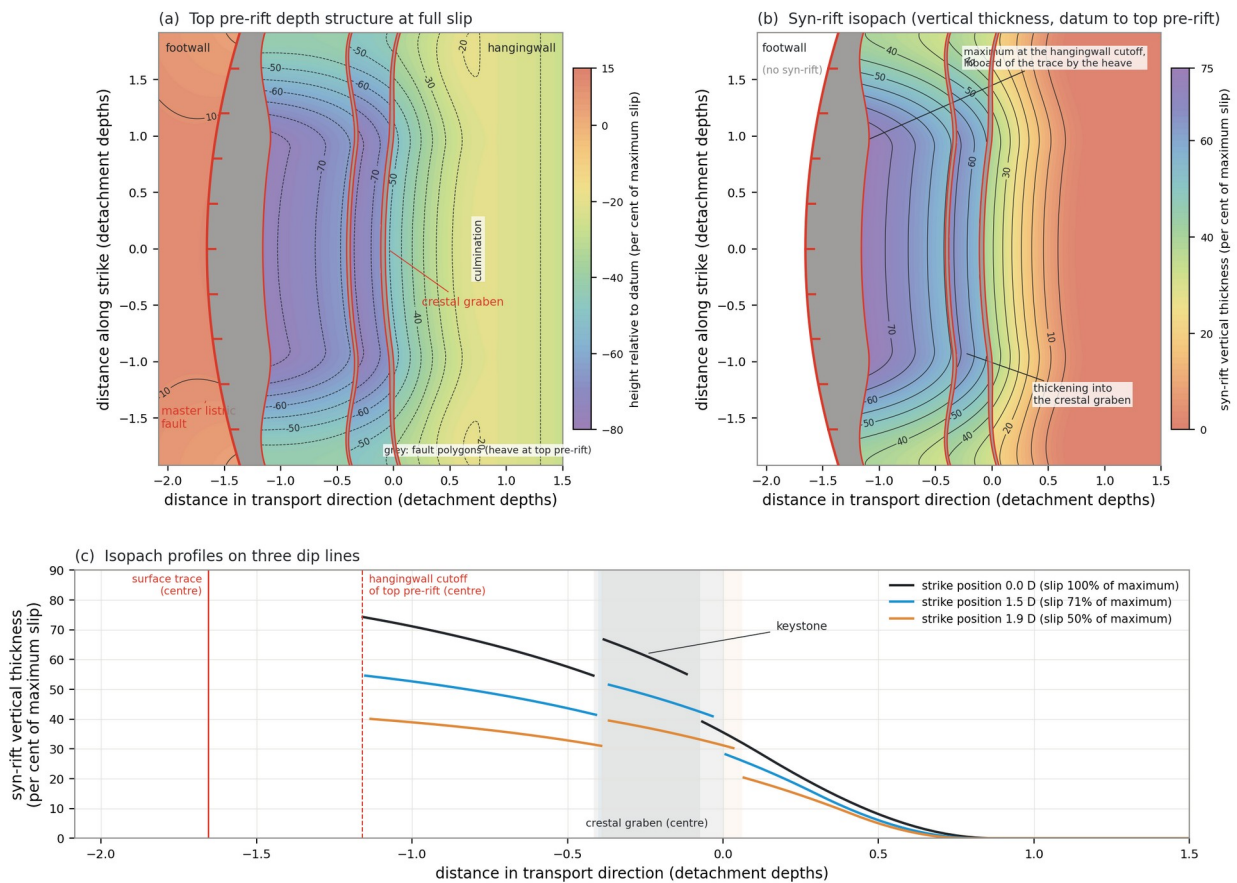


Figure 6. Maps and profiles are computed by the rules module at full slip. Distances are displayed in terms of distance in the transport direction and distance along strike. (a) Top pre-rift depth structure. This shows the deep zone at the hangingwall cutoff, the rising limb, and the graben as a step in the limb whose faults follow the bow of the trace and deflect towards the master fault where the slip has halved. (b) Syn-rift isopach. This shows the wedge with its maximum at the hangingwall cutoff, the thickening into the graben, and the along-strike decay of both. (c) Isopach profiles on dip lines positioned along the centre of the fault and towards its ends. The step within the shaded interval is the thickening into the keystone.

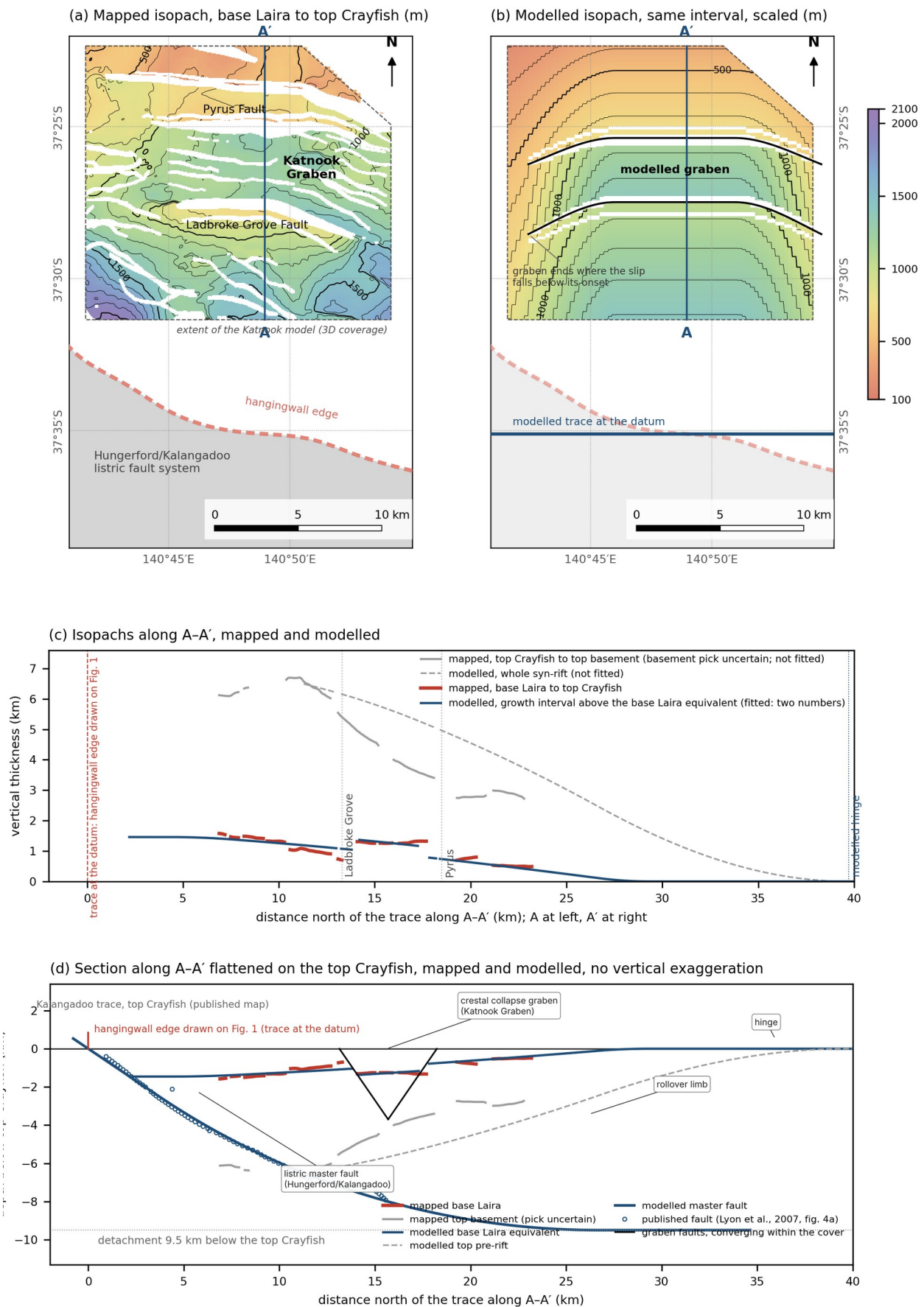


Figure 7. The results scaled to the Katnook data. (a) Mapped isopach of the base Laira to top Crayfish interval (m). The faults are left as gaps and the hangingwall edge from Figure 1 is shown. (b) Modelled isopach of the same interval. Transport is north-south. The fault trace is at the datum (top Crayfish) on the hangingwall edge. The

860 slip profile is set so that the graben ends where the mapped graben ends. (c) Isopachs along A-A'. This shows the
861 growth interval, mapped and modelled (fitted for the two parameters, the share of the slip pre-dating the base
862 Laira horizon and the keystone throw), and the basement to top Crayfish interval, mapped and modelled, not
863 fitted. (d) Section along A-A' flattened on the top Crayfish, no vertical exaggeration. This shows the mapped
864 base Laira and top basement against the modelled horizons, the modelled master fault with the published fault
865 as open circles, and the graben faults converging within the cover 3.7 km below the datum. Inputs from the data
866 are the fault traces from Figure 1, the dip of 34 degrees at the datum and the shape to 9 km from the published
867 section, the slip of 13 km from the top basement cutoff 6.5 km below the datum, and the graben position, width,
868 convergence depth and onset from the interpretation. Fitted: the proportion of the slip pre-dating the base
869 Laira horizon (0.80) and the keystone throw (810 m at the top Crayfish level, giving 350 m at the base Laira).
870 Detachment 9.5 km below the top Crayfish. Growth interval misfit 116 m root mean square.