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COMBINED SEISMIC–GRAVITY INTERPRETATION OVER THE DONNYBROOK ANTICLINE, CENTRAL QUEENSLAND

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Accurate modelling, using seismic and gravity data, has shown that the Donnybrook Gravity High, in central Queensland, is the result of a complex situation involving three discordant basins. The most significant is an old basin buried deep beneath the Drummond Basin, and apparently deposited in a valley carved out of a thick sequence of Silver Hills Volcanics and related acid volcanics. The Drummond Basin wedges out westwards under the Galilee Basin, and is bounded to the east by the same acid volcanics that subcrop near the Anakie Metamorphics. The illusion that the Donnybrook Gravity High is associated with the Donnybrook Anticline is the result of an intrabasement granite, which introduces a large negative component, cancelling the western flank of a much broader gravity high. After the cancellation, the granite is represented by a low of only 30 $\mu m.s^{-2}$. The already complex situation is further complicated by a topographic feature that introduces ambiguity in the most crucial area of the interpretation. This factor demonstrates the need to combine density profiling with forward modelling.

Introduction

The Donnybrook Anticline (Fig. 1.) is situated in a narrow zone of Permo-Carboniferous outcrops of the Drummond Basin in western Queensland (Olgers, 1972). This zone is bounded to the west by the Carboniferous to Triassic Galilee Basin, and to the east by Devonian to Carboniferous Silver Hills Volcanics and Lower Palaeozoic Anakie Metamorphics. The Bureau of Mineral Resources (BMR) carried out two combined seismic and gravity surveys in 1971 and 1976, over the 350 $\mu m.s^{-2}$ gravity high associated with the Donnybrook Anticline (Fig. 2). The gravity high is centred about the Donnybrook Anticline (Fig. 3), but the low to the east of it at H is offset from the Mistake Creek Syncline. Another gravity low at B is adjacent to a broad topographic feature, and the shape of the Bouguer profile there depends on the density chosen for the Bouguer correction.

The seismic survey carried out in 1971 crossed the western margin of the Galilee Basin and stopped just short of the Donnybrook Anticline. The reflection data revealed unconformities, wedges, and deep dipping events (Fig.4), but the deep events were not used in the interpretation and the gravity high was initially attributed to uplifted basement under the anticline (Harrison & others,1975). The model did not give a good fit for the gravity low at B, and a new model involving a reverse density contrast across a deep reflector was postulated (Flavelle & Anfiloff, 1976). In 1976, the seismic traverse was extended eastward as far as the Anakie Metamorphics, and revealed a discontinuous set of reflectors at various depths (Fig.4). The new reflection data were interpreted (Pinchin, 1978) in terms of a thrust bringing basement up slightly under the gravity high, but this structure does not account for the amplitude of the high, nor the shape of the low at B (Fig. 5). Pinchin & others (1979) presented alternative gravity models as part of an overall study of the Galilee Basin's eastern margin, but did not consider the Donnybrook High in detail.

Realisation of the importance of topography in the Donnybrook case was largely responsible for the coining of the term 'formal interpretation' (Anfiloff & Flavelle, 1979). A formal gravity interpretation accounts for the topographic effect by combining data reduction with modelling, and does not involve any steps unaccounted for in the final presentation. These rules are

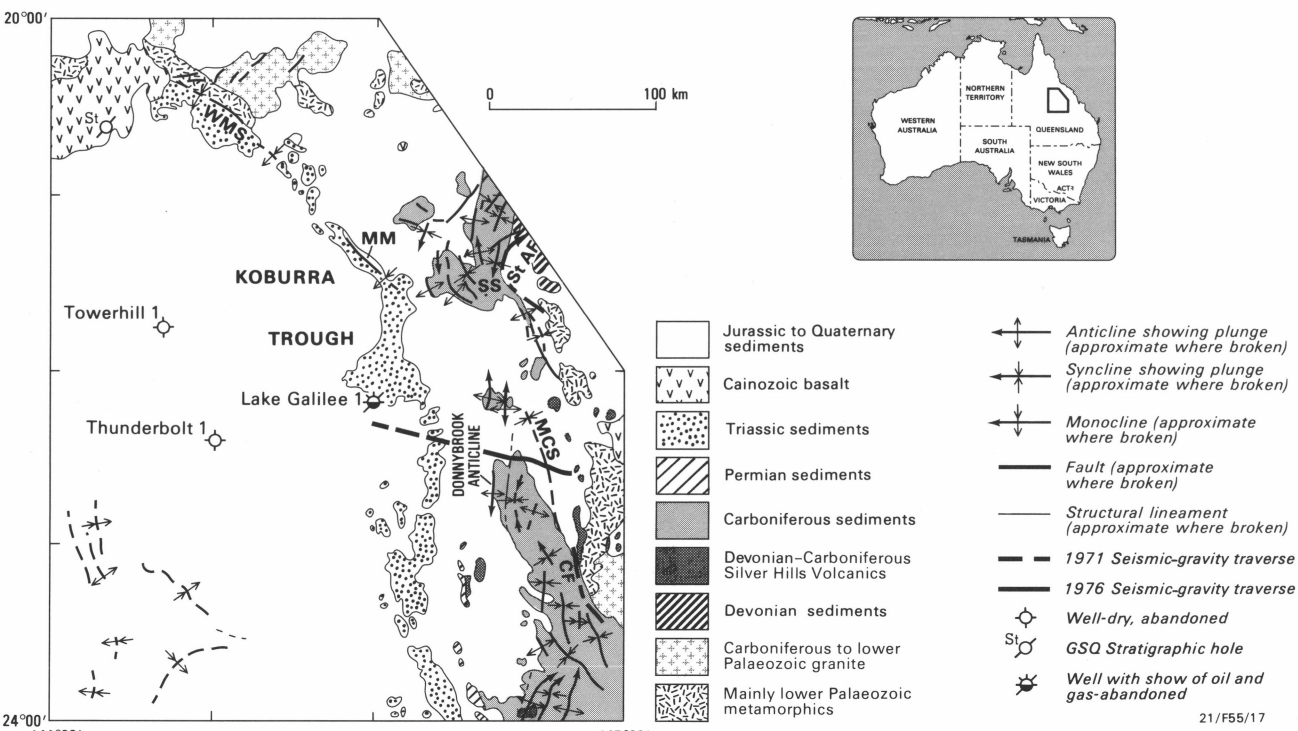

Figure 1. Geology, and location of the Donnybrook Anticline and seismic–gravity traverses.
From Pinchin (1978). MCS — Mistake Creek Syncline.

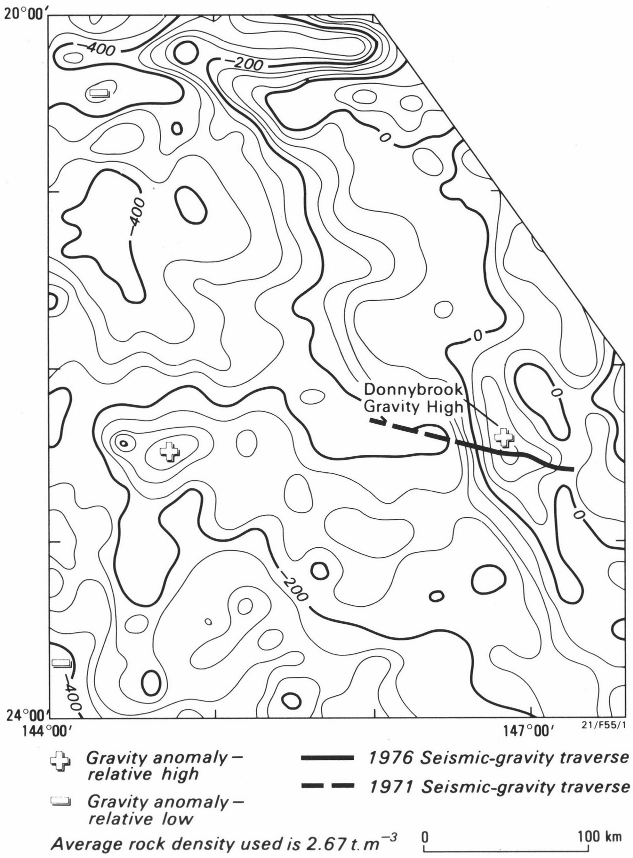

Figure 2. Reconnaissance gravity contours and location of seismic–gravity traverse.
Contour interval 50 μm.s^{-2}.

necessary to preserve integrity in gravity analysis, and in practice require that Nettleton's (1939) density profiling method be combined with forward modelling. The need for the formal interpretation concept is amply demonstrated by Fisher & Howard's (1980) attempt to interpret the Donnybrook gravity anomaly using an inversion method. As discussed by Anfiloff (1981), that attempt was unsuccessful because of a failure to use accurate data, to recognise the topographic problem, and because of the coarseness of the inversion method.

This paper extends the interpretation of Flavelle & Anfiloff (1976) eastwards, using the additional seismic and gravity data obtained in the 1976 survey. The extra data have a direct bearing on the Donnybrook anomaly, as they provide information on the Silver Hills Volcanics, which play a key role in the analysis. The analysis has been carried out by testing the following three possible explanations for the Donnybrook Gravity High: 1 — basement uplift; 2 — dense block in the basement; 3 — reverse density contrast between sediments and underlying Silver Hills Volcanics.

Seismic information

Seismic sections for the 1971 and 1976 surveys overlap, and SP1130 on the 1971 traverse coincides with SP2000 on the 1976 traverse (Fig. 4). The 1976 survey was designed to improve on the 1971 survey, and consolidate the exploration program, but instead revealed a complex picture involving numerous short segments of reflectors.

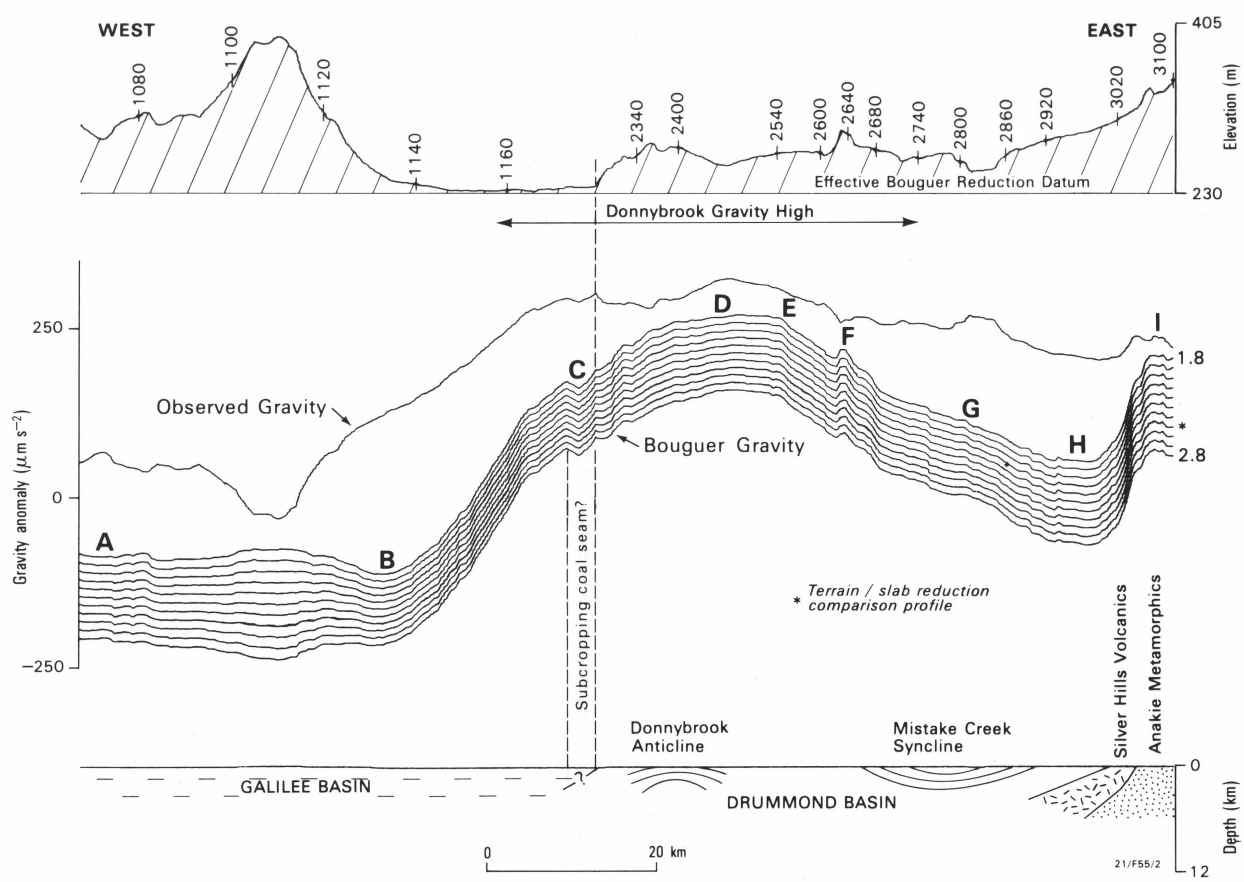

Figure 3. Gravity profiles and surface geology along the combined 1971–76 traverse.

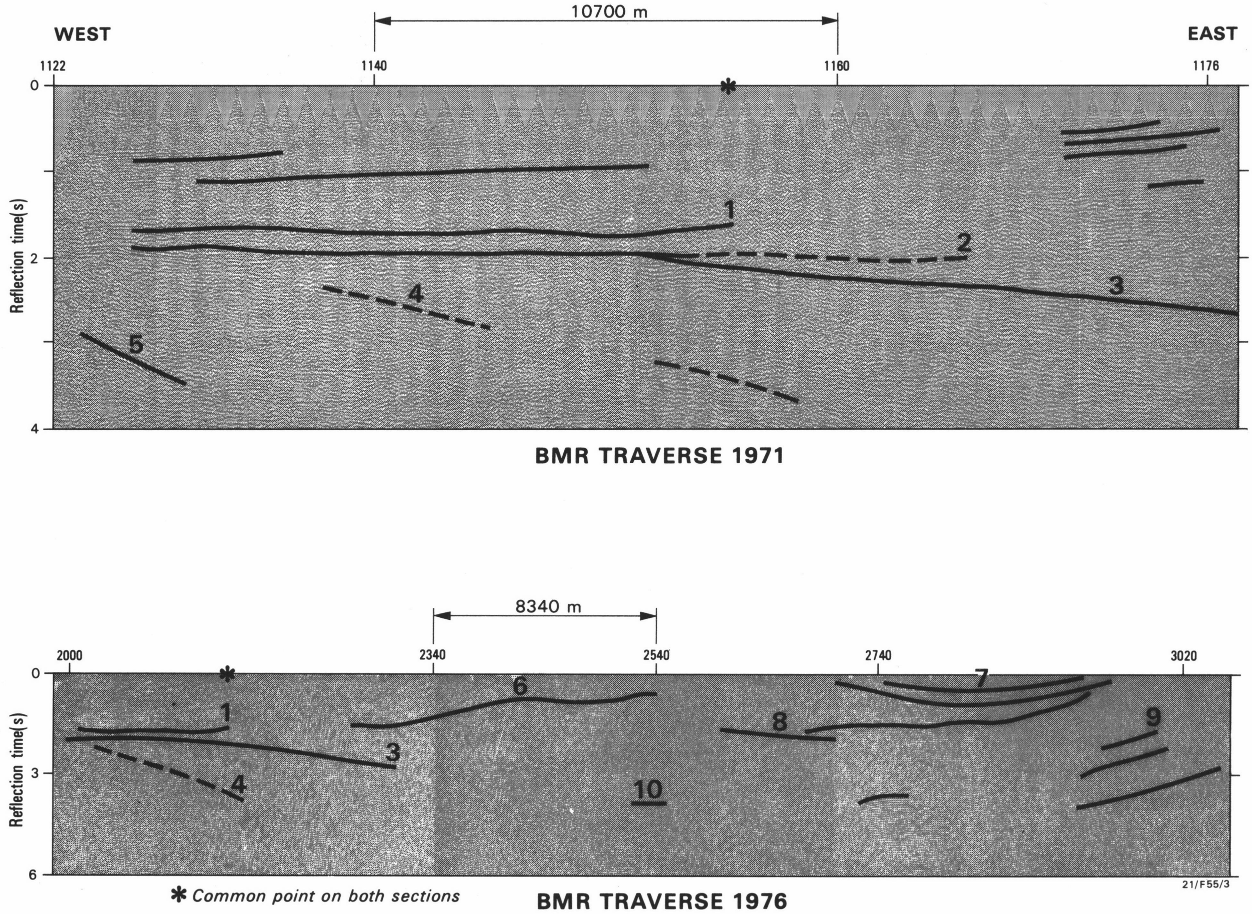

Figure 4. Reflection sections for the 1971 and 1976 seismic traverses, showing the main reflectors.
The sections overlap and have different horizontal and vertical scales. The discontinuous nature of reflectors results in considerable ambiguity.

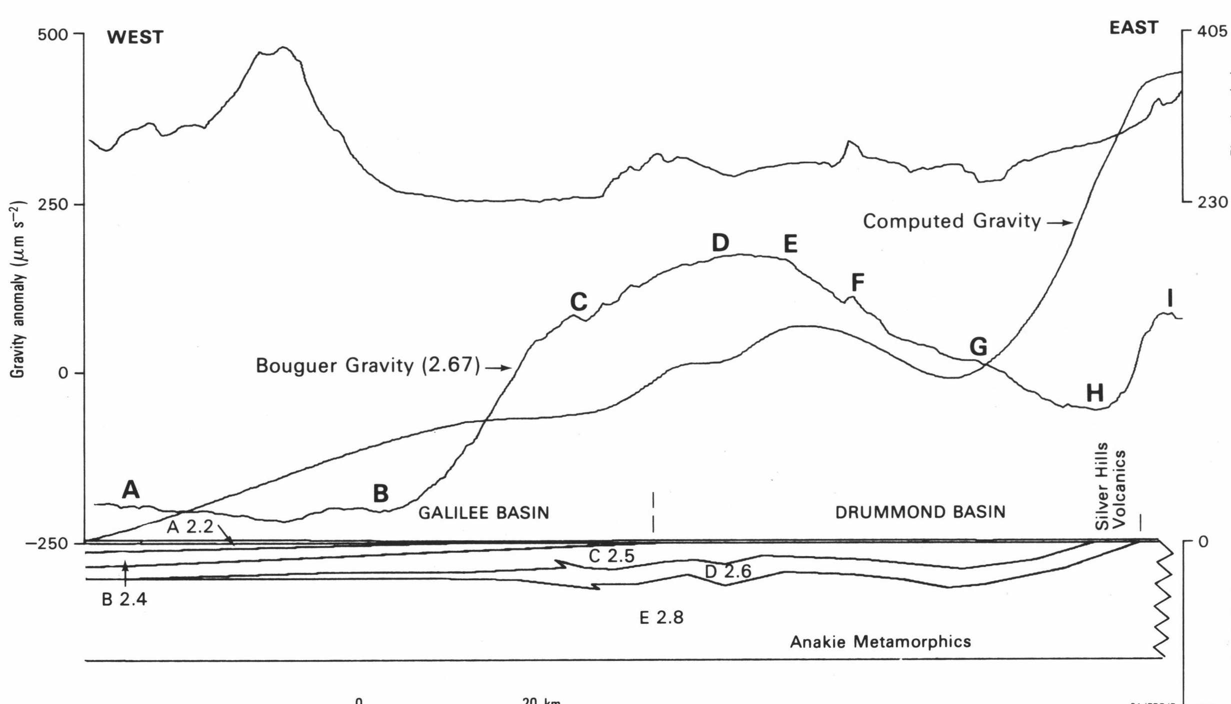

Figure 5. Gravity model of Pinchin's (1978) seismic interpretation.
This model shows that the seismic interpretation is inadequate and additional structures need to be invoked.

The 1971 section shows Galilee Basin sediments above 0.5 sec shallowing eastwards, but extrapolation to the surface is difficult, because there is a break in reflection continuity associated with the abrupt ending of reflector 1 at SP1154. Reflectors 2 and 3 and events 4 and 5 deeper in the section represent complex structures involving unknown rock types. Reflector 3 could represent Adavale Basin equivalents underlying the Drummond Basin, and indicates a considerable thickening of the total sedimentary section to the east. Event 4 was interpreted by Pinchin & others (1979) as a reflected refraction, but a change in reflection character across it suggests it could represent a series of diffractions arising from a dipping surface. Event 5 has both straight and curved components, suggesting reflections and diffractions from another dipping surface.

The 1976 section confirms reflectors 1 and 3 and event 4, but it is not obvious how these relate to reflectors 6,7,8 and 10, and a series of diffracting surfaces in the region of 9, where a fault indicated by these events corresponds to a strong gradient in the gravity anomaly. Reflector 6 shows the folds of the Donnybrook Anticline, but the connection with reflectors 7 and 8 of the Mistake Creek Syncline is not clear. An unconformity between reflectors 7 and 8 implies a degree of complexity in the Drummond Basin, and one of the surfaces at 9 may represent the base of the Silver Hills Volcanics. Reflector 10 is an isolated event deep in the section, and may correlate with reflector 3.

The overall picture is far from clear, because information is missing in crucial areas. The lack of clarity particularly affects the important area under the Donnybrook Anticline, where interpreted depth to basement can vary by a factor of three. The section can be interpreted in several ways, the main options being: 1 — connect reflectors 3,6 and 8 together; this implies uplift along a low-angle thrust, and a shallow basement under the Donnybrook Anticline (Pinchin, 1978); 2 — connect reflectors 1,6 and 8; connect reflectors 3 and 10; and connect events 4 and 9 to produce a deep basin under the Donnybrook Anticline.

Gravity information

The combined gravity data for the 1971 surveys are displayed in Figure 3. Symbols A-I are used to designate individual bumps and gravity levels discussed in the text. Each bump is important to the interpretation as it decreases ambiguity by providing an additional constraint on density contrasts and structure.

For the 2.5 t/m^3 Bouguer reduction, normal slab corrections and automatic 2-D terrain corrections (Anfiloff, 1976) have been applied separately, resulting in two profiles superimposed on one another for comparison. The profiles are almost identical, except for a slight thickening of the line in the region of the main topographic feature between A and B. This feature, which has a relief of 150 m, does not, therefore, require a terrain correction, and is hardly discernible in the elevation profile drawn at natural scale. Nevertheless the feature still causes a substantial change in the shape of the Bouguer profiles drawn for various densities, and in particular affects the shape of the gravity low at B. At the same time, the gravity low at B makes it impossible to determine the density of the topographic feature using Nettleton's (1939) minimum correlation principle, and the uncertainty in the topographic density in turn introduces uncertainty into the interpretation. The uncertainty cannot necessarily be removed, but the density profiling process at least enables the problem to be recognised.

The small gravity low at B (Fig. 3) has an amplitude of only 30 $\mu m.s^{-2}$, and does not correspond to any structures evident in the seismic section. This suggests that a major gravity low originating from within basement has cut into the western flank of the Donnybrook High, displacing it eastwards, and making it steeper. If this is the case, the cause of the Donnybrook High extends well west of the Donnybrook Anticline, and is unrelated to it. The gravity low at B is presumably caused by a granite, which cannot be shallower than the reflector at about 6 km.

The gravity low at H is east of the Mistake Creek Syncline, and must represent a large body of low-density material adjacent to the Anakie Metamorphics. The metamorphics consist of schist, slate, and sandstone, and would have a density in the range 2.6–2.7 t/m^3. To produce the anomaly between H and I, the body at H would have to have a density of 2.4–2.5 t/m^3, which is a relatively low value. The surface outcrops at H were identified as the Devono-Carboniferous Silver Hills Volcanics (Olgers, 1969), but the Telemon Formation, Mount Rankin beds, and Theresa Creek Volcanics could be included, as these contain low-density tuffs and acid volcanics. These formations have a widespread distribution, and, given that acid volcanics with a density of 2.42 t/m^3 were found to the west (Fig. 1) at the bottom of the Thunderbolt 1 well (Amerada, 1967a), it is possible that a thick low-density layer underlies the Galilee and Drummond Basins over the entire region. This layer appears to have been faulted against the Anakie Metamorphics at H and largely eroded from the upthrown block, leaving only scattered remnants.

The folds of the Donnybrook Anticline visible in the seismic section between SP-2340 and SP2540 (Fig. 4) have no gravity expression, implying that the anticline is underlain by rocks of similar density. This helps rule out the shallow basement option, and at the same time constrains the density in the lower part of the section. The bumps in the gravity at E and F are caused by density changes across formation boundaries at the surface. The bump at G is present only in the higher-density Bouguer profiles, and, being related to a dip in the elevation profile, suggests a low-density weathered layer at that location. The low at C has a short wavelength, and could be caused by subcropping Permian coal beds within the Galilee Basin sequence.

Interpretation

The basement uplift model

The abrupt termination eastwards of reflector 1 can be attributed to a thrust across which basement has been elevated. From the seismic data the total amount of uplift is limited (Fig. 4), and a large density contrast of 0.4 t/m^3 is needed to produce a sufficiently large gravity high (Fig. 6). However, the western flank of the computed anomaly is well offset from the true flank, and this cannot be altered, as reflectors 1 and 2 control the thrust position. This model, therefore, does not fit.

The dense basement block model

In Figure 7, an arbitrary horizontal datum is used to separate the Anakie Metamorphics from underlying basement, the metamorphics are extended, with a constant density, westwards under the section, and a dense block (body G) has been added to produce a gravity high. The gravity high extends the required distance to the west, while the granite (body F) cancels part of this high. The granite–dense block combination gives a reasonable anomaly in the first approximation, but there is a problem with matching the shape at B. A small granite produces a small low, but does not cancel enough of the

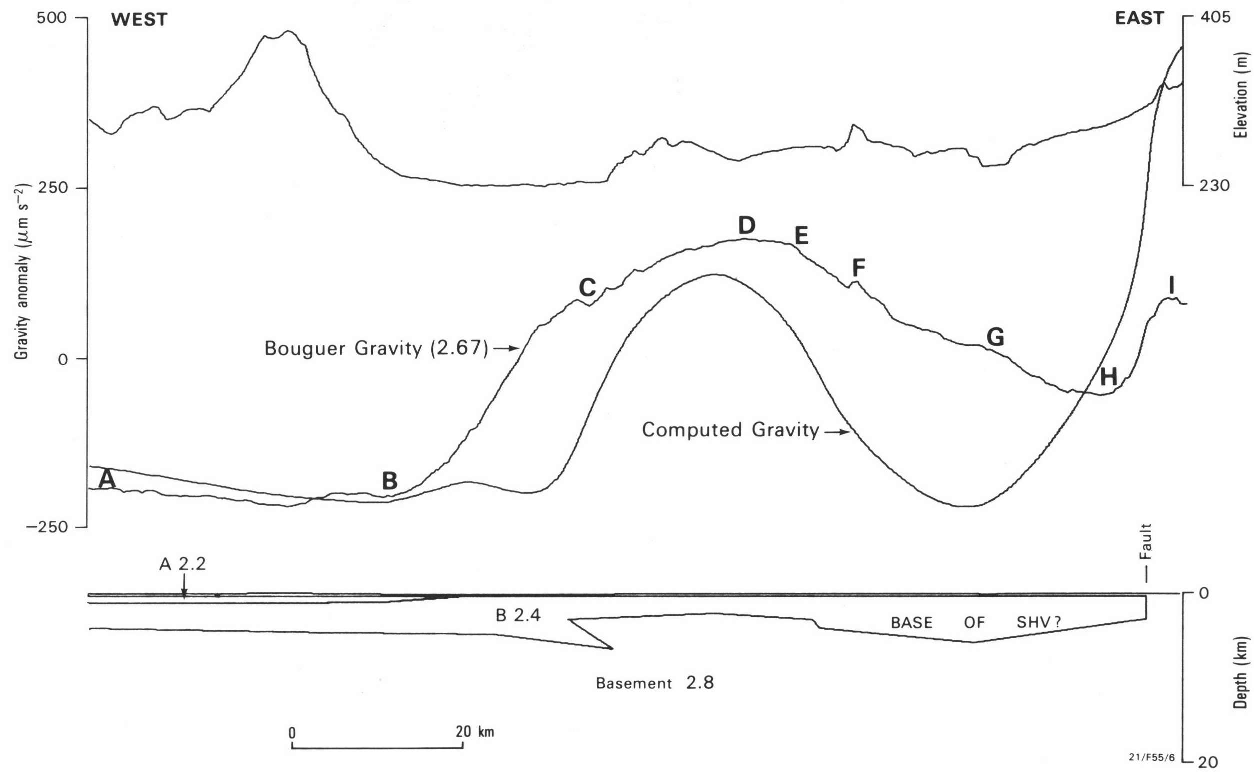

Figure 6. Gravity model, using basement uplift concept.
The interpreted thrust position is incompatible with the position of the western flank of the anomaly.

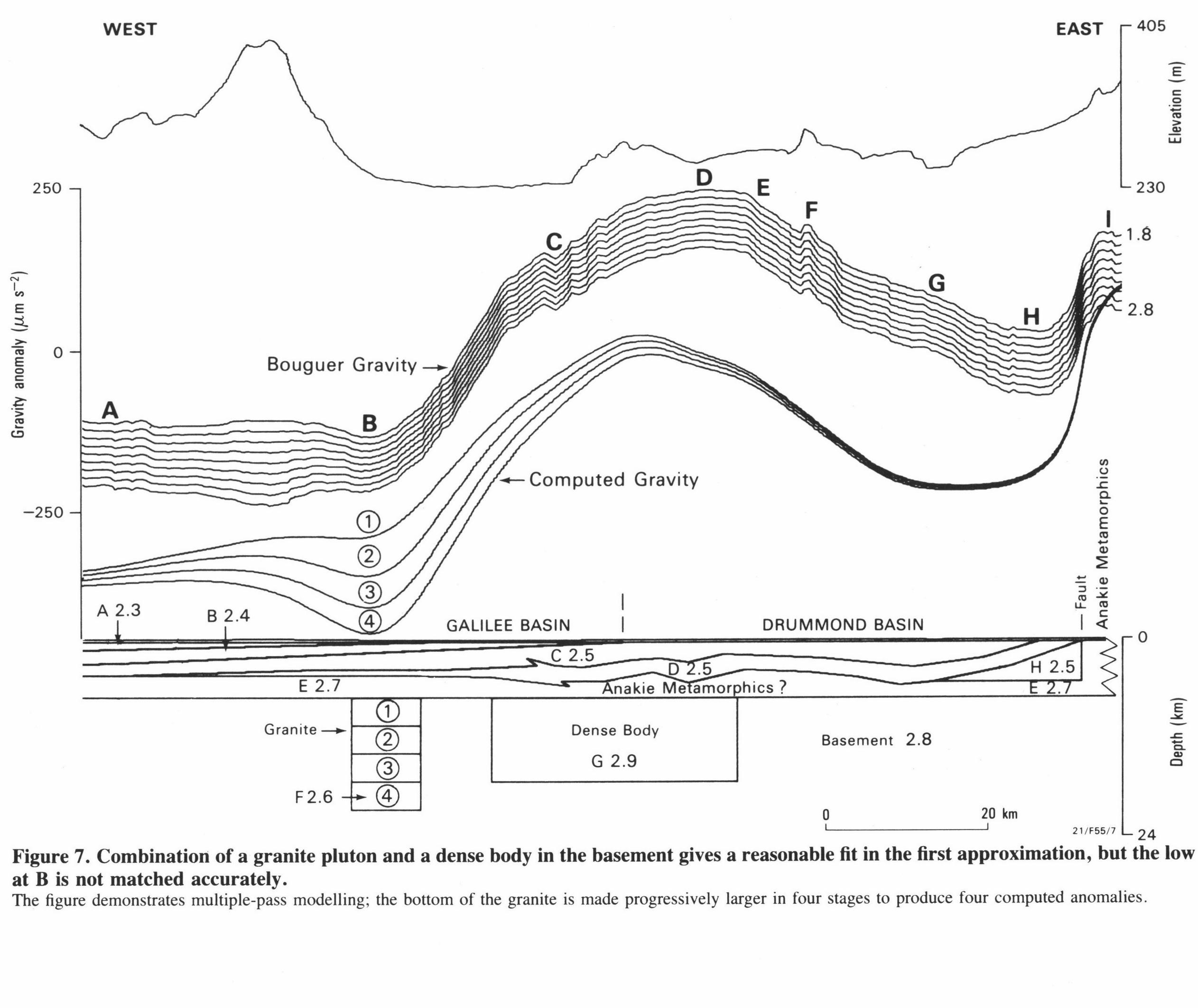

Figure 7. Combination of a granite pluton and a dense body in the basement gives a reasonable fit in the first approximation, but the low at B is not matched accurately.
The figure demonstrates multiple-pass modelling; the bottom of the granite is made progressively larger in four stages to produce four computed anomalies.

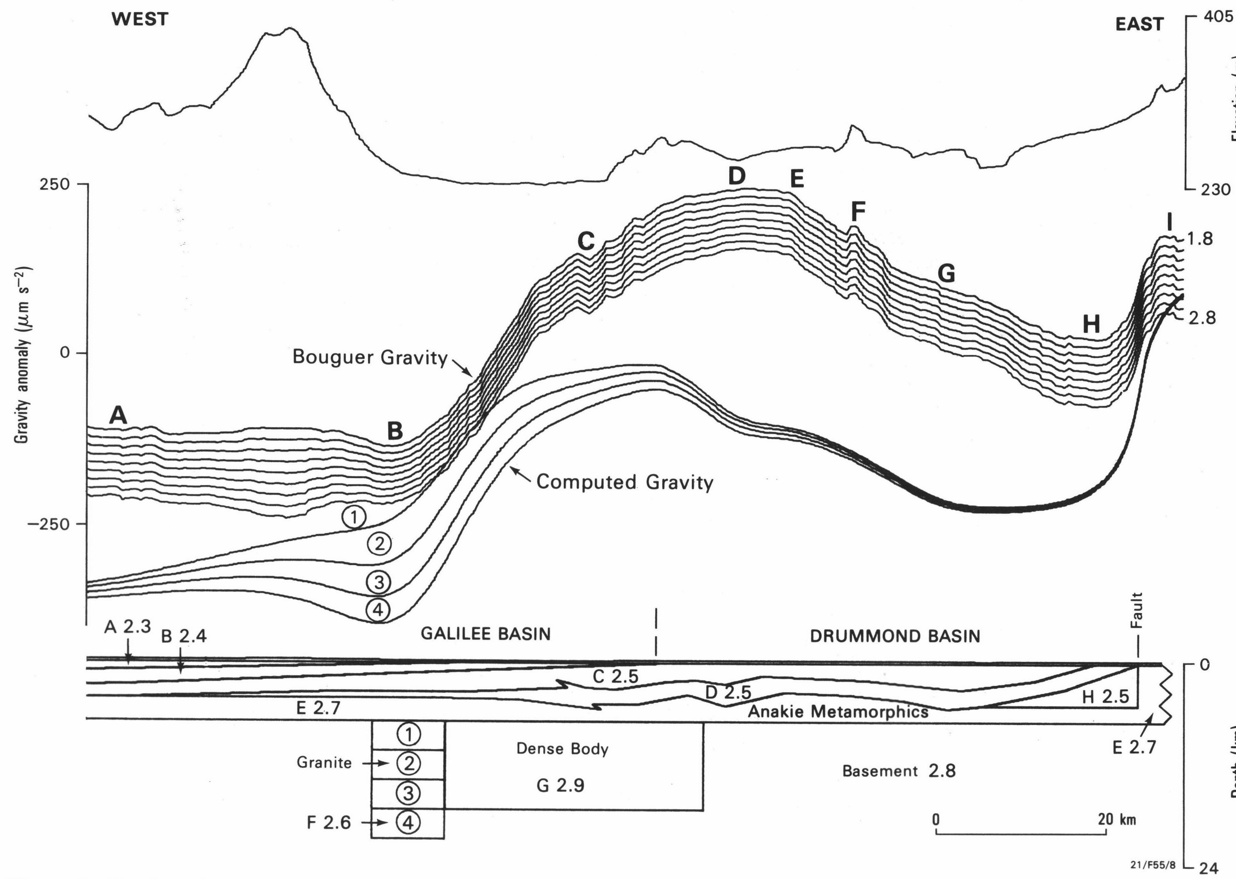

Figure 8. The dense body is moved next to the granite to produce better cancellation of anomalies.
The computed low at B is now smaller, but is still too large, and the interval A–B cannot be matched correctly.

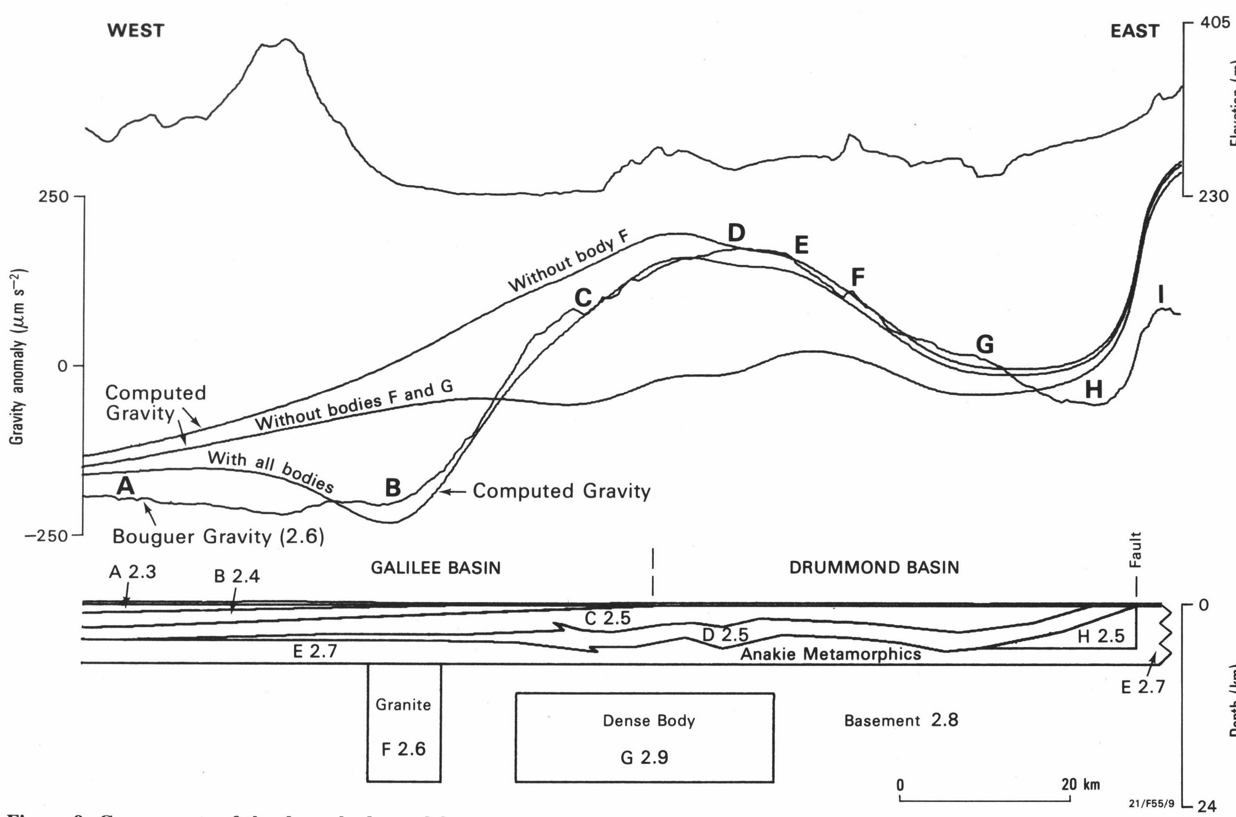

Figure 9. Components of the dense body model.
The curve at A and B is unsatisfactory and cannot be improved. The shape of the without-granite (body F) curve is critical and should be compared to that in Figure 10.

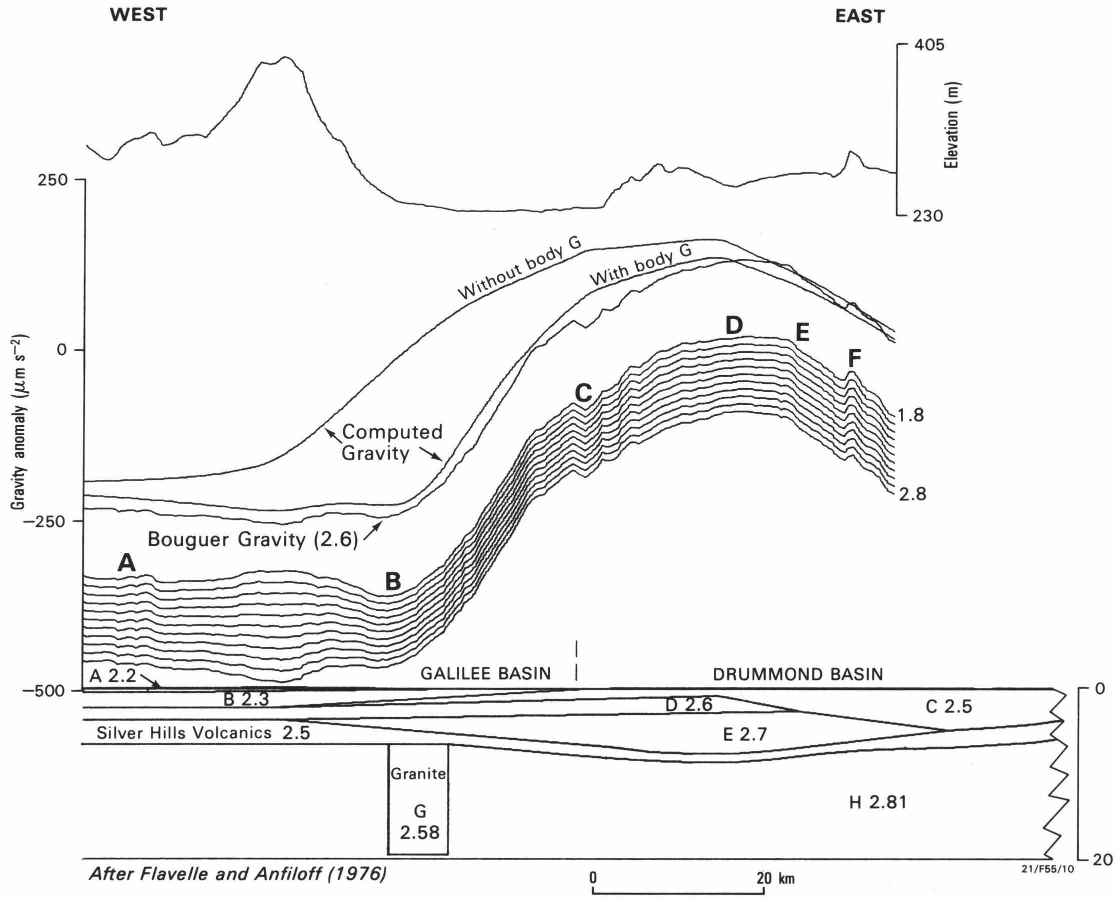

Figure 10. A reverse density contrast model based on the 1971 survey.
In this model a dense basin replaces less dense sub-basement (Silver Hills Volcanics) laterally, producing a good fit over the topographic feature with the 2.6–2.7t/m³ Bouguer profiles. The reverse contrast wedge is close to the top of the granite, and produces part of the required cancellation of anomalies.

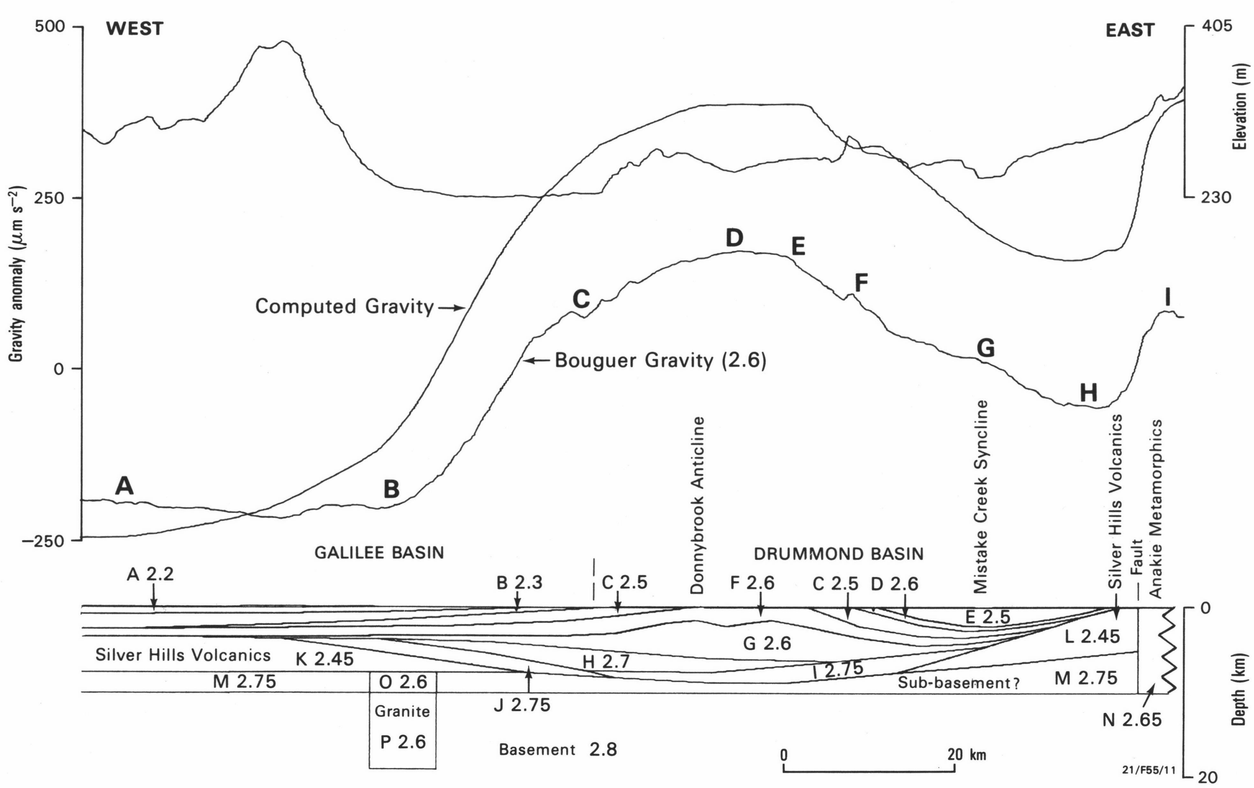

Figure 11. Extrapolation eastwards of the reverse contrast model, based on the 1976 seismic section.
The presence of a thick layer of Silver Hills Volcanics is established by the fault anomaly between H and I. The model suggests a complex depositional history and a deep basin under the Donnybrook Anticline. The fit at B is poor because the granite contribution is insufficient.

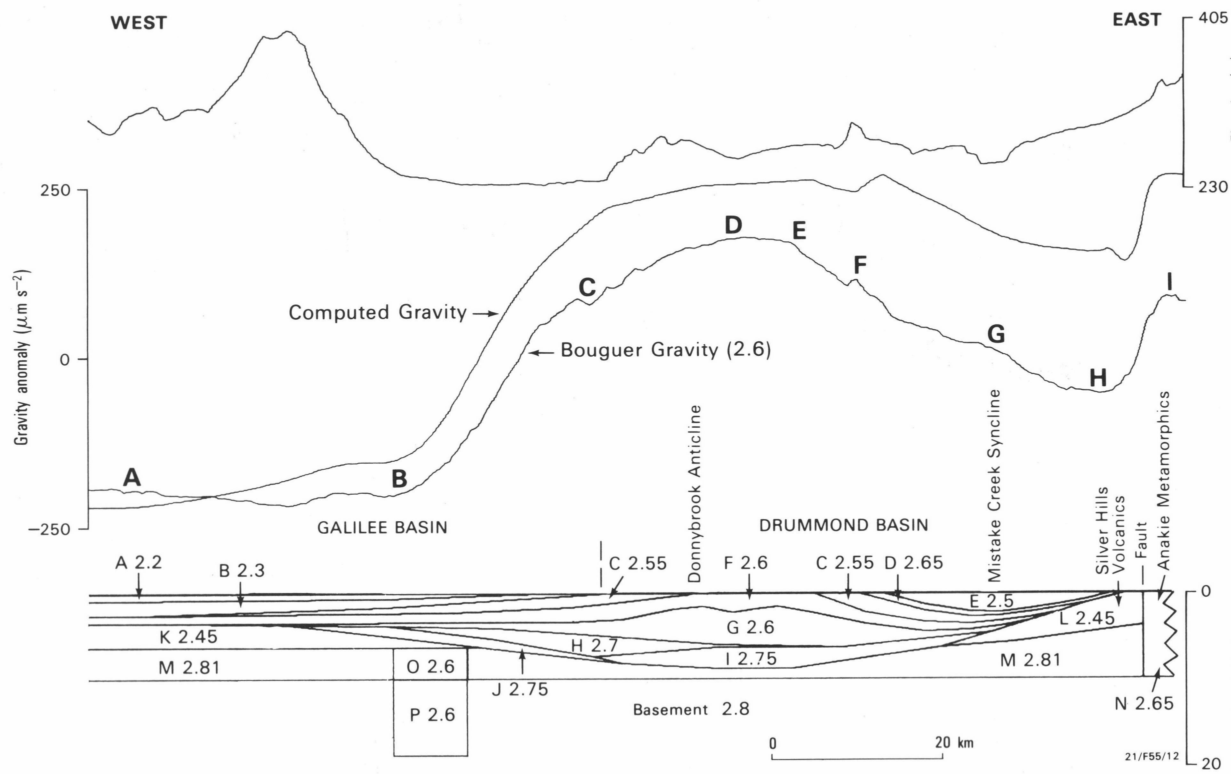

Figure 12. To give an improved fit at B, the model has to be modified to make the basement and granite shallower. The basin now protrudes too far into the basement, adversely affecting the level at D.

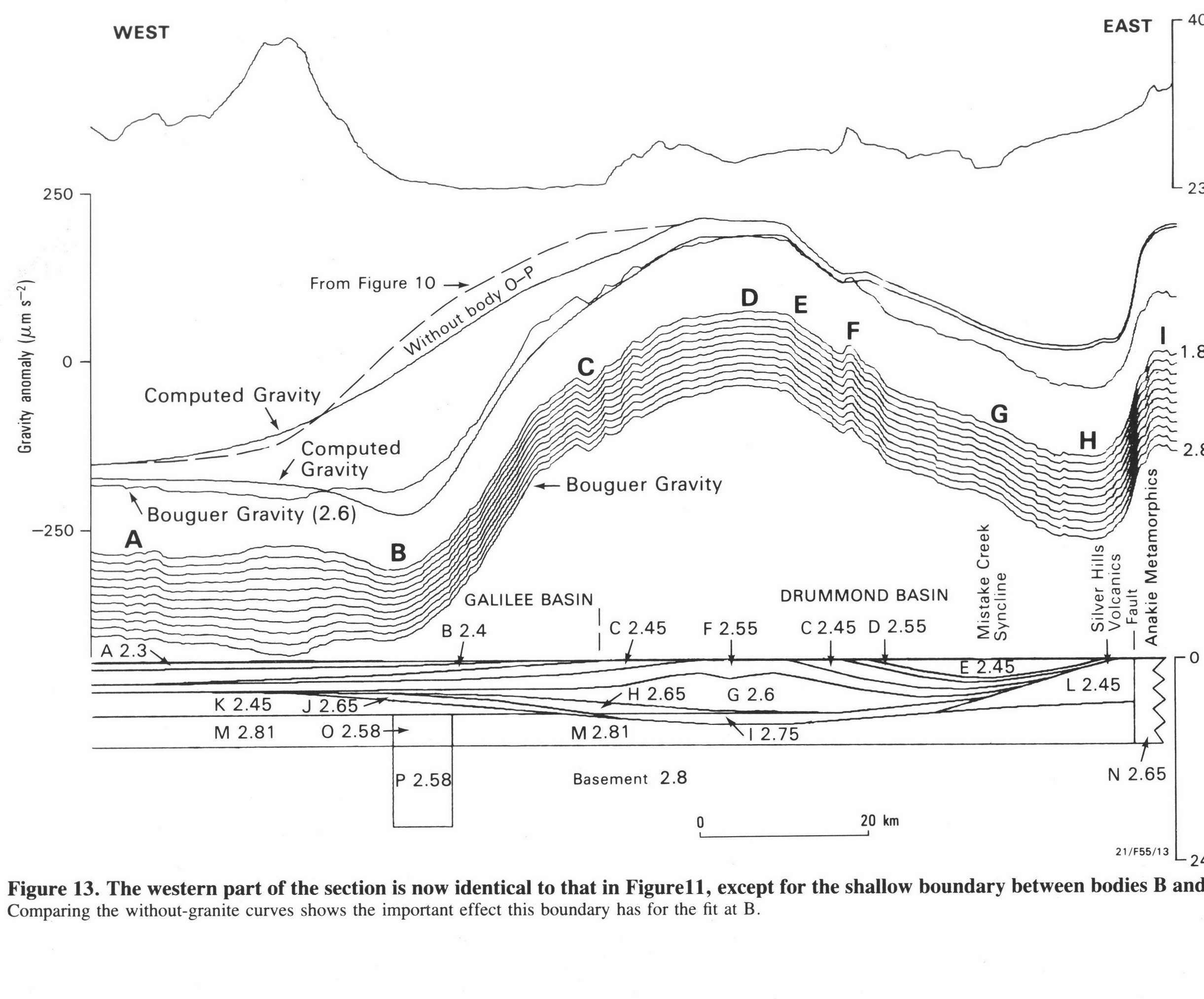

Figure 13. The western part of the section is now identical to that in Figure11, except for the shallow boundary between bodies B and C. Comparing the without-granite curves shows the important effect this boundary has for the fit at B.

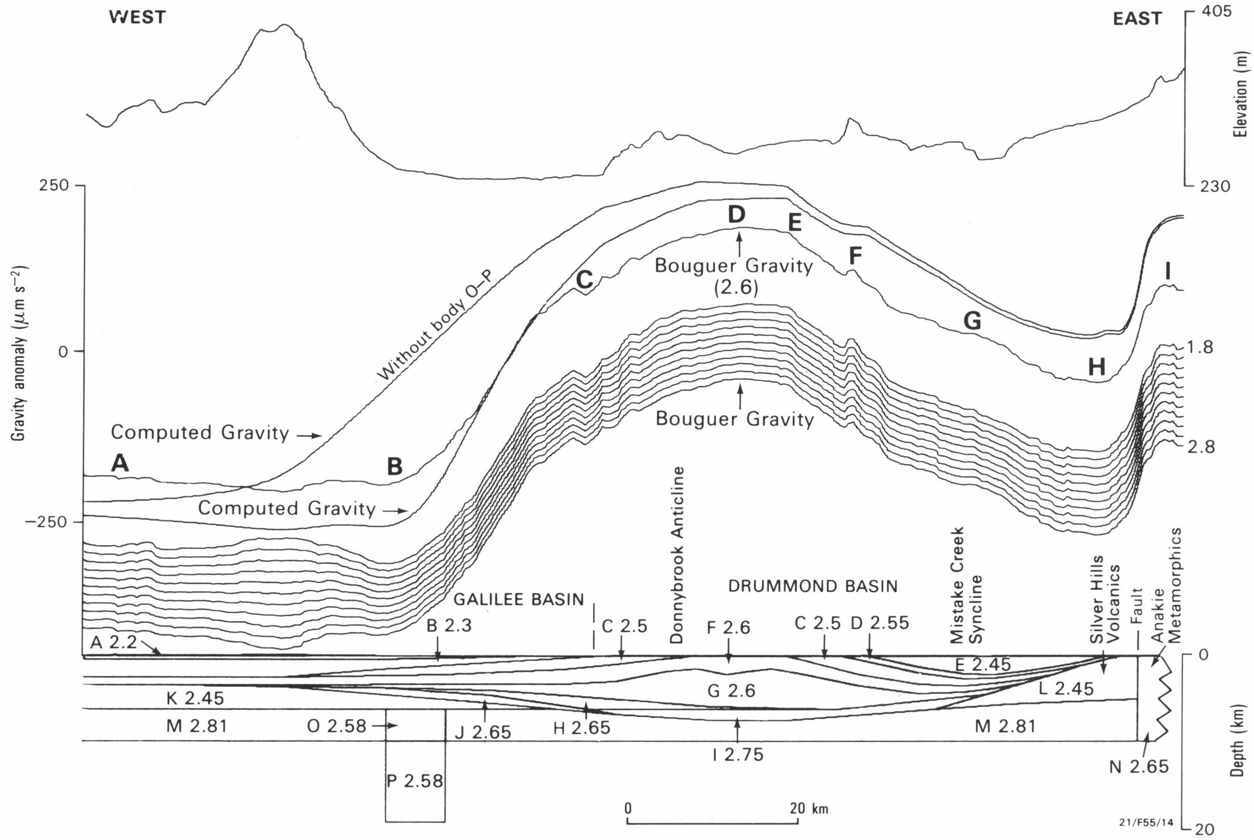

Figure 14. Making body C wedge out more rapidly westwards, as in the seismic interpretation of Harrison & others (1975), produces the correct fit at B, demonstrating the extreme sensitivity of the match to structural changes.

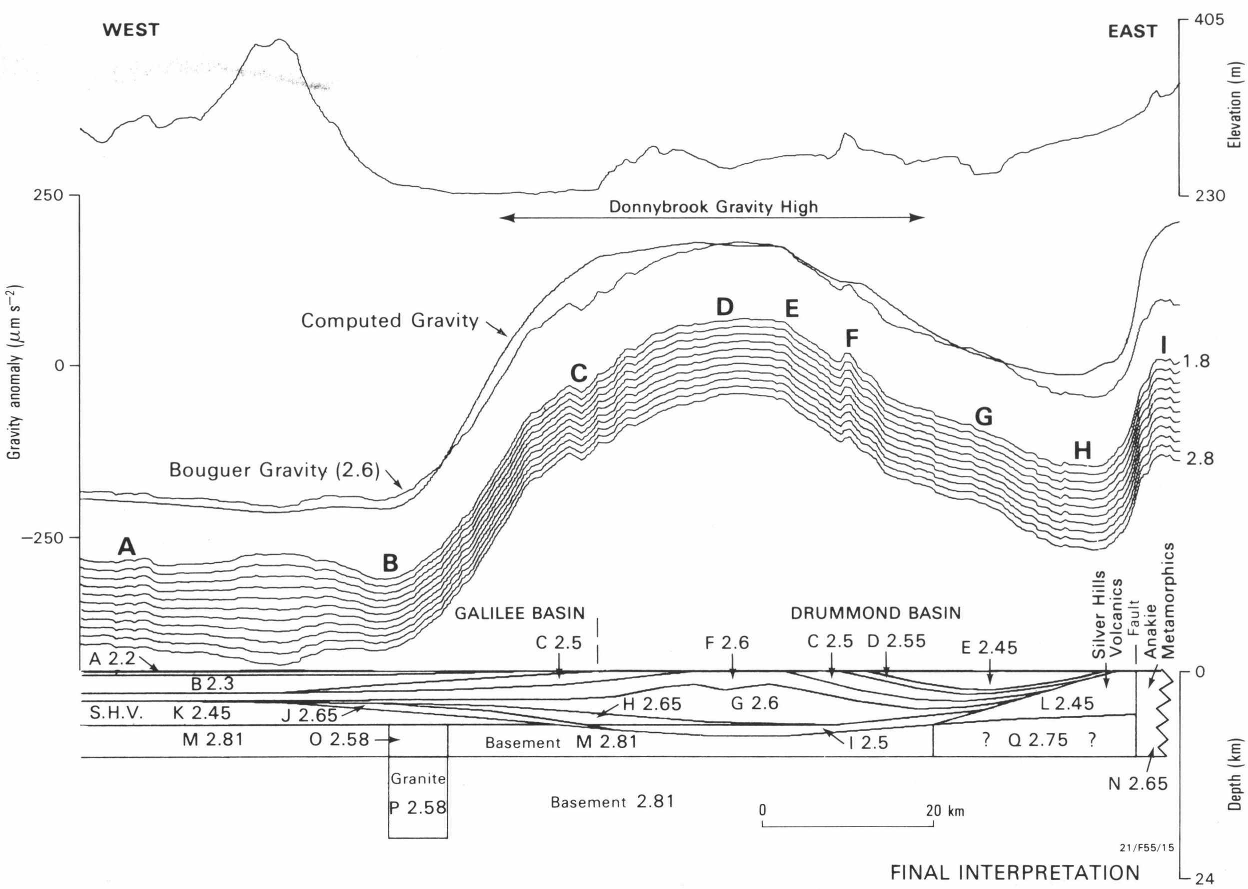

Figure 15: An arbitrary change to the density of body I and introducing body Q gives the necessary change in gravity levels to produce a satisfactory match over most of the section.

western flank of the Donnybrook Gravity High between A and B, while a large granite cancels the flank as required, but produces an excessively large low at B.

Figure 8 shows the improved effect of placing the dense basement block next to the granite; the cancellation is now more effective, but the low at B is still too large.

Figure 9 summarises the type of fit obtainable with the dense basement block model. Three computed anomalies are shown. One is the effect when neither the granite (body F) nor the dense block (body G) are present, a second shows the effect of introducing the dense block; the gravity high then extends considerably west of the actual anomaly. The third shows how the introduction of a granite body shifts the flank of the anomaly eastwards, modifies it, and produces a low at B. The fit could be considered to be reasonable, and this type of interpretation could be produced by an inversion program, which would adjust the two bodies in the basement until the R.M.S. error was minimised. In qualitative terms however, the fit is poor, because the correct anomaly shape has not been produced between A and B. Furthermore, as the true shape of the anomaly is not known, any automatic method would be guaranteed to fail. The solution requires a careful trial-and-error approach in which each computed curve is tested against each of the Bouguer density profiles.

The reverse density contrast model (1971 data)

Part of the Donnybrook Gravity High can be explained in terms of an older basin underlying the Drummond Basin. Events 3,4, and 5 in Figure 4, in combination with a thick low-density layer of Silver Hills Volcanics and related acid volcanics, form the basis of a reverse density contrast model, in which gravity increases as basement deepens. This relation also exists on Traverse R-56 of the Tower Hill seismic survey (Amerada, 1967b).

As about half the anomaly can be attributed to the transition from Galilee Basin sediments to denser Drummond Basin sediments, only about 200 $\mu m.s^{-2}$. needs to be accounted for. Given that tuffs and dacites can have a density of about 2.45 t/m^3, and that the material filling the older basin could include dense basalts, a reverse density contrast of about 0.2 t/m^3 could exist, operating over a section several kilometres thick. Using the 1971 seismic and gravity data, Flavelle & Anfiloff (1976) demonstrated how a reverse contrast model can produce a good match for the low at B. Their model, reproduced in Figure10, applies a reverse contrast across the easterly dipping event 5. This surface cuts across the top of the granite (body G) and produces the positive contribution needed to reduce the size of the low at B.

The low at B can be produced by a number of alternative granite bodies. The top of the granite cannot be deeper than about 7 km, while the seismic information restricts it to below about 6 km. The bottom of the granite can extend to 20 km, but not 25 km, and with a variety of cross-sectional shapes, can lie in the zone 15–20 km (Flavelle & Anfiloff, 1976).

In the zone A–B, the model produces a match with only the 2.6–2.7 t/m^3 Bouguer profiles, which is a reasonable density for the main topographic feature there, given that its existence as an erosional feature implies that its composition is not the same as Galilee Basin sediments generally.

The reverse density contrast model (1971 & 1976 data).

Figures 11-15 deal with the interpretation of the combined 1971 and 1976 data, using the reverse contrast concept. Figure 11 shows a comprehensive model based on 1971–76 seismic time-sections. It suggests a complex geological history: almost every boundary in the sedimentary section is an unconformity, and numerous episodes of movement are implied.

The boundary between bodies B and C is taken from the seismic interpretation of Pinchin (1978) (Fig. 5), and extends further west than the one mapped by Harrison & others (1975). The shallow formations (Fig. 11) are arranged to accord with the local bumps in the gravity. Body D produces the gravity high at F and must be at least 0.1 t/m^3 denser than adjacent bodies. The bump at E also indicates a 0.1 t/m^3 contrast between bodies C and F. The Donnybrook Anticline does not produce an anomaly, and the densities of bodies F and G must therefore be similar. The various bumps, when used in combination, mean that if a density is assigned to one formation, densities of the other formations are implied.

The deeper parts of the model are based on extrapolation of the seismic and geological data. Bodies G, H, I, and J represent formations deposited in a depression within the Silver Hills Volcanics (bodies K & L). Of these, bodies G, H, and J correspond to the three easterly-dipping events 3, 4 and 5.

The thickness of the Silver Hills Volcanics, and its density are constrained by the gravity low between H and I. At least 4km of the volcanics therefore appears to be faulted against the Anakie Metamorphics with a 0.2 t/m^3 contrast. It seems that the isolated pockets of Silver Hills Volcanics that occur over the Anakie Metamorphics are the remnants of a layer considerably thicker than previously thought.

Extending the interpretation eastwards causes major complications. The granite (bodies O & P) may penetrate two types of basement, the Anakie Metamorphics and an underlying denser Proterozoic basement. An arbitrary horizontal datum is used to separate the two, cutting the granite into bodies O and P. The model (Fig. 11) shows that if the Anakie Metamorphics have a density of 2.65 t/m^3 in the east, their density at B must be greater than 2.75 t/m^3 for the granite to cause a negative effect at a sufficiently shallow depth to produce the required low at B. The thickness of body K must also be decreased to raise the top of the granite as high as possible.

In Figure 12, the top of the granite is at 6 km. As the granite cannot be much less dense than 2.6 t/m^3, the basement density has to be increased to 2.81 t/m^3, which is presumably too dense for the Anakie Metamorphics. This arrangement is now beginning to produce the desired anomaly at B, but bodies H and I are now protruding too far into the basement, where they produce undesirable negative components.

In Figure 13, the section under the Donnybrook Anticline has been compressed to reduce the protrusion, and a new set of densities has been assigned to most of the bodies. There is now a good fit over most of the section, and the shape at B is improved. However, it is still larger than any of the lows in the Bouguer profiles for densities between 2.2 and 2.8 t/m^3, and is not the same as the low successfully matched in Figure 10. In fact the curves computed without the granite body are different. The curve from Figure 10, superimposed on the one in Figure 13, shows a steeper rise, reflecting the effect of a shallow structure. Although the models in Figures 10 and 13 have identical granites and reverse contrast wedges, they differ in the slope of the interface and the density contrast between the Galilee Basin (body B) and the Drummond Basin (body C). The interface represents a shallow wedge that generates a positive effect and cancels still more of the low at B, such that the 250 $\mu m.s^{-2}$ low generated by the granite registers as a low of only 20—30 $\mu m.s^{-2}$. Consequently, it appears that the steeper interface in the seismic interpretation of Harrison & others (1975) is more appropriate than the shallower one in the seismic interpretation of Pinchin (1978).

In Figure 14, the boundary between bodies B and C has been made identical to the one in Figure 10. This gives the same without-granite curve as in Figure10, and when the granite is added, the required anomaly shape is produced at B. It is remarkable that a small change in structure can so drastically alter the shape of the final anomaly, and that only a shallow structure can produce this change.

Also in Figure 14, the contrast between bodies B and C has been increased to 0.2 t/m^3 by making body C denser, and, because the relative densities between bodies C, F, and D have to be maintained to satisfy the constraints imposed by the bumps in the gravity at E and F, this has resulted in a regionally higher level of gravity over the eastern part of the section. This problem is rectified in the next model (Fig. 15) by making an arbitrary reduction in the density of body I and arbitrarily introducing body Q.

The final interpretation is not altogether satisfactory at the eastern end of the section, but further modelling is not justified until the gravity profile is extended further east to determine the complete fault signature and the representative gravity level over the Anakie Metamorphics.

Conclusions

The analysis of 247 gravity observations has necessitated major revisions to previously published interpretations of the seismic data. Moreover, the gravity has clarified even the better parts of the seismic section, and enabled analysis of the geological section at depths beyond the range of seismic penetration. The combination of density profiling, forward modelling, and multiple-pass display has allowed a large number of complex geological and geophysical constraints to be welded together, and the accuracy of the final result is borne out by the reasonable value of 2.6–2.7t/m^3 diagnosed for the density of the main topographic feature.

The exercise has demonstrated that if stratigraphic relations of formations are known, and if lateral continuity of their density can be assumed, then each bump in a gravity profile enables the deduction of an additional constraint on the overall interpretation. Consequently, in general, the ambiguity of gravity data along a traverse will decrease as the traverse is made longer.

The low on the western flank of the Donnybrook Gravity High is the sum of positive and negative components. A 250 μm.s^{-2} low, originating from a presumed granite in the basement, has been largely cancelled by the positive contributions from two sedimentary wedges, resulting in a low of only 20—30 μm.s^{-2}. The shallower wedge indicates that the upper part of the Drummond Basin does not extend far under the Galilee Basin, and the deeper wedge indicates an old basin underlying the Drummond Basin.

The Silver Hills Volcanics provide the low-density basement essential for the reverse density contrast model, and the gravity itself verifies the presence of a thick low-density layer faulted against the Anakie Metamorphics. To cause a positive gravity effect, the volcanics cannot be merely depressed: a basin has to be formed within the layer by erosion. At the present time, the same volcanic layer is being eroded in exposed anticlines in several areas, and the same could have happened after the tuffs were deposited subaerially in the Devonian—Carboniferous. Figure 16 shows a cycle in which the tuff is eroded from an anticline, and the anticline then subsides, forming a basin, which fills with denser sediments.

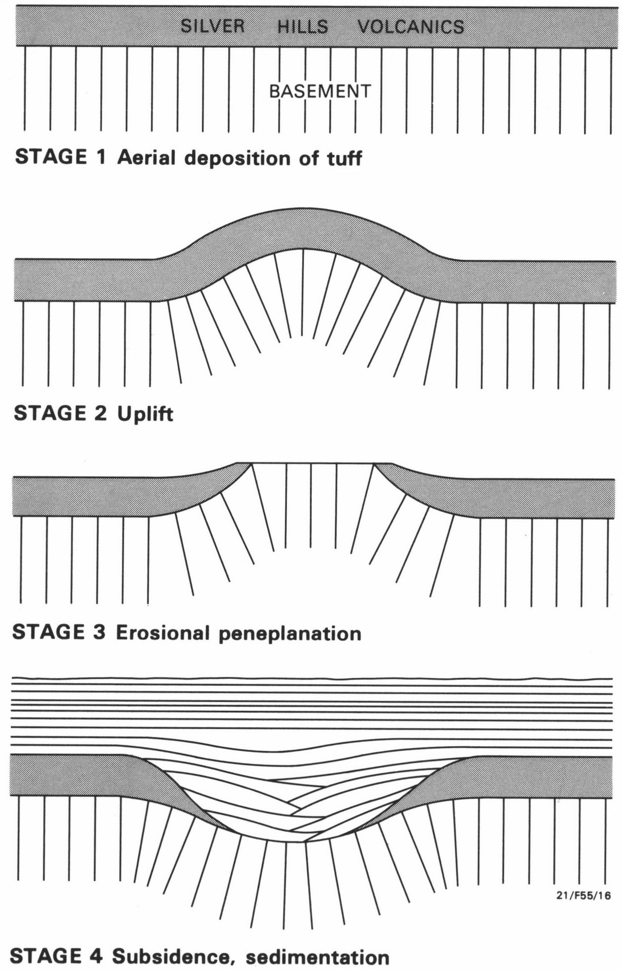

Figure 16. A generalised model that could produce a deep basin under the Donnybrook Anticline.

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