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Junee–Narromine Volcanic Belt, Macquarie Arc, Lachlan Orogen, New South Wales: components and structure

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The Junee–Narromine Volcanic Belt of Ordovician volcanic, volcaniclastic and intrusive rocks in central New South Wales is the most westerly structural belt of the now disrupted Macquarie Arc. Although more than 200 km long (far longer than other belts of Ordovician arc volcanics), most of this belt is concealed by younger Palaeozoic to Holocene cover. Most of our knowledge of this belt thus comes from scattered outcrops and drillhole information, augmented by the interpretation of aeromagnetic and gravity data and, to a lesser extent, information from deep seismic-reflection profiling. This combined geological and geophysical approach suggests that the Junee–Narromine Volcanic Belt consists of major separate igneous complexes, each consisting of lavas and volcaniclastic sediments intruded by various mafic to felsic intrusive porphyries. Variations in age and geochemical affinities are used to suggest that the Junee–Narromine Volcanic Belt approximates most closely the magmatic core of the Macquarie Arc. The present geometry of the Junee–Narromine Volcanic Belt reflects the interplay of two major ductile–brittle fault systems: the north-northwest-trending Gilmore Fault System mainly in the south and the north-trending Tullamore Fault System, mainly in the north and centre, together with local west-northwest cross faults. These systems were generated during deformation in the Early Silurian, Early Devonian and Carboniferous.

KEY WORDS: geology, geophysics, igneous complexes, Junee–Narromine Volcanic Belt, Lachlan Orogen, Macquarie Arc, Ordovician, structure.

INTRODUCTION

The Junee–Narromine Volcanic Belt, in central western New South Wales, is the westernmost of all the structural belts of Ordovician volcanic rocks that represent the dispersed remnants of the Ordovician Macquarie Arc in the Eastern Subprovince of the Lachlan Orogen (Glen *et al.* 1998) (Figure 1c). This paper reports on a study of the whole belt that was undertaken for several reasons: (i) it is the longest of all the belts, >200 km long; (ii) it is the most enigmatic belt with >50% covered by regolith; (iii) it has the most diverse geology and thus sheds light on our understanding of the evolution of the Macquarie Arc, particularly if this belt comes closest to the magmatic core of the arc (Glen *et al.* 1998); and (iv) it shows clear structural response of arc rocks to Silurian–Carboniferous deformation.

Interpreted geology of the Junee–Narromine Volcanic Belt is shown in Figure 2. Areas of significant outcrop are restricted to the Forbes–Parkes region, the geology of which has been described by several authors (Clarke 1990; Clarke & Sherwin 1990; Lyons *et al.* 2000; Simpson *et al.* 2005). The geology around the Northparkes mine (Figure 2), at the northern limit of outcrop north of Parkes, has been described by Heithersay and Walshe (1995), Hooper *et al.* (1996) and Simpson *et al.* (2005). Outcrop is very much restricted south of Forbes, with Ordovician volcanic rocks outcropping near Temora. Between Forbes and Temora, the geology around the non-outcropping Cowal deposit (Figure 2), described by Miles and Brooker (1998), is based solely on drillcore logging.

In such a situation of poor to non-existent outcrop, an understanding of the regional geology and structure, and thus evolution, of the Junee–Narromine Volcanic Belt relies heavily on interpretation of geophysical data. Our aim in this paper is to provide an interpretation of the geometry of this belt. To do this, we first address the causes of two of the strongest major gravity ridges in eastern Australia. Then we discuss the geophysical and,

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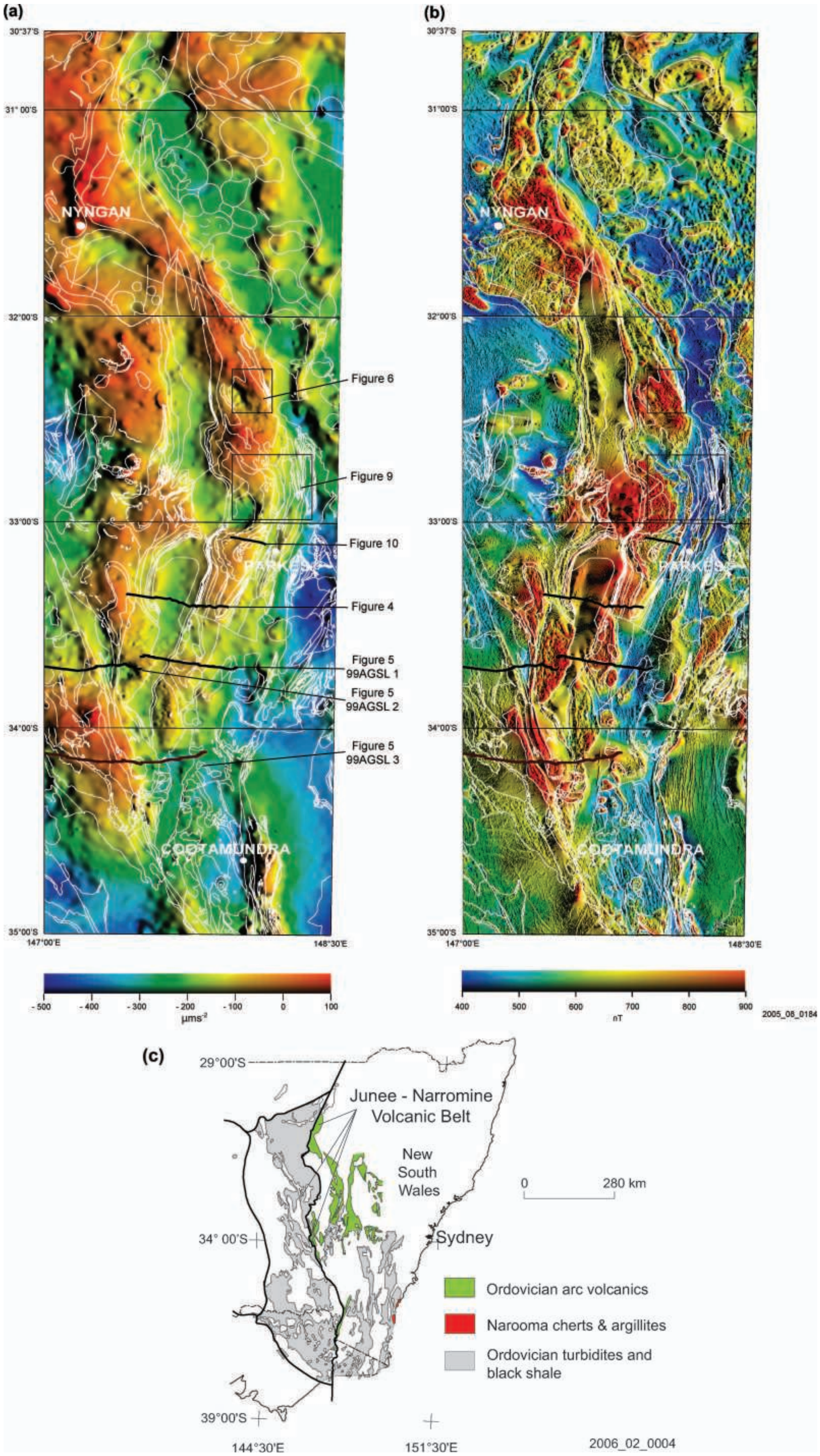

(a)
(b)
NYNGAN
PARKES
COOTAMUNDRA
Figure 6
Figure 9
Figure 10
Figure 4
Figure 5
99AGSL 1
Figure 5
99AGSL 2
Figure 5
99AGSL 3
147°00'E
148°30'E
µms⁻²
nT
2005_08_0184
(c)
29°00'S
Junee - Narromine
Volcanic Belt
New
South
Wales
0
280 km
34° 00'S
Sydney
Ordovician arc volcanics
Narooma cherts & argillites
Ordovician turbidites and
black shale
39°00'S
144°30'E
151°30'E
2006_02_0004

to a lesser extent, geological character of the different complexes we identify in the Junee–Narromine Volcanic Belt. To assist us, we extracted geophysical line data from national databases and also carried out ground gravity traverses across parts of the Junee–Narromine Volcanic Belt, which were then iteratively forward-modelled (Appendix 1). Details of lithology, geochemistry and petrology of some of the complexes are described by Crawford *et al.* (2007a, b). Finally, we discuss the major structural elements cutting the Junee–Narromine Volcanic Belt and their role in post-Ordovician evolution of the belt.

REGIONAL GRAVITY DATA

The most prominent gravity features in the Eastern subprovince of the Lachlan Orogen are two curved meridional linear gravity highs in central New South Wales, separated by an intervening linear low (Figure 1a) (Spencer 2004).

Extracts from the Australian National Gravity Database (Wynne & Bacchin 2004) show that the eastern and western gravity highs have anomalies of 300–400 μms^{-2} above values further to the east and west and 200–250 $\mu m/s^2$ above the intervening low (Figure 3). The eastern and western highs have similar amplitudes (Figure 3).

Eastern gravity high

Comparison of Figures 1 and 2 shows that the eastern gravity high coincides with outcrop of igneous rocks of the Junee–Narromine Volcanic Belt and also with aeromagnetic highs developed over them. The linear north-northwest-trending northern part of this high coincides with the Canonbar Igneous Complex. Individual highs farther south correspond with the Narromine Igneous Complex, the Northparkes Group (north and south of a prominent gravity low coincident with the Wombin Volcanics) and the Currumburrama Igneous Complex. The combined ground gravity and magnetic profile of Figure 4 shows that one part of the eastern high can be successfully represented by the Upper Ordovician Northparkes Group.

Western gravity high

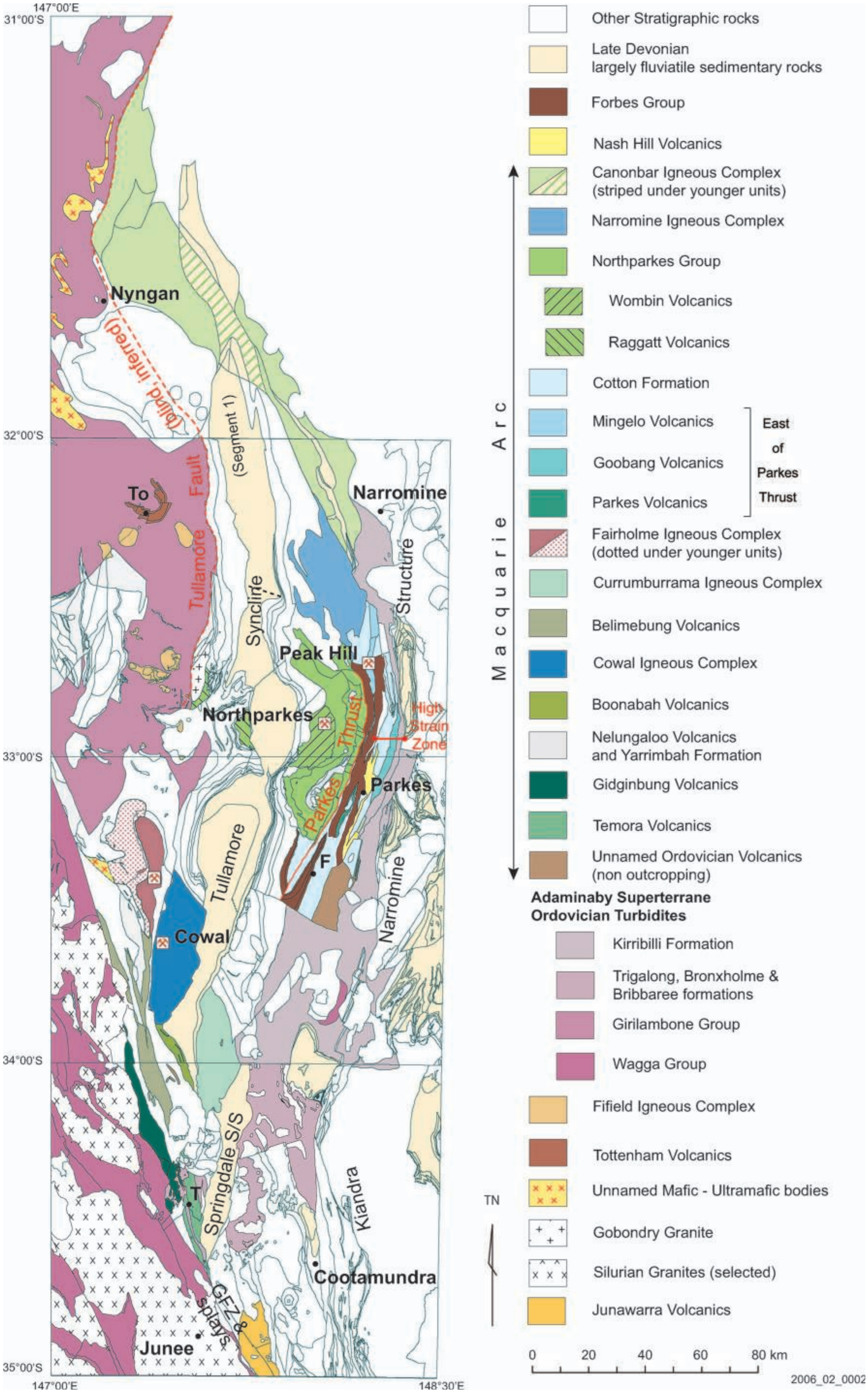
The western gravity high can be resolved into three smaller highs with superimposed high-frequency peaks that coincide with zoned ultramafic–intermediate intrusive complexes—the Alaskan-type, Fifield igneous complexes described by Suppel (1974) (Figures 1a, 2). The nature of this western high is complex. The northern high (32–32.6°S) coincides with outcropping Ordovician quartz-rich turbidites of the Girilambone Group. However, in the Tottenham area, this gravity high underlies narrow bodies of mafic schist that are part of the Tottenham Volcanics (Glen *et al.* 2004) described by Suppel (1974) and Sherwin (1996). The southern body, centred on 34°S (Figures 1, 2), also coincides with Ordovician turbidites (Wagga Group) and Silurian granites, although part of it coincides with a small outcrop of the mafic Narragudgil Volcanics, interpreted as tholeiitic volcanics of probable Ordovician age (Duggan & Lyons 1999; Duggan 2000a). The central part of this western gravity high consists of several smaller highs, with an axe-like shape, extending from 32.9 to 33.6°S. The southern parts of the western high underlie outcrop of the Fairholme Igneous Complex. Modelling of ground potential-field data suggests this complex can produce the gravity high (Figure 4). In the north, the gravity high underlies Silurian–Devonian sedimentary and felsic $\pm$ mafic volcanic strata.

Since the densities of the Ordovician turbidites are 2.60–2.72 t/m^3, Silurian–Devonian sedimentary rocks 2.40–2.66 t/m^3 and Silurian–Devonian volcanic rocks 2.40–2.80 t/m^3 (Direen *et al.* 2001a, b), we conclude that the bodies responsible for the northern and central gravity highs consist of dense mafic to intermediate igneous rocks at depth (Direen *et al.* 2001a, b). Their presence at depth is consistent with interpretation of regional deep seismic-refection data (99AGS lines 1, 2, 3: Glen *et al.* 2002). Figure 5 shows that modelling of a west-dipping slab of Ordovician volcanics beneath Ordovician quartz-rich turbidites is able to produce the (aeromagnetic and) gravity data acquired along the three seismic lines.

Central gravity low

The linear gravity low between the highs corresponds to fluvial sandstone, conglomerate, siltstone and mudstone of the Upper Devonian Hervey Group that occurs as scattered outcrop in the core of the Tullamore Syncline (Lyons *et al.* 2000; Glen *et al.* 2004). The segmented nature of this gravity low reflects the complex underlying substrate as discussed below. Modelling in one area (Figure 4) suggests that the Hervey Group is ~3.75 km thick, thicker than the estimates of ~2 km summed from thicknesses of widely scattered outcrops reported in Lyons *et al.* (2000). The presence of magnetic highs, especially in the western limb of the syncline was

Figure 1 (a) Gravity image of central New South Wales, showing two highs and intervening low, with superimposed geological formation polygon boundaries. (b) Aeromagnetic image of central New South Wales, showing separate magnetic bodies, with superimposed geological formation polygon boundaries. Polygon boundaries are taken from the Eastern Lachlan Orogen synthesis study (Glen *et al.* 2004); stratigraphic units are identified in Figure 2. Comparison of Figures 1a, b and 2 shows that the eastern curved belt of gravity and magnetic highs corresponds with elements of the Junee–Narromine Volcanic Belt. In contrast, most of the western belt of gravity highs overlies low-density Ordovician quartz-rich turbidites: the exceptions are discussed in the text. Circular polygon boundaries in gravity low east of Nyngan are inferred Devonian igneous complexes referred to in text. Location of seismic lines and other figures also shown. (c) Coeval Ordovician terranes in the Eastern and Central subprovinces of the Lachlan Orogen. The extent of the Junee–Narromine Volcanic Belt, the western belt of rocks of the now disrupted Macquarie Arc, is highlighted.



147°00'E
31°00'S
32°00'S
33°00'S
34°00'S
35°00'S
147°00'E
148°30'E
Nyngan
(blind, inferred)
(Segment 1)
Tullamore Fault
To
Narromine
Syncline
Structure
Peak Hill
Northparkes
High Strain Zone
Parkes Thrust
Parkes
F
Tullamore
Narromine
Cowal
Springdale S/S
Kiandra
T
Cootamundra
GFZ & splays
Junee
TN
Other Stratigraphic rocks
Late Devonian largely fluviatile sedimentary rocks
Forbes Group
Nash Hill Volcanics
Canonbar Igneous Complex (striped under younger units)
Narromine Igneous Complex
Northparkes Group
Wombin Volcanics
Raggatt Volcanics
Cotton Formation
Mingelo Volcanics
Goobang Volcanics
Parkes Volcanics
East of Parkes Thrust
Fairholme Igneous Complex (dotted under younger units)
Currumburrama Igneous Complex
Belimebung Volcanics
Cowal Igneous Complex
Boonabah Volcanics
Nelungaloo Volcanics and Yarrimbah Formation
Gidginbung Volcanics
Temora Volcanics
Unnamed Ordovician Volcanics (non outcropping)
Macquarie Arc
Adaminaby Superterrane Ordovician Turbidites
Kirribilli Formation
Trigalong, Bronxholme & Bribbaree formations
Girilambone Group
Wagga Group
Fifield Igneous Complex
Tottenham Volcanics
Unnamed Mafic - Ultramafic bodies
Gobondry Granite
Silurian Granites (selected)
Junawarra Volcanics
0 20 40 60 80 km
2006_02_0002

successfully modelled as magnetic rocks at depths of ~5–10 km (Figure 4). Following Raymond *et al.* (2001), we attribute these anomalies to Silurian–Devonian strata below the Hervey Group, and part of the Jemalong Trough of Raymond *et al.* (2001), renamed the Jemalong Shelf by Pogson and Glen (2004).

COMPONENTS OF THE JUNEE–NARROMINE VOLCANIC BELT

Using outcrop and geophysical data, the Ordovician Junee–Narromine Volcanic Belt is inferred to comprise 21 separate stratigraphic units, with five of these being components of the Northparkes Group (Figure 2). Of these, 10 show moderate to very poor outcrop and as a result their boundaries and internal structuring are best determined from a combination of potential-field and outcrop data. Four units (Narromine Igneous Complex, Fairholme Igneous Complex, Currumburrama Igneous Complex and Cowal Igneous Complex) are best defined from geophysical data supplemented by exploration drillhole data. To date, the Canonbar Igneous Complex is inferred solely from geophysics, as is a unit of inferred unnamed Ordovician volcanics south of Parkes (Figure 2). Not shown on Figure 2 are two possible additional Ordovician complexes inferred from geophysics and overlain by Silurian–Devonian strata between the Northparkes Group and the west-northwest-trending fault south of Forbes. On the western side of the Tullamore Syncline, the Fairholme Igneous Complex and the Raggatt Volcanics are linked by an irregular gravity ridge (around 33°S) that is inferred to represent Ordovician igneous bodies that do not outcrop.

Several features of the Junee-Narromine Volcanic Belt (Figure 2) are: (i) the slightly curvilinear overall shape that is suggestive of modification by a left-lateral shear couple on bounding north-northwest-trending structures (see later); (ii) the presence of most of its constituent units east of the Tullamore Syncline, cored by the Upper Devonian Hervey Group, except in the north and south where igneous complexes occur to the west; and (iii) the presence of two main high-strain areas, reflected at map scale by the elongate shapes of igneous bodies, and at outcrop scale by the presence of one or more steep, well-developed cleavages: the southern area occurs along splays of the Gilmore Fault Zone, while the northern area, east of the Parkes Thrust (Figure 2), trends northeast, is 10 km wide and is regarded as part of the Kiandra–Narromine Structure of Packham (1987); it was called the Parkes Fault Zone by Lyons (2000). Elsewhere, the low total strain enables us to identify the approximate original shapes of the complexes.

These bodies are now described from north to south, with reference to Figures 1 and 2.

Canonbar Igneous Complex

The Canonbar Igneous Complex is the northernmost complex in the Junee–Narromine Volcanic Belt. The absence of outcrop and drillhole data means that our knowledge is restricted to the interpretation of potential-field data. These data suggest that the complex consists of two bodies linked under the Carboniferous Tullamore Syncline—a (~50 × 12 km) triangular body to the west and an elongate ~52 km long north-northwest-trending body to the east. The complex is inferred to terminate to the north around 31.25°S: we find no evidence in gravity or airborne magnetic data for any Ordovician volcanics to the north.

Narromine Igneous Complex

The Narromine Igneous Complex is a ~40 × 15 km body, with north-northwest-trending prongs in the north (Figure 1b), completely buried beneath Tertiary and Mesozoic sediments. The inferred geology of the northern part of this complex (Figure 6a) is based on unpublished geophysical (Appendix 2) and drill data interpretation by Renison Goldfields Company Limited and Resolute Limited. It consists of basaltic and andesitic lavas and volcaniclastic rocks intruded by two sets of intrusives rocks: plutons varying in composition from gabbro to quartz monzodiorite and a younger set of dacitic and granodioritic porphyries (Crawford *et al.* 2007a).

Two ground traverses show the inferred geometry. Traverse 4 in the south (Figure 6b) models subvertical dips in the west and steep easterly dips in the east, for intrusive monzodiorites and diorites as well as the andesites. Traverse 1 in the north (Figure 6c) suggests the northerly prong of andesite represents the tip of a broad body, a possible anticlinal hinge, intruded on the east by an east-dipping granodiorite and flanked on the east by Devonian sedimentary rocks.

Nelungaloo Volcanics and Yarrimbah Formation

The Lower Ordovician Nelungaloo Volcanics and Yarrimbah Formation outcrop in the core of the Forbes Anticline, which is probably faulted. They were most recently described by Simpson *et al.* (2005) and are further described by Glen *et al.* (2007a) and Percival and Glen (2007). They are referred to in Appendix 2 but not discussed further.

◄

Figure 2 Regional geology of the Junee–Narromine Volcanic Belt and adjacent units, based on outcrop and interpretation of regional gravity and aeromagnetic datasets of Figure 1. The Junee–Narromine Volcanic Belt consists of Ordovician arc rocks identified in the legend. Other adjacent units are labelled where discussed. Uncoloured units are not relevant. Geology polygons from Eastern Lachlan Orogen synthesis study (Glen *et al.* 2004). F, Forbes; T, Temora; To, Tottenham. The unnamed mine symbol north-northwest of Cowal encompasses the Fairholme, Dungarvan and Boundary prospects of Newcrest Mining Limited.

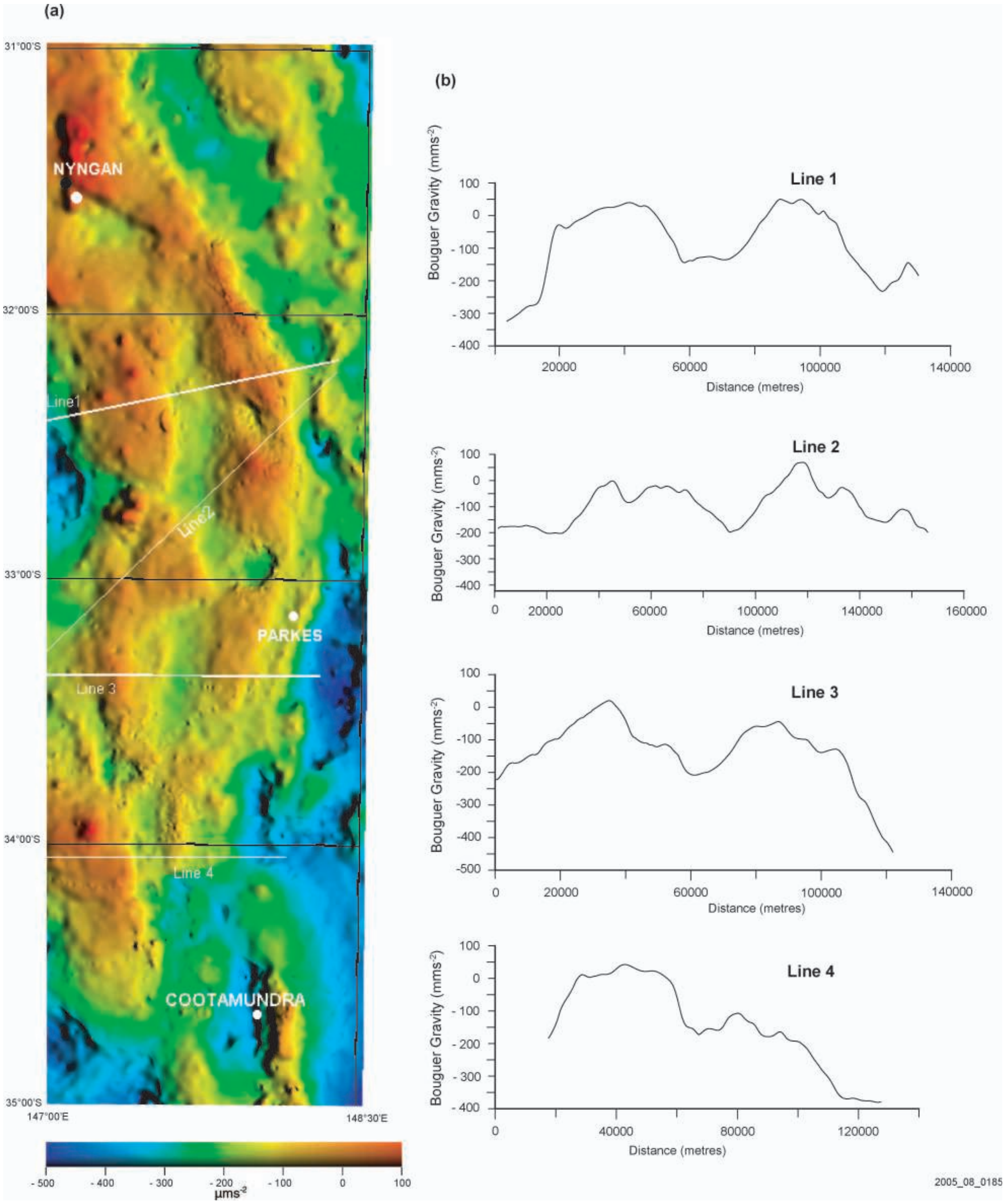


Figure 3 (a) Enlargement of twin gravity highs and intervening gravity low of Figure 1a, showing locations of profile lines 1–4. (b) Profile lines. Traverses were constructed from the National Gravity Database (Wynne & Bacchin 2004).

Northparkes Group

The Northparkes Group is a large curvilinear body that hosts the Endeavour deposits at Goonumbla in the non-outcropping northern part north of 33°S (Figures 2, 7). The Cu deposits at Goonumbla occur in vertical magnetite-rich quartz monzonite porphyries intruding volcaniclastic rocks of the Wombin Volcanics (Heithersay & Walshe 1995; Hooper *et al.* 1996; Lickfold *et al.* 2003; Cooke *et al.* 2007). The geophysical response of the unit is summarised in Appendix 2.

The southern part occupies the limbs of the doubly plunging Forbes Anticline (Figure 7) that is cored by

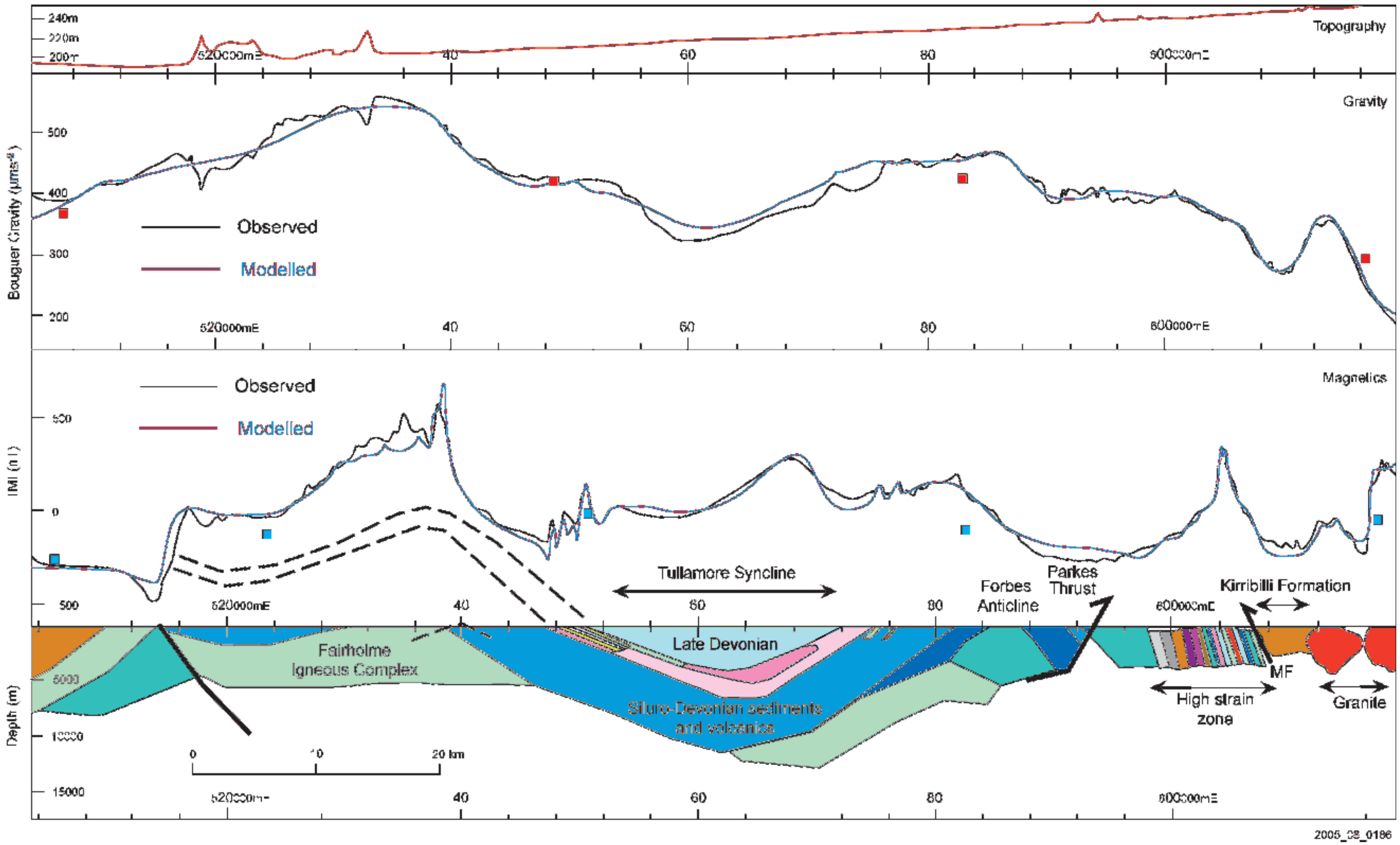


Figure 4 Ground profile section (see Figure 1a for location), showing observed and modelled ground gravity and magnetics with inferred geology at depth. See text for discussion. Note that the Parkes Thrust is not well modelled on this section, since the traverse passes through an area where the thrust dies out in the Cotton Formation on the eastern limb of the Forbes Anticline.

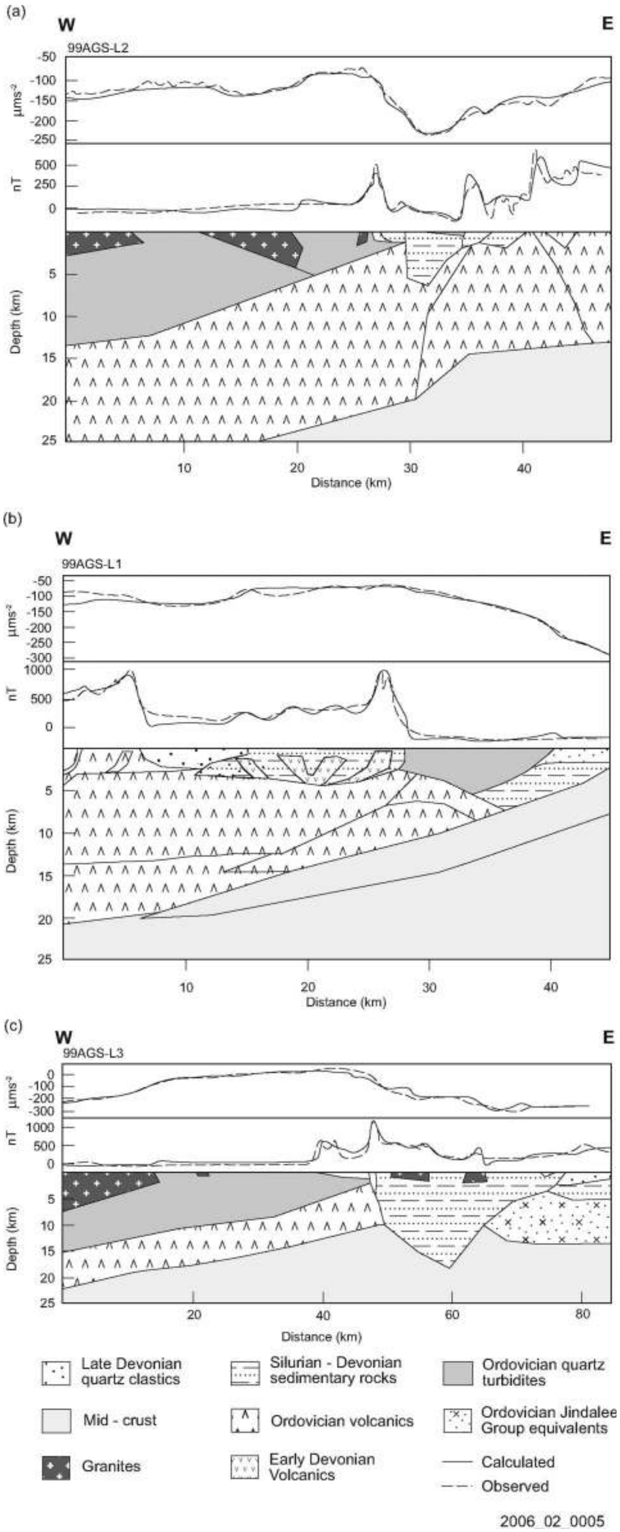


Figure 5 Cross-sections along seismic lines 99AGS-L1, 2, 3 (see Figure 1a for location), showing observed and modelled ground gravity and aeromagnetic data (from Direen *et al.* 2001b with permission of the Australian Society of Exploration Geophysicists). (a) Line 2; (b) line 1; (c) line 3.

the older (Early Ordovician) Nelungaloo Volcanics and Yarrimbah Formation and intruded by monzonites and monzodiorites (Butera *et al.* 2001). The internal geology of the Northparkes Group has been most recently described by Percival (2000)* and Simpson *et al.* (2005), and is described by Crawford *et al.* (2007a), and Percival and Glen (2007). Stratigraphically, it is divided into three units: a basal unit of volcaniclastic sediments and limestones; a middle unit of limestones interbedded with a thin volcanic interval in the west overlain by siltstone and passing eastwards into the more common volcanic and volcaniclastic rocks (Goonumbla Volcanics); and an upper unit, traditionally called the Wombin Volcanics, which consist of hematite-rich volcanic and volcaniclastic rocks. Facies and lithologies have been described by Simpson *et al.* (2005).

RAGGATT VOLCANICS

The Raggatt Volcanics (Appendix 2) outcrop as three small bodies west of the Tullamore Syncline (Sherwin 1997). Sherwin (1996) recorded andesitic and trachyandesitic volcanic rocks, volcaniclastic rocks and monzonitic intrusives. Associated limestone float contains a Late Ordovician fauna.

Ordovician volcanics east of the Parkes Thrust

Several kilometre-long, elongate bodies of mafic to intermediate volcanic rocks occur east of the Northparkes Group, in a poorly outcropping high-strain zone, defined by the presence of intense subvertical cleavage(s), that is bounded to the west by the Parkes Thrust and to the east by the Hervey Thrust (see below: Figure 7). Outcrop is generally poor, and the paucity of both good exposures and age constraints obscures any relationships between the constituent units. Based largely on aeromagnetic data, narrow elongate bodies (lenses) of high magnetic response are interpreted as being embedded in a low magnetic response background that is either a Cotton Formation (Figures 2, 7) and/or a Cotton Formation-like siltstone lithology (Figure 8) (Glen *et al.* 2004). Boundaries between rock packages are interpreted to be faults (Glen & Fleming 2000; Raymond *et al.* 2000; Glen *et al.* 2004). Interpretation of aeromagnetic data suggests that there is also internal disruption of individual lenses within this high-strain zone: in map and section views (Figure 8), these lenses contain internal magnetic fabrics that have been folded and truncated by faults. Thus, we believe that the lenses are the internally disrupted remnants of larger bodies. The intensity of this deformation and the inferred fault-bounded nature of contacts with enclosing sedimentary rock make correlation difficult between individual volcanic bodies, and also with the igneous complexes west of the Parkes Thrust.

*Percival (2000) erected a new name, Northparkes Volcanic Group, which contained both constituent volcanics and sediments. We prefer to use the term Northparkes Group to refer to these rocks. Elsewhere, we use the term igneous complex to refer to spatially constrained collections of igneous rocks (e.g. lavas, volcaniclastic sediments and intrusive bodies) where rock relationships are not understood, or where recognition is based on interpretation of remotely sensed geophysical data.

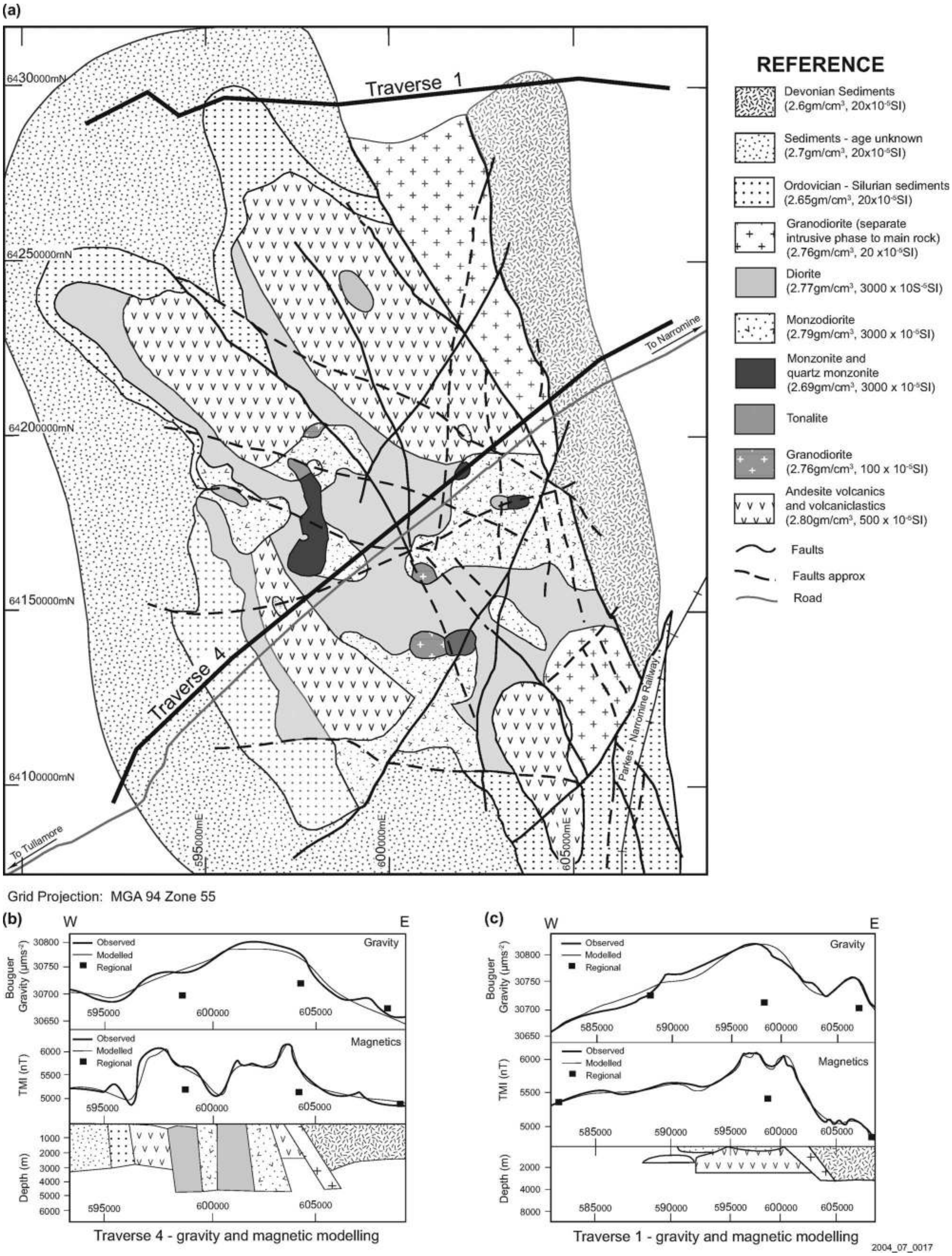
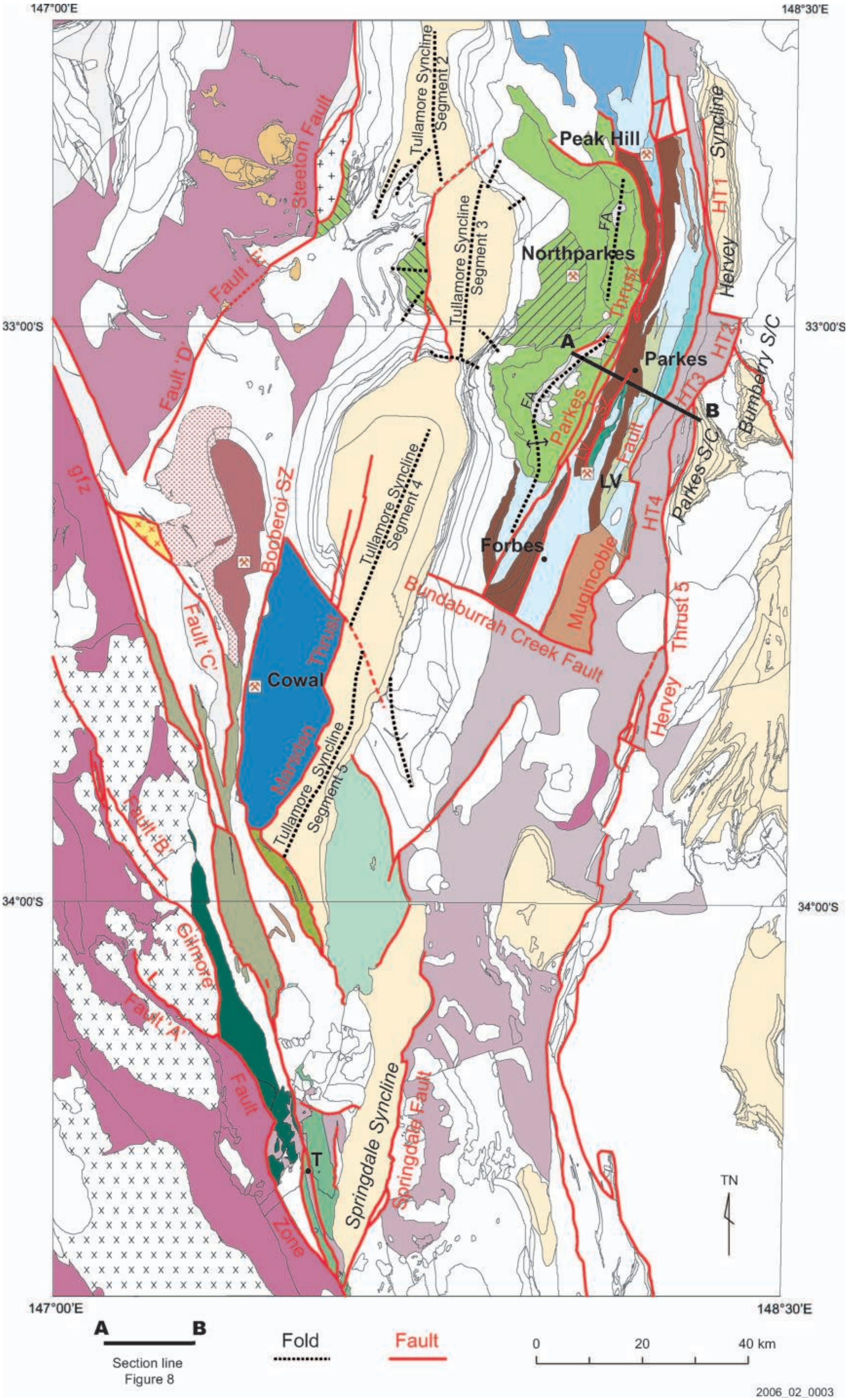


Figure 6 (a) Basement interpretation map of Narromine Igneous Complex based on drilling results, showing location of ground traverses 1 and 4 (see Figure 1a for location). Map courtesy Renison Goldfields Company Exploration and Resolute Exploration. (b) Interpretation of steep dips of lavas and intrusives along traverse 4. (c) Interpretation of shallow dips of lavas (possible antiform) along traverse 1.


147°00'E
148°30'E
33°00'S
34°00'S
Tullamore Syncline Segment 2
Tullamore Syncline Segment 3
Tullamore Syncline Segment 4
Tullamore Syncline Segment 5
Steeton Fault
Fault 'E'
Fault 'D'
Fault 'C'
Fault 'B'
Fault 'A'
Gilmore Fault Zone
Peak Hill
Northparkes
Parkes
Forbes
Cowal
LV
T
A
B
FA
Syncline
HT1
HT2
HT3
HT4
Hervey
Bumberry S/C
Parkes S/C
Parkes Thrust
Parkes SZ
Parkes Fault
Booberoi SZ
Marsden Thrust
Bundaburrah Creek Fault
Hervey Thrust 5
Mugincoble
Springdale Syncline
Springdale Fault
TN
Section line Figure 8
Fold
Fault
0
20
40 km
2006_02_0003

Igneous bodies east of the Parkes Thrust include the Nash Hill, Bushmans, Parkes, Mingelo and Goobang Volcanics. Of these, the Nash Hill Volcanics and the very small Bushman Volcanics in Parkes township (not shown on the map) are considered to be Early Silurian in age on the basis of geochemical data (Crawford *et al.* 2007b) and their interpreted interfingering relationships with the Cotton Formation. Bodies of inferred Ordovician age, based largely on geochemical similarity with the Northparkes Group, are the Parkes Volcanics (including the Daraboolgie Volcanics) and the Mingelo Volcanics (Crawford *et al.* 2007b). At this stage, the poorly exposed Goobang Volcanics are still regarded as Ordovician in age.

The Mingelo Volcanics occur as a narrow band of fault-bounded volcanic rocks ~40 km long and up to ~1.5 km wide, surrounded by mapped and regolith-covered inferred sedimentary rocks of the Silurian Forbes Group in the south and Ordovician volcaniclastic rocks (Cotton Formation) in the north (Figures 2, 7). They are best known from Peak Hill, where they host the gold deposit (Krynen *et al.* 1990b). Lithologies range in composition from basaltic to trachytic andesites (Clarke 1990; Crawford *et al.* 2007b) and probably correlate with the basal Goonumbla Volcanics of the Northparkes Group (Crawford *et al.* 2007b). Aeromagnetic data suggest that this unit widens north of Peak Hill, to host the Tomingley deposits and narrows to the south. North of Parkes, it occurs as a narrow strip of volcanics with a higher magnetic response than the surrounding Forbes Group.

The undated Parkes Volcanics between Parkes and Forbes occur as scattered outcrops surrounded by regolith (Krynen *et al.* 1990a; Raymond *et al.* 2000) and bounded on the west by the east-dipping London–Victoria Fault, a thrust juxtaposing volcanics over highly deformed rocks of the Forbes Group (Clarke 1990; Scott 1999) (see below). Geologically, the Parkes Volcanics consist of andesite, basaltic andesite and conglomerate that are compositionally distinct from both the Northparkes Group and the Nelungaloo Volcanics (Crawford *et al.* 2007b). Aeromagnetic data provide continuity between scattered outcrops and indicate that the volcanics form a narrow, elongate body (~21 × 1.5 km) that occupies the local faulted and upthrust (anticlinal) core of a regional syncline otherwise cored by the Silurian Forbes Group (Figure 8).

Fairholme Igneous Complex

The Fairholme Igneous Complex is the name given to a non-outcropping large (50 × 25 km) igneous body outlined by the potential-field data (Figures 1, 2). The central part of this body is covered by regolith. The northern and western parts are inferred to extend under Silurian cover (Figures 2, 4), based on drillcore from the Boundary, Dungarvan and Fairholme prospects held by Newcrest Mining Limited (Figure 2). Crawford *et al.* (2007a) recognise the presence of clinopyroxene-phyric basaltic lavas and breccias intruded by diorite, microdiorite and gabbro, and monzodioritic and doleritic dykes, and correlate the lavas at the Boundary prospect with the Nelungaloo Volcanics. High-level monzonitic or monzodioritic stocks have affinities with monzonitic intrusions into the Northparkes Group. The complex runs into the elongate Belimebung Igneous Complex in the south, implying that the latter may represent the deformed southern part of the Fairholme Igneous Complex. The Belimebung Igneous Complex was named from the Cootamundra 1: 250 000 map sheet area by Warren *et al.* (1995).

Cowal Igneous Complex

The Cowal Igneous Complex (~44 × 16 km) lies between the Booberoi Shear Zone on the west and the Marsden Thrust on the east (Figure 7). At the Cowal minesite, Miles and Brooker (1998) recognised the following stratigraphy: basal Cowal conglomerate unit (sandstone, siltstone, mudstone and conglomerate with clasts of reworked volcanic rocks), the middle Golden lava unit (trachyandesitic lavas and breccias) and the upper Great Flood unit that consists of redeposited pyroclastic deposits. Intruding these is the Muddy Lake Diorite (with a hornblende K–Ar age of 456 ± 5 Ma: Perkins 1993 cited in Miles & Brooker 1998) and mafic to intermediate dykes. Elsewhere in the complex are large granodiorite (with an Ar–Ar date of 465.7 ± 1 Ma: Perkins 1993 cited in Miles & Brooker 1998), and monzogabbroic to monzogranitic intrusions (Crawford *et al.* 2007a). A late dyke at the Cowal minesite with a U–Pb age of 447 ± 7 Ma produced an Ar–Ar date of 460–450 Ma (Bastrakov 1994 and Perkins 1993, respectively, cited in Miles & Brooker 1998).

The elongate north-northwest-trending Boonabah Volcanics at the southern end of the Cowal Igneous Complex (Figures 2, 7) contain basalt, andesite, andesitic breccia and volcaniclastic rocks intruded by quartz diorite dykes (Warren *et al.* 1995).

Currumburrama Igneous Complex

The ~44 × 16 km Currumburrama Igneous Complex east of the Tullamore Syncline is inferred from potential-field data (Warren *et al.* 1996; Glen *et al.* 2004). Bedrock drilling intersected basalt to andesitic lavas (used to describe old, cold coherent volcanic rocks) and volcaniclastic rocks intruded by monzonite to monzodiorites (B. Mowatt pers. comm. 2005). We include the Upper Ordovician Jingerangle Formation (Warren *et al.* 1995) in the complex (Percival & Glen 2007).

Figure 7 Enlargement of Figure 2, highlighting the central and southern parts of Junee–Narromine Volcanic Belt, surrounding units and major faults named and discussed in text. Segments 2–5 only of the Tullamore Syncline are shown on this figure; segment 1 lies further north (see Figure 2). See Figure 2 for legend. From Glen *et al.* (2004). Abbreviations: FA, Forbes Anticline; GFZ, Gilmore Fault zone (north); LV, London Victorian mine; LVSZ, London Victoria Shear Zone.

Table 1 Tullamore Syncline.

Segment	Western edge	Internal structure	Eastern edge	Southern edge
1	In N, Canonbar Igneous Complex thrust over or unconformably overlain by Upper Devonian strata. To S, Nyngan Intrusive Complex (Hilyard *et al.* 1996) has been thrust over the Hervey Group. Further S, probable unconformity with underlying Devonian strata.	Unclear: ?simple syncline with volcanics at depth.	Canonbar Igneous Complex on NE side. To S, Devonian and Upper Silurian strata with probable unconformable contact.	NW-trending cross-structure on magnetics.
2	Probable unconformity with underlying Devonian strata.	NE-trending folds in SW corner outlined by older strata. NW-trending folds outlined by older units in NW-trending fold/fault corridor on E side. Probable NNE-trending fractures.	Probable unconformity with underlying Devonian strata.	NE-trending cross-structure.
3	W-dipping thrust separates a hangingwall consisting of the Raggatt Volcanics and Silurian–Devonian rocks outlining a faulted E–W anticline (Glen *et al.* 2004).	NNW-trending E-dipping Hervey Group in the footwall. Inferred doubly plunging fold.	Silurian–Devonian strata folded into a broad E–W syncline.	WNW anticlinal cross-fold (part of Lachlan Transverse Zone).
4	Inferred unconformity above Devonian strata.	W limb broadly synclinal, and internally segmented, with NNE-trending faults inferred from aeromagnetic data and from truncations of folds in older Silurian–Devonian rocks.	Silurian–Devonian strata N of Bundaburrah Creek Fault: folded Carawandool Volcanics to S.	NW-trending probable fault.
5	The W-dipping (J. Holliday pers. comm. 1999) Marsden Thrust on E margin of Cowal Igneous Complex in the hangingwall. The Marsden Thrust is cut by WNW tear faults: one is a positive flower structure in deep seismic-reflection data (Glen *et al.* 2002 figure 7a). The thrust approximates to a change in the character of aeromagnetic response, from a flat response over the Upper Devonian Hervey Group to a high-frequency, high-amplitude response over the igneous complex. In S, NNW fault.	Inferred simple syncline in N; more complex along W margin in S.	Unconformable contact above Currumburrama Igneous Complex.	Inferred intersecting faults.

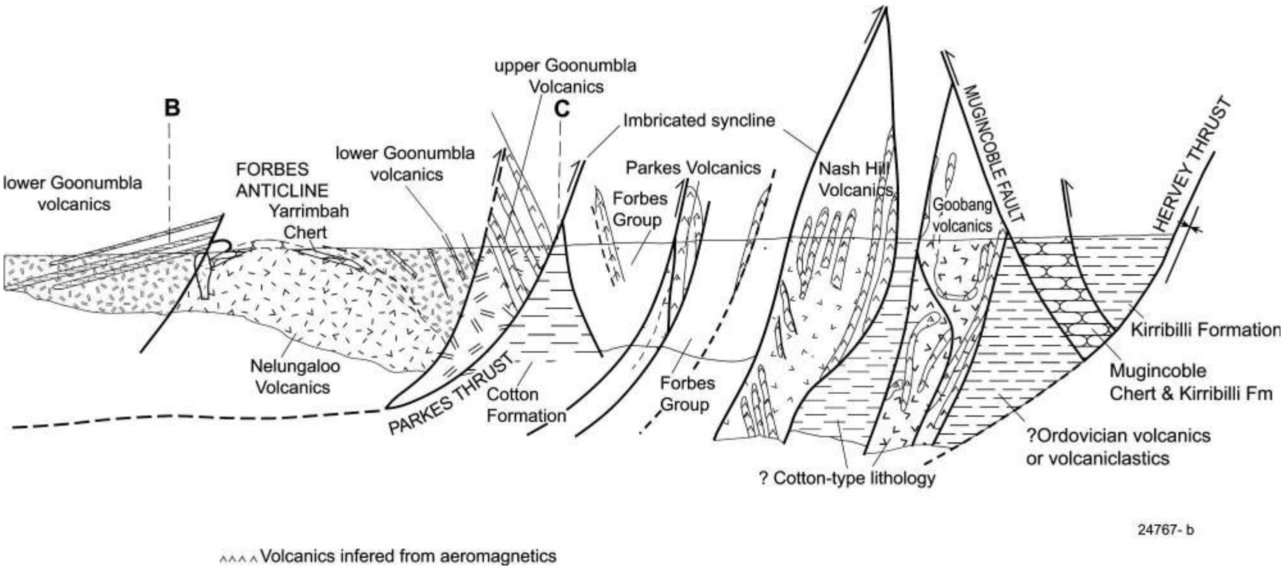


Figure 8 Cross-section A–B (see Figure 7 for location) from core of Forbes Anticline in northwest to Hervey Thrust in southeast just south of Parkes. Key features of the section are the shallowing of the Parkes Thrust, faulted core of the footwall synclinorium occupied by Forbes Group and local upthrust Parkes Volcanics, internal imbrication of the Goobang Volcanics and the Llandovery Nash Hill Volcanics and eastwards dip of the Mugincoble Fault. Section was originally drawn for Parkes 1:100 000 geological sheet (Raymond *et al.* 2000).

Gidginbung and Temora Volcanics

The Gidginbung and Temora Volcanics were described by Warren *et al.* (1995). These bodies are all elongated north-northwest, parallel to the Gilmore Fault Zone. Seismic reflection work suggests that they may be thin, east-dipping thrust sheets that sole into volcanic rocks at depth (Glen *et al.* 2002). Aeromagnetic data indicate that the Gidginbung Volcanics form a $\sim<7$ km-wide, ~ 66 km-long belt of intermediate volcanic and volcaniclastic rocks, dominated by altered andesite, associated with volcaniclastic sediments and intruded by range of bodies from granodiorite to monzodiorite (Warren *et al.* 1995). Extensively altered breccia and mudstone at Gidginbung may be proximal to a volcanic centre (Lawrie *et al.* 1997). Host-rocks, dated at 435 Ma by SHRIMP 1 (Perkins *et al.* 1995) are probably too young. Geochemically, the volcanics plot as andesites and latites and have probable shoshonitic affinity (Wyborn 1996). Hornblende from the Rain Hill Quartz Monzonite that intrudes these volcanics has yielded an Ar–Ar date of 434.9 ± 2.3 Ma (Wormald 1993 cited in Wyborn 1996).

Aeromagnetic data indicate that the Temora Volcanics outcrop as two belts, partly intruded and overlain by younger rocks, with a length of ~ 46 km and combined width of <6 km. Lithologically, they consist of lavas and volcaniclastic rocks (siltstone, sandstone, conglomerate) as well as lapilli tuff. Lavas include basaltic andesite, andesite and trachyandesite. Conglomerate contains fragments of diorite and lavas (Warren *et al.* 1995). The basaltic rocks are shoshonitic in composition according to Wyborn (1996) who also suggested that the high values of the HFSE contents suggested similarities to Early and Middle Ordovician rocks rather than those Upper Ordovician Macquarie Arc lavas. In contrast to the Early Ordovician chemical character of the Temora Volcanics, the Mother Shipton Monzodiorite (the source of gold at Temora) has a Late Ordovician chemistry in that it is richer in incompatible elements and lower in HFSE than the Temora Volcanics (A. Crawford pers. comm. 2006).

At present, we include in the Temora Volcanics the calc-alkaline Dobroyde Volcanics of Wyborn (1996). These were removed from the tholeiitic Junawarra Volcanics of Warren *et al.* (1995) because of their different geochemical affinities.

REGIONAL FAULTS AND FOLDS

North- and north-northeast-trending folds and faults affecting Upper Devonian strata

The most obvious north-trending faults and folds deform Upper Devonian rocks and are thus Carboniferous in age. The Tullamore Syncline (centre of Figures 2, 7) is the most prominent of these, with a strike length of ~ 250 km and width of up to 15 km. Other Carboniferous folds include the Springdale Syncline, an *en échelon* extension of the Tullamore Syncline to the south and an unnamed *en échelon* extension to the north. In the east of the study area, the Hervey Thrust is another Carboniferous structure with Upper Devonian rocks in scattered footwall synclines.

TULLAMORE SYNCLINE

The Tullamore Syncline is divided into five segments that are identified by changes in trends of formations or bedding or by differences in structural style (Figures 2, 7; Table 1). Segments are bounded by cross-faults or plunge changes, and these are reflected in variations in the width of syncline. Three segments are bounded (or part bounded) on their western edges by thrust faults.

SPRINGDALE SYNCLINE

The Springdale Syncline (Figure 7) appears to be *en échelon* with the Tullamore Syncline and southeast of the Currumburrama Igneous Complex, although there are very few outcrops of Upper Devonian rocks and the presence and extent of the syncline is mainly inferred from low magnetic responses west of the Springdale Fault (Warren *et al.* 1995; Bacchin *et al.* 1999). However, interpretation of seismic-reflection data along 99AGS line 3 (Glen *et al.* 2002) suggests the map interpretation needs modification since continuous reflectors suggestive of Upper Devonian strata exist east, not west, of that fault.

HERVEY THRUST

The Hervey Thrust refers to the Carboniferous faults that juxtapose Ordovician turbidites of Kirribilli Formation on the west against scattered Carboniferous synclinoria cored by Upper Devonian rocks lying unconformably above Silurian–Devonian strata on the east (Glen *et al.* 2004) (Figure 7). The Hervey Thrust is interpreted as a Carboniferous element of the Kiandra–Narromine Structure (Packham 1987), renamed the Coolac–Narromine Suture by Krynen *et al.* (1990a) following Scheibner (1987), although here we use the original name. It appears to lie in relay with other elements of the Kiandra–Narromine Structure farther south. These are dominated by a major fault system separating the Ordovician Jindalee Group of tholeiitic volcanics and related sedimentary rocks from Ordovician quartz-rich turbidites on the west from the Silurian Young Granodiorite on the east. As the Kirribilli Formation passes upsection to the south into Silurian strata, the fault-bounded Jindalee Group lies near or along the eastern margin of the deformed Silurian Tumut Trough.

As shown in Figure 7 and Table 2, the Hervey Thrust is divided into five segments separated by cross-faults or changes in strike.

North-northeast faults cutting the Junee–Narromine Volcanic Belt

The three largest faults that cut Ordovician arc rocks of the Junee–Narromine Volcanic Belt are the Booberoi Shear Zone near Cowal and west of the Tullamore Syncline, the Parkes Thrust, west of Parkes and east of the Tullamore Syncline, and the London–Victoria Shear Zone east of the Parkes Thrust (Figure 7).

BOOBEROI SHEAR ZONE

The Booberoi Shear Zone is defined by strong fabrics in the Siluro-Devonian Mana Conglomerate that separates the Cowal Igneous Complex from the southeastern part of the Fairholme Igneous Complex to the west (Lyons 1999) (Figure 7). The southern part of this shear zone shows west-block-up, reverse-sense kinematics (Lyons 1999; Scott 1999). However, sinistral movement occurs on steeply east-dipping shears in the northern part of this shear zone (Lyons 1999), just south of the intersecting northwest-trending fault that bounds the northern part of the Cowal Igneous Complex (Figure 7). Lyons (2000) reported that a deformation age of 411 ± 2 Ma from an Ar–Ar plateau on sericite (sample DG92-125: Foster *et al.* 1999) came from the Booberoi Shear Zone. This deformation is thus inferred to be middle Early Devonian in age: it may post-date an earlier biotite-grade fabric formed at a higher grade (Scott 1999).

PARKES THRUST

The Parkes Thrust is the main internal fault on the eastern side of the Tullamore Syncline (Figure 7). Krynen *et al.* (1990a) mapped this fault as having a north-northeast-trend, passing through Forbes and 5 km west of Parkes. Sherwin (1997) suggested that the fault swings to the northwest on the Narromine 1:250 000 geological sheet area further north, around a younger northeast-trending cross-fold and into a major northwest-trending fault that lies between the Northparkes Group and the Narromine Igneous Complex clearly inferred from regional aeromagnetic data (Glen *et al.* 2004). For much of its length, the Parkes Thrust coincides with the eastern boundary of a narrow strip of poorly outcropping Goonumbla Volcanics (best defined from aeromagnetic data) that is also faulted along its western margin. These two faults intersect midway between Parkes and Forbes, excising the Goonumbla Volcanics, so that to the south the Parkes Thrust cuts through Cotton Formation and loses displacement to the south in the core of the south-plunging Forbes Anticline that terminates on the west-northwest-trending Bundaburrah Creek Fault (Figure 7). As part of this general loss of displacement, a splay fault swings east off the Parkes Thrust mid-way between Parkes and Forbes, separating uncleaved uppermost Silurian Calarie Sandstone on the west from a thin sliver of cleaved upper Lower to Upper Silurian Forbes Group on the east (too small to show on Figure 7) that passes east into Cotton Formation. This splay fault was shown as the main Parkes Thrust by Krynen *et al.* (1990a).

Krynen *et al.* (1990a) suggested the Parkes Thrust dips east. Glen (1992) used this to suggest that the fault splayed off a detachment at depth that had a ramp-flat geometry reflected by formation of the Tullamore Syncline and Forbes Anticline. Subsequent discussions with North Exploration (B. Hooper pers. comm. 1992) suggested that it was more likely that the Parkes Thrust has a westerly dip. In light of the importance of the fault and the uncertainty of its dip, new gravity and magnetic data were acquired across the Parkes Thrust (Figure 9). Note that on the Parkes 1:100 000 geological sheet (Raymond *et al.* 2000), the name Parkes Thrust was not used, being supplanted by the Parkes Fault Zone, a $\sim$12 km wide zone of faults that here corresponds to part of the high-strain zone of the Kiandra–Narromine Structure.

Three ground gravity and magnetic profiles were obtained as part of this study (Figure 9). Data were collected at 400 m intervals and showed that there are marked changes in ground gravity and magnetic rock

Table 2 Hervey Thrust.

Hervey Thrust segment	Hangingwall	Footwall	Southern boundary
1. Generally N trend	Kirribilli Formation	Asymmetrical Hervey Syncline cored by Upper Devonian Hervey Group. Dips are steeper in the W limb except in N where it is occupied by Middle Devonian Rocky Ponds Group ('Dulladerry Volcanics') (Powell *et al.* 1979; Sherwin 1997). The syncline is internally structured, consisting of two *en échelon* synclines separated by a NE-trending, W-dipping reverse fault that is interpreted to be an out-of-syncline thrust (Powell *et al.* 1979). Powell *et al.* (1979) also recognised a N- to NE-trending cleavage in Upper Devonian rocks in the southern part of the syncline.	E–W accommodation fault with down-to-the-north separation (Kirribilli Formation to S, Rocky Ponds Group to N).
2. NNE trend	Kirribilli Fm, wider than in segment 1.	Rocky Ponds Group to N; tip of Bumberry Syncline cored by Upper Devonian Hervey Group. to S. W Limb is occupied by Middle Devonian Rocky Ponds Group and Devonian granite to south.	NE-trending oblique ?accommodation fault with Moura Formation (Goonigal Group) to E, between two *en échelon* synclines.
3. NE trend	Duplex system best outlined by the aeromagnetic response of quartz-magnetite-manganese units in the Kirribilli Formation and Jindalee Group.	In N, doubly plunging Parkes Syncline, internally imbricated with overturned and thinned western limb (Powell *et al.* 1979; Raymond *et al.* 1999).	Swing in strike from NE to NNE.
4. NNW trend	Kirribilli Formation, possibly duplexed and locally granite.	Footwall passes downsection from Upper Devonian through Upper Silurian sedimentary rocks (Glen Isla Formation) and then into Lower Devonian intrusive granites.	Swing in strike from NNW to NNE.
5. Curvilinear trend, N in north and NNE trend in south.	Locally Jindalee Gp in N, but mainly Kirribilli Formation. Local granite.	Lower Devonian intrusive granites, local Kirribilli Formation in S.	Fault appears to lose displacement on WNW cross-fault that links it in relay with major fault to W that bounds Jindalee Group.

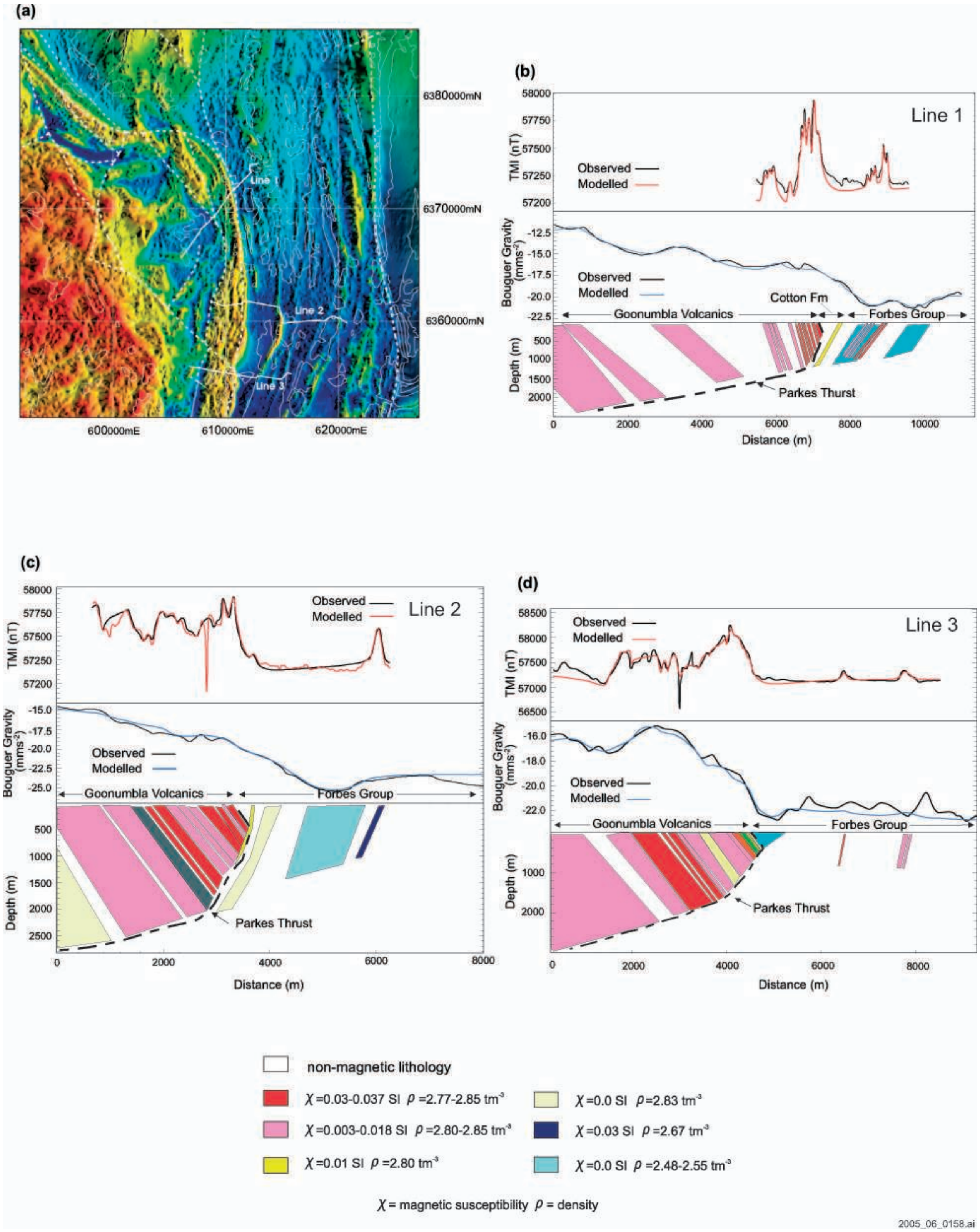


Figure 9 Magnetic and gravity profiles across the Parkes Thrust. (a) Aeromagnetic map with stratigraphic polygons from Eastern Lachlan Orogen synthesis study (Glen *et al.* 2004), showing location of lines 1–3. (b) Line 1; (c) line 2; (d) line 3. Coloured polygons of Goonumbla Volcanics reflect different ranges of density and magnetic susceptibility used in modelling. All models support a west-dipping listric Parkes Thrust truncating Goonumbla Volcanics at depths <2500 m.

properties across the northern part of the Parkes Thrust (Figure 9a). The Goonumbla Volcanics west of the thrust have densities of 2.70–2.85 t/m^3 and magnetic susceptibilities of 0.001–0.05 SI. Sandstone and mudstone of the Forbes Group and siltstone of the Cotton Group east of the Parkes Thrust exhibit low magnetisation and low

Bouguer gravity values, reflecting their very low susceptibility and lower range density values (Figure 9a). For modelling, densities of 2.65–2.67 t/m^3 and zero magnetic susceptibilities were used for the Forbes Group sedimentary rocks.

All three profiles have steep magnetic and gravity gradients coincident with the mapped location of the Parkes Thrust (Figure 9b–d). The magnitude of these gradients increases to the south. Line 1, the most northern line, crosses a narrow magnetic high zone, with a maximum amplitude of 750 nT. A coincident gravity anomaly of 6 $\mu m/s^2$ is also present. On Line 3 in the south, the magnetic anomaly coincident with the thrust is $\sim$1000 nT, and the gravity anomaly is $\sim$8 $\mu m/s^2$. The source of the low-density zone east of the Northparkes Group on all lines requires further investigation.

The presence of interbedded magnetic and nonmagnetic units in ground magnetic data over the Goonumbla Volcanics (Figures 9b–d) correlates with the andesitic lavas and sills interbedded with volcaniclastic sandstone and conglomerate (Sherwin 1996; Simpson *et al.* 2005).

The model presented here suggests that $\sim$55–80° east-dipping bodies in the Goonumbla Volcanics extend in the subsurface down to $\sim$2000–2500 m before being truncated by a west-dipping surface inferred to be the Parkes Thrust. Near the surface, we believe the Parkes Thrust steepens in dip and projects to the surface either along the contact of the Goonumbla Volcanics and the Cotton Formation (Line 1, Figure 9) or within the Forbes Group, east of the eastern edge of the Northparkes Group, as mapped by Sherwin (1997). These relationships are consistent with those north of Forbes (Krynen *et al.* 1990a), and locally northwest of Parkes (Raymond *et al.* 2000), where the Parkes Thrust lies in poorly outcropping rocks of the Cotton Formation. An alternative to this interpretation is that a west-dipping Parkes Thrust is replaced near the surface by an east-dipping thrust that lies subparallel to units in the Northparkes Group. Such an east-dipping fault could reflect overturning of the Parkes Thrust, or the thrust dying out just below the surface and replaced by a east-dipping back-thrust higher up. This is unlikely since one might expect the leading edge of the thrust to break the surface over a strike length >100 km.

We thus infer that the Parkes Thrust dips and shallows to the west. Some support for shallowing of dip of the Parkes Thrust comes from a trial seismic line acquired across part of the Forbes Anticline by Geco-Prakla for the Geological Survey of New South Wales in 1995 (Figure 10). Historically, this survey was the first acquisition of regional seismic-reflection data by Vibroseis in the hard-rock Lachlan Orogen. Unfortunately, details of acquisition and processing are no longer available. The Forbes Anticline was selected as an economically relevant test area in which low-angle dips could be reliably inferred from surface mapping. With the caveat that these reflection data are of poor quality, Figure 10 suggests that the core of the Forbes Anticline is characterised by a flat-lying structural fabric, in which the upper $\sim$3 km (1 s TWT) approximately matches the surface dip data that define the Forbes Anticline. This regional fabric is cut by inferred faults that have flat to shallow west dips to depths of $\sim$6 km (to 2 s TWT). The listric fault in the top-right corner of Figure 10c (at $\sim$0.5 s under station 658) lies approximately downdip from the surface trace of the Parkes Thrust and is labelled accordingly. The seismic data thus allow the suggestion that there may be major stacking of Ordovician volcanic strata in the core of the Forbes Anticline: if so, this answers the question as to what lies below the basal Ordovician Nelungaloo Volcanics (Glen *et al.* 2007a; Percival & Glen 2007).

LONDON–VICTORIA SHEAR ZONE

The London–Victoria Shear Zone is a north-northeast-trending, subvertical to steeply east-dipping high-strain zone that lies 2–3 km east of the Parkes Thrust. It separates Ordovician Parkes Volcanics ± Cotton Formation on the east from the Llandovery (Silurian) Forbes Group on the west (Figure 7). The zone can be traced from the latitude of Parkes south for $\sim$10 km (Clarke 1990; Krynen *et al.* 1990a; Raymond *et al.* 2000). There is a pronounced westward increase in strain in the quartz-rich variant of the Cotton Formation towards the zone, with development of a downdip stretching lineation. Sense-of-shear indicators are, unfortunately, ambiguous.

In the vicinity of the London–Victoria goldmine, the strongly deformed Parkes Volcanics occur in a high-strain zone in the hangingwall of the London–Victoria Shear Zone. The geochemical contrast between these volcanics, which have compositions matched only by the Darriwilian–Gisbornian Cargo Volcanics of the Molong Volcanic Belt, 70–100 km to the southeast (Crawford *et al.* 2007b) and the Northparkes Group to the west, suggests the shear zone accommodated a substantial displacement.

Sedimentary rocks between the London–Victoria high-strain zone and the Parkes Thrust [i.e. feldspathic Cotton Formation and unconformably overlying Lower Silurian (Wenlock) Forbes Group] are overprinted by a spaced disjunctive cleavage, similar to, but less intensely developed than, that to the east.

MUGINCOBLE FAULT AND KIRRIBILLI FORMATION

The eastern margin of the Junee–Narromine Volcanic Belt, and the contact with the quartz-rich turbidites of the Kirribilli Formation, occurs in the high-strain Kiandra–Narromine Structure, about 10 km east of the Parkes Thrust (Krynen *et al.* 1990a; Glen & Fleming 2000; Raymond *et al.* 2000). The boundary between the two stratigraphic units is the inferred Mugincoble Fault (Figure 7). This fault is inferred to dip east, putting the Kirribilli Formation over the internally disrupted Goobang Volcanics (Figure 8) (Raymond *et al.* 2000). To the south, it appears to terminate on the Bundaburrah Creek Fault (Figure 7).

Northeast of Parkes and east of the Mugincoble Fault, fine-grained, thinly bedded quartz-rich turbidites have been previously mapped as Cotton Formation (Krynen *et al.* 1990a; Sherwin 1997). Since they have a greater petrographic similarity to the Kirribilli Formation than to the fine-grained plagioclase-rich turbidites of the

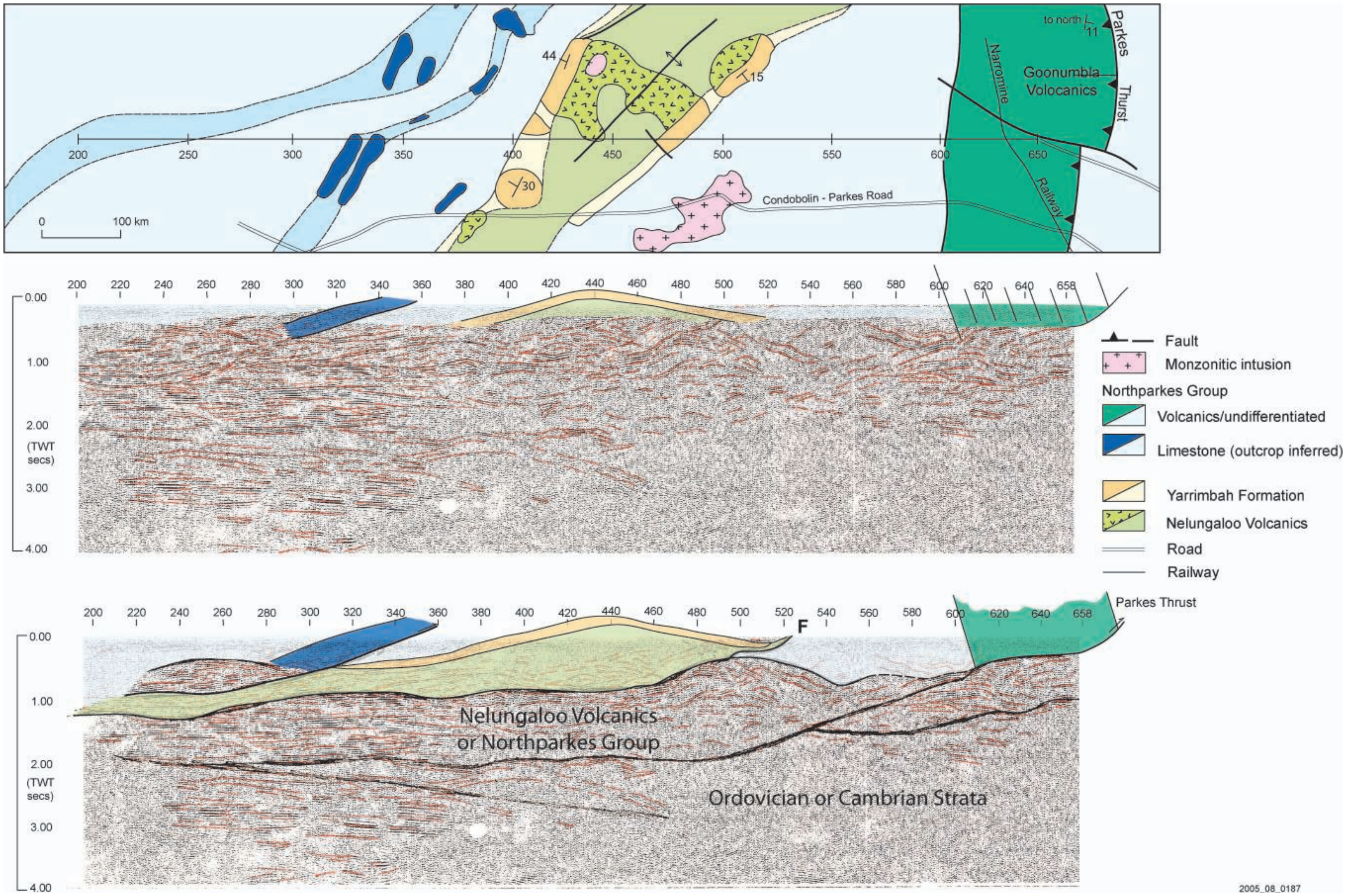


Figure 10 Trial seismic profile acquired across the Forbes Anticline. (a) Strip map of profile area (based on Krynen *et al.* 1990a and Raymond *et al.* 2000, with some additional dip data). (b) Processed (poor-quality) data with interpreted low shallowly dipping reflectors in red and surface geology from (a). (c). Structural interpretation of data in (b), based on inference that the reflectors are real. Interpretation shows low-angle west-dipping thrusts such as the Parks Thrust just east of the seismic line, inferred thrust bounding the eastern margin of the Yarrimbah Formation and underlying Nelungaloo Volcanics, and thrust bounding limestone horizons to the west. Core of Forbes Anticline is inferred to comprise stacked volcanics above Ordovician or Cambrian basement data.

Upper Ordovician–Lower Silurian Cotton Formation further west, we have shown them as Kirribilli Formation (Figures 2, 7).

The Mugincoble Fault, with an inferred east dip, separates Ordovician volcanics and volcaniclastic rocks on the west from the Kirribilli Formation to the east, which consists of quartz-rich turbidites (monotonous series of thinly to moderately thickly interbedded siltstone, sandstone and shale) with a major radiolarian-bearing chert member (Mugincoble Chert) that contains Late Ordovician conodonts (I. R. Stewart & R. A. Glen unpubl. data *in* Lyons & Wallace 1999; Lyons *et al.* 2000). This chert is structurally duplicated in the western part of the formation and may also occur as lenses in the eastern part where it appears similar lithologically to the Hoskins Chert Member (Da3–Gi1) of the Brangan Volcanics (Jindalee Group). Sand-sized detritus in the Kirribilli Formation is almost entirely quartz, but in rare instances either plagioclase or lithic fragments comprise up to 10% of the clasts. No clinopyroxene or definitive volcanic fragments were identified in any of the more than 100 thin-sections of Kirribilli Formation examined for this project.

The Kirribilli Formation is generally poorly exposed, and its internal structure is complex (Krynen *et al.* 1990b; Raymond & Wallace 2000). Bedding is commonly either not apparent in outcrop or highly attenuated ($\pm$ isoclinally folded), parallel to a moderately to strongly developed cleavage or chlorite–white mica schistosity (i.e. phyllites). There are at least four phases of folding and cleavage development in the Kirribilli Formation south and east of Parkes. The dominant fabric is a steeply dipping north-northwest- to north-northeast-trending, finely spaced disjunctive or crenulation cleavage (S_2 or even S_3) that is best developed in pelitic layers and axial planar to the dominant meso-scale open to tight folds in the area. S_2 overprints both an earlier, poorly preserved continuous mica fabric (S_1) and fine grained (<50–100 μm) syn- to post-S_1 chlorite $\pm$ biotite porphyroblasts, both of which are generally only visible in thin-section. S_2 is defined by a lower greenschist chlorite–white mica assemblage. However biotite is locally preserved both within the S_1 fabric, and as late syn- to post-S_1, pre-S_2 porphyroblasts, suggesting that D_1 deformation was at a higher temperature, although the thermal peak apparently followed the main phase of deformation. S_2 is locally overprinted by at least two generations of generally poorly developed, finely to widely spaced crenulation cleavage and kink bands. These younger cleavages are best developed in domains of higher strain such as that adjacent to the Kiandra–Narromine Structure.

S_1 in the Kirribilli Formation is generally parallel to or at a low angle to bedding, but geometric relationships between S_1 and bedding are difficult to establish owing to back-rotation of the fine-grained micas defining S_1 within the narrow S_2 microlithons during development of the later cleavage. As a result, the style and overall geometry of the F_1 folds is not well understood. However, changes between upward- and downward-facing F_2 folds occuring in a zone of strongly developed S_1 in a small gully 16 km southeast of Parkes, coupled with the gently dipping enveloping surface of F_2 folds, suggest the presence of a hinge or sheared-out hinge of a major recumbent F_1 fold pair (Meffre *et al.* 2007).

Correlation of the moderately to weakly developed cleavage in the Forbes Group east of the Parkes Thrust, with the dominant cleavage in the quartz-rich variant of the Cotton Formation and S_2 in the Kirribilli Formation, suggests that the main deformation (i.e. D_2 in Kirribilli Formation) is Late Silurian or younger. D_1, which is developed only in the Kirribilli Formation, is therefore most likely to be Early Silurian or older and occurred prior to or (more likely) during initial juxtaposition of the Kirribilli Formation and the Macquarie Arc. The generally well-developed cleavage and westward vergence of D_2 structures across the high-strain zone contrast with the lack of a widely developed cleavage associated with the clearly younger (Early Carboniferous) east-directed thrusting on the Parkes and Hervey Thrusts.

LINKED NORTH-NORTHEAST-TRENDING FAULT SYSTEM (STEETON FAULT AND FAULTS D AND E)

The Steeton Fault, west of segment 2 of the Tullamore Syncline, lies along the western side of the Gobondry Granite (Sherwin 1997) and locally bounds part of the Raggatt Volcanics on the west (Figure 7). Interpretation of aeromagnetic and gravity data suggests that the southern part of this fault joins up with a northeast-trending linear (inferred fault E, Figure 7) which links into a north-northeast-trending fault (inferred fault D) to the south that is inferred to lie near the northern end of the Fairholme Igneous Complex. These three faults form a linked system that joins northwards into the blind Tullamore Fault and southwards into the north-northwest-trending splay fault C that is part of the Gilmore trend.

TULLAMORE FAULT ZONE

North of the Steeton Fault, the Tullamore Fault is an inferred blind fault that separates Ordovician quartz-rich turbidites of the Girilambone Group on the west from volcanic and volcaniclastic units of the Junee–Narromine Volcanic Belt on the east. The existence of such a fault was first postulated beneath the Tullamore Syncline on terrane grounds by Leitch and Scheibner (1987), and as a cryptic suture subsequently named the Tullamore Suture, by Stevens (1991). The 1995 North Parkes Discovery 2000 geophysical data (Hilyard *et al.* 1996) suggested that Ordovician volcanics lie beneath and locally west of the Tullamore Syncline. As a result, we infer that this fault lies in the western limb of the syncline. We have not been able to locate this fault more precisely because of the masking effect of the gravity high to the west (Figure 1a).

North-northwest-trending structures

North-northwest-trending structures mainly affect the southern part of the Junee–Narromine Volcanic Belt (Figure 7). They include the Gilmore Fault Zone and several linked splay faults (A, B, C). Other faults with this trend cut the northern margin of the Cowal Igneous Complex, and the eastern margin of the Currumburrama

Igneous Complex. Farther north, the northern part of the Parkes Thrust rotates into this trend, as does the fault along the eastern edge of the southern, elongated and ?deformed body of the Canonbar Igneous Complex.

GILMORE FAULT ZONE

In the southern part of the Junee–Narromine Volcanic Belt, the north-northwest-trending Gilmore Fault Zone juxtaposes arc rocks (Gidginbung Volcanics and locally Temora Volcanics) on the east against turbidites of the Ordovician Wagga Group and Silurian granites on the west (Warren *et al.* 1995; Bacchin *et al.* 1999; Glen *et al.* 2002, 2004). Map relationships suggest that this fault loses displacement to the north-northwest, with similar stratigraphies preserved on both sides. We infer that displacement was taken up by unnamed splay faults A, B, C and the northern Gilmore Fault Zone (Figure 7). Splay faults A and B lie in turbidites of the Wagga Group. To the northeast, the northern Gilmore Fault Zone and splay fault C contain magnetically responsive Ordovician volcanics as well as serpentinite on fault C. Seismic-reflection work (Glen *et al.* 2002) suggested that arc rocks of the Junee–Narromine Volcanic Belt have been overthrust by the Wagga Group turbidites along a west-dipping blind fault. Their presence at depth below the Wagga Belt rocks may explain the gravity high between the Gilmore Fault Zone and fault A to the west (Figures 1a, 5b). Southeast of the area shown in Figure 7, Stuart-Smith (1991) showed that the Gilmore Fault Zone has undergone multiple deformation, inferred to consist of Late Silurian or Early to mid-Devonian deformation sinistral-reverse slip followed by Devonian or Carboniferous lower-grade dextral reverse (west-side-up) movement. A component of left-lateral slip on the Gilmore Fault Zone is consistent with elements of the Junee–Narromine Volcanic Belt becoming rotated into this fault system from the north.

Other structures

The west-northwest-trending Bundaburrah Creek Fault (Figure 7) juxtaposes arc volcanics in the north against turbidites of the Ordovician Kirribilli Formation in the south and appears to have map-scale dip-slip contractional movement.

A west-northwest-trending structural corridor runs through the Parkes area, reflected by the anticlinal cross-fold in the Tullamore Syncline and Forbes Anticline, and by atypically shaped Carboniferous synclinoria further east (Figure 7). Glen and Walshe (1999) suggested these features were reflections of the Lachlan Transverse Zone. West-northwest-trending zones of demagnetisation in aeromagnetic data have been interpreted as faults cutting the Mingelo Volcanics at the Tomingley prospect (Chalmers *et al.* 2006) and also cutting the Cowal Igneous Complex (Barrick Gold pers. comm. 2006). One of these corresponds with a cross-structure in the Carboniferous Marsden Thrust interpreted from seismic data as a flower structure by Glen *et al.* (2002).

DISCUSSION

Significance of regional gravity highs

In early modelling, Tenison Woods (1990) suggested that the regional gravity highs reflect pre-Ordovician basement rising from depths of 12–15 km to a depth of ~9 km under the Parkes Gravity Ridge, the term she used for the two linear highs and the intervening low. However, using more recent geophysics and mapping, we argued above that the eastern high corresponds to outcropping Ordovician complexes. The western low reflects inferred Ordovician igneous rocks at a depth below quartz-rich turbidites of the Girilambone and Wagga Groups.

The similarity of the responses of the eastern gravity high, due to (near-) outcropping Ordovician volcanics, and the western high, caused by buried igneous rock, suggests that the source of the western high must be more dense than the eastern one—either more mafic or with a lesser volcaniclastic component. The tectonic affinity of these buried igneous rocks is conjectural: either underthrust arc volcanics or backarc-like volcanics associated with turbidites. Clues come from two areas. Interpretation of deep seismic-reflection data (Figure 5) suggests that parts of the Junee–Narromine Volcanic Belt have been thrust below Ordovician turbidites of the Wagga Group and Early Silurian granitoids (Glen *et al.* 2002). Direen *et al.* (2001a, b) showed that this geometry can successfully model the observed gravity high, with the top of a dense body (2.83 t/m^3) of arc rocks ramping down to 14–15 km some 40 km west of the western margin of the Junee–Narromine Volcanic Belt (Figure 5). The lower gravity response in seismic lines 1 and 2 compared to seismic line 3 (Figure 5) was interpreted as reflecting low-density granites at the surface.

Alternatively, igneous rocks could be tholeiitic MORB-like rocks that locally outcrop along the western side of the Gilmore Fault Zone and Tullamore Fault Zone—the Ordovician Nacka Nacka Complex (Basden 1990), the Junawarra Volcanics (Wyborn 1996) in the south, and farther north at 34°S the probable Narragudgil Volcanics intruded by Ordovician dykes (Duggan & Lyons 1999; Duggan 2000a). Farther north, around 32.5°S, the mafic schists associated or interlayered with Girilambone Group around Tottenham (Suppel 1974; Sherwin 1996: the Tottenham Volcanics of Glen *et al.* 2004) are associated with a broad gravity high that may reflect more material at depth. Recent work (Muir 1999) has suggested that these schists also have tholeiite-like chemistry and thus may represent the top of a welt of MORB-like mafic volcanics. The location and chemical affinity of these volcanics fits with their being backarc volcanics to the Macquarie Arc (Glen *et al.* 2004; Glen 2005). The gravity high around 33°S coincides with outcrop of the Girilambone Group overlain by felsic less dense Silurian–Devonian volcaniclastic strata but is again inferred to reflect dense mafic Ordovician volcanics at depth (Figure 1).

The linear gravity low between the two flanking highs coincides with the Tullamore Syncline cored by the Upper Devonian Hervey Group. Magnetic data indicate the presence of volcanic strata especially in the western limb. In the absence of volcanic rocks in outcrop of the Hervey Group, it is concluded that the volcanics lie in the underlying Upper Silurian–Lower Devonian strata and that the linear gravity low reflects the density distribution of both rock packets.

Junee–Narromine Volcanic Belt

EXTENT OF JUNEE–NARROMINE VOLCANIC BELT

The Canonbar Igneous Complex is the most northern component of the Junee–Narromine Volcanic Belt. We find no evidence that the belt extends northwards into Queensland as suggested by Scheibner and Basden (1998), and instead suggest that the geological bodies inferred farther north from interpretation of aeromagnetic and gravity data are instead Early Devonian igneous units (V. David & R. A. Glen unpubl. data). They resemble, and include at their southern end, Devonian silicic caldera complexes inferred from aeromagnetic interpretation and drilling by Hilyard *et al.* (1996).

CONSTITUENTS OF THE JUNEE–NARROMINE VOLCANIC BELT

Despite extremely poor outcrop, it is possible to gain an insight into the igneous composition of the Junee–Narromine Volcanic Belt by using the scattered outcrop, coupled with drillhole data and the interpretation of aeromagnetic and gravity data. These combined datasets suggest that the belt contains at least 16 different igneous complexes distributed along its length. While largely identified from geophysical properties, these complexes have differences not only in stratigraphy, but also in intrusive histories and chemistries (Appendix 2). Although some of these complexes are dominated by volcaniclastic rocks (e.g. Northparkes Group: Simpson *et al.* 2005; Crawford *et al.* 2007b), significant areas of other complexes contain large amounts of lavas and intrusive bodies. Coupled with the variation in geochemical affinity between different complexes in the Junee–Narromine Volcanic Belt, and different ages and intrusion histories, this distribution supports the suggestion that the separate igneous complexes represent to a significant extent separate igneous centres spread along the Junee–Narromine Volcanic Belt.

This contrasts with other belts of Ordovician volcanics (Figure 1c). The eastern (Rockley–Gulgong) Volcanic Belt consists largely of volcaniclastic strata except for mafic and ultramafic volcanics south of the Bathurst Granite, along the Lachlan Transverse Zone of Glen and Walshe (1999) (see Pogson & Watkins 1998; Meakin & Morgan 1999). The central (Molong) Volcanic Belt between the two is largely volcaniclastic in the north: between Orange and Wellington, a distance of $\sim$100 km, the only lavas are the pillow basalts and some andesitic lavas in the Fairbridge Volcanics. South of Orange, coherent lavas and volcanic centres are more prevalent (Cargo Volcanics, Walli Volcanics, Forest Reefs Volcanics, Blayney and Byng Volcanics: Pogson & Watkins 1998; Meakin & Morgan 1999; Crawford *et al.* 2007b; Percival & Glen 2007), but lie along a west-northwest-trending zone—the Lachlan Transverse Zone. As a result, we suggest that the Junee–Narromine Volcanic Belt approximates the magmatic core of the Macquarie Arc more closely than any other of the preserved Ordovician volcanic belts.

Structural geology

The complex geometry of the Junee–Narromine Volcanic Belt is the result of a number of separate igneous complexes deformed during accretion of the Macquarie Arc to the Gondwana margin (Glen 2005) and specifically by interplay over time of two major fault systems: the north- to north-northeast-trending Tullamore System mainly in the centre, and the north-northwest-trending Gilmore System mainly in the south but also in the north.

TULLAMORE TREND

The central part of the belt reflects the influence of the north- to north-northeast-trending bounding structures of the Tullamore trend. Individual igneous complexes are broadly elongate north–south or north-northwest, and deformation is generally low except in the high-strain zone between the Parkes Thrust and the Hervey Thrust to the east, and adjacent to the Booberoi Shear Zone. In this interpretation, the *en échelon* trend of three complexes—Fairholme Igneous Complex, Cowal Igneous Complex and Currumburrama Igneous Complex—parallel to the Gilmore Fault Zone is more apparent than real and does not take into account the large amounts of shortening inferred on elements of the Tullamore trend.

Regional fold–fault relationships suggest that elements of the Tullamore system have had a prolonged history of movement. The earliest juxtaposition of arc rocks with Ordovician turbidites of the Girilambone Group was probably in the Early Silurian (see Glen *et al.* 2007b; Meffre *et al.* 2007) and produced the S_1 cleavage in the Kirribilli Formation. The major change in provenance across the Mugincoble Fault suggests that it may have also formed in this accretion event as a terrane boundary (Glen *et al.* 2007b; Meffre *et al.* 2007). A Devonian age for some of the high-strain ductile deformation east of the Parkes Thrust reflects the involvement of the late Early Silurian Forbes Group and probably Early Silurian Nash Hill Volcanics (Crawford *et al.* 2007b) in the deformation. Ar–Ar sericite ages of 409.3 ± 4.2 Ma at Peak Hill (Perkins *et al.* 1995) and the 411 Ma sericite age from the Booberoi Shear Zone probably reflect this deformation. This ductile cleavage-forming event may have produced S_2 in the Kirribilli Formation, which correlates with cleavage in the Forbes Group east of the Parkes Thrust, and the dominant cleavage in the quartz-rich variant of the Cotton Formation. These cleavages were then overprinted by a later, brittle, Carboniferous deformation best recorded from deformation of Upper Devonian fluvial successions.

Our interpretation is that the Parkes Thrust, Forbes Anticline and the Tullamore Syncline to the west are parts of a linked fault–fold system. The Parkes Thrust is interpreted to be a west-dipping listric fault, consistent with the interpretation that the Forbes Group east of the fault occupies a footwall synclinorium, albeit internally imbricated, and that the Forbes Anticline to the west is a hangingwall anticline (Figure 7). A shallowing of the dip of the thrust west beneath the Forbes Anticline suggests that the anticline may be a ramp fold. Further west, segments 2 and 3 of the Carboniferous Tullamore Syncline may have formed as ramp synclines. This in turn implies a Carboniferous age for at the late-stage brittle movement stage of the Parkes Fault that cuts, and thus post-dates deposition of, the Early Silurian Forbes Group. The Parkes Thrust cuts a high-strain zone that probably originated in the Early Silurian and which is an early expression of the Kiandra–Narromine Structure.

GILMORE TREND

First-order effects of the Gilmore Fault Zone consist of several north-northwest-trending splay faults that can be followed from the southern edge of map area (Figure 7) to the western edge near 33°S. These are best inferred or mapped where they separate slivers of Ordovician volcanics from Ordovician quartz-rich turbidites or granites. South of 34°S, the main Gilmore Fault Zone lies on the western margin of the Gidginbung Volcanics, but we also infer faults on the edges of the Temora Volcanics to the east. Note the presence of splay fault A to the southwest, which lies along the boundary of granite and Ordovician turbidites of the Wagga Group. North of 34°S, the main Gilmore Fault Zone loses displacement to the northwest and becomes a fault along granite–turbidite contact, the same as fault B just to the northeast. A northern planar Gilmore Fault Zone to the northeast is localised along the margins of the Belimebung Volcanics and extending with a straight trace to the edge of the map near 33°S, by which stage it has migrated away from the volcanics into the Wagga Group (Figure 7) and is thus no longer a terrane boundary. Involvement of Ordovician volcanics (and ultramafic rocks) along the Gilmore Fault Zone and its splays dies out progressively from southwest to northeast.

Aeromagnetic data suggest that the southern parts of the Fairholme Igneous Complex and Cowal Igneous Complex have been rotated into the Gilmore trend, then become aligned along splay faults as thrust sheets before being truncated by the fault and overthrust in the third dimension by Ordovician turbidites on a west-dipping thrust $\pm$ strike-slip fault zone. The Gidginbung and Temora Volcanics occur as elongate bodies parallel to this structure. Seismic-refection profiling (Glen *et al.* 2002) suggests that they are only thin sheets.

In the south, the Gilmore system has Early Silurian movement (Glen *et al.* 2007b), with evidence of reactivation in the Late Silurian or Early to mid-Devonian (Stuart-Smith 1991). Unlike the Tullamore trend structures, there is no clear field evidence for Carboniferous movement on the Gilmore trend structures, which seem to be Middle Devonian and older. These deformations are constrained stratigraphically by the emplacement of syn-tectonic granites in the Wagga Belt to the west (433 $\pm$ 2 Ma at Ungarie Granite: Duggan 2000b) and by alunite ages between 420 and 400 Ma from the Gidginbung deposit (Perkins *et al.* 1995).

There are two other significant structures with Gilmore trends. The first is the northwest-trending fault that lies at the northern margin of the Parkes Thrust (Figure 7). Rotation of that thrust suggests that this fault has apparent left-lateral displacement. The presence of Silurian–Devonian strata along this fault suggests major displacement in the Devonian or later. The second element controls the eastern edge of the Canonbar Igneous Complex (Figure 2). Again, apparent left-lateral displacement on this north-northwest-trending blind structure is suggested by curvature of the northern part of the Junee–Narromine Volcanic Belt and the northern part of the Canonbar Igneous Complex in particular.

A complicated accommodation zone between these Tullamore and Gilmore trend structures occurs where the southern part of the Booberoi Shear Zone, the most southerly fault with a Tullamore trend, interacts with north-northwest-trending splay faults of the Gilmore system. The structurally controlled Cowal deposit (Miles & Brooker 1998) lies near these intersecting trends.

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APPENDIX 1: GROUND GRAVITY TRAVERSES

Collection

Gravity traversing along an east–west line through Forbes was undertaken jointly by the Australian Geological Survey Organisation and New South Wales Department of Mineral Resources in December 1998 during the mapping of the Forbes 1:250 000 map sheet area, and was partially funded by the Discovery 2000 Initiative. Gravity measurements were acquired by the Australian Geological Survey Organisation at a spacing of 350 m, with gravity traversing carried out using a LaCoste and Romberg G132 G101 gravity meter with an accuracy of 0.2 $\mu m/s^2$. Processing was carried out by Alan Willmore of the Geological Survey of New South Wales.

The traverses over the Narromine Igneous Complex and Parkes Thrust were carried out using a Lacoste and Romberg Model G-651 gravity meter that has a sensitivity of 0.01 milligal. Gravity measurements were acquired at a spacing of 500 m over the Narromine Igneous Complex and 400 m over the Parkes Thrust. Positioning was controlled by a Javad GPS differential unit, at an accuracy of 10 cm in the horizontal and vertical directions. The Narromine Igneous Complex traverses were acquired and processed by Alan Willmore in February 2000. The traverses across the Parkes Thrust were acquired and processed by Ross Spencer in February 2001.

To control the drift of the gravity meter, a local gravity base was located on a concrete slab outside unit 4 in the Rose Gardens Caravan Park in Narromine. Base-station readings were taken at the start and finish of each survey day, and usually twice during the day.

This local gravity base was then tied to the National Gravity Network by tying to an Australian Geological Survey Organisation station in Dubbo (6491.1113). To check the consistency of observations, daily gravity readings were digitised each evening. Approximately eight of the survey stations were reoccupied, with all repeat stations within the 0.1 milligal threshold for acceptable data. Instrument drift, latitude, the free-air and Bouguer (density 2.67 t/m^3) corrections were all calculated and applied using standard formulae as defined by Telford *et al.* (1978). Terrain corrections were not applied to the data as the traverses lay over the flat terrain of the Great Artesian Basin where the relative levels for all lines varied by no more than $\pm$13 m. The corresponding total magnetic intensity data were extracted from the Discovery 2000 aeromagnetic grid, flown for the Geological Survey of New South Wales over the Narromine 1:250 000 map sheet area.

Modelling

The ground gravity and corresponding aeromagnetic profile were imported into Encom's ModelVision software for forward modelling. Modelling over the Narromine Igneous Complex was constrained by the basement geological map produced by Goldfields Exploration from a systematic grid-drilling program. Suitable diamond drill cores from Resolute Limited (managers of the Goldfields project) were sampled for density measurements. Great Australian Basin sedimentary thickness were also obtained from Resolute Limited and incorporated into the models. Magnetic susceptibilities used in the modelling were assigned from look-up tables. Petrophysical data are given in Table 3.

Results of modelling the Parkes Thrust traverses show that a significant gravity gradient is coincident with the location of the fault. Computer modelling of the data was then conducted using the interpreted proposed geological cross-sections as a seed for the computer models. Modelling of the airborne magnetic data coincident with the gravity profiles was also carried out to assist in determining the dip of the sources and is included on the diagrams of the gravity data and models (Figure 9).

Table 3 Measured density values and assigned magnetic susceptibilities of diamond drillhole core samples from the Narromine Igneous Complex.

Rock type	Density (t/m^3)	Magnetic susceptibility ($\times 10^{-5}$ S.I.)
Granodiorite	2.76	100
Monzodiorite	2.79	2000
Granophyre	2.75	Not modelled
Monzonite	2.69	Not modelled
Andesite	2.80	5000
Monzogranite	2.79	Not modelled
Diorite	2.77	3000
Gabbro	2.97	Not modelled
Devonian sedimentary rocks	2.63	20
Sedimentary rocks unknown age	2.70	20
Ordovician–Silurian sedimentary rocks	2.65	20

APPENDIX 2: CHARACTERISTICS OF MAJOR IGNEOUS COMPLEXES (EXCLUDING THOSE EAST OF PARKES THRUST)

Canonbar Complex (no outcrop)

Boundaries North body: sharp gravity and magnetic gradients to west (inferred fault against Girilambone Group). South boundary intruded by Silurian Nyngan Intrusive Complex of Hilyard *et al.* (1996). South body: sediment rich, may interfinger with Narromine Igneous Complex to south.

Internal makeup North body: triangular-shaped, moderate to high gravity response (from 40 gu to 140 gu). TMI data suggest a north-northeast-trending western part and a northwest-trending southern part with high-frequency fabric ?due to volcaniclastic rocks. Possible fold limbs, with core overlain by thin Silurian–Devonian strata. South body: linear grain (? due to sediment content) and strain, and overlain in the middle by a narrow strip of faulted sediments with magnetic character similar to that of the Upper Devonian Hervey Group. May be subdivisible in future.

Narromine (no outcrop)

Boundaries West margin: gradual aeromagnetic and gravity gradients reflecting increasing sediment cover. Inferred east-dipping fault, further west than inferred from subsurface mapping. East margin: sharp aeromagnetic gradient suggesting faulted contact with (?Upper) Devonian strata.

Internal makeup Broad north-northwest-trending gravity ridges with a central low. Aeromagnetic data shows two north-northwest-trending prongs with some internal parallel fabric. South part has more curvilinear trends suggestive of intrusions.

Age ? Lavas Early Ordovician (Crawford *et al.* 2007a).

Intrusions Older suite of monzonites and monzodiorites at 466–460 Ma and a younger (Copper Hill) suite of granodiorite and dacite with *ca* 448–443 zircon rims (Crawford *et al.* 2007a).

Geochemical affinity Lavas: low- to medium-K, akin to Nelungaloo Volcanics (Crawford *et al.* 2007a). 465 Ma intrusives: high-K calc-alkaline to shoshonitic affinities. 455–450 Ma intrusives: medium-K calc-alkaline.

Nelungaloo Volcanics and Yarrimbah Formation

Boundaries Inferred core of anticline but probably faulted in part.

Internal makeup Poor to high-frequency response, commonly masked by intrusions.

Age Early Ordovician 481 Ma (Glen *et al*. 2007a).
Geochemical affinity High-K calc-alkaline.

Northparkes Group (outcrop in south)

Boundaries West margin unconformably overlain by Silurian–Devonian strata. East margin truncated by the Parkes Thrust (Figures 7, 8).
Internal makeup Threefold subdivision. Lower two parts show moderate to high magnetic responses. The lowest part is magnetically quiet, especially in the east limb of the Forbes Anticline (Figure 9). The middle part (Goonumbla Volcanics, Billabong Creek Limestone and Gunningbland Formation) is associated with a magnetic fabric that correlates with thin volcanic units and which outlines a folded stratigraphy. A faulted slice of Goonumbla Volcanics in the eastern limb shows a strong magnetic character (Figure 9). The upper part, the Wombin Volcanics, has a noisy high magnetic signature that persists, with loss of the high-frequency component, beneath cover sediments to the west (Figure 1b). Intrusions have positive magnetic response. The lower two units are associated with a broad gravity high. The Wombin Volcanics coincide with a gravity low that coincides with the intrusions into the upper part of the complex and which may reflect the presence of a large intrusive body at depth (Heithersay & Walshe 1995).
Age ?Early Darriwilian to late Bolindian (Percival & Glen 2007).
Intrusions Monzonitic porphyries dated at 451 Ma and *ca* 439 Ma (Butera *et al*. 2001).
Geochemical affinity Lower part: ??high TiO_2 lavas, not shoshonitic. Middle–upper parts: shoshonitic. 439 Ma intrusives: shoshonitic.

Northparkes Group (Raggatt outcrop)

Boundaries To east cut-off by fault. To west intruded by Gobondry Granite.
Internal makeup High-frequency aeromagnetic pattern over the Raggatt Volcanics is similar to that over the Wombin Volcanics (Figure 1b). Continuity between the two beneath the Tullamore Syncline is suggested by attenuation beneath Devonian cover (Figure 1b).
Age Late Ordovician, based on Late Ordovician limestone (Percival & Glen 2007).
Geochemical affinity Geochemistry matches the shoshonitic Wombin Volcanics to the east (Sherwin 1996; Crawford *et al*. 2007b).

Fairholme (no outcrop)

Boundaries East side: steep gravity and aeromagnetic gradients against the Booberoi Shear Zone (Figures 1b, 2, 7). West side: gentle gravity and aeromagnetic gradients indicate extends to a depth of ~6 km, beneath Silurian–Devonian sediments. Extends west to a fault locally hosting ultramafic rocks (Figure 4).
Internal makeup The complex is represented by a north–south elongate gravity high (values between −40 gu & +40 gu) and a ~8 km-wide broad north-northwest-trending magnetic high that passes westwards into a high-amplitude broad (and deeper) zone. The magnetic high is divided into three parts: north, a circular anomaly; centre, moderate amplitude and high-frequency magnetic ridge with an internal fabric of north-northwest and curved trends; south, northwest fabric that is faulted off on east and which runs into the elongate Belimebung Igneous Complex to the south.
Age Undated basalts and basaltic breccias (Crawford *et al*. 2007a).
Intrusions Boundary prospect: late dykes and older suite of microgabbros to granodiorites. Dungarvan prospect: diorites to gabbros (Crawford *et al*. 2007a).
Geochemical affinity Boundary prospect: lavas, like Nelungaloo Volcanics. High-K calc-alkaline high-level monzo(dioritic) stocks: shoshonitic.

Cowal (no outcrop)

Boundaries East and west boundaries: sharp aeromagnetic boundaries reflecting truncation by the Marsden Thrust and Booberoi Shear Zone.
Internal makeup Gravity data show a low in the southwest corner with an arcuate ridge to the southeast and a broad plateau to the north. Aeromagnetic data suggest a north-northeast strip along the west part of the complex (adjacent to the Booberoi Shear Zone) has a north-northeast linear magnetic fabric. Aeromagnetic patterns further east vary from circular to curvilinear and irregular. They probably reflect the presence of numerous intrusions. The south part of the Cowal Igneous Complex (= Boonabah Volcanics) has been deformed into a curvilinear north-northwest trend (Figure 7).
Age At Cowal, volcaniclastic rocks and lavas. Eastonian limestones in E part of complex near Quandialla (Percival & Glen 2007).
Intrusions At Cowal, intrusive 465 Ma diorite and late dykes at *ca* 447 Ma (see text). Elsewhere large 466 Ma granodiorite and monzogabbroic to monzogranitic intrusions (see text).
Geochemical affinity Lavas at Cowal: high-K calc-alkaline affinity like lavas in the Nelungaloo Volcanics. Intrusives at west Cowal & Marsden: high-K calc-alkaline affinity like Nelungaloo type magmas. Intrusives at North Cowal: shoshonitic like the Goonumbla Igneous Complex (Crawford *et al*. 2007a).

Currumburrama (almost no outcrop)

Boundaries West and northeast margins have low gravity gradients on. East and southeast margins have-steep gradient reflecting an inferred fault against Upper Devonian sediments, part of the Springdale Fault System.
Internal makeup The complex is characterised by a north–south elongate, flat gravity plateau, with moderate to low gravity values (−140 gu to −120 gu). Magnetically,

the complex has a moderate amplitude and frequency, with highs in the southeast and north. Internal fabric trends north, but is attenuated to the west, reflecting increasing cover of the Upper Devonian Hervey Group. Small intrusions possibly present. Circular–irregular high-amplitude magnetic patterns in south and southeast corner reflect different complexes at depth.
Age Undated lavas and igneous rocks, but Late Ordovician graptolites in south.

Temora, Gidginbung and Belimebung volcanics (outcrop in part)

Boundaries Fault-bounded north-northwest-trending elongate bodies, aligned parallel to the Gilmore Fault Zone. Faults are inferred to be oblique contractional.
Internal makeup Gidginbung Volcanics are too narrow to have a clearly defined regional gravity signature. Magnetically, they are associated with a dumbbell shaped north-northwest-linear zone. The Temora Volcanics have a slight gravity high and a narrow north-northwest-trending magnetic ridge. The Belimebung Volcanics are associated with a strong linear magnetic high, truncated by a fault to north.
Age Zircons from Temora mine andesite flow 435 ± 5 Ma (Perkins *et al.* 1990).
Intrusions Rain Hill Quartz Monzonite has an Ar–Ar date of 434.9 ± 2.3 Ma (Wormald 1993 cited by Wyborn 1996). Mother Shipton Monzodiorite is shoshonitic with 'Late Ordovician' chemistry (Wyborn 1996).
Geochemical affinity Gidginbung Volcanics have high-K calc-alkaline to shoshonitic affinities. The Temora Volcanics are shoshonitic (Wyborn 1996).

Unnamed complexes (under cover)

Boundaries Several possible Ordovician complexes beneath Palaeozoic cover are interpreted from gravity and aeromagnetic data (Figure 7). Two are south of the Northparkes Group, with dimensions ~10 km across. Both may be dyke sets. Smaller gravity highs, without coincident magnetic highs, occur north of the Fairholme Igneous Complex
Internal makeup The gravity signatures consist of broad diffuse highs, while aeromagnetic images show linear west-northwest-trending linears for the northern body and north-northwest-trending linears for the southern one.