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Crustal structure of the central Bowen Basin, Queensland

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During May-June 1973, a deep crustal seismic refraction survey was undertaken in the Bowen Basin, Queensland. Blasts from open-cut coal mines in the Basin were used as sources of seismic energy, and recordings were made at twenty-two sites on a 375 km-long line along the axis of the Basin between Gonyella in the north and Moura in the south. A four-layer crust was interpreted from the seismic data, with P-wave velocities of 4.00 ± .22, 5.33 ± .08, 6.39 ± .07 and 7.07 ± .02 km/s respectively. The total thickness of the 4.00 and 5.53 km/s layers is about 6 km under Goonyella, and slightly more under Dingo 130 km north of Moura. Earlier magnetic and gravity work indicates that these two layers thin southwards towards Moura. They comprise folded Permian-Triassic sediments and possibly also Early to Middle Palaeozoic rocks. The 6.39 km/s layer probably represents the igneous or granitised basement. A lower crustal layer with a velocity of 7.07 km/s and thickness ranging between 5 and 6 km has been interpreted. The total crustal thickness at the centre of the traverse is 36 km, and the upper mantle P-wave velocity is 8.10 ± .11 km/s. A southward-dipping Moho may be interpreted, with the crustal thickness increasing from 35 km, 30 km south of Peak Downs, to 37 km near Dingo. The gravity field calculated from the model conflicts with the observed gravity, suggesting a more complex model than that defined by the seismic refraction data alone.

Introduction

The Bowen Basin in central Queensland (Fig. 1) has been known for its extensive coal measures since the last century (Jack, 1879). Though coal has been mined for many years, it was only when markets developed and open-cut methods were introduced in the early 1960s that substantial production began. To extract the coal, the overburden, which is about 30 metres thick, is broken up by blasting and removed by dragline. The charges, which usually range in size from 50 to 300 tonnes of ammonium nitrate explosive, are recorded regularly at the University of Queensland's seismological observatory at Charters Towers 260-640 km away. During May-June 1973, the Bureau of Mineral Resources (BMR) and the University of Queensland undertook a seismic refraction survey to define the crustal structure and upper mantle relief of the basin, using these explosions as seismic energy sources. A reversed refraction line, about 375 km long, was surveyed between the Goonyella and Peak Downs mines in the north, and the Moura and Kianga mines in the south (Fig. 1). Shots were also recorded from the Blackwater mine, 150 km northwest of Moura.

Previous work

The geology of the region has been described in a publication of the Department of National Development (1966), and by Dickens & Malone (1973). Darby (1966) explained the tectonic framework of the region in terms of the genesis of the Tasman Geosyncline. The eastern zone (Fig. 1) corresponds to the zone of central uplift of the geosyncline, with its associated ultrabasic and granitic intrusions; the Bowen Basin was a marginal trough formed at the time of uplift.

The Basin extends from basement outcrop near Collinsville in the north, to Springsure in the south where it is overlapped by Mesozoic rocks of the Great Artesian Basin (Fig. 1). It is probably continuous with the Sydney Basin beneath this younger cover. To the northwest it is bounded by the Anakie High and Drummond Basin, to the east by the Connors Arch and to the west by the Birkhead axis, which separates it from the Galilee Basin.

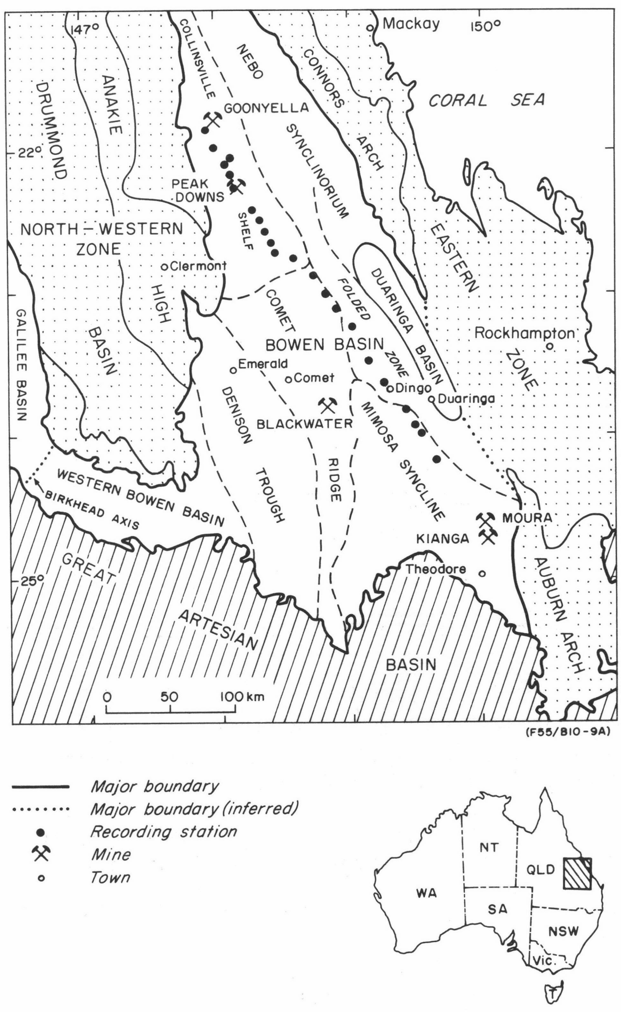

Figure 1. Location of shots and recording stations, and major structural units.

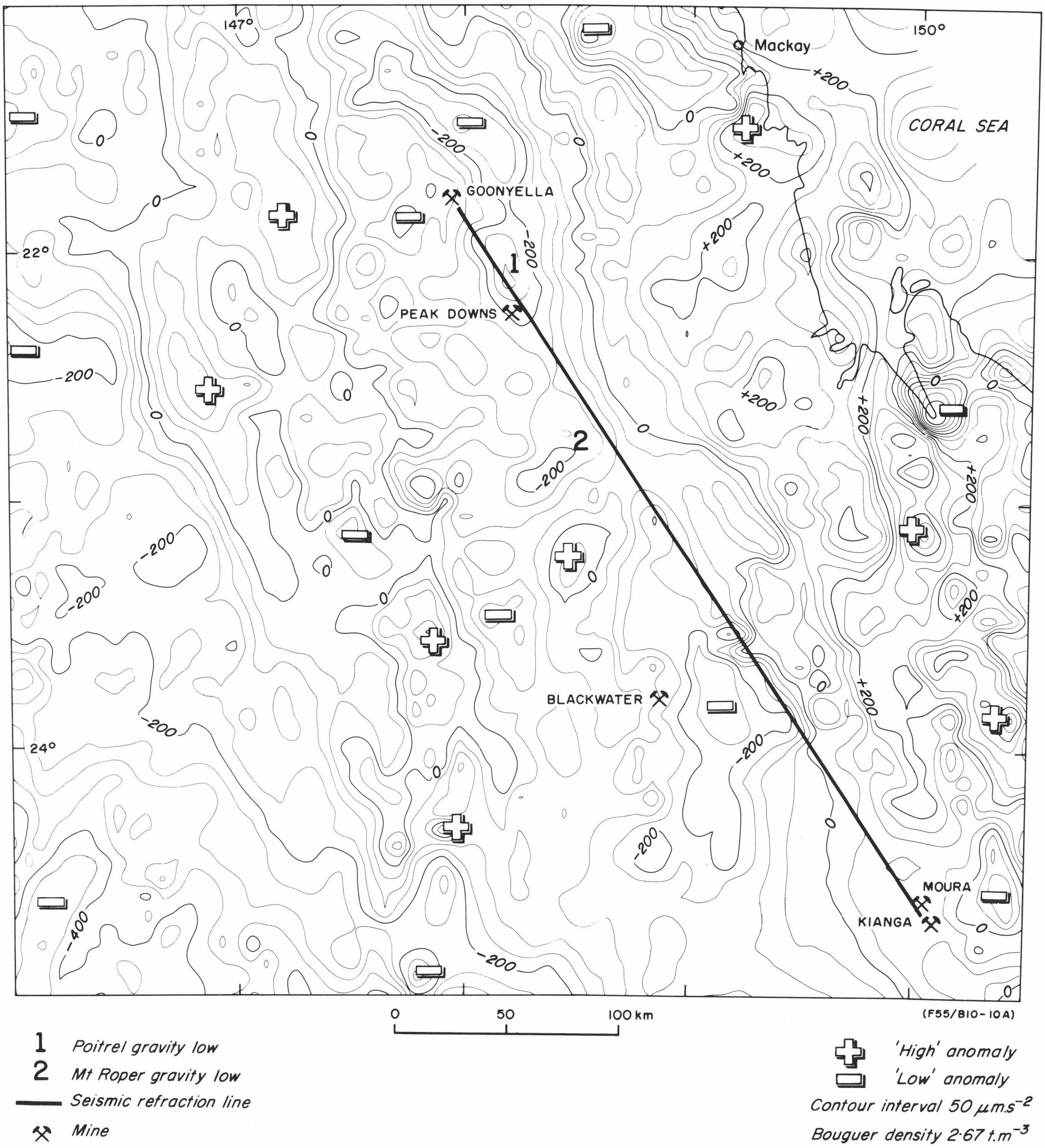

Figure 2. Bouguer anomaly map of the Bowen Basin.

Sedimentation began in the Early Permian, when thick, terrestrial sediments, including numerous coal beds, were deposited. The main centres of deposition were in the Denison Trough and in a trough on the present site of the Connors Arch and Nebo Synclinorium (Fig. 1). Contemporaneous volcanism occurred along the eastern margin. Subsequently, the sea transgressed westwards, and marine and fluviatile sedimentation, accompanied by deepening and expansion of the Denison Trough, continued from the Early to the Late Permian.

Towards the end of the Permian, thick freshwater sediments and extensive coal measures were laid down in the central and western areas of the Basin. In the Early Triassic, the main centre of sedimentation shifted from the area that is now the Nebo Synclinorium to that now occupied by the Mimosa Syncline, where rapid subsidence occurred during the middle to late Triassic. A total thickness of 5500 m of sediments accumulated during this period. Uplift and igneous intrusion in the east proceeded at the same time as the subsidence. Deposition ceased in the Late Triassic, and the sediments were subsequently uplifted and eroded. Tertiary terrestrial sediments are widespread, typically about 200 m thick, but with a maximum thickness of about 1 km in the Duaringa Basin. Contemporaneous basalt flows have been largely removed by erosion.

Previous geophysical surveys in the region were undertaken mainly in the search for minerals, particularly petroleum and coal. Extensive reflection seismic surveys were carried out, mainly in the southern and southwestern area between Clermont, Springsure, and Theodore (Fig. 1), on the Anakie High, Denison Trough, and Mimosa Syncline—but most of this work is remote from the refraction line described in this paper. Early surveys were reported by Smith (1951), and Shell (Qld) Development (1952). Deep seismic reflections were recorded in the Comet area during a reconnaissance reflection and refraction survey between Emerald and Duaringa (Robertson, 1961, 1965).

Gravity surveys have been conducted by BMR and private companies (Lonsdale, 1965; Darby, 1966); the gravity anomalies (Fig. 2) mostly reflect variations in the depth to basement. Positive anomalies exist over the Anakie High in the west, the Connors Arch and Auburn Arch in the east, and the Comet Ridge in the central Bowen Basin, while negative anomalies are found over the Denison Trough, Mimosa Syncline, and Nebo Synclinorium.

An aeromagnetic survey was undertaken by BMR from 1961 to 1963 (Wells & Milsom, 1966), and estimates of the depths to magnetic basement were in reasonable agreement with those expected from a structural interpretation.

Deep crustal seismic refraction studies have been carried out to the north of the present survey area, across Cape York Peninsula and south as far as Charters Towers (Finlayson, 1968). A three-layer crust was interpreted, with a total crustal thickness along the centre of Cape York Peninsula, and at Charters Towers, of about 45 km, decreasing to about 25 km on either side of the Peninsula. The depth to the intermediate crustal layer was found to be approximately 25 km under the interior of the peninsula, decreasing to 10 km near the coast. A refraction traverse was later extended into the Galilee Basin (Cull & Riesz, 1972) from Charters Towers south to a point about 80 km west of Clermont (Fig. 1). Interpreted depths to the Moho and intermediate layer were 35-40 km, and 20-25 km, respectively. Seismic velocities of about 6 km/s for the upper crust below the sediments, 6.75 km/s for the lower crust and 8.0 km/s for the upper mantle were obtained in both surveys.

Field operations

During the survey reported here shots were recorded from the Utah Development Company mines at Goonyella, Peak Downs, and Blackwater, and the Thiess Peabody Mitsui Coal Pty Ltd (now Thiess Dampier Mitsui Coal Pty Ltd) mines at Moura and Kianga. All mine managements co-operated by facilitating on-site shot timing, and providing information such as shot sizes and positions.

Nineteen shots were recorded, ranging in size from 2.7 tonnes to 300 tonnes, with an average of about 60 tonnes. Typically, the explosive was placed in 6 rows of holes and detonated with a delay of 17 milliseconds between each row. Recordings at Charters Towers observatory showed that the amplitudes of the seismic arrivals depended on the total weight of explosive, and were apparently independent of the delays in the shot. The time of detonation of each shot with respect to VNG radio time signals was obtained, on most occasions, with a manually operated recorder at the shot site. A 200-m ten-geophone spread was used for shot timing at Goonyella. Because of the frequency of shots at Peak Downs mine, an automatic recording system was placed near that mine for the duration of the survey, and used for shot timing.

For the field observations nine BMR automatic seismic tape-recording systems with Willmore Mk 2 seismometers were used; each system recorded a vertical component seismic signal at two gain levels, as well as clock and radio time signals. These recorders occupied 22 stations on a line about 375 km long between Goonyella and Moura (Fig. 1). Station spacing at the northern end was approximately 10 km, and at the southern end approximately 20 km. There were no observations on the southernmost 50 km of the line owing to lack of time. A detailed description of the field work has been given by Connelly & Collins (1973).

Data quality

Shot and station positions were determined to within 0.1 minute of arc, or about 0.2 km. Shot times were read to 0.01 s and corrected for shot-to-timing recorder distance assuming a velocity of 4.0 km/s. This velocity was obtained at Goonyella, and it is expected to be the same at the other mines because of the similar lithology.

Field recording tapes were played back into an analogue chart recorder and the travel-times of seismic arrivals determined from these records. Arrival times at the recording stations could be read to 0.01 s when the arrival was impulsive, for instance, at stations near the shot points; in most other cases, arrivals could be read to 0.1 s. Some arrivals could not be read to this accuracy and were used only as an additional check on the interpreted model.

The gain levels of the recorders near the shot points were set too high, causing saturation; only first arrivals could be read at these stations. Record quality was otherwise generally good, though at the more distant stations the arrivals were in some cases too emergent to be timed accurately.

Interpretation

The travel times were plotted against shot distance after clock error and head parallax corrections had been applied. Figure 3 (a, b, c) shows a plot of travel-times from Goonyella and Peak Downs mines in the north, Moura and Kianga mines in the south, and Blackwater mine near the centre of the traverse. Apparent velocities and intercept times for the various seismic phases were determined by linear regression.

Various velocity-depth models were computed from the travel-time data, assuming planar dipping layers. The reciprocal method of interpretation (Hawkins, 1961) was used where reversed data were available. Where possible, seismic travel-times were tested for consistency from shots at both ends of the traverse, and from Blackwater near the centre of the traverse; a number of possible interpretations were eliminated in this way. Not all seismic arrivals could be identified unambiguously because of a low signal-to-noise ratio on some of the recordings.

Travel times from the models were compared with record sections constructed from the original analogue records (Fig. 4a, b). The data show that the structure may be interpreted as being simple and almost planar; the apparent velocities from both the northern and southern shots are similar for each layer, indicating that the dips are small. The preferred four-layer model is shown in Figure 5. This model was treated by seismic ray tracing programs, which trace seismic ray paths through a given model, and compute the travel

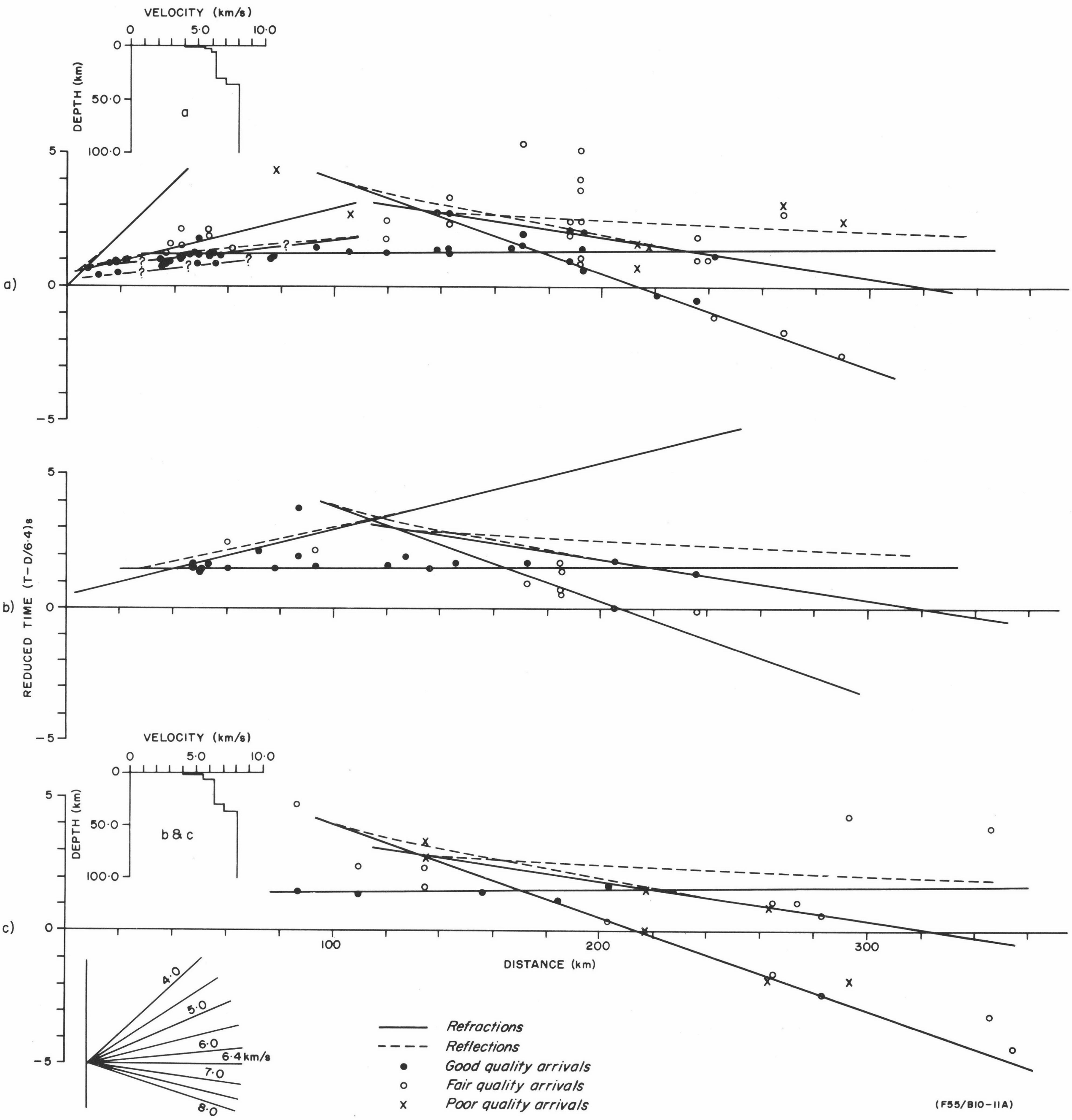

Figure 3. Travel-time curves from shots at (a) Goonyella, (b) Blackwater and (c) Moura and Kianga.

times for the various paths at stations along the surface. GEOTRACE (Cull, 1973) was used for initial interpretation; only horizontal-layered models can be used in this program. SEISRAY, a program to test dipping-layer models, was developed during this interpretation. In general, the agreement is good. Variations from the computed travel-time curves may be due to near-surface conditions at each recording site, and refractor topography.

No first arrivals from the uppermost layer of the model were recorded, except on the 200-m ten-geophone spread used for shot timing at Goonyella. The existence of a low velocity surface layer was inferred from the intercept time of the shallowest layer recorded. An upper limit to its velocity was determined from the travel times to the nearest stations. A velocity of 4.00 ± 0.22 km/s was obtained from the geophone spread and was assumed to apply along the length of the traverse. This agrees with the results of Smith (1951), who found velocities between 3.47 and 4.63 km/s at Comet, near the centre of the traverse; and Robertson (1965), who recorded velocities of 3.57 to 5.06 km/s within the uppermost 1.2 km between Comet and Dingo. A surface layer with a velocity of 4.00 km/s, 1.2 km thick, was therefore adopted in the north, and assumed to be continuous to the south. Recording stations were not placed sufficiently close to the shot-points for any detailed data on near-surface layers to be obtained.

The 5.53 ± 0.08 km/s layer, commencing at a depth of 1.2 km, was derived from good arrivals near Goonyella and Peak Downs, and arrivals from Blackwater. The shot-to-station distance in the south was too great for first arrivals to be recorded from this layer. The

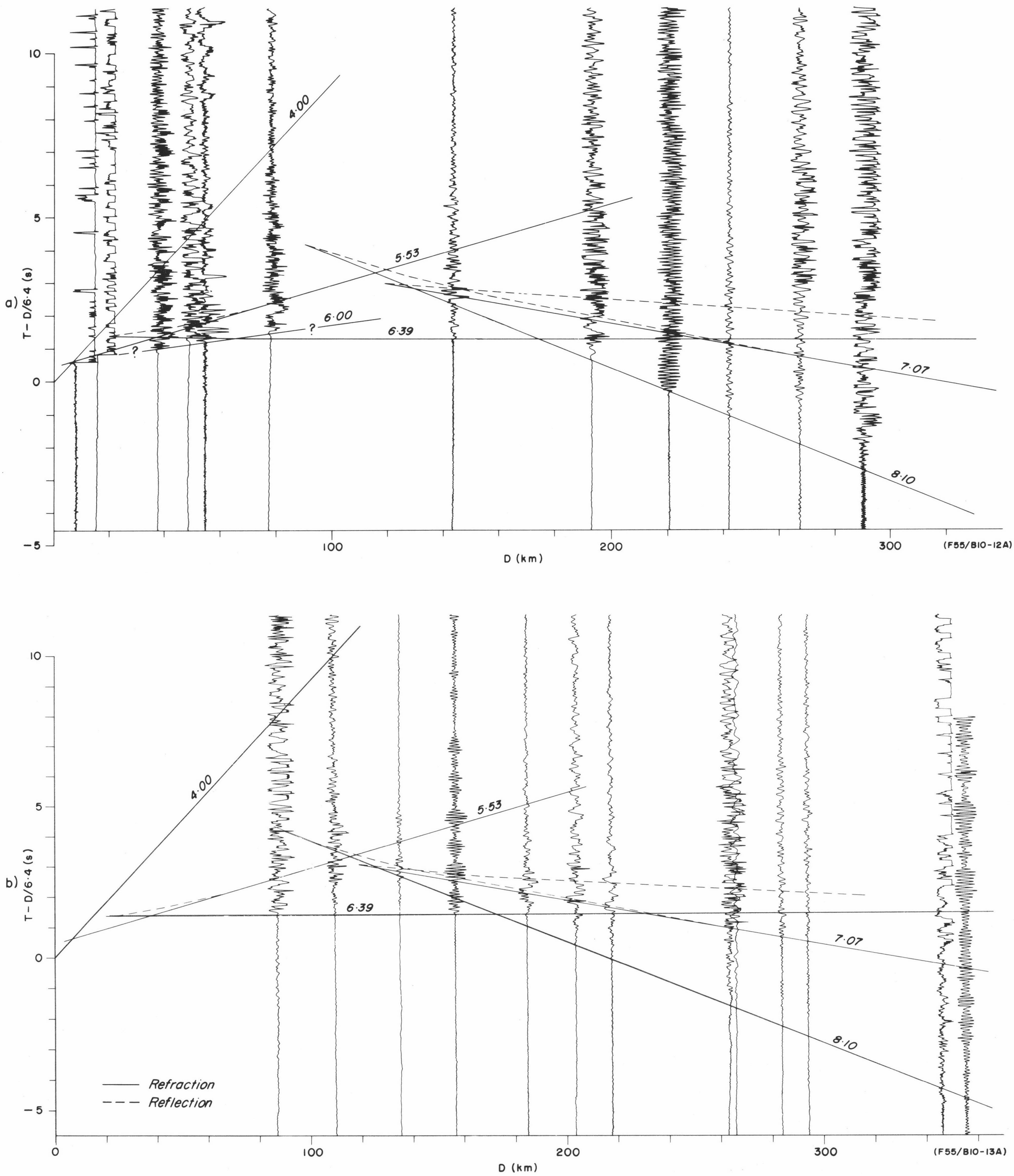

Figure 4. Record sections from shots at (a) Goonyella and Peak Downs and (b) Moura and Kianga.

thickness of the layer is about 5 km under the northern and central parts of the traverse. This agrees with the results of Smith (1951), who found a velocity of 5.49 km/s at a depth of 1.1 km near the axis of the Comet Ridge, and of Robertson (1965), who established a velocity of 5.33 km/s at a depth of 1.2 km between Comet and Dingo. In both cases, the layers dip eastwards, and if continuous, would be deeper under Dingo; however, there is a possible fault zone just west of Dingo, and it may be invalid to extrapolate the structures.

A 6.00 ± .04 km/s layer may be inferred from early arrivals recorded at some stations within 60 km of Goonyella and Peak Downs (Figs. 3a, 4a). However, not all stations within this distance range recorded such arrivals, indicating that the layer has limited extent. A 6.00 km/s layer was reported at a depth of 2.4 km between Comet and Dingo (Robertson, 1965), but does not necessarily occur along the entire refraction traverse. Travel times computed from a model which includes this layer, fit the data from upper crustal layers in the north for northern shots, but are too early for lower crustal and mantle arrivals at stations in the south. They are also too early for all arrivals from southern shots.

Below this, at a depth of 6.3 km, a 6.39 ± 0.07 km/s layer is well defined from both the northern and southern shots. This is the shallowest layer for which arrivals were recorded from the south (Fig. 3c). Near Dingo, 6.7 km of folded sediments, overlying a basement of igneous rocks or granitised sediments, were found by seismic reflection (Robertson, 1965) and a basement velocity of 6.40 km/s was adopted in that survey.

The model includes a lower crustal layer, with a velocity of 7.07 ± .02 km/s, though this was inferred from the later arrival data only (Fig. 3). The reciprocal time at Moura for these arrivals from the north is 59.08 seconds, and from the south, at Goonyella, is 59.43 seconds. On the basis of similar apparent velocities, intercepts and reciprocal times, these later arrivals were considered to be refracted energy from a relatively thin layer above the Moho. The depth of this layer is 30 km at the centre of the traverse; its thickness increases from 5 km below Peak Downs, to 6 km below Dingo.

The travel-time equation adopted for upper mantle arrivals from shots in the north is

$$T = D/8.07\ (\pm\ 0.09) + 6.86\ (\pm\ 0.33),$$

and from shots in the south is

$$T = D/8.22\ (\pm\ 0.11) + 7.44\ (\pm\ 0.37)$$

where T is the travel time in seconds and D is the shot distance in kilometres.

The depth of the Moho at the centre of the traverse is 36 km, and the mean upper-mantle sub-Moho velocity is 8.13 km/s. Correcting for the earth's curvature (Mereu, 1967) reduces this velocity by about 0.4 percent to 8.10 km/s.

The least squares velocities and intercepts indicate that the Moho dips southwards at 0.7 degrees. However, the apparent velocities are based on limited data (Fig. 3), and they are not significantly different at confidence levels greater than 75 percent. Confirmation of a southward-dipping Moho would require additional, more detailed, field observations.

Strong late arrivals with a velocity of about 4.7 km/s were recorded; this corresponds closely to the velocity expected of upper mantle S-waves.

The crustal model derived here was incorporated in the starting model used by Mills & Fitch (1977) in their surface-wave analysis of the Picton (near Sydney) earthquake of 9 March 1973. The models they finally derived from their analysis gave sub-crustal S-velocities of 4.20-4.32 km/s, which imply unrealistically high Poisson's ratios (0.30-0.32), unless the P-velocity is reduced to 7.6-7.8 km/s. These P-velocities are lower than any found from seismic refraction surveys in eastern Australia. Cleary & Doyle (1962), and Doyle & others (1966) have quoted sub-crustal S-velocities of about 4.7 km/s for southeast Australia; this value agrees with the velocity observed here from the late arrival data, and gives a reasonable value of Poisson's ratio (0.25) for a P-velocity of 8.10 km/s.

Wide-angle reflections were not used in the interpretation because of the difficulty in correlating late arrivals over any appreciable distance. Reflection times calculated from the preferred model could not be matched with any distinct set of recorded arrivals.

Deep vertical reflections were recorded 10 km east of Comet during the Emerald-Duaringa survey (Robertson, 1961, 1965). The arrivals were poor in quality, with two-way travel times between 7.6 and 8.3 seconds. Assuming an average crustal velocity of 6.25 km/s, the depth to the reflector is about 24 to 26 km, which does not correspond to any of the layers derived from the refraction data. The reflections may be from structures associated with the Comet Ridge, and these structures may not extend further east towards the axis of the basin.

Discussion of gravity observations

The observed Bouguer gravity increases along the traverse from an average of $-100\ \mu ms^{-2}$ in the north to about 50 μms^{-2} in the south (Fig. 2). This conflicts with the gravity field computed from the seismic model of Figure 5, for which a southward decrease is expected —up to 700 μms^{-2} if the depths and dips are extrapolated to the ends of the traverse. A possible explanation for this discrepancy is outlined below.

The southern end of the traverse is adjacent to the Auburn Arch, at the eastern edge of the Bowen Basin, where high density rocks may be present at shallower depth. Along the eastern margin of the basin there is an easterly positive gradient of about 220 μms^{-2} per 50 km, which Darby (1966) suggests is due to the hinge line between the Bowen Basin and the axis of central uplift of the Tasman Geosyncline. Superimposed on this regional gradient are the Duaringa gravity highs related to the rise in the pre-Permian basement. The shallowing of basin sediments is also reflected by the interpreted magnetic basement, which rises from deeper than 12 km in the Mimosa Syncline (Fig. 1) to about 4 km along the eastern margin (Wells & Milsom, 1966). Along the traverse, the magnetic basement lies between 6 and 8 km depth below the northern 150 km and between 4 and 5 km beneath the southern 50 km. From well data, the magnetic basement lies at least 1.5 km below the Permo-Triassic sedimentary sequence, and probably represents the Early to Middle Palaeozoic basement. It appears to correspond with the boundary between the 5.33 to 6.39 km/s layer. This is in agreement with the reflection results near Dingo, which give similar depths and velocities to the refraction data. Robertson also recorded a westerly dipping refractor with a velocity of 5.20 km/s at a depth of 0.3 km east of Duaringa, It is therefore apparent, from the magnetic, seismic reflection, and gravity data, that the 5.53 and 6.39 km/s layers shallow in the south, and the dips found from the refraction data should not be extrapolated. Thinning of the sediments could account for the discrepancy between the gravity and seismic refraction data at the southern end of the traverse.

The negative Bouguer gravity in the northern part of the traverse is enhanced by two features described by Darby (1966). The first is the Poitrel gravity low, about 40 km from Goonyella (Fig .2), with an amplitude of about $-200\ \mu ms^{-2}$ which may be due to either an area of increased subsidence, or to a deep-seated low-density plutonic intrusion. However, neither of these explanations is entirely satisfactory; there is seismic reflection evidence against thickening sediments, and it is unusual for large batholiths to occur in areas of subsidence. The second feature, the Mount Roper gravity low, is about 110 km from Goonyella and has an amplitude of about $-50\ \mu ms^{-2}$ where it intersects the traverse. It is possibly due to a pile of acid volcanics north of the Comet Ridge, rather than a thickening of the Permian sediments. Both these features tend

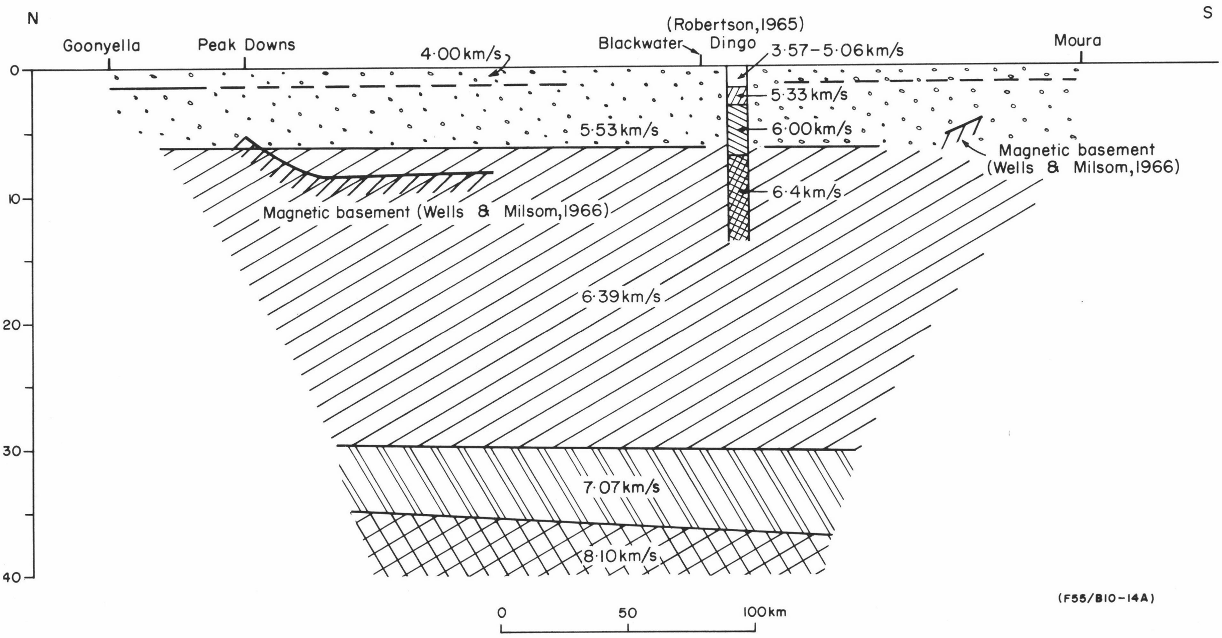

Figure 5. Preferred crustal model of the central Bowen Basin.

to give the observed gravity a negative gradient northwards, which is not caused by a thickening of sediments.

Because of seismic offset distances, the lower crustal and upper mantle interpretation is limited to the central 200 km of the traverse and it may not be valid to extrapolate under the whole traverse length.

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References

CLEARY, J. R., & DOYLE, H. A., 1962—Application of a seismograph network and electronic computer in near earthquake studies. *Bulletin of the Seismological Society of America,* **52**, 673-82.

CONNELLY, J. B., & COLLINS, C. D. N., 1973—Bowen Basin Seismic refraction survey, May-June 1973: Operational report. *Bureau of Mineral Resources, Australia—Record* **1973/212** (unpublished).

CULL, J. P., 1973—Seismic ray tracing in a spherical earth using computer models. *Bureau of Mineral Resources, Australia—Record* **1973/122** (unpublished).

CULL, J. P., & RIESZ, E. M., 1972—Deep crustal seismic reflection/refraction survey between Clermont and Charters Towers, Queensland, 1971. *Bureau of Mineral Resources, Australia—Record* **1972/97** (unpublished).

DARBY, F., 1966—North Bowen Basin reconnaissance gravity survey, central Queensland, 1963. *Bureau of Mineral Resources, Australia—Record* **1966/209** (unpublished).

DEPARTMENT OF NATIONAL DEVELOPMENT (CANBERRA), 1966—Geology map sheet and booklet, Fitzroy Region, Queensland. *Resources Series.*

DICKINS, J. M., & MALONE, E. J., 1973—Geology of the Bowen Basin, Queensland. *Bureau of Mineral Resources, Australia—Bulletin* **130**.

DOYLE, H. A., UNDERWOOD, R., & POLAK, E. J., 1966—Seismic velocities from explosions off the Central Coast of New South Wales. *Journal of the Geological Society of Australia,* **13**, 355-72.

FINLAYSON, D. M., 1968—First arrival data from the Carpentaria Region Upper Mantle Project (CRUMP). *Journal of the Geological Society of Australia,* **15**, 33-50.

HAWKINS, L. V., 1961—The reciprocal method of routine shallow seismic refraction investigations. *Geophysics,* **26**, 806-19.

JACK, R. L., 1879—The Bowen River Coalfield. *Publication of the Geological Survey of Queensland,* **4**.

LONSDALE, G. F., 1965—Southern Queensland contract reconnaissance gravity survey using helicopters, 1964. *Bureau of Mineral Resources, Australia—Record* **1965/251** (unpublished).

MEREU, R. F., 1967—Curvature corrections to Upper Mantle Seismic refraction Surveys. *Earth and Planetary Science Letters,* **3**, 469-75.

MILLS, J. M., & FITCH, T. J., 1977—Thrust faulting and crust-upper mantle structure in East Australia. *Geophysical Journal of the Royal Astronomical Society* **48**, 351-84.

ROBERTSON, C. S., 1961—Emerald-Duaringa seismic survey. *Bureau of Mineral Resources, Australia—Record* **1961/150** (unpublished).

ROBERTSON, C. S., 1965—Emerald-Duaringa seismic survey, Queensland, 1960. *Bureau of Mineral Resources, Australia—Record* **1965/2** (unpublished).

SHELL (QLD) DEVELOPMENT PTY LTD, 1952—General report on investigations and operations carried out by the Company in the search for oil in Queensland, 1940-1951. *Geological Survey of Queensland A-P Report* **640** (unpublished).

SMITH, E. R., 1951—Report on seismic refraction traverse at Comet, Queensland. *Bureau of Mineral Resources, Australia—Record* **1951/9** (unpublished).

WELLS, R. R., & MILSOM, J. S., 1966—Bowen Basin aeromagnetic and radiometric survey, Queensland, 1961-1963. *Bureau of Mineral Resources, Australia—Record* **1966/208** (unpublished).