ABSTRACT

Three Cainozoic intraplate volcanic suites in the Bingara to Inverell area, northeastern New South Wales, have been discriminated on the basis of differing geophysical responses and contrasting K–Ar ages. Major isotopic and chemical characteristics can also be used to distinguish the three suites. These newly defined suites are the Middle Eocene–Early Oligocene Maybole Volcanic Suite; the Late Oligocene–Early Miocene Delungra Volcanic Suite; and the Middle Miocene Langari Hill Volcanic Suite. Four basaltic volcanic units within the Delungra Volcanic Suite have also been distinguished: Mount Russell Volcanics; Derra Derra Volcanics; Inverell Volcanics; and Bingara Volcanics. The Maybole Volcanic Suite is dominated by mafic volcanic rocks of alkaline affinity. These rocks include hawaiite, transitional basalt, basanite and rare phonolite (not included in this study). Volcanogenic and non-volcanogenic sedimentary units are minor but significant components, hosting world-class concentrations of sapphires in the Inverell–Glen Innes region. The Maybole Volcanic Suite occupies the eastern portion of the study area, forming ridges that outline the radial drainage pattern of the deeply eroded Eocene–Oligocene Maybole shield volcano. The Delungra Volcanic Suite is geochemically diverse and consists of alkaline members (Inverell and Bingara Volcanics) and tholeiitic members (Mount Russell and Derra Derra Volcanics). These are dominated by mafic lava flows with minor interflow sedimentary horizons. The Delungra Volcanic Suite forms broad elevated plains and prominent plugs in the central and western portions of the study area. Diamond occurrences in the Bingara district are spatially associated with the Bingara and Derra Derra Volcanics. The Langari Hill Volcanic Suite consists of a mafic tholeiitic lava flow that is spatially restricted to a prominent east–west ridge east of Inverell overlying the Maybole Volcanic Suite. The Langari Hill Volcanic Suite is significantly younger than the Maybole and Delungra Volcanic suites and represents the youngest recognised volcanic episode in the Bingara–Inverell area.

KEYWORDS: sapphire, mapping, geophysics, geochronology, geochemistry, Cainozoic, intraplate volcanism, Maybole Volcanic Suite, Delungra Volcanic Suite, Langari Hill Volcanic Suite

INTRODUCTION

A revised geological interpretation has been established for selected Cainozoic igneous rocks from the Central Province (McDougall & Wilkinson 1967) of the New England Orogen (Figure 1). The study area lies within the Northern Tablelands of New South Wales and encompasses the towns of Bingara, Delungra, Inverell and Warialda. Cainozoic igneous rocks from this area have been subdivided into three newly defined volcanic suites — utilising recently acquired petrographic, geochronological, geophysical and geochemical data.

The study area incorporates part of the world-class Glen Innes–Inverell sapphire province, which attained a maximum 70% to 80% of the world’s sapphire production during the 1970s and 1980s (Coenraads 1990; McEvilly et al. 2004). Other studies have demonstrated a spatial and genetic association between sapphires and the eastern alkaline volcanic rocks (Barron 1987; Pecover & Coenraads 1989; Sutherland et al. 1993; Oakes et al. 1996). Similarly, a spatial relationship has been
recognized between diamond occurrences and the western tholeiitic association, due in part to deep-lead occurrences in the Copeton and Bingara districts (Davies et al. 2002).

In 2003 the Geological Survey of New South Wales (GSNSW) completed a new geological compilation for the Nandewar Bioregion Assessment area (Figure 1). This paper is an outcome of the Nandewar Bioregion Assessment (Dawson et al. 2004; McEvilly et al. 2004), a project undertaken by the GSNSW for the Resource and Conservation Assessment Council as part of the whole-of-government Western Regional Assessment of New South Wales. The study reported here was limited to the basalts within the Nandewar Bioregion. Coordinates used in this paper are to Map Grid Australia (MGA94), Zone 56.

**REGIONAL GEOLOGY**

In the study area, basement rocks are part of the southern New England Orogen, and consist of three distinct rock packages (Tamworth Belt, Woodroffe Melange and the Central Block) that accreted at the palaeo-Pacific margin of Gondwanaland in the Late Carboniferous (Flood & Atchison 1988) (Figure 2). The Tamworth Belt is the westernmost package and regionally includes faulted and gently to moderately folded, mildly metamorphosed Middle Cambrian to earliest Permian sedimentary and volcanic rocks (Cawood 1980). Roberts et al. 2004). To the east of the Tamworth Belt are moderately to strongly deformed Silurian to Carboniferous sedimentary and volcanic rocks (Armitage & Brownlow 1987). Separating the Tamworth Belt from the Central Block along the Peel Fault is the Woodroffe Melange: serpentinitised ophiolites of Middle Cambrian age (Atchison et al. 1988). These three packages are stitched by voluminous, dominantly felsic, plutons constituting the Late Carboniferous to Middle Triassic New England Batholith. In the study area, the New England Batholith is represented by the Late Permian to Middle Triassic Uralla Supersuite (I-type; Bryant et al. 2003), and the Early Permian Bundarra Supersuite (S-type; Bryant et al. 2003).

Unconformably overlying the accreted Cambrian to earliest Permian basement packages are many basins preserving Early Permian to Early Cretaceous marine and terrestrial sedimentary rocks, and Late Permian felsic volcanic rocks. The basins include the Barnard Basin (Letch 1988), the Ashford Basin (Kimber 1977), the Surat Basin (Hawke & Cransie 1984) and the Warialda Trough (Bourke 1980). The Late Permian volcanic units include the Wardsworth Volcanic Group (Barnes et al. 1991).

Uplift associated with the onset of spreading of the Coral Sea in the Paleocene (~ 65 Ma) activated erosion and deposition of high-level gravels, which were overlain by lavas and pyroclastic material from central volcanoes (e.g. Nandewar Volcanic Complex; Stolz 1985) and lava-field provinces (e.g. Central Province, McDougall & Wilkinson 1967) from the Eocene to Miocene.

**REFERENCES**

- Major town
- Road
- River
- Tertiary volcanic rocks
- Nandewar Bioregion

ERROR Province or volcano name

**QUARTERLY NOTES**

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The information contained in this publication is based on knowledge and understanding at the time of writing (June 2006). However, because of advances in knowledge, users are reminded of the need to ensure that information upon which they rely is up to date and to check currency of the information with the appropriate officer of NSW Department of Primary Industries or the user’s independent adviser.
FIELD OBSERVATIONS FOR THE CAINozoIC IGneous ROcks

The Cainozoic igneous rocks in the study area have previously been referred to as the Central Province (McCDougall & Wilkinson 1967). This province occurs as a northeast to southwest belt that extends from Armidale in the northeast to North Star (Wellman & McC Dougall 1974, Figure 1). Geochem ical, petrographic, and geochemical work prior to the present study led to a simple division of the Central Province igneous rocks into an Older and Newer series (Sutherland 1985; Pecover 1992), or West Central Province and East Central Province (Coenraads 1988). A 32 Ma to 40 Ma undersaturated (alkali) basaltic suite in the east is  associated with sapphires, and a 19 Ma to 23 Ma saturated (alcaline) basaltic suite to the west is spatially associated with diamonds (Coenraads 1990). In the study area, the two suites overlap in the Inverell district. Newly acquired geophysical, geochemical, isotopic and geochemical data, as well as geological mapping recently completed for the Nandewar Bioregion assessment (Dawson et al. 2004) over the Central Province, has enabled the delineation of three volcanic suites of Cainozoic igneous rocks. These new stratigraphic units (Maybole Volcanic Suite, Delungra Volcanic Suite and Langari Hill Volcanic Suite) are described in the Appendix. This delineation had previously been accomplished only at localised scales (Duggan 1972; Brown & Pecover 1988a, b). Petrographic and stratigraphic descriptions of the three volcanic suites and constituent units can be found in the Appendix. For the remainder of this chapter, the stratigraphic name Central Province (McDougall & Wilkinson 1967; Wellman & McC Dougall 1974, Coenraads 1991; Sutherland et al. 1993). Regionally, the Maybole Volcanics show an elevated radial drainage away from ‘Maybole’ which can be observed on a digital elevation model (DEM) or composite radioelement images (see Geophysics section).

DELUNGRA VOLCANIC SUITE

Previously known as the West Central Province (Coenraads 1988) or Newer series (Sutherland & Pecover 1997), the Delungra Volcanic Suite is a geochemically diverse suite that includes volcanic and volcaniclastic rocks in the Delungra, North Star, Bingara and Inverell regions. In this study, the Delungra Volcanic Suite crops out from Inverell in the east, to the west of Bingara and Warralda (Figure 2). Composition of the basaltic rocks varies from undersaturated alkaline rocks to quartz and olivine tholeiites. The Delungra Volcanic Suite is divided into four units based on petrography, geochemistry, geophysical signature and location. The Delungra Volcanic Suite is Late Eocene to Early Oligocene age of between 40 Ma and 32 Ma (McDougall & Wilkinson 1967; Wellman & McC Dougall 1974; Coenraads 1991; Sutherland et al. 1993). Regionally, the Maybole Volcanics show an elevated radial drainage away from ‘Maybole’ which can be observed on a digital elevation model (DEM) or composite radioelement images (see Geophysics section).

MAYBOLE VOLCANIC SUITE

The Maybole Volcanic Suite consists of rocks that were erupted from a central ‘type’ volcano that is located on the centre of ‘Maybole’, 15 kilometres west of Glencoe. This suite was previously known informally as the East Central Province (Coenraads 1988) or Older series (Sutherland 1985; Pecover 1992). In the study area, outcrops of the Maybole Volcanic Suite extend from south of the Macintyre River near Dorrigo (GR 334800mE 6684900mN, MGA94 Zone 56) north to the Severn River (Figure 2). Only one constituent formation, the Maybole Volcanics, has been recognised in this study. This unit is dominated by undersaturated alkali olivine and transitional basalts, with volumetrically minor lithic volcaniclastic and epiclastic units. Rare plugs, dykes and sills have also been recognised. Minor non-volcanogenic interflow sedimentary units occur within the unit. The small phonolite plug at Sugarloaf Mountain is included in the Maybole Volcanic Suite (but is not discussed here). Shallow diamond drillholes and detailed mapping were undertaken by the then New South Wales Department of Mineral Resources as part of a sapphire project (Brown & Pecover 1988a, b) at two localities; ‘Braemar’ and Kings-Plains (see later discussion with Figure 5). The mapping and drilling revealed sapphire-bearing altered basalt and volcaniclastic and epiclastic units with narrow basaltic flows and non-volcanogenic sedimentary horizons. A stratigraphic sequence has not been established for the Maybole Volcanics in this study due to poor outcrop and paucity of drilling data. Previously reported K–Ar geochronology yields a Middle Eocene to Early Oligocene age of between 40 Ma and 32 Ma (McDougall & Wilkinson 1967; Wellman & McC Dougall 1974; Coenraads 1991; Sutherland et al. 1993). Regionally, the Maybole Volcanics show an elevated radial drainage away from ‘Maybole’ which can be observed on a digital elevation model (DEM) or composite radioelement images (see Geophysics section).

DELUNGRA VOLCANIC SUITE

Previously known as the West Central Province (Coenraads 1988) or Newer series (Sutherland & Pecover 1997), the Delungra Volcanic Suite is a geochemically diverse suite that includes volcanic and volcaniclastic rocks in the Delungra, North Star, Bingara and Inverell regions. In this study, the Delungra Volcanic Suite crops out from Inverell in the east, to the west of Bingara and Warralda (Figure 2). Composition of the basaltic rocks varies from undersaturated alkaline rocks to quartz and olivine tholeiites. The Delungra Volcanic Suite is divided into four units based on petrography, geochemistry, geophysical signature and location. The Delungra Volcanic Suite is Late Eocene to Early Oligocene age in age, with previously published K–Ar geochronology ages of between 24 Ma and 19 Ma (McDougall & Wilkinson 1967; Wellman & McC Dougall 1974). The following units are recognised in this study.

- Mount Russell Volcanics
  These rocks dominate the study area (Figure 2), with extensive areas of basaltic lava flows, volcaniclastic units and minor plugs that form the high plateaux between Inverell and Warralda. The Mount Russell Volcanics are characterised by quartz and olivine tholeiites. Outcrop is poor away from the plugs, with deep soil profiles developed. Residual basaltic deposits are quite common in the areas to the northeast and south of Inverell. In the Copeton Dam area, the Mount Russell Volcanics overlie diamond-bearing Cainozoic deep leads.

- Inverell Volcanics
  The Inverell Volcanics form restricted flat-topped hills to the west of Inverell (Figure 2) and conformably overlie the Mount Russell Volcanics. The Inverell Volcanics is a series of highly undersaturated alkali basaltic volcanic flows, each no more than five metres thick, interbedded with volcaniclastic horizons. Duggan (1972) was the first to recognise this unit based on petrography and geochemistry. However, the unit had not been formally named until this study.

- Derra Derra Volcanics
  Outcrops of the Derra Derra Volcanics (Figure 2) on the hills to the west of Bingara are interbedded with the Bingara Volcanics. The unit consists of tholeiitic basalt and associated volcaniclastic units, as well as diamond-bearing, non-volcanogenic sediments. The diamond-bearing wash at the Historic Monte Christo diamond mine occurs at the base of the Derra Derra Volcanics. Burton (1988) described and mapped this unit based on petrography and geochemistry, but the unit was not formally named until this study. One previous K–Ar geochronological age by Cooper (1988) yielded an age of 27.3 Ma.

- Bingara Volcanics
  The Bingara Volcanics (Figure 2) outcrops to the west of Bingara and is interbedded with the Derra Derra Volcanics. Rocks of the Bingara Volcanics are predominantly basaltic and occur both as lava flows up to 20 m thick and as volcaniclastic units. Outcrops are limited to a small area near the Monte Christo mine, and toward the top of the plateau to the west of Bingara.

LANGARI HILL VOLCANIC SUITE

In the study area, the Langari Hill Volcanic Suite outcrops as two east–west elongate belts to the east of Inverell, to both the north and south of the Gwydir Highway (Figure 2). Only one constituent formation, the Langari Hill Volcanics, has been recognised in this study. Lithologies of the Langari Hill Volcanics are basaltic flows of tholeiitic composition, with minor volcaniclastic rocks. Brown (2006) first recognised the Langari Hill Volcanics as a separate unit, based on geophysical data. However, this unit had not been formally named until this study.

GEOPHYSICS

Extensive aerial geophysical surveys were undertaken by the GSNW from 1997 to 2006 as part of the Discovery 2000 and subsequent Exploration NSW state government mineral exploration initiatives. A survey, in part over the study area (Inverell Survey), was flown in 2002 utilising 250-kilometre spaced east–west flight lines at an elevation of 60 m. Magnetic and radioelement data were acquired and a digital elevation model (DEM) produced utilising GPS-gathered elevation data. Full details of the survey, and a comprehensive preliminary interpretation were provided by Brown (2006). A first vertical derivative of total magnetic intensity (TMI) image and composite radioelement RGB image of the study area are presented as Figures 3 and 4, respectively.
Figure 3: Grayscale image of the Vertical Derivative of Total Magnetic Intensity for the study area.

Figure 4: Stretched composite radioelement image of the study area (RGB: potassium = red; thorium = green; and uranium = blue).
very low levels of thorium and uranium). Figure 4 highlights radioelement signature similarities between the Mount Russell Volcanics and Derra Derra Volcanics, showing dark, low total count emissions.

The Bingara Volcanics exhibit moderate to high radioelement emissions (Figure 4) with thorium and uranium being the dominant radioelements. Composite radioelement RGB images of the Bingara Volcanics are bright green to bright green–blue (indicating low levels of potassium and high levels of thorium and uranium). Moderate to high magnetic susceptibilities of hand specimens for the Bingara Volcanics ($272 \times 10^{-5}$ to $2039 \times 10^{-5}$ SI) are similar to the Derra Derra Volcanics. A zone of reversely polarised magnetic anomalies of moderate to high amplitude corresponds with the Bingara Volcanics and Derra Derra Volcanics. A bimodal contrast between the high-magnetic-susceptibility units Derra Derra Volcanics and Bingara Volcanics with minor, diamond-bearing, low-magnetic-susceptibility sediments gives a slightly mottled magnetic anomaly pattern.

The Inverell Volcanics exhibit a moderate to high radioelement response, with thorium and uranium being the dominant radioelements. Composite radioelement RGB images of the Inverell Volcanics are bright green to bright green–blue (indicating low levels of potassium and high levels of thorium and uranium). A northeast-trending linear belt of Inverell Volcanics was recognised from radioelement images by Dawson et al. (2004) and Brown (2006). That belt of Inverell Volcanics is manifest as a number of flat-topped hills (with bright blue–green colour on a composite radioelement RGB image (Figure 6a)). On these hills, fresh basalt outcrop is abundant, with little weathering, no regolith development or transported material. The radioelement response is therefore interpreted as a primary bedrock response. Flanking these plateaus of elevated radioelement response are areas exhibiting lower levels of uranium, thorium and potassium response, producing a duller blue–green colour on composite radioelement RGB images. This response is most likely the result of prolonged weathering causing mobility of uranium and thorium, with less significant influences — such as anthropogenic effects, vegetation, re-distribution and unroofing of Tertiary deep leads or a primary rock response — reducing the total radioelement count (Brown 2006).

The Inverell Volcanics produce a moderate to high, heterogeneous, magnetic response (Figure 3). Magnetic susceptibility measurements of hand specimens reflect this heterogeneity, ranging from $85 \times 10^{-5}$ to $3607 \times 10^{-5}$ SI. On the 1VD image (Figures 3, 6b) the Inverell Volcanics cannot be differentiated from the Mount Russell Volcanics.

The Langari Hill Volcanics emit little gamma radiation, resulting in dark areas on composite radioelement RGB images (Figures 4, 5). A clear contrast in gamma radiation can be observed between the Maybole Volcanics (low to moderate potassium, very low thorium and uranium) and the Langari Hill Volcanics (very low potassium, thorium and uranium) in the ‘Braemar’ area east of Inverell (Figure 5). A hand specimen of the Langari Hill Volcanics has a moderate to low magnetic susceptibility (average $116 \times 10^{-5}$ SI). Low-amplitude magnetic anomalies which contrast with the highly mottled (high frequency and moderate to high amplitude) magnetic anomaly pattern of the Maybole Volcanics. The 1VD magnetic image thus indicates significant contrast between the Maybole Volcanics and the Langari Hill Volcanics.
PETROGRAPHY

MAYBOLE VOLCANIC SUITE

Typically fine- to medium-grained olivine-phyric alkaline rocks with subophitic (locally intersertal) textures dominate the Maybole Volcanic Suite (Photograph 1). Early-formed olivine phenocrysts (10–15 mode %) rarely attain up to 4 mm in length, but often form glomerocrysts of several small euhedral olivine crystals, with marginal green chlorite or red–brown ferric alteration. Subhedral to euhedral pink clinopyroxene (25%–30%) is present, with the euhedral phenocrysts up to 2 mm in diameter. Pyroxene may contain olivine inclusions and is typically strongly zoned with quite distinct pink-purple rims. The groundmass consists of subophitic intergrowths of pyroxene with (40%–50%) slender, elongate plagioclase laths of plagioclase (up to 3 mm in length) that may form radiating sheaves. Small euhedral olivine crystals are scattered throughout, and there is up to 3% ilmenite. Locally, interstices between feldspar laths wholly or partly consist of near-isotropic colourless analcime showing dark grey interference colours and complex twinning, giving rise to interstitial textures. Flow alignment of elongate olivine phenocrysts and groundmass plagioclase laths may or may not be present.

The crystallisation sequence for the Maybole Volcanic Suite is olivine–clinopyroxene–plagioclase–ilmenite–analcime.

DELUNGRA VOLCANIC SUITE

Mount Russell Volcanics

Medium-grained hypocrystalline olivine- and plagiodiopside-phryic (tholeiitic) basaltic of the Mount Russell Volcanics show predominantly interstitial, locally subophitic, textures. Early-formed subrounded, rarely embayed euhedral olivine (5% to 10%) forms phenocrysts up to 2 mm in diameter.

The crystallisation sequence for the Mount Russell Volcanics is: olivine–plagioclase–clinopyroxene–magnetite.

Derra Derra Volcanics

The tholeiitic basaltic rocks of the Derra Derra Volcanics are: fine- to mainly medium-grained, predominantly optically hyalophytic intergrowths of colourless or brownish pink clinopyroxene and plagiodiopside feldspar, with typically very small scattered euhedral olivine microphenocrysts (sometimes forming glomerophyric dotty), and rare early-formed olivine phenocrysts up to 1.5 mm in width. Locally poikilitic domains form numerous short banded plagiodiopside crystals surrounded by optically continuous arched plagioclase clinopyroxene (maximum dimension 2 mm). Plagioclase laths show parallel alignment, particularly evident within individual arched clinopyroxene oikocrysts. Hypocrystalline varieties include domains which show plagiodiopside laths and subophitic pyroxene embedded in ‘poools’ of olivine to deep tan–brown glass, giving rise to a distinctive bluish appearance in thin section (Photograph 3). Vesicles up to 3 mm are present.

The crystallisation sequence for the Derra Derra Volcanics is: olivine–plagioclase–clinopyroxene–magnetite.

Inverell Volcanics

Rocks of the Inverell Volcanics are fine-grained basanites containing sparse phenocrysts of olivine (typically 1 mm) and rare squash to hexagonal mosaic-like aggregates of alkali feldspar/zoisite (<1 mm), as well as abundant microphenocrysts of olivine (<1 mm; 5–10 mode %; Photograph 3). The groundmass consists of arched olivine (up to 5% of the groundmass), abundant pale greenish brown twinned clinopyroxene prisms (40% of the groundmass), occurring sometimes as sheaf-like skeletal prisms. Further, the groundmass contains scarce laths of multiply twinned plagioclase, widely distributed iron oxides, and abundant poikilitic patches of turbid, unzoned, near-isotopic nepheline (up to 1.5 mm) constituting up to 50% of the groundmass. These rocks show an affinity with schlieren of malignitic (nepheline-bearing alkali syenite) composition from late stages of crystallisation reported for these rocks and described by Wilkinson (1977). The nepheline is rich in clinopyroxene inclusions and is penetrated at the margins by slender clinopyroxene prisms (0.3 mm). Low-refractive-index, first-order birefringent cancrinite is sometimes associated with nepheline, and some nepheline is replaced by analcime with dark grey interference colours and complex twinning in more than one orientation. Olivine phenocrysts and microphenocrysts are zoned with distinct, frequently strongly embayed rims. The presence of nepheline and limited plagioclase distinguishes these rocks from alkali olivine basalt. Inverell Volcanics basanites contain inclusions showing complex reaction coronas, consistent with disaggregation of peridotite and rarer granulite xenoliths. They include: (i) rounded red–brown spinel with an opaque (iron–oxide) rim, typical of spinel from disaggregated peridotite; (ii) irregular inclusions of orthopyroxene from peridotite (0.5 mm) with rims heavily loaded plagioclase ‘oikocrysts’ suggest magma mixing (see Geochemistry discussion).

The crystallisation sequence for the Bingara Volcanics is: olivine–clinopyroxene–plagioclase–ilmenite–analcime.

Bingara Volcanics

Fine-grained hawaiites characterised by distinctive poikilophytic plagioclase (10%) containing olivine and clinopyroxene inclusions, and heavily embayed zoned olivine phenocrysts (10%), typically 0.5 mm in diameter (Photograph 4). These occur in an intersteral groundmass of pink prismatic clinopyroxene (0.1 mm long) (40%), some forming radiating clusters; small euhedral olivine microphenocrysts (10%), scant plagioclase, hexagonal apatite; and iron oxide (5%) — embedded in turbid brown–pink, near-isotopic analcime (40%). In some rocks there are also highly irregular patches (mostly <1 mm) of colourless turbid analcite.

Of special interest are the large (4 mm long) twinned subhedral plagioclase ‘oikocrysts’ loaded with myriad elongate prismatic chadacrysts of pink to pale brown clinopyroxene and iron oxide, as well as a few small euhedral olivine chadacrysts. Margins of the plagioclase are subophitically heavily penetrated by numerous slender euhedral to subhedral prismatic groundmass clinopyroxene optically identical to those within the feldspar. Although a ‘phenocryst’ phase, plagioclase appears to be late crystallising. Rapid growth of clinopyroxene from relatively few nucleation sites is evident, contrasting with abundantly nucleated clinopyroxene (in an undercooled melt?). Strong embayment of zoned olivine phenocrysts, and pyroxene–loaded plagioclase ‘oikocrysts’ suggest magma mixing (see Geochemistry discussion).
The crystallisation sequence of the Langari Hill Volcanic Suite is: dolivne–plagiclace–clinopyroxene–magnetite. The Langari Hill Volcanic Suite includes fine-grained hypocrystalline (tholeiitic) basalt containing 5% olivine phenocrysts (maximum dimension 1 mm; Photograph 6).

The olivine phenocrysts are set in a predominantly intergranular, locally interstitial ‘groundmass’ of early-formed anhedral equant olivine microphenocrysts (5%), and plagioclase laths (82%) (mostly 0.5 mm in length) lacking any preferred orientation. Furthermore, the groundmass contains pale brown to greenish olivine phenocrysts (4%) and opaque grains, sometimes enclosed in cloudy olive–brown glass (2%). Some olivine phenocrysts are skeletal and are intergrown with, but preclude, plagioclase.


The crystallisation sequence of the Maybole Volcanic Suite is: olivine–plagioclasce–clinopyroxene–magnetite.

The Langari Hill Volcanic Suite is enriched in incompatible elements, and is marked by high Nb/Zr (5.5–64), low Y (8–36 ppm), high Rb (+10%), and high- and low-Fe tholeites (Figure 7a). The Maybole Volcanic Suite shows wide ranges in concentrations of SiO2 (44.8–48.8 wt%), Al2O3 (14.0–16.7 wt%), MgO (6.2–10.3 wt%), CaO (7.1–10.3 wt%), Na2O (2.7–3.8 wt%), K2O (0.9–2.2 wt%), P2O5 (0.2–3.1 wt%), TiO2 (28–79 ppm), Nb (28–79 ppm), and Zr (151–399 ppm) (Table 2). The Maybole Volcanic Suite shows twin sub-parallel chemical trends (black lines in Figure 7a) of increasing Al2O3, TiO2, and Zr with decreasing MgO and Ni levels, as well as high- and low-diffusion trends (black lines in Figure 7a) on the classical normative ne–di–ol–hy–qz diagram of Yoder and Tilley (1962). The Maybole Volcanic Suite is enriched in incompatible elements, with high abundances of LREE, P2O5, TiO2, Nb, and Zr, although K2O and Rb show significant depletion relative to the other incompatible elements (Figures 7a and 7b). TiO2/Zr ratios (65–94) are high, and K/Nb (130–400), Zr/Nb (6–30) and Ba/Nb (<7), as well as La/Yb (6–30) and Dy/Yb (1.5–2.3) ratios are low.

**Geochronology**

For this study, six samples were selected for K–Ar radiometric dating. These include two samples from the Maybole Volcanic Suite, three from the Delungra Volcanic Suite and one sample from the Langari Volcanic Suite. Study of thin sections cut for each of the samples assured that the samples were suitable (fresh) for K–Ar radiometric dating. Geochronology measurements were performed at the Australian National University, Canberra. Results are presented in Table 1.

### Table 1: Results of K–Ar radiometric analyses of six whole-rock samples from the Inverell to Bingara area

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Unit</th>
<th>MGAEm</th>
<th>MGAnm</th>
<th>K wt% (mean)</th>
<th>Rad40K (10^-15 mol/g)</th>
<th>%40Ar*</th>
<th>Mean age ± 1σ (Ma)</th>
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<tr>
<td>G03 557</td>
<td>Langari Hill Volcanics</td>
<td>346030</td>
<td>6705553</td>
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<td>55.27</td>
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<td>Inverell Volcanics</td>
<td>312801</td>
<td>6704700</td>
<td>1.5852</td>
<td>54.67</td>
<td>28.66</td>
<td>19.8 ± 0.2</td>
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<td>G03 598</td>
<td>Derra Derra Volcanics</td>
<td>257377</td>
<td>6689181</td>
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<td>6.336</td>
<td>11.06</td>
<td>22.6 ± 0.5</td>
</tr>
<tr>
<td>G03 593</td>
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<td>6690670</td>
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<td>55.27</td>
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</tr>
<tr>
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<td>52.46</td>
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<td>6709694</td>
<td>0.7753</td>
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<td>56.25</td>
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K = potassium

%40Ar* is percent radiogenic argon of isotopic mass 40

Decay constants are λp = 0.581 x 10^-10 y^-1 and λ40K = 4.962 10^-10 y^-1

Analyses performed by W.I. Dunlap, Australian National University, Canberra. Potassium analyses were conducted by flame photometry, using an IEL 433 instrument, and Ar was measured in a MS-10 mass spectrometer.
Table 2: Major and trace element analyses of representative rocks from volcanic suites in the Bingara to Inverell region

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Sample</th>
<th>FeO</th>
<th>FeO/Sm</th>
<th>Sm</th>
<th>Yb</th>
<th>Sc</th>
<th>Pr</th>
<th>U</th>
<th>O</th>
<th>O/O=O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maydog Volcanics</td>
<td>[Sample Details]</td>
<td>[Values]</td>
<td>[Values]</td>
<td>[Values]</td>
<td>[Values]</td>
<td>[Values]</td>
<td>[Values]</td>
<td>[Values]</td>
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<td>[Values]</td>
</tr>
<tr>
<td>Inverell Volcanics</td>
<td>[Sample Details]</td>
<td>[Values]</td>
<td>[Values]</td>
<td>[Values]</td>
<td>[Values]</td>
<td>[Values]</td>
<td>[Values]</td>
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<td>[Values]</td>
</tr>
</tbody>
</table>

| Maydog Volcanics | [Sample Details]        | [Values]  | [Values] | [Values] | [Values] | [Values] | [Values] | [Values] | [Values] | [Values] |
| Inverell Volcanics | [Sample Details]        | [Values]  | [Values] | [Values] | [Values] | [Values] | [Values] | [Values] | [Values] | [Values] |

**Note:** All analyses were performed at ALS laboratories in Brisbane. Major element oxide analysis — ICP (Inductively Coupled Plasma) technique; Ba, Nb, Sr, Zr, Sc — XRF (X-Ray Fluorescence spectroscopy) technique; Cr, Ni, Co, Hf, Th, Ce, Sm, Eu, Gd. D1 = Silicic; D2 = Basaltic; D3 = Dolerite; D4 = Diorite; N = normal; O = Oceanic.
DELUNGRA VOLCANIC SUITE

Mount Russell Volcanics

Basaltic volcanic rocks from the Mount Russell–Black Springs area are qz-tholeiites that possess high SiO$_2$ (51.9–54.4 wt%), Al$_2$O$_3$ (14.7–15.3 wt%), and low TiO$_2$ (1.4–1.6 wt%), MgO (6.8–7.8 wt%), Zr (93–129 ppm), La/ Nb, (5–6) and Dy/Yb, (1–2.5) (Table 2; Figure 8b). These comparative comments are relative to the Inverell and Bingara Volcanics (Figure 7a). The Mount Russell Volcanics also possess relative K and Rb depletions, similar to the strongly depleted Bingara and Inverell Volcanics (Figure 9a). Some of the tholeiites also have high K/Nb (>400) and La/Nb (~1), and low T/U (57) ratios, together with high Ba/Nb (12.9), K (up to 18 ppm) and Pb/Nb (up to 1.5). Rb levels (1.8–12 ppm) and K$_2$O contents (0.2–0.5 wt%) are low to very low.

Derra Derra Volcanics

These ol- and qz-tholeiites from near Bingara are chemically similar to the Mount Russell Volcanics. Overall they possess only slightly lower SiO$_2$ (50.0–51.7 wt%), TiO$_2$ (1.3–1.5 wt%), Zr (79–109 ppm), Zr/Nb (6.5–7.5), La/Yb, (4–5) and Dy/Yb, (1.4–1.7), similar MgO (7.2–8.1 wt%), and slightly higher Al$_2$O$_3$ (15.4–15.5 wt%) (Table 2; Figures 7b; 8a, b; and 9b). Compared to tholeiites from typical eastern Australian central-type intraplate volcanoes (e.g. the Miocene Ebor Shield to the southeast of the study area, Figure 1), lower TiO$_2$, Zr, La/Nb, K/Nb and D.I., and higher MgO indicate that the Derra Derra and Mount Russell Volcanics represent less-differentiated magmas.

Inverell Volcanics and Bingara Volcanics

These basanites and hawaiites include the most strongly depleted volcanic rocks analysed in this study, with rCr ranging from 6.5% to 13%, and with highest di contents (22–27%) (Figure 7a). They also have the highest CaO (10–11.4 wt%), P2O$_5$ (1.0–1.7 wt%), Zr (350–530 ppm) and Nb (110–180 ppm) contents, high Na$_2$O (5.4–4.2 wt%) and K$_2$O (0.7–1.9 wt%), and the lowest Al$_2$O$_3$ (<13.5 wt%) and SiO$_2$ (43.9–45.4 wt%) levels of the investigated volcanic suites (Table 2). TiO$_2$ contents decrease with increasing Al$_2$O$_3$ (Figure 7b). Importantly, they possess the highest Dy/Yb, (2.5–3.2) and La/Yb, (34–57) ratios of the analysed lavas (Figure 8b). Like the Maybole Volcanic Suite, these strongly alkaline rocks show significant Rb and K depletions relative to other incompatible elements (Figure 9b), as well as high T/U (71–104) ratios, and the lowest K/Nb (<120), Zr/Nb (<3.5), and Y/Nb (<0.25) ratios.

LANGARI HILL VOLCANIC SUITE

The Langari Hill Volcanic Suite includes hawaiite and ol-tholeiite that possess the highest Al$_2$O$_3$ (>16 wt%), and Na$_2$O (3.9–4.4 wt%), and lowest CaO (6.9–8.3 wt%), and TiO$_2$ (c1.1 wt%) contents of the analysed rocks (Table 2; Figure 7b). Furthermore, this unit has overall low MgO (5.6–8.0 wt%), and low levels of incompatible elements (e.g. LREE, Zr and Nb) (Figures 8a and 9a). K$_2$O contents (0.4–0.7 wt%) are higher, and SiO$_2$ (3.4–4.2 wt%) and K$_2$O (0.7–1.9 wt%) contents decrease with increasing Al$_2$O$_3$ (Figure 7b). Importantly, they possess the highest Dy/Yb, (2.5–3.2) and La/Yb, (34–57) ratios of the analysed lavas (Figure 8b). Like the Maybole Volcanic Suite, these strongly alkaline rocks show significant Rb and K depletions relative to other incompatible elements (Figure 9b), as well as high T/U (71–104) ratios, and the lowest K/Nb (<120), Zr/Nb (<3.5), and Y/Nb (<0.25) ratios.
**Sr AND Nd ISOTOPES**

Markedly contrasting Sr and Nd isotopic signatures are observed for temporally distinct volcanic rocks from the Maybole, Delungra, and Langari Hill Volcanic Suites (Table 3).

Transitional basalt (G03 530) and hawaiite (G03 558) samples from the Maybole Volcanic Suite show very high initial Nd ratio ($^{144}Nd/^{148}Nd = 0.51299$) and low initial Sr ratio ($^{87}Sr/^{86}Sr = 0.70404$) (Figure 3, Figure 10). These are among the most strongly depleted compositions in the Nd–Sr isotopic array for New South Wales Tertiary lavas, similar to values for volcanic rocks from Grabben Gullen, Doughboy Province, and the highest initial Nd lavas from the Southern Highlands (Zhang et al. 1999) (Figure 10).

Strongly undersaturated Bingara Volcanics (G03 593) and Inverell Volcanics (G03 560) samples possess Sr–Nd isotopic values (Table 3) ($^{143}Nd/^{148}Nd = 0.51278$, $^{87}Sr/^{86}Sr = 0.70404$ and $^{143}Nd/^{148}Nd = 0.51299$, $^{87}Sr/^{86}Sr = 0.70404$) akin to those which characterise the Australian mantle plume ($^{143}Nd/^{148}Nd = 0.51282$, $^{87}Sr/^{86}Sr = 0.70404$) (Sun et al. 1989). The Mount Russell Volcanics sample (G03 548) shows only slightly lower initial Nd ($^{143}Nd/^{148}Nd = 0.51273$, somewhat higher initial Sr ($^{87}Sr/^{86}Sr = 0.70478$) (Figure 10), indicating a similar (plume-related) source, albeit with additional (crustal) source components (see Discussion).

The Langari Hill Volcanic Suite sample (G03 557) has a significantly lower radiogenic Nd isotope value ($^{144}Nd/^{148}Nd = 0.51259$, Table 3) than the other samples and lies toward the low initial Nd end of the linear Nd–Sr mantle array for New South Wales basalts (Zhang et al. 1999) (Figure 10).

Figure 7a) of the studied rocks. They do not share the significant Rb and K depletions of the other volcanic rocks in the Inverell region (Figure 9c). Ti/V ratios (~30) are low, and K/Nb ratios are high (300–800). Despite these features, some samples (e.g. G03 557) also have low La/Hb (0.8), Pb (1–2 ppm), Rb (~8 ppm) and Rb/Sr (~0.04), and lack normative qz.

![Graphs for MORB-normalised incompatible element ‘spidergrams’ for Bingara to Inverell region basalts of the (a) Maybole Volcanic Suite, (b) Delungra Volcanic Suite, and (c) Langari Hill Volcanic Suite. Normalisation values are after Sun and McDonough (1989).](image)

**Figure 9:** MORB-normalised incompatible element ‘spidergrams’ for Bingara to Inverell region basalts of the (a) Maybole Volcanic Suite, (b) Delungra Volcanic Suite, and (c) Langari Hill Volcanic Suite. Normalisation values are after Sun and McDonough (1989).

**Table 3:** Sr and Nd isotope data for basaltic volcanic rocks of the Bingara to Inverell region

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample no.</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>$^{87}Sr/^{86}Sr$</th>
<th>Sm (ppm)</th>
<th>Nd (ppm)</th>
<th>$^{143}Nd/^{144}Nd$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LANGARI HILL VOLCANIC SUITE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hawaiite</td>
<td>G03 557</td>
<td>8.3</td>
<td>205</td>
<td>0.7042±11</td>
<td>2.4</td>
<td>8.2</td>
<td>0.512595±9</td>
</tr>
<tr>
<td><strong>DELUNGRA VOLCANIC SUITE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>qz-tholeiite, Mount Russell Volcanics</td>
<td>G03 548</td>
<td>3.2</td>
<td>245</td>
<td>0.7047±11</td>
<td>3.7</td>
<td>12.0</td>
<td>0.512732±9</td>
</tr>
<tr>
<td>basanite, Inverell Volcanics</td>
<td>G03 560</td>
<td>52.9</td>
<td>2000</td>
<td>0.7040±11</td>
<td>16.8</td>
<td>98.9</td>
<td>0.512801±16</td>
</tr>
<tr>
<td>hawaiite, Bingara Volcanics</td>
<td>G03 593</td>
<td>26.1</td>
<td>1340</td>
<td>0.7042±11</td>
<td>12.6</td>
<td>70.1</td>
<td>0.512800±8</td>
</tr>
<tr>
<td><strong>MAYBOLE VOLCANIC SUITE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>transitional basalt</td>
<td>G03 550</td>
<td>11.2</td>
<td>511</td>
<td>0.7032±11</td>
<td>3.8</td>
<td>14.7</td>
<td>0.512990±5</td>
</tr>
<tr>
<td>hawaiite</td>
<td>G03 558</td>
<td>10.2</td>
<td>969</td>
<td>0.7029±10</td>
<td>6.3</td>
<td>28.9</td>
<td>0.512993±6</td>
</tr>
</tbody>
</table>

![Graph: Plot of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ for basaltic rocks of the Bingara to Inverell region. Fields are also shown for other eastern Australian Tertiary basalt provinces (DP – Dobytho Province; Ebor ol- and qz-tholeiites; W – Warrumbungle Mountains; S Hlds – Southern Highlands; WH – Weebar Hill; C – Canobolas; GG – Grabben Gullen; M – Monaro; K – Kandos; Barr – Barrington; OB – Oberon; New B – Newer Basalts; N Qld – north Queensland and 8 Mt – Blue Mountain). DFM – depleted (MORB-source) asthenospheric mantle; EM1 – enriched mantle reservoir 1, SCLM – sub-continental lithospheric mantle, AFC – assimilation fractional crystallisation. The Australian plume has given rise to the Cainozoic basaltic plutonism (Sun et al. 1989). Data sources: Stolz (1985); Nelson et al. (1986); Ewart et al. (1988); Schon (1999); Sun et al. (1989); O’Reilly and Zhang (1995); Zhang and O’Reilly (1997); Ghorbani (1999); Zhang et al. (2001); Sivell et al. (2004); and Sivell (unpublished data).](image)

![Figure 10: Plot of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ for basaltic rocks of the Bingara to Inverell region. Fields are also shown for other eastern Australian Tertiary basalt provinces (DP – Dobytho Province; Ebor ol- and qz-tholeiites; W – Warrumbungle Mountains; S Hlds – Southern Highlands; WH – Weebar Hill; C – Canobolas; GG – Grabben Gullen; M – Monaro; K – Kandos; Barr – Barrington; OB – Oberon; New B – Newer Basalts; N Qld – north Queensland and 8 Mt – Blue Mountain). DFM – depleted (MORB-source) asthenospheric mantle; EM1 – enriched mantle reservoir 1, SCLM – sub-continental lithospheric mantle, AFC – assimilation fractional crystallisation. The Australian plume has given rise to the Cainozoic basaltic plutonism (Sun et al. 1989). Data sources: Stolz (1985); Nelson et al. (1986); Ewart et al. (1988); Schon (1999); Sun et al. (1989); O’Reilly and Zhang (1995); Zhang and O’Reilly (1997); Ghorbani (1999); Zhang et al. (2001); Sivell et al. (2004); and Sivell (unpublished data).](image)
Discussions

MayboLe Volcanic Suite

Overall enrichment of incompatible elements (e.g. P2O5, TiO2, Nb, Zr, and REE) in Maybole volcanic rocks, and with relative depletions in K2O and Rb levels, low K/Nb, Zr/Nb, and Ba/Nb ratios, and high Ti/V ratios, are features considered to be inherited from their mantle source rocks (O’Reilly & Zhang 1995). Low La/Yb and Dy/Yb ratios suggest generation of these lavas mainly by low-degree melt of spinel-bearing mantle (Thirlwall et al. 1994; Beccaluva et al. 1998; Sutherland et al. 2003). Sub-parallel chemical trends (Figure 7b), as well as high- and low-diff trends for these rocks on the normal ne-di–ol–hy–qz plot of Yoder and Tilley (1962) (Figure 7a), most likely reflect fractional crystallisation of parental magmas derived from a single asthenospheric mantle plume. The trend of decreasing TiO2 with increasing Al2O3 reflects progressive melting of mantle in the presence of garnet as a key Al-bearing residual phase. Plume-like Sr–Nd isotopic values for undersaturated Bingara and Inverell Volcanics, akin to those which characterise the Australian plume (Sun et al. 1989), are compatible with geochemical results which indicate melting of fertile garnet peridotite, most likely the hot head of an ascending plume.

Inverell Volcanics and Bingara Volcanics

Highest di values (22–27%) in strongly undersaturated Inverell Volcanics and Bingara Volcanics (i.e. up to 13%) reflect a fertile clinopyroxene-bearing mantle source. Very high Dy/Yb and La/Yb ratios indicate significant components derived from low-degree melts of garnet-bearing mantle (Thirlwall et al. 1994). The trend of decreasing TiO2 with increasing Al2O3 reflects progressive melting of mantle in the presence of garnet as a key Al-bearing residual phase. Plume-like Sr–Nd isotopic values for undersaturated Bingara and Inverell Volcanics, akin to those which characterise the Australian plume (Sun et al. 1989), are compatible with geochemical results which indicate melting of fertile garnet peridotite, most likely the hot head of an ascending plume.

Langari Hill Volcanic Suite

Low La/Yb and Dy/Yb and high Zr/Nb and Yb/Nb ratios, together with the low normative di (di75%) in the Langari Hill Volcanic Suite, are consistent with moderate to high degrees of melting of spinel lherzolite (Thirlwall et al. 1994). Ti/V ratios are low, and K/Nb ratios are high, but low La/Nb, Pb, Rb, and Ba/Sr, and the absence of normative qz, suggest that these characteristics are inherited from lithospheric mantle source rocks (rich in enriched mantle reservoir E-type) material rather than due to extensive crustal interaction.

Implications for Sapphire Exploration

Sapphires are associated with intraplate alkaline basalts and their alluvial deposits along the western Pacific margin in Australia (Anake in Queensland and Barrington Tops and New England in New South Wales, South East Asia (Laos, Vietnam, Thailand, Cambodia), eastern China and eastern Russia. They are also found in Africa and Madagascar (e.g. Hollis & Sutherland 1985; Guo et al. 1992; Oakes et al. 1996; Sutherland 1996, 1999; Sutherland et al. 1996, 1999; Sutherland & McEvilly 2004). In the study area, alluvial sapphire-bearing deposits are intimately associated with the Maybole Volcanic Suite and help delineate the radial drainage pattern of the Maybole Volcanic Suite. Geochemistry and isotopic analysis performed in this study indicate a mantle source where physical conditions were conducive to sourcing and transporting sapphire xenocrysts. Volcanism commenced as multiple shallow explosive eruptions from flat-floored craters initially producing volcaniclastic rocks, which progressed to lava-dominated volcanism. These volcaniclastic rocks were recognised as the host rocks for sapphires after a comparison was made between New England deposits and those in China (Lishmund & Oakes 1985). Following that recognition, detailed mapping was completed as part of the sapphire project (Brown & Pecover 1988a, b; Pecover & Coenraads 1989).

The Delungra Volcanic Suite consists of strongly undersaturated alpine rocks and of quartz and olivine tholeiites. The geochemistry and isotopic signatures of the four members indicate a different source to the Maybole Volcanic Suite. Few sapphire occurrences are spatially associated with the Delungra Volcanic Suite, and along with predominantly tholeiitic geochemistry and plume source, a genetic relationship between these basalts and sapphires is doubtful. However, this Suite has the potential to form deep leads overlying sapphire-bearing volcaniclastic units in the lowest portion of the Maybole Volcanic Suite at Braemar near Elmore (Coenraads 1990). Olivine tholeiites of the Langari Hill Volcanic Suite crop out on the plains of the Maybole Volcanic Suite at Braemar near Elsmore (Coenraads 1990).

Sapphire occurrences in the Delungra Volcanic Suite were historically associated, along with a lithosphere-contaminated plume source, with the Maybole Volcanic Suite. However, these basalts may carry major deep-lead reworked sapphire-bearing volcaniclastic horizons and alluvial sapphire deposits of the Maybole Volcanic Suite. This study and the Nandewar Boreage assessment (McEvilly et al. 2004; Dawson et al. 2004) highlight the application of geophysical imagery to sapphire exploration. Radiometric imagery has assisted accurate mapping and discrimination of the Maybole Volcanic Suite, Mount Russell Volcanics and Langari Volcanic Suite. Furthermore, radiometric imagery has also been used to differentiate lava flows, volcaniclastic horizons and their weathered products within the Maybole Volcanic Suite. Radiometric imagery confirms the close spatial relationship between alluvial sapphire-bearing deposits with the Maybole Volcanic Suites and the drainage channels from the Maybole Volcanic Suite. Paleogeodrainage indicated by Coenraads (1991) as an important alluvial sapphire target has also been clearly distinguished using radiometric imagery (McEvilly et al. 2004).

Volcaniclastic and epilastic units at the base of the Maybole Volcanics are distinguished in radiometric imagery by a dark green colour on composite radiolocation RGB images (low thorium and very low uranium and potassium). These rocks host sapphire deposits in the study area, notably at the Braemar deposit (Pecover & Coenraads 1989). These volcaniclastic units are thin, poorly exposed and are commonly altered to iron-rich clays. In places, the volcaniclastic rocks have been deposited into and immediately reworked by streams and lakes to form concentrated bands of heavy minerals, including sapphires. Erosion and weathering of the primary and reworked volcaniclastic source rocks have formed Canzoan alluvial deposits. Subsequent lavas have flowed down river channels, commonly diverting stream systems, inventing topography and covering reworked sapphire-bearing volcaniclastic rocks, forming deltaic inlets in palaeochannels (Coenraads 1991, McEvilly et al. 2004). The volcaniclastic (volcano-fluvial) and fluvial geological settings have produced the highest grades of sapphire, with examples at ‘Braemar’ and Kings Plains (Brown & Pecover 1988a, b; Pecover & Coenraads 1989, 1994).

Conclusions

High-resolution airborne geophysical data have been utilised effectively to delineate three petrographically, chemically, and isotopically different Canzoan volcanic suites in the Inverell to Bingara area of northeastern New South Wales. Volcanic suites include the previously recognised, but now formally defined, Eocene–Oligocene Maybole Volcanic Suite of alkali affinity and the Early Miocene Delungra Volcanic Suite of tholeiitic affinity to the Maybole Volcanic Suite. This study has also defined a third association, the Middle Miocene Langari Hill Volcanic Suite of tholeiitic composition.

The Maybole Volcanic Suite is the product of a central shield-type volcano producing a radial distribution of volcanic output. This radial distribution is clearly delineated using both radiometric and geophysical imagery (Brown 2006). The Maybole Volcanic Suite produces a comparatively Kr-rich radiolocation response (in airborne geophysical data) compared to the Delungra and Langari Hill Volcanic Suites, reflecting its alkali composition. This Suite is also distinguished by an elevated magnetic response. High initial Ns and low initial Sr ratios of all the volcanics involved in the study are conducive to sourcing and transporting sapphire xenocrysts.

The Delungra Volcanic Suite is a sapphire-bearing association, which has produced basaltic outcrop over an extensive area from Inverell to Bingara, extending north of the study area. Tholeiitic basaltic flows of the Mount Russell and Derra Derra Volcanics dominate this association, with minor highly undersaturated lava flows of the Inverell Volcanics and Bingara Volcanics. Tholeiitic rocks carry the greatest potential to form deep leads overlying sapphire-bearing volcaniclastic rocks (Pecover & Coenraads 1989).
abundances. In contrast, the highly undersaturated flows are characterised by elevated K, Th and U, producing a brighter response, with particularly elevated U and Th. Plume-like Sr–Nd isotopic values for the Late Oligocene–Early Miocene (~24–19 Ma) Inverell and Bingara Volcanics (mainly basaltic), along with very high Dy/Yb, La/Yb, and Nd/Nd, are consistent with low-degree melting of garnet–herzolite, most likely in an ascending mantle plume. Corresponding low Sr–Nd isotopic characteristics of the Mount Russell and Derra Derra Volcanics with the highly undersaturated Bingara and Inverell rocks, as well as features characteristic (high Al₂O₃, Zr/ Nb, low TiO₂, Zr, La/Yb, and Dy/Yb) of the theoleites, indicate that they are large-volume melts, chiefly of spinel–herzolite, within the same plume-related source. Assimilation of crustal components may have contributed to higher initial Sr, Pb/Ho, Ba/Nb and normative zr, and lower Ti/Y and initial Nd of some of the theoleites.

The Langhi Hill Volcanic Suite is newly recognised and consists of one of the youngest volcanic rocks that have been recognised in the district, at 14 Ma. It is present as two elongate east–west trends of the deposits. Geophysical data can therefore provide significant improvements in exploration for the sapphire industry.

Author contributions

The authors would like to thank Phil Blevin, Morie Duggan and Larry Baron for reviewing the manuscript. Warwick Swell is acknowledged for providing the isotope data. Richard Facer is thanked for editing the manuscript. Thank you to

Simone Meakin and Genevieve Cox for their patient, meticulous editing.

And to Bob Brown for providing data and advice on the Maybole Volcanic Suite and the sapphire deposits of the Glen Innes–Inverell district. Dave Barnes is acknowledged for providing excellent photomicrographs. Thanks to Cheryl Horman for reproducing our figures to stunning effect.

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APPENDIX — descriptions of stratigraphic units

MAYBOLE VOLCANIC SUITE (NEW NAME)

Name

After the locality of Maybole, 15 km west of Glencoe (Glen Innes 110 000

topographic map sheet area)

Distribution

Outcrop of the Maybole Volcanic Suite extends from Bukkulla (Ashford

110 000 map sheet area) in the northwest, east to Torrington (Clive

110 000 map sheet area) and south to Guyra (Guyra 110 000 map sheet

area).

Constituent formations

The Maybole Volcanic Suite only contains one recognised constituent unit,

the Maybole Volcanics.

Lithology

Lithologies of the Maybole Volcanic Suite include mafic flows, tuffs,

intrusions and volcaniclastic rocks of alkaline affinity.

Age

Published K–Ar ages, including this study, range from 40 Ma to 32 Ma

(Middle Eocene to Early Oligocene).

Maybole Volcanics (new name)

Name

After the locality of Maybole, 15 km west of Glencoe (Glen Innes 110 000

topographic map sheet area)

Distribution

This unit forms part of the Central Province of McDougall and Wilkinson

(1967). Outcrop of the Maybole Volcanics extends from Bukkulla (Ashford

110 000 map sheet area) in the northwest, east to Torrington (Clive

110 000 map sheet area) and south to Guyra (Guyra 110 000 map sheet

area).

Type section/area

A type area is proposed in the ‘Western Distributor’ palaeodrainage of the

Kings Plains area (GR 350000mE 6714800mN, MGA94 Zone 56).

Thickness

The areas of thickest development of the Maybole Volcanics occur in the

Glen Innes area (Glen Innes 110 000 map sheet area). The thickness in this

area cannot be easily established. However, it is estimated to exceed 400 m. In the type

area the thickness of the Maybole Volcanics does not exceed 100 m.

Lithology

Alkaline olivine and transitional basalt flows and pluses, with red and white

sapphire-bearing tuffs and sapphire-bearing volcaniclastic rocks.

Deposition

Flows of alkali basalt with common development of tuffs, maars and

volcanic plugs. Valley-confined channels of reworked volcaniclastic

deposits and minor lacustrine development.

Relationships

The Maybole Volcanics unconformably overlies Cambrian to Middle

Triassic constituents of the southern New England Orogen (Flood &

Atchison 1988). Unconformably overlying the Maybole Volcanics are the

Late Oligocene to Early Miocene Delungra Volcanic Suite and the Middle

Miocene Langari Hill Volcanic Suite.

Age

Published K–Ar ages, including this study, range from 40 Ma to 32 Ma

(Middle Eocene to Early Oligocene).

<table>
<thead>
<tr>
<th>Name</th>
<th>After the locality of Maybole, 15 km west of Glencoe (Glen Innes 110 000 map sheet area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
<td>Outcrop of the Maybole Volcanic Suite extends from Bukkulla (Ashford 110 000 map sheet area) in the northwest, east to Torrington (Clive 110 000 map sheet area) and south to Guyra (Guyra 110 000 map sheet area).</td>
</tr>
<tr>
<td>Constituent formations</td>
<td>The Maybole Volcanic Suite only contains one recognised constituent unit, the Maybole Volcanics.</td>
</tr>
<tr>
<td>Lithology</td>
<td>Lithologies of the Maybole Volcanic Suite include mafic flows, tuffs, intrusions and volcaniclastic rocks of alkaline affinity.</td>
</tr>
<tr>
<td>Age</td>
<td>Published K–Ar ages, including this study, range from 40 Ma to 32 Ma (Middle Eocene to Early Oligocene).</td>
</tr>
</tbody>
</table>
DELUNGRA VOLCANIC SUITE (NEW NAME)

<table>
<thead>
<tr>
<th>Name</th>
<th>After the township of Delungra (Bingara 1:100 000 map sheet area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
<td>The Delungra Volcanic Suite is widespread and extends from Copeton Dam and Inverell in the south and east, respectively, west to Gravesend and north to North Star to have dimensions of approximately 150 km north–south by 100 km east–west.</td>
</tr>
<tr>
<td>Constituent formations</td>
<td>Four formations constitute the Delungra Volcanic Suite. These formations are the Mount Russell Volcanics, the Derra Derra Volcanics, the Inverell Volcanics and the Bingara Volcanics.</td>
</tr>
<tr>
<td>Lithology</td>
<td>Lithologies of the Delungra Volcanic Suite include mafic flows, intrusions and volcaniclastic rocks of tholeiitic and alkaline composition.</td>
</tr>
<tr>
<td>Age</td>
<td>Published K–Ar ages, including this study, extend from Late Oligocene (24 Ma) to Early Miocene (19 Ma).</td>
</tr>
</tbody>
</table>

**Mount Russell Volcanics (new name)**

<table>
<thead>
<tr>
<th>Name</th>
<th>After Mount Russell (hill), 5 km to the east of Delungra (GR 297200mE 6717000mN, MGA94 Zone 56, Bingara 1:100 000 map sheet area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
<td>This unit forms part of the Central Province of McDougall and Wilkinson (1967). Outcrops of the Mount Russell Volcanics are the most widespread (over 80%) of the surface distribution of the Delungra Volcanic Group. The outcrops extend from Copeton Dam and Inverell in the southeast, to North Star in the north, to Gravesend in the east.</td>
</tr>
<tr>
<td>Type section/area</td>
<td>The type area is at Mount Russell (GR 297200mE 6717000mN, MGA94 Zone 56) and immediate surrounds.</td>
</tr>
<tr>
<td>Thickness</td>
<td>The thickest development of the Mount Russell Volcanics occurs in the type area at Mount Russell. In this area the top of the Mount Russell Volcanics has been removed by Neogene and Quaternary erosion.</td>
</tr>
<tr>
<td>Lithology</td>
<td>Rocks of the Mount Russell Volcanics are tholeiitic basalt and dolerite (lavas and plugs) with minor volcaniclastic deposits, claystone and rare diamond-bearing gravels.</td>
</tr>
<tr>
<td>Deposition</td>
<td>Flows of tholeiitic basalt dominate, with lesser tuffaceous volcanic units and volcanic plugs. Valley-confined channels of reworked volcaniclastic deposits and minor lacustrine deposits have also been formed.</td>
</tr>
<tr>
<td>Relationships</td>
<td>The Mount Russell Volcanics unconformably overlie the Middle Triassic constituents of the Warialda Trough (Bourke 1983), Middle Jurassic to Early Cretaceous units of the Surat Basin (Hawke &amp; Cramsie 1984), and the Cambrian to Middle Triassic constituents of the southern New England Orogen (Flood &amp; Atchison 1988). Conformably overlying the Mount Russell Volcanics is the Inverell Volcanics.</td>
</tr>
<tr>
<td>Age</td>
<td>Published K–Ar ages, including this study, extend from Late Oligocene (24 Ma) to Early Miocene (19 Ma).</td>
</tr>
</tbody>
</table>

**Derra Derra Volcanics (new name)**

<table>
<thead>
<tr>
<th>Name</th>
<th>After the Parish of Derra Derra (Bingara and Gravesend 1:100 000 map sheet areas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
<td>This unit forms part of the Central Province of McDougall and Wilkinson (1967) and occurs 5 km to 20 km west and southwest of Bingara.</td>
</tr>
<tr>
<td>Type section/area</td>
<td>A north to south section from above the basal Palaeogene gravels at the Monte Christo mine (GR 257250mE 6690690mN, MGA94 Zone 56) to the top of a hill to the south-southeast (GR 258330mE 6688900mN, MGA94 Zone 56) is proposed. This is a vertical section up the hill to the south of the Monte Christo mine.</td>
</tr>
<tr>
<td>Thickness</td>
<td>In the type section, the Derra Derra Volcanics is estimated to have a cumulative thickness of 80 m. A maximum thickness is reached further to the west where the Derra Derra Volcanics attains a thickness of 150 m.</td>
</tr>
<tr>
<td>Lithology</td>
<td>The main rock types of the Derra Derra Volcanics are tholeiitic basalts with minor volcaniclastic rocks and diamond-bearing gravels.</td>
</tr>
<tr>
<td>Deposition</td>
<td>A series of mafic lava flows up to 20 m thick with interbedded diamond-bearing fluvial sediments in a lacustrine environment.</td>
</tr>
<tr>
<td>Relationships</td>
<td>The Derra Derra Volcanics unconformably overlies the Devonian to Carboniferous Parry Group of the Tamworth Belt, southern New England Orogen. It unconformably overlies Palaeogene gravels and interfingers with the Bingara Volcanics.</td>
</tr>
<tr>
<td>Age</td>
<td>One sample yielded a K–Ar age of 23 Ma (Early Miocene). Other unpublished ages are 28 Ma (Late Oligocene).</td>
</tr>
</tbody>
</table>

**Bingara Volcanics (new name)**

<table>
<thead>
<tr>
<th>Name</th>
<th>After the town of Bingara (Bingara 1:100 000 map sheet area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
<td>Part of the Central Province (McDougall &amp; Wilkinson 1967), this unit lies on top of a plateau, approximately 7 km to 12 km west and southwest of Bingara.</td>
</tr>
<tr>
<td>Type section/area</td>
<td>The type section area covers a small area near the Bingara–Narrabri road from GR 256890mE 6688760mN (MGA94 Zone 56) towards the east-southeast for approximately 2.4 km along a prominent east-striking ridgeline.</td>
</tr>
<tr>
<td>Thickness</td>
<td>The Bingara Volcanics is estimated to attain a thickness of 60 m.</td>
</tr>
<tr>
<td>Lithology</td>
<td>Alkali olivine basalt and basaltic lavas with minor volcaniclastic rocks and diamond-bearing gravels make up the Bingara Volcanics.</td>
</tr>
<tr>
<td>Deposition</td>
<td>A series of basanitic flows up to 20 m thick, interbedded with volcaniclastic deposits. Minor diamond-bearing gravels were deposited in erosional channels carved into the volcaniclastic deposits.</td>
</tr>
<tr>
<td>Relationships</td>
<td>The Bingara Volcanics unconformably overlies the Devonian to Carboniferous Parry Group of the Tamworth Belt, southern New England Orogen. It unconformably overlies Palaeogene gravels and interfingers with the Derra Derra Volcanics.</td>
</tr>
<tr>
<td>Age</td>
<td>One sample yielded a K–Ar age of 24 Ma (Late Oligocene to Early Miocene).</td>
</tr>
</tbody>
</table>
**Inverell Volcanics (new name)**

**Name**  
After the town of Inverell (Inverell 1:100 000 map sheet area)

**Distribution**  
This unit forms part of the Central Province of McDougall and Wilkinson (1967). Outcrops of the Inverell Volcanics are limited to two areas: on the top of a plateau in the Inverell lookout area (GR 314100mE 670400mN, MGA94 Zone 56) and on the top of a line of hills striking 030°, 15 km east of Delungra.

**Type section/area**  
The type area is nominated at the Inverell lookout (GR 314100mE 670400mN, MGA94 Zone 56).

**Thickness**  
In the type area the Inverell Volcanics is less than 20 m thick. A maximum thickness of approximately 80 m is attained to the north of the Copeton Dam Road at (GR 308900mE 6705200mN, MGA94 Zone 56).

**Lithology**  
Basanite and weathered volcaniclastic rocks.

**Deposition**  
A series of basanite volcanic flows each no more than 5 m thick, interbedded with volcaniclastic horizons.

**Relationships**  
The Inverell Volcanics conformably overlies the Mount Russell Volcanics.

**Age**  
One sample yielded a K-Ar age of 20 Ma (Early Miocene).

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**LANGARI HILL VOLCANIC SUITE (NEW NAME)**

**Name**  
The name was derived from Langari Hill near Elsmore (GR 336200 6706000, Inverell 1:100 000 map sheet area)

**Distribution**  
Outcrops of the Langari Hill Volcanic Suite occur in two parallel east–west elongate areas north and south of the Gwydir Highway to the east and northeast of Elsmore.

**Constituent formations**  
The Langari Hill Volcanic Suite consists of one unit, the Langari Hill Volcanics.

**Lithology**  
Tholeiitic basalt with minor volcaniclastic rocks

**Age**  
One sample yielded a K-Ar age of 14 Ma (Middle Miocene).

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**Langari Hill Volcanics (new name)**

**Name**  
After Langari Hill near Elsmore (Inverell 1:100 000 map sheet area)

**Distribution**  
This unit forms part of the Central Province of McDougall and Wilkinson (1967). Outcrops of the Langari Hill Volcanics occur in two parallel east–west elongate areas to the north and south of the Gwydir Highway, east and northeast of Elsmore. The northern outcrop is approximately 13 km long and 4 km wide. The southern outcrop is approximately 10 km long and up to 5 km wide at the western end.

**Type section/area**  
A type area is proposed to be from ‘Bellview’ station (GR 345800mE 6705000mN, MGA94 Zone 56) to Windy Ridge (GR 344100mE 6705200mN, MGA94 Zone 56) area, near the Gwydir Highway.

**Thickness**  
A maximum thickness of no more than 80 m is attained at GR 337800mE 6705400mN (MGA94 Zone 56) for the Langari Hill Volcanics. In the type area the thickness is approximately 40 m.

**Lithology**  
Tholeiitic basalt with minor volcaniclastic rocks

**Deposition**  
A series of basanite volcanic flows each no more than 5 m thick, interbedded with volcaniclastic horizons.

**Relationships**  
The Langari Hill Volcanics unconformably overlies parts of the southern New England Orogen, Maybole Volcanic Suite, and Palaeogene gravels.

**Age**  
One sample yielded a K-Ar age of 14 Ma (Middle Miocene).
The Nardoo and Mount Woowoolahra Inliers are 100 km north and 90 km north-northwest, respectively, of Broken Hill, in far western New South Wales (Figure 1). Both inliers contain rocks belonging to the Palaeoproterozoic (Statherian) (Plumb 1992) Willyama Supergroup and are surrounded by Adelaidean cover rocks. The Nardoo Inlier contains a significant amount of pegmatite and intermixed pegmatite and granitoid while Mundi Mundi type granite is common in the Mount Woowoolahra Inlier. Structural fabrics and metamorphic mineral assemblages considered to form part of the Paragon Group. However, it is not clear if they can be correlated with other occurrences of the Group. The recent finding that the Paragon Group in the Broken Hill Block is a time equivalent of stratigraphic units which host its distribution and characteristics has, hence, become important.

Keywords: Nardoo Inlier, Mount Woowoolahra Inlier, Paragon Group, Willyama Supergroup, Broken Hill, lead–zinc–silver mineralisation potential.

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