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# PALAEOMAGNETIC RECONNAISSANCE OF UPPER PALAEOZOIC VOLCANICS, NORTHEASTERN QUEENSLAND



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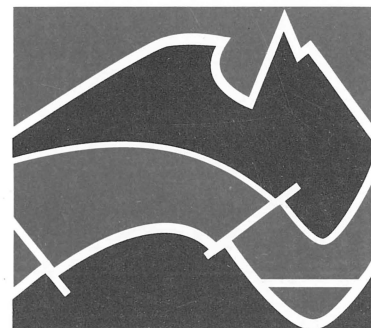
*by*

*C Klotwijk, J W Giddings, & P Percival*

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**A U S T R A L I A N  
G E O L O G I C A L S U R V E Y  
O R G A N I S A T I O N**

1993/36

**PALAEOMAGNETIC RECONNAISSANCE OF  
UPPER PALAEOZOIC VOLCANICS,  
NORTHEASTERN QUEENSLAND**

**Palaeomagnetism Project 224.03**

**Chris Klootwijk, John Giddings, and Peter Percival  
Australian Geological Survey Organisation**



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## **DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY**

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Secretary: Greg Taylor

## **AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION**

Executive Director: Harvey Jacka

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**ISSN: 1039-0073**

**ISBN: 0 642 19863 2**

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**KLOOTWIJK, C., GIDDINGS, J.W. & PERCIVAL, P., 1993.** Palaeomagnetic reconnaissance of upper Palaeozoic volcanics, northeastern Queensland. Australian Geological Survey Organisation, Record 1993/36.

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## ABSTRACT

Palaeomagnetic studies of upper Palaeozoic volcanic sequences in northeastern and eastern Queensland provide evidence for pervasive overprinting during the late Palaeozoic "Kiaman" Reverse Polarity Interval. Pole positions for this pervasive "Kiaman" overprint and for the few primary magnetizations determined support the "alternative" late Palaeozoic apparent polar wander path (APWP) for Australia proposed by Klootwijk and Giddings (1988a,b). Palaeomagnetic overprinting appears to be complete in the Cv sequence of the Bulgonunna Volcanics, yet SHRIMP zircon dates were interpreted in terms of closed U-Pb isotopic systems, unaffected by the processes that caused remagnetization. These contrasting interpretations warrant further determination of regional severity of magnetic overprinting and further geochronological proof for isotopic stability.

Detailed thermal and alternating field demagnetization studies on mainly ignimbritic sequences show the pervasive presence of a steep downward, southerly component of reverse "Kiaman" polarity. This reverse component is of primary origin in the Featherbed Volcanics (Late Carboniferous to Early Permian) and possibly the Carmila Beds (Early Permian), and of syn-sagging, extrusion-related origin in the Cb ignimbrites (Late Carboniferous) of the Bulgonunna Volcanic Field. It is, however, of secondary post-tectonic origin in the Cv (Late Carboniferous) and Cls<sub>1</sub> (Early Carboniferous, Star of Hope Formation volcanics) sequences of the Bulgonunna Volcanic Field, the Silver Hills Volcanics (Late Devonian to Early Carboniferous), and probably so in the Lizzie Creek Volcanics (Early [Middle?] Permian). Acquisition of this secondary component has completely remagnetized the Cv sequence. Oxygen isotope studies in the Bulgonunna Volcanic Field indicate regional hydrothermal activity at temperatures in excess of 300°C. This suggests a thermochemical, and probably thermoviscous origin for the pervasive "Kiaman" overprint. Hydrothermal activity at such temperatures and possibly over a long time, could have affected the stability of isotopic systems, and prompts the question as to whether U-Pb (SHRIMP) zircon ages for the Cb and Cv sequences, which concentrate around 305-290 Ma represent primary crystallization ages, or possibly reset ages for the Cv sequence related to extrusion of the Cb sequence. Resolution of this question has important implications for interpretation of SHRIMP data in general and for the stratigraphy of the Bulgonunna Volcanics in particular. We regard the regionally and globally pervasive nature of the "Kiaman" magnetic resetting to be sufficiently suggestive of conditions that favour isotopic resetting as to warrant further geochronological proof for isotopic stability.

Primary magnetic components of Early Carboniferous and Late Devonian-to-Early Carboniferous age have been identified in the Star of Hope Formation volcanics (Cls<sub>1</sub>) and in the Silver Hills Volcanics respectively. The pole positions documented here for primary and "Kiaman" overprint magnetizations have important implications for the shape of the late Palaeozoic APWP for Australia and Gondwana, and consequently the evolution of the Tasman Fold Belt, the evolution of the Gondwana-Laurussia contact, and the formation of Pangea. The new Queensland data together with a compilation of late Palaeozoic pole positions for Australia provide firm support for the "alternative" late Palaeozoic APWP proposed by Klootwijk and Giddings. This KG-path with its eastward Devonian-Carboniferous loop advocates continuing Gondwana-Laurussia contact during the Devonian and Carboniferous, in contrast to the SLP-path, compiled on the basis of data advocated by Schmidt, Li and Powell (cf. Schmidt et al., 1990, Li et al., 1990, Powell et al., 1990), whose westward loop implies (Middle?) Devonian-(Early?) Carboniferous reopening of an oceanic basin.

## INTRODUCTION

This study describes and interprets preliminary palaeomagnetic and magnetic fabric data from several upper Palaeozoic volcanic fields in northeastern and eastern Queensland (Oversby et al., 1980; Oversby, 1988). The results are derived from large, but areally limited, sample collections of the Bulgonunna Volcanic Field and the Featherbed Volcanics, and from limited collections of the Lizzie Creek Volcanics, the Carmila Beds, and the Silver Hills Volcanics.

The study was initiated in 1987 as a reconnaissance palaeomagnetic contribution to the Northern Drummond Basin Project (a cooperation between the then Bureau of Mineral Resources and BHP Gold Mines Ltd.) that focussed on the following aims: (i) delineation and dating of the magnetic evolution of the northern Bulgonunna Volcanic Field in relation to tectonic/plumbing phases; (ii) determination of the palaeolatitude history of the volcanic fields during the large-scale Carboniferous movement of Eastern Gondwana from an equatorial to a south-polar location; (iii) provision of control on bedding and transport directions of ignimbrite sequences and control on the orientation of major fault zones using the technique of magnetic fabric analysis (MFA); (iv) establishment of a basis for comparison with results from the Carboniferous/Permian volcanic province of the Tamworth Belt and control on oroclinal deformation of the southern New England Orogen; (v) further detailing of the late Palaeozoic apparent polar wander path (APWP) for Australia/Gondwana particularly with respect to the controversy on its shape (discussed in Klootwijk, 1987, 1988; Klootwijk and Giddings, 1988a); and (vi) further delineation and dating of the Late Carboniferous-Early Permian phase of pervasive magnetic overprinting throughout Australia and Pangea. Initial aims regarding provision of groundtruth data for aeromagnetic studies and for magnetostratigraphic correlation and dating of the ignimbrite sequences have not been pursued in this preliminary study.

The palaeomagnetic results and interpretations presented in this record are based on results from pilot samples, obtained through standard thermal and alternating field (AF) techniques and analysis techniques. Extensive bulk demagnetization studies are in progress. Combined pilot and bulk demagnetization results for the present collection and for a planned additional collection of, in particular, the Bulgonunna Volcanic Field will be reported elsewhere. The additional datasets may lead to some adjustments in the palaeomagnetic results and interpretations described herein. The MFA results are based on representative sample selections, and no further study of the present collection is planned.

The upper Palaeozoic of the Tasman Orogenic System in northeastern and eastern Queensland has received little attention from palaeomagnetism. Results available from earlier studies are confined to the Upper Devonian Dotswood Red Beds (Chamalaun, 1968), interpreted by the author as a secondary magnetization of Late Carboniferous age, and preliminary results from the Newcastle Range Volcanics (M. Idnurm, pers. comm., 1985). Studies by the CSIRO rockmagnetic group on the Featherbed Volcanics (Clark, 1980) and on the Bulgonunna Volcanic Field (Lackie et al., 1992) are not publicly available; they are "restricted investigation reports". Although the present study adds significantly to the palaeomagnetic data available for the region, the knowledge base still remains narrow. All interpretations advanced here, therefore, have to be treated as provisional.

## GEOLOGICAL SETTING

### Tasman Orogenic System, relationship of tectonic entities

The palaeomagnetic results presented in this study (from the Bulgonunna Volcanic Field, the Featherbed, Lizzie Creek and Silver Hills Volcanics, and the Carmila Beds) come from four different

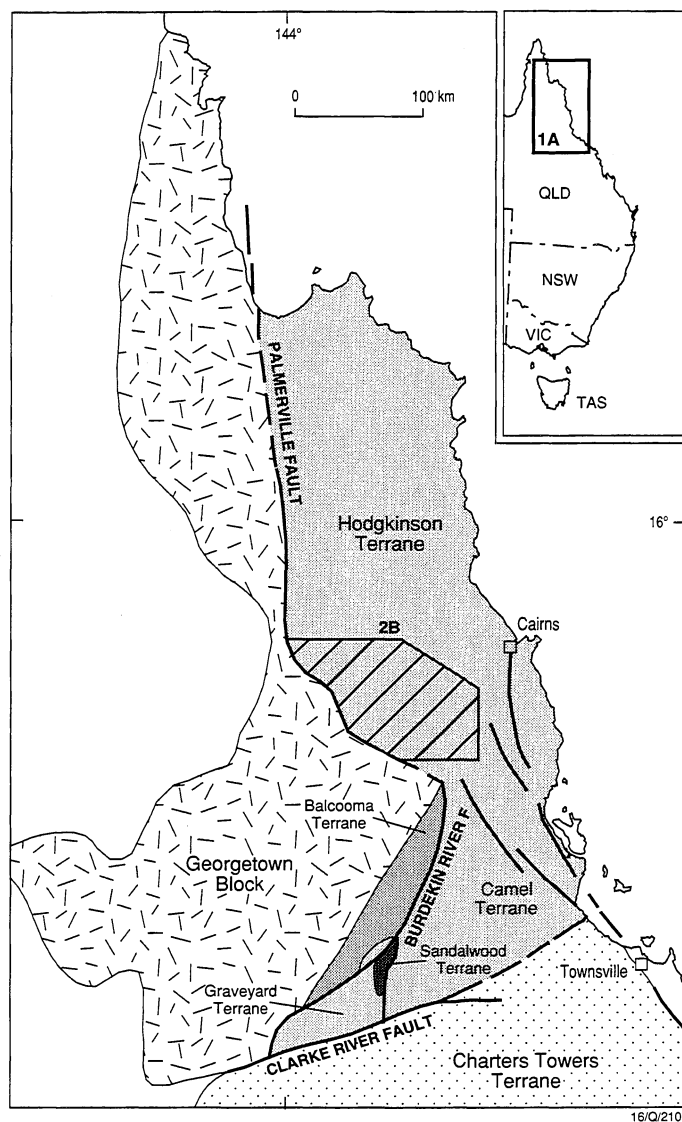


Figure 1. Principal tectonic features and terrane identification of the Hodgkinson-Broken River Province (A) and the Greater New England Orogen (B), simplified after Coney et al. (1990). The overview insets locate the areas covered in figures A and B. Figure 1B shows the Thomson fold belt (Anakie Inlier-Charter Towers terrane) and adjacent terranes of the Greater New England composite terrane. Insets 2A-D refer to regional maps with sampling locations, detailed in figure 2.

tectonic entities (Coney et al., 1990) in northeastern and eastern Queensland (Fig. 1A, B). The Bulgonunna Volcanic Field results come from successions that lie unconformably on the Lolworth-Ravenswood block (Charter Towers terrane, Fig. 1A), the Anakie inlier and Drummond Basin rocks.

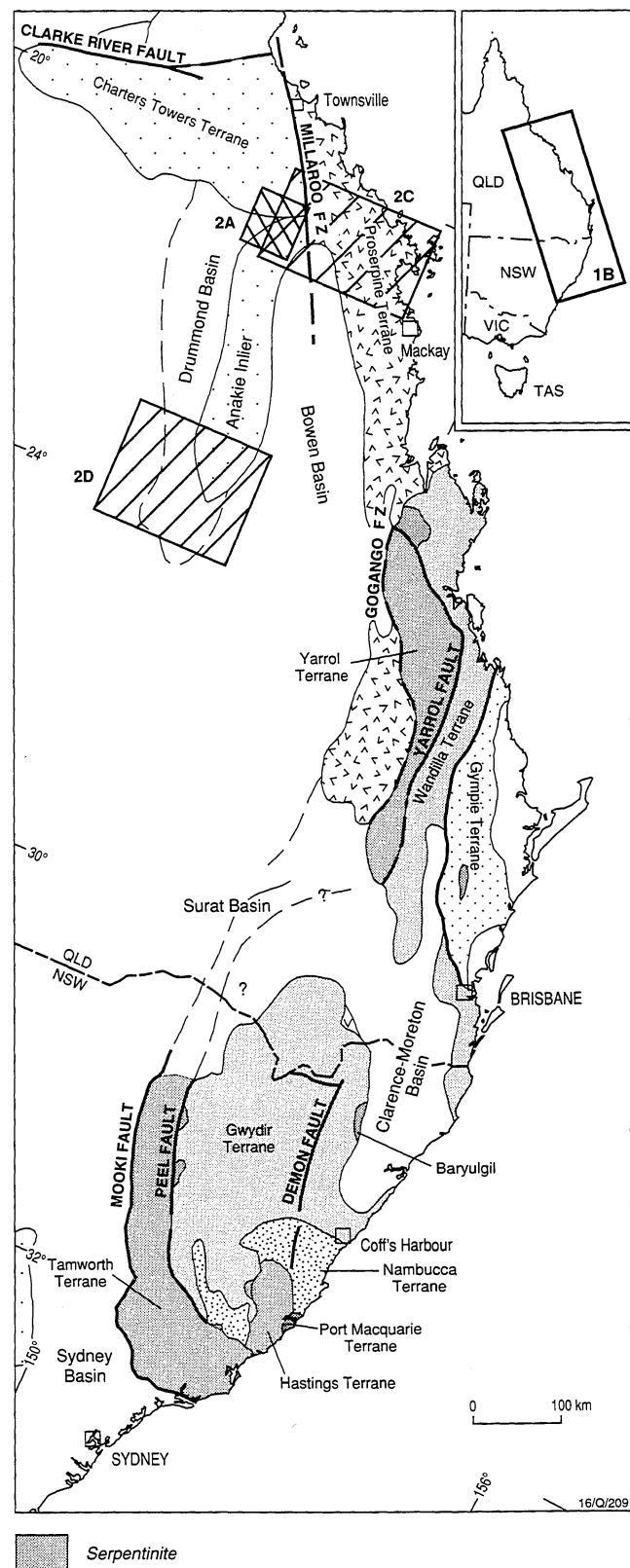


Figure 1B

### *Geological setting*

The Featherbed Volcanics results are from successions that lie on Hodgkinson Basin rocks (Hodgkinson-Broken River Fold Belt, Hodgkinson terrane, Fig.1A). The Silver Hills Volcanics results are from the southern Drummond Basin (Fig.1B) in the Thomson Fold Belt, and the Lizzie Creek Volcanics and Carmila Beds results are from successor sequences to the Upper Devonian-Lower Carboniferous tract of the Proserpine terrane (Coney et al,1990) (Fig.1B). Other regional results already mentioned are from the Dotswood Red Beds of the Dotswood Group, part of the Late Devonian-Early Carboniferous Drummond Basin-Clarke River assemblages that overlie the Precambrian(?) to lower Palaeozoic tract of the Charters Towers terrane (Coney et al,1990), and from the Newcastle Range Volcanics of the Georgetown block (Fig.1A). We follow the current naming convention of these entities in terms of blocks, fold belts (systems), orogens, and terranes, without implying adherence to genetic connotations.

The Tasman Orogenic System (TOS) of Queensland and New South Wales lacks, as yet, a sound palaeomagnetic database from which clearcut tectonic conclusions can be drawn. As a basis for understanding the tectonic evolution of TOS therefore, we prefer uncommitted reference to a number of recent papers with seminal interpretations: Scheibner (1985,1989), Leitch and Scheibner (1987), and Coney et al. (1990) for a terrane analysis of TOS; Murray et al. (1989), Murray and Scheibner (1990), and Wellman (1990) for a regional geological interpretation of gravity and magnetic patterns of TOS; Henderson (1980), and Murray (1986) for an overview of the tectonic entities and development of TOS in Queensland; Cawood and Leitch (1985), Harrington and Korsch (1985), Korsch and Harrington (1987), Murray et al. (1987), and Korsch et al. (1990) for the tectonic evolution of the New England Orogen and its accretion to TOS; and Findlay et al. (1991) for an overview of the Palaeozoic evolution of TOS.

For proper assessment of the significance of the reported palaeomagnetic results in terms of definition of the Australian APWP and/or terrane analysis, the relationships of the four tectonic entities to neo-cratonic Australia need to be defined. The Thomson Fold Belt, Charters Towers terrane, and the Georgetown block are generally interpreted to form part of neocratonic Australia by mid- to Late Devonian time (Murray,1986; Coney et al.,1990). The palaeomagnetic results discussed here for all late Palaeozoic sequences from, or overlying, these tectonic units are thus considered representative for the Australian craton. Cratonization of the Hodgkinson-Broken River fold belt was not completed until the Late Carboniferous-Early Permian (Bell,1980; Scheibner,1985; Shaw et al.,1987; Henderson,1987). The latest Carboniferous-earliest Permian Featherbed Volcanics succession which was sampled is only lightly disturbed. Whilst the Featherbed Volcanics *sensu strictu* occur entirely east of the Palmerfield Fault (MacKenzie,1987,1988), associated volcanics straddle the Palmerville Fault separating the Hodgkinson-Broken River fold belt and the Georgetown block (Shaw et al.,1987). The Featherbed Volcanics results are also taken, therefore, to be representative of the Australian craton. The Bulgonunna Volcanic Field succession, situated to the west of the Millaroo Fault zone, and the Silver Hills Volcanics from the southern Drummond Basin likewise seem to be autochthonous with respect to the craton.

The relationship between the Hodgkinson-Broken River fold belt, and the Proserpine terrane and successor sequences of the New England Orogen is not clear. They are commonly considered to represent separate entities. However, Henderson's (1980) interpretation that they comprise a single orogenic zone is supported by a recent interpretation of regional gravity data (Murray et

al.,1989). Thus, the western bounding faults of the two entities - the Palmerville and Millaroo Faults - may be connected directly (Oversby et al,1980; Henderson,1987; Murray et al.,1989), or by the Burdekin and Clarke River fault systems in the sense of Bell's (1980) Big Bend hypothesis. The relationship between the Proserpine terrane with successor sequences and that part of the New England Orogen farther south is also uncertain. Two evolutionary models have been proposed (Murray et al.,1987; Korsch and Harrington,1987), suggesting large-scale oroclinal bending and strike-slip movements. This affects the usefulness of the Lizzie Creek Volcanics and Carmila Beds results in defining the Australian reference APWP. The two models differ in their interpretation of structural (Flood and Fergusson,1982) and magnetic observations (Wellman,1990) regarding a Z-shaped megafold in the Texas-Coffs Harbour region, and in their explanation of the localized presence of Middle Carboniferous-Early Permian volcanic and intrusive activity in both northeastern Queensland (Bowen-Townsville-Cairns) and the Tamworth Belt of the southern New England Orogen, and the apparent absence of such activity in between. The Murray et al. (1987) study emulates a model for the Tertiary evolution of the North American Cordillera. It explains both the spatial igneous activity and the oroclinal bending in terms of a model invoking oblique subduction of a mid-ocean ridge/transform fault system beneath an outwardly-concave continental margin-trench system, with subsequent inward stepping of a major dextral transform fault zone (Gogango-Baryulgil fault zone). Korsch and Harrington's (1987) and Korsch et al.'s (1990) model, in contrast, emphasizes unfolding of the Texas-Coffs Harbour Orocline in relation to the Mooki-Goondiwindi-Gogango strike-slip zone. An earlier version of their model (H.J.Harrington, pers. comm.,1984; Harrington and Korsch,1985), emphasized the similarity between the volcanic provinces of the Tamworth Belt and northeastern Queensland, and proposed large-scale strike-slip movement between both provinces. Whilst oroclinal bending and large-scale strike slip movement have been generally accepted (Flood and Fergusson,1982; Harrington and Korsch,1985; Murray et al.,1987; Korsch et al.,1990), the location of the main western strike-slip fault zone and the timing of movement remain unclear. Murray et al. (1987) suggest 500+ km of dextral strike-slip movement along the Gogango-Baryulgil fault zone between about 310 Ma and 300 Ma. Korsch and Harrington (1987) and Korsch et al. (1990) suggest that movement was similar in magnitude but located along the Mooki-Gogango fault zone, and occurred later, between 280 Ma and 265 Ma. Harrington and Korsch (1985) included the Proserpine terrane and successor sequences within the dextral strike-slip system (Mooki-Goondiwindi-Eungella-Cracow zone). It is only under this last interpretation that the results for the Lizzie Creek Volcanics and the Carmila Beds may be questioned as representative of neo-cratonic Australia.

#### Palaeomagnetic contribution to evolution of the Tasman Orogenic System

The new palaeomagnetic data may advance our understanding of the regional geological evolution of northeastern Queensland (Introduction: study objectives [i]-[iii]). Importantly, however, they will facilitate a direct palaeomagnetic comparison with the Early Carboniferous to Early Permian acid volcanics of the Tamworth Belt of the southern New England Orogen ([iv], study in progress) with the aim to constrain the magnitude and timing of the proposed strike-slip/oroclinal bending system. Depending on which of the two evolutionary model is preferred, the Carboniferous-Permian deformation of the New England Orogen occurred either towards the end of a period of a very extensive southward movement of Eastern Gondwana from equatorial to high southern palaeolatitudes (Murray et al.,1987), or during a subsequent counterclockwise rotation (Korsch and Harrington,1987). The timing of the southward (clockwise) movement is currently no better defined than between Late Visean and Early Permian, whilst the timing of the subsequent counterclockwise



## Geological setting

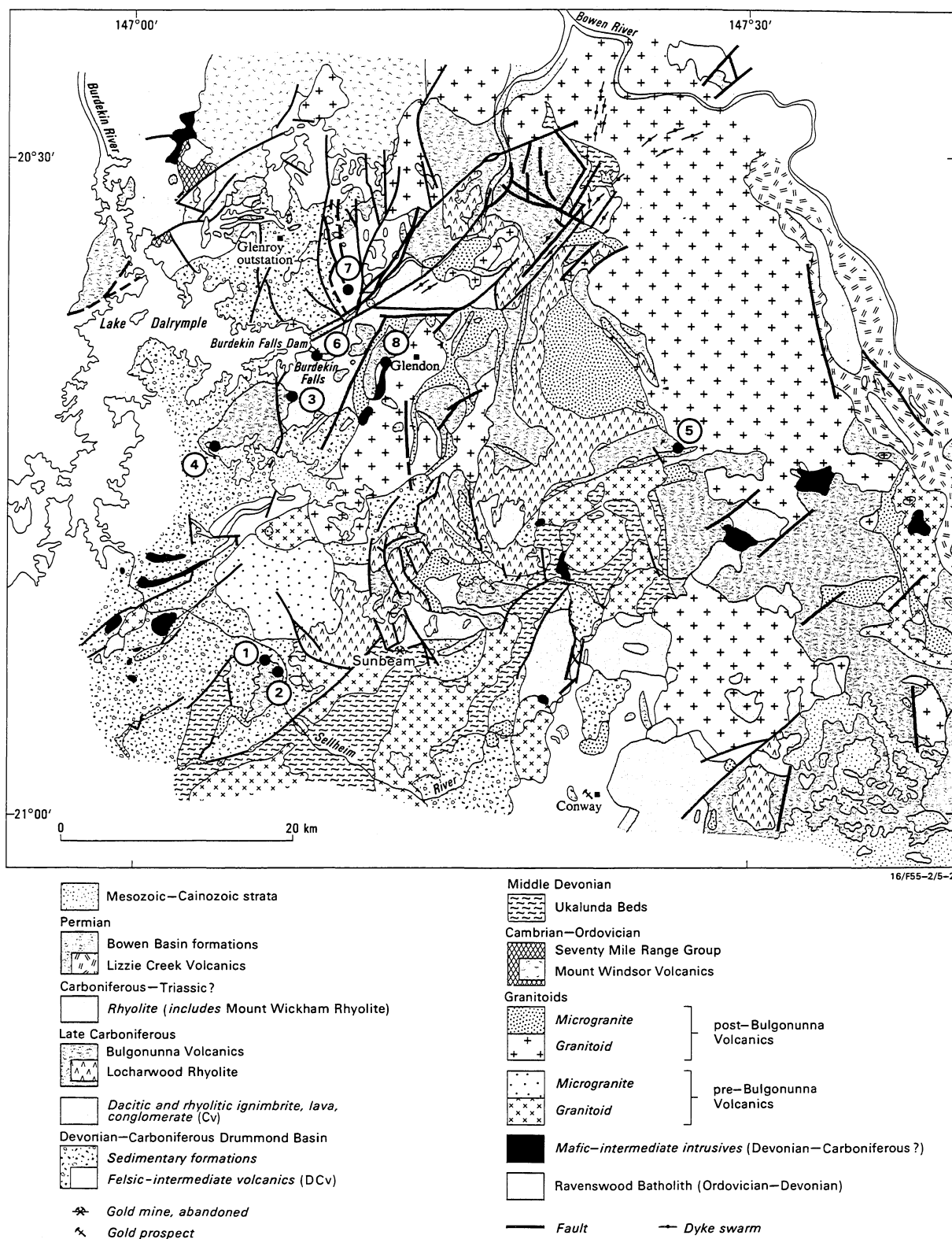
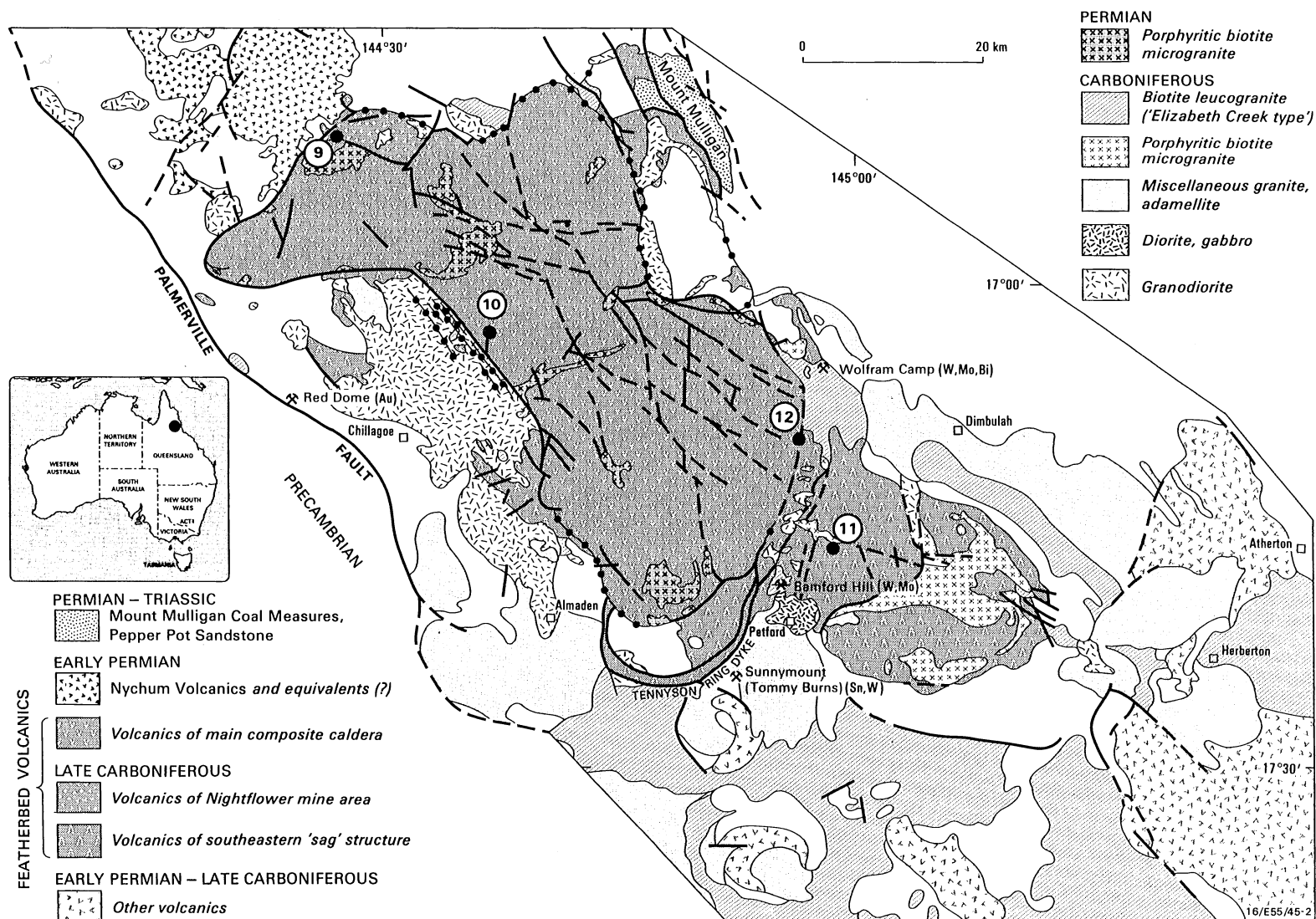


Fig.2A, caption on page 12.

Fig.2B, caption on page 12.



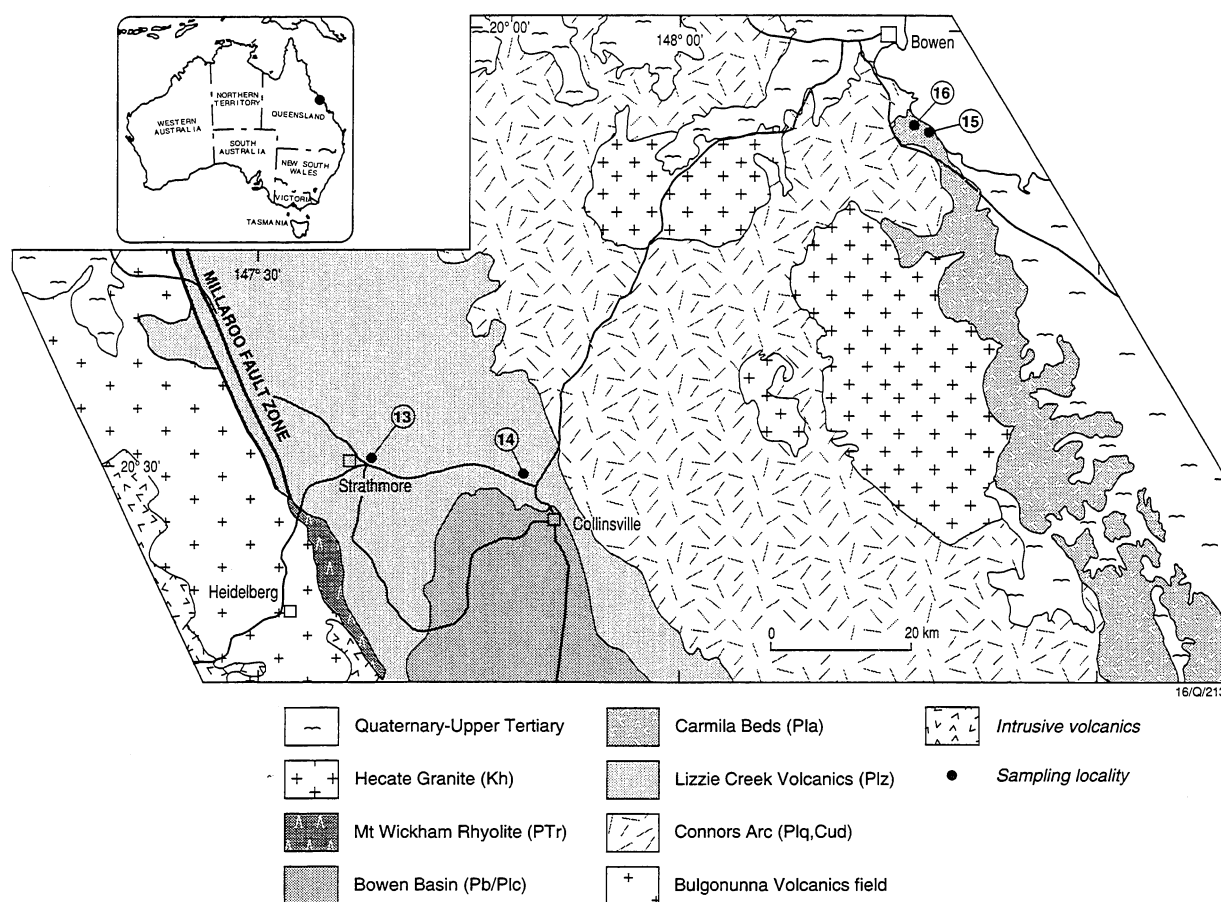


Fig.2C

Figure 2. Generalized geological maps: A) Bulgonunna Volcanic Field (after Black et al.,1989; McPhie et al.,1990); B) Featherbed Volcanics (after MacKenzie,1987); C) Lizzie Creek Volcanics and Carmila Beds (after Levingston,1981); D) southern Drummond Basin (after Olgers,1972). Numbers refer to sampled locations as detailed in table 1.

movement is no better defined than Stephanian-Autunian (300-270 Ma). Palaeomagnetic results from the current study and forthcoming results from a parallel study on the Tamworth Belt are expected to further constrain the timing of the Carboniferous-Permian deformation; they may even shed some light on a possible causative relationship between the counterclockwise movement and oroclinal deformation of the New England Orogen due to drag along the freeboard of TOS.

#### Upper Palaeozoic volcanics northeastern Queensland: overview

Northeastern Queensland's late Palaeozoic volcanic fields and co-magmatic granitoid belts have extruded across, and intrude, cratonized tectonic entities, and are probably the product of westward subduction of an oceanic plate beneath eastern Australia's continental crust. A suture zone, however, has yet to be recognized.

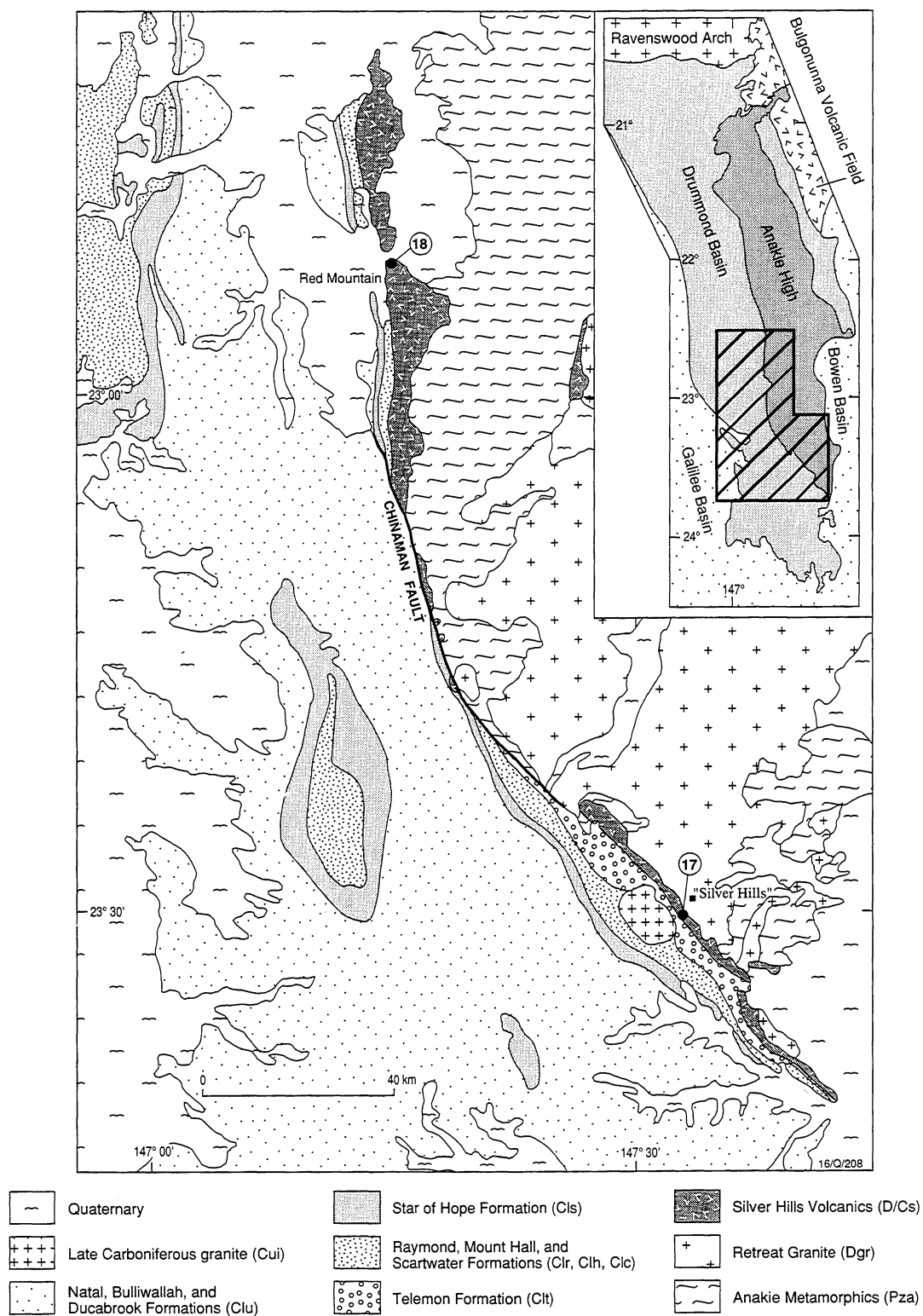


Fig.2D

## Geological setting

Oversby et al. (1980) identified three distinct volcanic fields inland of the Townsville-Cairns region: the Newcastle Range-Featherbed Volcanic Field; the Bulgonunna (*sensu lato*) Volcanic Field; and the Lizzie Creek Volcanic Field which possibly includes the Carmila Beds. Extrusion appears to be controlled by regional fracture zones with a history of prolonged activity (Johnson and Henderson, 1991). The first two fields are characterized by voluminous ignimbrite eruptions. These were rarely, if ever, accompanied by catastrophic caldera collapse. The bedding of the ignimbrites can thus be taken as an indication of the palaeohorizontal. This, and the general occurrence of deuteric oxidation in ignimbrites (providing the conditions for stable magnetizations) makes the volcanic fields very attractive for palaeomagnetic investigation. Sample collections were therefore taken from all three fields. Richards (1980 [Figs.5,14]) has described belts of granitoid intrusives in the study region which he regards as either exclusively I-type and co-magmatic with the late Palaeozoic volcanic activity, or which represent the younger part of an Ordovician-Devonian suite. Substantial late Palaeozoic A-type volcanics and some A-type granitoids are now known in the Featherbed Volcanics (MacKenzie, 1987, 1988).

### Bulgonunna Volcanic Field

We follow here the stratigraphic nomenclature for the Bulgonunna Volcanic Field defined in the field compilation sheets (Oversby et al., 1991). A revised nomenclature is used in the 1:100,000 geological map and the map commentary (Oversby et al., 1993).

Two Late Carboniferous volcanic sequences occur closely together in the northern part of the Bulgonunna Volcanic Field in the Burdekin Falls area (Fig.2A). Field investigations during the 1987-1989 BMR-GSQ mapping program were initially interpreted (McPhie et al., 1990; Oversby et al., 1990) in terms of an older (previously Cv) and a younger (previously Cb) sequence, but have been reinterpreted as laterally interfingering on the basis of indistinguishable U-Pb (SHRIMP) zircon age ranges (Black, 1993) for the two sequences. They consist of amongst others (i) mixed volcanic-sedimentary associations including an upper "Smedley" rhyolite-dacite association (part of previously mapped Cv sequence), with compositionally diverse ignimbrites, lavas and conglomerates, and (ii) rhyolitic ignimbrite dominated associations including an upper "Arundel" and a lower "Locharwood" rhyolite-dominated association (part of previously mapped Cb sequence), locally less deformed than Cv, that were identified as the Bulgonunna Volcanics *sensu stricto*. The Cv-associations include dacitic and quartz-rich, rhyolitic ignimbrites, a variety of lavas, and probably fluvial clastic sedimentary rocks. The Cv ignimbrites are commonly more lithic than the ignimbrites of the Cb-associations. The latter are dominated by thick (tens of meters) widespread, welded, rhyolitic ignimbrites with volumetrically minor, flow-banded rhyolitic lavas. Thin intervals of conglomeratic and tuffaceous sandstone occur locally. These two sequences are underlain by several older and more deformed volcanic units. These are a younger volcanic member (previously CIs<sub>2</sub>) in the Star of Hope Formation, which is dominated by andesitic pyroclastic rocks and lavas and volcanigenic sedimentary rocks, and older and more deformed volcanic units, the Stones Creek Volcanics of northern occurrence (including the previously mapped DCv undivided) and the Bimurra Volcanics of southeastern occurrence. These older units may be equivalent to the lower, volcanic-rich depositional Cycle-1 of the Drummond Basin (Olgers, 1972) that includes the Silver Hills Volcanics. The Silver Hills Volcanics in the southern Drummond Basin are stratigraphically separated from the younger Cv and Cb sequences, that occur near to the northernmost Drummond Basin, by Lower (to Middle?) Carboniferous sedimentary rocks of the Drummond Basin sequence, which includes the

younger Star of Hope Formation belonging to Cycle-3. In some localities, however, Cv and Cb rocks lie directly (unconformably) on Star of Hope Formation volcanics (including Cls<sub>1</sub>) and DCv rocks.

The Cb sequence is generally gently dipping as a result of sagging in response to limited caldera subsidence and accompanying faulting, understandably so in view of the voluminous nature of the ignimbrites. Where the Cv and Cb sequences occur together, the Cv sequence is lower and more steeply dipping, and more disrupted by faults. Where they overlie the Drummond Basin sequence, an unconformity has been identified. Facies variations within the volcanic pile and thickness variations indicate volcanic source areas in the central and northern parts of the mapped region (Fig.2A).

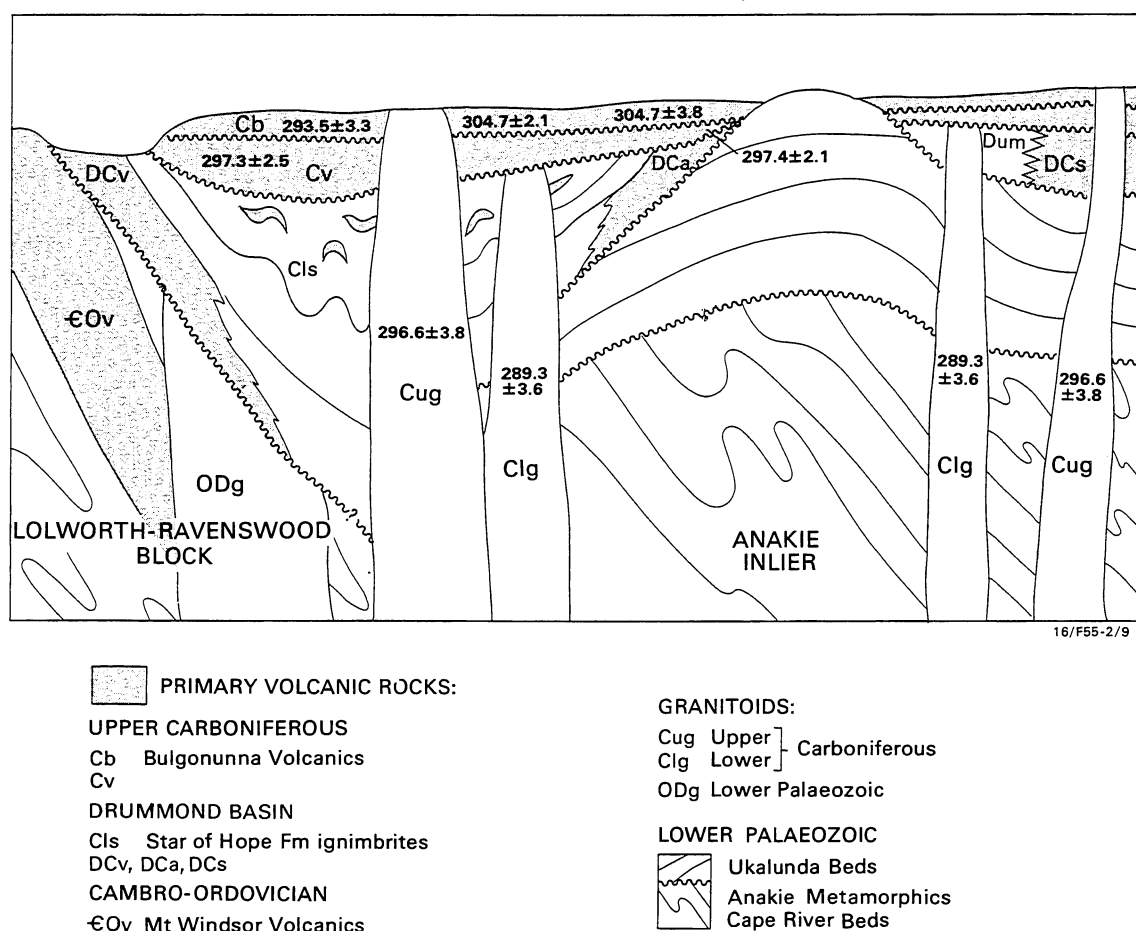


Figure 3. Schematic overview of an earlier tentative interpretation of stratigraphic relationships in the Bulgonunna Volcanic Field based on field evidence (McPhie et al., 1990 [Fig.3]), emphasizing primary volcanic sequences: Mt. Windsor Volcanics, Drummond Basin volcanic-dominated formations (DCv, DCa, DCs) and Late Carboniferous volcanics (Bulgonunna Volcanics and Cv). Dum, Mount Wyatt Formation. The stratigraphic relationships were reinterpreted more recently, as discussed in the text, on the basis of now available U-Pb (SHRIMP) zircon dates (Black, 1993). These dates have been added to the original figure of McPhie et al. in order to highlight some discrepancies with the earlier field-based stratigraphic compilation. Note the previous (McPhie et al., 1990) and now superseded (Oversby et al., 1991, 1993) nomenclature.

### *Geological setting*

Granite intrusions in the mapped region are substantial and are all I-types. An older group of granitoids is non-conformably overlain by the Late Carboniferous sequences. A younger group intrudes the probably co-magmatic sequences.

U-Pb (SHRIMP) zircon dating (Black,1993) did not lend support to the tentative stratigraphy that was deduced initially from the field mapping program (Ewers et al,1989; McPhie et al.,1990). In the absence of clear evidence to the contrary (lack of clear stratigraphic relationships in the field), the limited SHRIMP dates have been accepted at face value and the stratigraphy has been adapted accordingly. In particular, indistinguishable ages of around 295 Ma for the Cb and Cv associations have been re-interpreted in terms of repetition and lateral interfingering of both sequences, despite field evidence for a greater degree of structural complexity locally in the Cv sequence. This re-interpretation depends heavily on the presumption that the SHRIMP ages are of primary magmatic origin. Hereafter, we pose the question as to whether these ages indeed represent primary crystallization ages or might represent reworked ages, based on such observations as: the presence of pervasive and complete late Palaeozoic remagnetization of the Cv associations discovered in the palaeomagnetic results; the presence of widespread hydrothermal activity at temperatures of around, and in excess of, 300°C indicated by a pattern of oxygen-isotope depletion (Ewers et al.,1991; Ewers et al.,1993) on a regional scale, and by fluid inclusion data (Etminan et al.,1988; Ewers,1991; Ewers and Hoffmann,1992) on a local prospect-scale; and the widespread tectonic disturbance of TOS and the Australian craton at around 300 Ma. In order to illustrate the discussion, we reproduce a schematic overview (Fig.3) of the stratigraphic relationships in the Burdekin Falls area (McPhie et al.,1990 [Fig.3]) based on field mapping, along with the conflicting SHRIMP ages.

The Late Carboniferous volcanics of the Bulgonunna Volcanic Field are similar to ignimbrite-dominated volcanic sequences of that age that occur widely elsewhere in northeastern Queensland, such as the Newcastle Range Volcanics and the Featherbed Volcanics. Similarity to ignimbrite sequences in the Tamworth Belt of the southern New England Orogen (NEO) also has been suggested (H.J.Harrington, pers. comm.,1984; Harrington and Korsch,1985). The latter are traditionally regarded as Late Carboniferous in age but are now dated using U-Pb (SHRIMP) zircon analysis as mid-Carboniferous (Roberts et al.,1991a). Their source region has not been identified in outcrop. As previously noted, the northeastern Queensland and the Tamworth Belt volcanic sequences could represent the remnants of continental margin arcs separately developed both to the north and to the south of a subducting mid-ocean ridge complex (Murray et al.,1987), or could possibly stem from the same source region with subsequent dispersion through large-scale, strike-slip motion (H.J.Harrington, pers. comm.,1984; Harrington and Korsch,1985).

#### Featherbed Volcanics

The Featherbed Volcanics are mainly confined to a composite cauldron, east of, and close to, the Palmerville Fault zone, the western boundary of the Hodgkinson-Broken River Fold Belt (Figs.1B,2B, MacKenzie,1987,1988). The volcanic field is made up of a spatially less extensive Late Carboniferous I-type suite, and an Early Permian A-type suite. The former suite consists of andesitic to rhyolitic ignimbrites and minor andesitic lavas, and crops out in a sag-structure to the southeast. The A-type suite is made up of rhyolitic ignimbrite and relatively minor volumes of lava, and constitutes the main cauldron of the Featherbed Volcanics complex. Rb-Sr ages range between 320 Ma and 300 Ma for the I-type suite (Black,1978; Black et al.,1978), and between 300 Ma and 280 Ma



TABLE 1: SAMPLING DETAILS

LOCATION (Grid coordinates)	ACRONYM	FMN	AGE <sup>1</sup>	SITES	SAMPLES	BEDDING <sup>2</sup>
<b>A) Bulgonunna Volcanic Field</b>						
(Glendon 1:100,000)						
1 147.10E,20.88S (104909)	BFBB	Cb		9	72	51.6/23.4
2 147.12E,20.90S (123893)	BFBC	Cb	304.7 <sup>3</sup>	9	72	158.9/20.5
3 147.13E,20.68S (135132-132132)	BFBA	Cb		7	56	179.2/10.0
4 147.06E,20.72S (063089)	BFBF	Cb	293.5	4	32	(239.7/37.5) <sup>4</sup>
4 147.06E,20.72S (060086)	BFBG	Cb		3	24	326.5/27.7 <sup>5</sup>
5 147.44E,20.39S (460083)	AFBH-K	Cb		4	40	H,I J K 50.6/37.2 55.5/20.8 14.4/7.3
8 147.10E,20.68S (200136)	AFGA	post-Cv <sup>6</sup>		1	10	unknown
(203143)	AFGB	post-Cv <sup>6</sup>		1	10	unknown
3 147.13E,20.68S (139131)	BFBE	Cv		2	20	167.0/24.8
6 147.14E,20.65S (145170-140159)	AFBA-G,BFBD	Cv	297.3	10	100	217.1/20.0
7 147.16E,20.61S (167212-166208)	BFBH	Cls <sub>1</sub>		6	60	(1-30) 153.7/19.4 (31-60) 163.9/15.8
<b>B) Featherbed Volcanics</b>						
(Bellevue 1:100,000)						
9 144.44E,16.84S (262354-276354)	BBFA		~280	8	64	subhor.
(Chillagoe 1:100,000)						
10 144.62E,17.06S (468114-464132)	BBFB		~290	8	64	subhor.
11 144.99E,17.27S (837899-855896)	BBFC		~305	5	40	subhor.
12 144.93E,17.16S (793815-820020)	BBFD		~290	8	64	subhor.
<b>C) Lizzie Creek Volcanics and Carmila Beds</b>						
(Collinsville 1:100,000)						
13 147.63E,20.50S (655330)	AFLA-B	E(M?) Permian		2	20	137.5/10.0
14 147.81E,20.52S (844309)	AFLC-D	E(M?) Permian		2	20	6.8/14.4
(Bowen 1:100,000)						
15 148.29E,20.11S (351758)	AFCA-B	E Permian		2	20	353.9/24.9
16 148.28E,20.11S (344761)	AFCC-D	E Permian		2	20	348.7/30.7
<b>D) Silver Hills Volcanics</b>						
(Rubyvale 1:100,000)						
17 147.54E,23.49S (553015)	ADSA-D	L Dev/E Carb		4	40	194.8/18.7
(Monteagle 1:100,000)						
18 147.24E,22.87S (247712)	ADSE-H	L Dev/E Carb		4	40	193.6/27.4
<sup>1)</sup> U-Pb (SHRIMP) ages for Bulgonunna Volcanic Field, errors specified in Black (1993), generally $\pm$ 2-4 m.y.; Rb-Sr ages for Featherbed Volcanics (Black,1980; D.MacKenzie, pers. comm.,1991). <sup>2)</sup> Bedding detailed as strike and dip in degrees (strike 90° counterclockwise from dip direction). <sup>3)</sup> Not locally determined, general age for Locharwood Rhyolite and equivalents. <sup>4)</sup> Local bedding observation from columnar jointing. Regional bedding of sheet is taken according to BFBG observation. <sup>5)</sup> Regional bedding also applied to overlying cooling unit sampled at BFBF. <sup>6)</sup> AFGA sampled in post-Cv granitoid, AFGB presumably so. This granitoid is intrusive in the Smedley Dacite (Cv <sub>4</sub> , previously Cvi <sub>3</sub> and Cvi <sub>2</sub> ). Relationship with Cb cannot be reliably inferred.						

for the A-type suite. Cauldron collapse of the Early Permian suite did occur, but all sites in both the A-type and the I-type suite have been sampled in subhorizontal sheets (Table 1). Extensive hydrothermal alteration has occurred, in particular near the cauldron margins and cross-cutting fault zones, and was evident in the field at location 10 (Table 1, Fig.2B).

#### Lizzie Creek Volcanics and Carmila Beds

The Lizzie Creek Volcanics represent the lowermost formation of the Bowen Basin sequence, successor to the Proserpine terrane, and crop out immediately north of, and on the northeastern limb of the Bowen Basin, where the sequence abuts against the Connors-Auburn belt (Figs.1B,2C,

### *Geological setting*

Malone et al.,1964,1966; Paine and Cameron,1972; Paine et al.,1974; Livingston,1981; Murray,1983). The sequence is dominated by andesitic volcanics, abundant pyroclastics and minor interbedded sediments. The age of the Lizzie Creek Volcanics is generally considered to be Early Permian. Murray (1983), however, emphasized the occurrence at the top of the Lizzie Creek sequence of marine Fauna II beds, and consequently proposed a Middle Permian age.

The Lizzie Creek Volcanics are correlated with the Carmila Beds which flank the Connors-Auburn belt to the west. The Carmila Beds are dominated by rhyolitic and dacitic volcanics with widespread andesitic lavas and pyroclastics, and contain a higher proportion of sediments than the Lizzie Creek Volcanics.

### Silver Hills Volcanics

The Silver Hills Volcanics consist of a sequence of continental volcanics, widely distributed in confined zones throughout the southern part of the Drummond Basin (Figs.1B,2D). The sequence unconformably overlies the metamorphics of the Anakie Inlier, lower Middle Devonian volcanics and limestone, and the Upper Devonian Retreat Granite. The volcanics have been correlated with similar volcanic sequences that underlie the Bulgonunna Volcanic Field, the Stones Creek Volcanics (northern DCVs, extruded along the northern margin of the Drummond Basin) and the Bimurra Volcanics (southeastern DCVs) as defined by Oversby et al. (e.g.1991), although these represent most probably different eruption centres. The age of the Silver Hills Volcanics is no better defined than Late Devonian to Early Carboniferous.

## **SAMPLING**

Relevant descriptive information on the sampled localities is detailed in Appendix A, and Table 1. Sampled locations are indicated on figures 2A-D. Samples were collected with a portable drilling machine as standard drillcores of 2.5 cm diameter and about 10 cm length, and were oriented with both a magnetic and a solar compass. Bedding at the sampled sites was determined mostly from flame orientations in ignimbrites and mapped outlines of the flows (Bulgonunna Volcanic Field), from bedding of adjacent sediments (Lizzie Creek Volcanics and Carmila Beds, location 17 of the Silver Hills Volcanics, location 7 of the Bulgonunna Volcanic Field), and from topographic observations (location 18 of the Silver Hills Volcanics). Detailed mapping of the Featherbed Volcanics (McKenzie,1987,1988; D.Mackenzie, pers. comm.,1988) indicated that flows were subhorizontal at the sampled localities. The subhorizontal attitude of these flows was not checked in detail during field sampling, but magnetic fabric results obtained in the laboratory support subhorizontal bedding for all but location 11.

### Bulgonunna Volcanic Field:

Sampling of the Bulgonunna Volcanic Field was carried out under guidance of Brian Oversby (Fig.2A, see Oversby et al.,1991) at the end of AGSO's 1987 and 1988 mapping seasons. The rhyolite-dominated associations (previously Cb) were sampled extensively in both limbs of two synclinal structures (Pyramid Range: now Pyramid Rhyolite, locations 1 and 2; Myall-Coopers Creek region: now Arundel Rhyolite, locations 3 and 4). Sampling of the dacite-rhyolite association (previously Cv) was confined to an extensive section (location 6) of the Smedley Dacite (previously

Cv<sub>d</sub>, "Dam ignimbrite") and a limited section in Coopers Creek (location 3). The volcanics in the Star of Hope Formation were sampled in a single section southeast of Glenroy Outstation (location 7).

#### Featherbed Volcanics:

Reconnaissance sampling was carried out in 1988 on the basis of information provided by Doug MacKenzie (Fig.2B, see MacKenzie 1987,1988). Sampling was confined to four locations, three in the Early Permian A-type volcanics and one in the Late Carboniferous I-type volcanics.

#### Lizzie Creek Volcanics and Carmila Beds:

Cursory sampling (Fig.2C) was carried out in 1987 and was confined to some acid volcanics and welded lithic tuffs in the Lizzie Creek Volcanics and to some dacitic-andesitic volcanics in the Carmila Beds.

#### Silver Hills Volcanics:

Cursory sampling (Fig.2D) in 1987 was confined to the type section at Silver Hills Homestead, comprising mainly spherulitic rhyolite and trachyte (Veevers et al.,1964a [Fig.10]) in close proximity to a granitic pluton of unspecified Permian age, and to a massive flow-banded rhyolite section at Red Mountain (Veevers et al.,1964b).

## METHODS

All samples (888) were sandblasted to remove possible metal residues from drilling, sliced into standard cylinders of 2.3 cm height, and cleaned on the top and bottom surfaces using a diamond lap to remove possible contaminants from slicing. On the basis of initial NRM and susceptibility measurements of all specimens (2681), a total of 529 specimens was selected for pilot thermal (427) and pilot alternating field (102) demagnetization.

Thermal demagnetization was carried out in large-volume furnaces (McElhinny et al.,1971) at the centres of feedback-controlled Rubens-Helmholtz coil systems which reduce the ambient Earth's magnetic field to less than 5 nT (1nT=1 $\gamma$ ). To minimize oxidation, an argon atmosphere was maintained during the heating cycle (1 hr), but not during the forced-cooling cycle in air (0.5 hr). The samples were demagnetized in up to 30 steps, to peak temperatures of 695<sup>0</sup>C. Magneto-chemical changes were monitored by making low-field susceptibility measurements on the specimens after each demagnetization step, using a DIGICO bulk-susceptibility bridge. Alternating field demagnetization, in up to 28 steps, to peak AF-fields of 100 mT was carried out using a Schönstedt AF demagnetizer (model GSD-5) with self-reversing tumbler.

Nearly all measurements on samples from the Bulgonunna Volcanic Field, the Lizzie Creek Volcanics, the Carmila Beds, and the Silver Hills Volcanics were carried out on a three-axis, through-bore, 2G-Enterprises cryogenic magnetometer (model SRM 760R), fitted with an automated sample handler. Very high intensity samples were measured on a DIGICO spinner magnetometer. Measurements on the generally lower intensity samples from the Featherbed Volcanics were carried out on a two-axis ScT cryogenic magnetometer; the few higher intensity samples were measured on the 2G cryogenic magnetometer.

## *Methods*

Demagnetization progress was monitored using real-time display of Zijdeveld (1967) plots. These plots, which display the cartesian components of the remanence vector for each demagnetization step, showed all relevant data for each specimen at its time of measurement. The data were stored on a central database on an HP-A600 minicomputer, which also controlled data-acquisition from all measuring instruments used (Giddings,1985; Giddings et al.,1985). All demagnetization data were subsequently transferred to AGSO's ORACLE field and laboratory measurements database, housed on a DG/MV20000 minicomputer.

All specimens were analyzed individually for linear directions, planar elements and Hoffman-Day directions with the use of an interactive-graphics analysis program (Giddings,1985), linked to the database and based in part on Kirschvink's (1980) Principal Component Analysis (PCA) method. We followed a two-pass procedure for directional analysis of the generally multicomponent magnetization patterns. In the first pass, Zijdeveld and equal-area plots of demagnetization data for each individual specimen were scrutinized with the interactive-graphics analysis program, and all linear and Hoffman-Day components were determined which showed a good fit to the data. This determination was routinely carried out in the geographic reference frame. Based on our experience, such a scrutiny of individual specimen results by a skilled operator, although necessarily somewhat subjective, is preferable to a batch-type analysis of specimens following more objective, but preset and rigid acceptance criteria. In the second pass contoured density distributions in geographic and stratigraphic coordinates of all linear and Hoffman-Day directions thus determined were scrutinized for concentrations and/or distributions that could be interpreted meaningfully in terms of the Australian APWP, and/or the geological evolution of the region. Directional concentrations were also analyzed for common trends in thermal and/or AF stability spectra. Mean directions of meaningful concentrations and corresponding pole positions were determined for both the linear and Hoffman-Day directions. Mean results for both direction types generally showed close agreement. To avoid unwarranted duplication of data, only the linear results are presented. The mean results were then interpreted in relation to different versions of the Australian APWP and to the tectonic evolution of the region.

Magnetic fabric studies were carried out with a CSIRO-modified DIGICO bulk-susceptibility and susceptibility-anisotropy unit and with CSIRO's susceptibility anisotropy software package. Bulk susceptibility for the Featherbed Volcanics specimens was determined using a newly constructed (1991) bulk bridge. It was discovered afterwards that the new bulk bridge had affected the tuning of the CSIRO-provided, auto-ranging interface, possibly resulting in slightly incorrect inter-range calibration values for the 8 ranges. This may have slightly affected the magnitude of the anisotropy parameters, but probably not the shape and orientation of the ellipsoids.

## **PALAEOMAGNETIC RESULTS**

Thermal and alternating field demagnetization measurements generally produced low scatter, high quality, Zijdeveld plots. Individual components generally could be separated and determined throughout the study with high precision. However, samples from the Featherbed Volcanics, in particular, showed composite breakdown of two main components over very considerable temperature and magnetic intensity intervals. This overlap resulted in extensive streaking of the end-

point vectors, with the uncontaminated, residual hard component often isolated within only the remaining few percent of magnetization. As a consequence thermal demagnetization procedures had to be continued in great detail to high temperatures. Bulk susceptibility generally showed no significant change.

Generally two main components could be identified and interpreted in a geologically meaningful way: (i) a soft component  $C1$ , sometimes distinguishable into a softer component  $C1_s$  and a slightly harder component  $C1_h$ , with a direction close to either the present local field direction, the expected normal or reverse polarity Tertiary field direction, or the expected Early Tertiary/Late Cretaceous field direction (particularly for the Featherbed Volcanics); and (ii) a hard to very hard component  $C2_h$  with a steeply-downward and generally southerly direction which is close to the expected Late Carboniferous-Early Permian direction for the region. Thermal demagnetization generally showed that isolation of component  $C2_h$  was preceded by breakdown of a slightly softer and site-wise less coherent component  $C2_s$ , which had a comparable inclination but a declination close to, but different from, the harder component. In those cases with no apparent directional variation, the Late Carboniferous-Early Permian component is denoted as  $C2$ .

In some of the locations other components could be identified, generally identified as  $C3$ , that appear to represent either: (i) equatorial directions of primary Late Devonian-Early Carboniferous origin (Star of Hope Formation volcanics, Silver Hills Volcanics); (ii) reverse polarity components of Recent or Tertiary origin (Star of Hope Formation volcanics, Featherbed Volcanics); (iii) hard to very hard normal polarity components of Recent or Late Cretaceous origin (Featherbed Volcanics); and (iv) site-wise consistent but spurious directions for which no clear interpretation can be presented at this stage. On a few occasions a softer subcomponent  $C3_s$  and a harder subcomponent  $C3_h$  could be identified.

A detailed description of remanence characteristics of the sampled locations and sites is given in Appendix B. Results for all components and subcomponents are listed in Tables 2 to 5. Representative Zijderveld plots are shown in figures 4A-D, and plots showing the normalized decay of intensity and normalized susceptibility change during progressive demagnetization are presented in figures 5A-D and 6A-D. All Zijderveld plots are shown in field-coordinates, uncorrected for bedding.

## **MAGNETIC FABRIC RESULTS**

Magnetic fabric studies were carried out on samples from the Bulgonnuna Volcanic Field and the Featherbed Volcanics, with the aim of determining primary, and possibly, secondary fabric structures within the ignimbritic flows. Planar structures may be used for the determination of bedding control (primary) and to establish deformational effects of major fault zones (secondary); linear structures may be used for determining flow transport and therefore possibly for locating eruption centres. These centres are most likely sources of hydrothermal and mineralisation activity.

TABLE 2: MEAN DIRECTIONS, COMPONENT C1 (RECENT FIELD OR EARLY TERTIARY/LATE CRETACEOUS?)

IN SITU						BEDDING CORRECTED					SOUTH POLE POSITIONS						
SITE	DECL	INCL	K	α95	N¹	DECL	INCL	K	α95	IN SITU		(BED.COR)		IN SITU		PALLAT	
										LAT	LONG	LAT	LONG	dp	dm		
										(°S)	(°E)	(°S)	(°E)	(°)	(°)	(°S)	
A) BULGONUNNA VOLCANIC FIELD																	
<u>Bulgonunna Volcanic Group rhyolite-dominated association (previously Cb)</u>																	
AFGA-B²	329.2	-47.9	16.3	19.5	5	-----	-----	-----	-----	81.7	151.8			16.6	24.5	29.0	
BFBB	15.9	-63.8	12.3	10.0	19	-----	-----	-----	-----	62.1	122.8			12.6	15.8	45.5	
BFBC	6.3	-62.5	30.9	7.6	13	-----	-----	-----	-----	66.4	135.7			9.2	11.8	43.9	
BFBA	23.0	-60.3	30.5	16.9	4	-----	-----	-----	-----	61.7	108.9			19.5	25.7	41.3	
BFBF	356.6	-47.7	30.9	11.0	7	-----	-----	-----	-----	81.3	167.2			9.4	14.4	28.8	
BFBG	359.7	-48.5	63.4	5.2	13	-----	-----	-----	-----	81.2	148.5			4.5	6.9	29.5	
AFBH-K	2.9	-59.4	29.3	10.4	8	-----	-----	-----	-----	70.3	140.9			11.7	15.6	40.2	
<u>Bulgonunna Volcanic Group dacitic-rhyolitic association (previously Cv)</u>																	
BFBE	349.4	-55.2	16.3	23.4	4	-----	-----	-----	-----	72.3	176.6			23.7	33.3	35.7	
AFBA-G,BFBD	13.6	-59.2	14.3	6.9	32	-----	-----	-----	-----	67.5	119.1			7.8	10.4	40.0	
<u>Star of Hope Formation volcanics (previously CIs,)</u>																	
BFBH	352.8	-53.6	54.9	5.0	16	-----	-----	-----	-----	75.0	170.9			4.9	7.0	34.2	
B) FEATHERBED VOLCANICS																	
BBFA	356.6	-57.2	26.4	12.0	7	-----	-----	-----	-----	68.8	152.0			12.7	17.4	37.8	
BBFB	354.7	-61.1	29.2	4.7	31	-----	-----	-----	-----	64.5	153.8			5.7	7.5	42.2	
(BBFB C1 <sub>h</sub> )	2.8	-70.2	140.7	4.1	10	-----	-----	-----	-----	52.8	141.9			6.1	7.1	54.2)³	
BBFC	3.9	-63.9	22.5	6.3	25	-----	-----	-----	-----	61.5	139.3			7.9	9.9	45.6	
(BBFC C1 <sub>r</sub> )	198.5	41.4	43.0	5.7	16	-----	-----	-----	-----	71.6	78.6			4.2	6.9	23.7)⁴	
BBFD	329.3	-70.5	22.4	7.5	18	-----	-----	-----	-----	45.7	170.0			11.2	12.9	54.7	
C) LIZZIE CREEK VOLCANICS AND CARMILA BEDS																	
<u>Lizzie Creek Volcanics</u>																	
AFLA-D	358.7	-55.5	40.7	5.7	17	-----	-----	-----	-----	74.4	151.4			5.8	8.1	36.1	
<u>Carmila Beds</u>																	
AFCA-D	1.4	-65.8	68.3	4.4	17	-----	-----	-----	-----	62.0	146.3			5.8	7.1	48.1	
D) SILVER HILLS VOLCANICS																	
ADSA-D	341.3	-54.1	31.3	7.2	14	-----	-----	-----	-----	70.3	161.1			7.1	10.1	34.6	
ADSE-H	2.6	-55.3	31.2	6.5	17	-----	-----	-----	-----	76.8	137.9			6.6	9.2	35.9	

- <sup>1)</sup> N = number of specimens(samples), i.e. 1 (pilot) specimen per oriented sample.  
<sup>2)</sup> Post-Cv granitoids, age relationship with Cb sequence uncertain.  
<sup>3)</sup> Origin uncertain, could be a (N-polarity,sic!) Late Permian component.  
<sup>4)</sup> Probably a middle Tertiary (R-polarity) overprint.

TABLE 3A: MEAN DIRECTIONS, COMPONENT C2, (LATE CARBONIFEROUS-EARLY PERMIAN)<sup>1</sup>

SITE	IN SITU					BEDDING CORRECTED					SOUTH POLE POSITIONS					
	DECL	INCL	K	$\alpha 95$	N	DECL	INCL	K	$\alpha 95$		IN SITU		BEDDING CORRECTED			
											LAT	LONG	PALLAT	LAT	LONG	PALLAT
											(°S)	(°E)	(°S)	(°S)	(°E)	(°S)
<b>A) BULGONUNNA VOLCANIC FIELD<sup>2</sup></b>																
<u>Bulgounna Volcanic Group, rhyolite dominated association (previously Cb)</u>																
AFGA-B <sup>3</sup>	206.1	80.8	37.5	10.0	7	-----	-----	-----	-----	-----	36.5	137.5	72.1	-----	-----	-----
BFBB	239.8	70.5	21.3	6.3	26	186.6	62.1	21.3	6.3		34.2	109.9	54.7	66.8	134.9	43.4
BFBC	255.8	84.5	34.4	5.1	24	250.4	64.1	34.4	5.1		23.2	135.6	79.1	28.3	99.0	45.8
BFBA	-----	-----	-----	-----	-----	-----	-----	-----	-----		-----	-----	-----	-----	-----	-----
BFBF	300.0	71.9	10.8	13.2	13	15.4	65.0	10.8	13.2		2.3	118.8	56.9	20.9N	158.3	46.9
BFBG	213.2	74.9	88.3	5.5	9	80.1	75.0	88.4	5.5		43.1	126.2	61.7	13.6	175.6	61.9
AFBH-K	264.3	76.9	43.3	7.0	11	172.2	69.1	29.4	8.6		21.1	120.8	65.1	57.6	156.3	52.6
<u>Bulgounna Volcanic Group, dacitic-rhyolitic association (previously Cv)</u>																
BFBE	230.3	76.0	35.2	10.3	7	246.7	52.2	35.4	10.3		35.7	122.0	63.4	30.1	83.8	32.8
AFBA-G,BFBD	218.6	82.5	59.9	3.7	26	285.2	68.4	277.7	3.7		31.9	136.3	75.2	7.1	110.0	51.6
<u>Star of Hope Formation volcanics (previously CIs.)</u>																
BFBH	171.3	76.6	55.3	5.4	14	215.3	66.8	62.2	5.1		45.7	152.5	64.5	49.9	111.5	49.4 <sup>4</sup>
<b>B) FEATHERBED VOLCANICS<sup>5</sup></b>																
BBFA	190.8	76.0	35.4	4.6	28	-----	-----	-----	-----		42.7	137.9	63.5	-----	-----	-----
(BBFB)	183.7	64.3	11.2	10.8	18	-----	-----	-----	-----		60.8	139.4	46.1	-----	-----	-----) <sup>4</sup>
BBFC	223.0	70.2	34.6	6.8	14	-----	-----	-----	-----		40.4	113.5	54.3	-----	-----	-----
BBFD	175.1	77.4	18.6	8.2	18	-----	-----	-----	-----		41.2	147.6	65.9	-----	-----	-----
<b>C) LIZZIE CREEK VOLCANICS AND CARMILA BEDS<sup>2</sup></b>																
AFLA-D	179.6	83.3	84.2	5.0	11	147.0	77.7	38.6	7.4		33.8	147.7	76.7	39.5	164.1	66.4
<b>D) SILVER HILLS VOLCANICS<sup>2</sup></b>																
ADSA-D	231.4	71.5	59.4	7.2	8	257.0	56.9	59.7	7.2		40.5	112.6	56.2	24.0	89.7	37.5
ADSE-H	-----	-----	-----	-----	-----	-----	-----	-----	-----		-----	-----	-----	-----	-----	-----

- <sup>1</sup>) Softer of two related components (C2<sub>1</sub>,C2<sub>n</sub>), see text.
- <sup>2</sup>) Late Carboniferous-Early Permian overprint magnetization.
- <sup>3</sup>) Post-Cv granitoids, age relationship with Cb sequence uncertain.
- <sup>4</sup>) Suspect, could be a (R-polarity) Late Cretaceous overprint.
- <sup>5</sup>) Probably Late Carboniferous-Early Permian primary magnetization.



TABLE 3B: MEAN DIRECTIONS, COMPONENT C<sub>2n</sub>, (LATE CARBONIFEROUS-EARLY PERMIAN)<sup>1</sup>

SITE	IN SITU					BEDDING CORRECTED				SOUTH POLE POSITIONS					
	DECL	INCL	K	$\alpha 95$	N	DECL	INCL	K	$\alpha 95$	IN SITU LAT (°S)	LONG (°E)	PALLAT (°S)	BEDDING CORRECTED LAT (°S)	LONG (°E)	PALLAT (°S)
<b>A) BULGONUNNA VOLCANIC FIELD<sup>2</sup></b>															
<b><u>Bulgonunna Volcanic Group, rhyolite-dominated association (previously Cb)</u></b>															
AFGA-B <sup>3</sup>	159.7	79.2	68.5	6.3	9	-----	-----	-----	-----	39.9	156.5	69.2	-----	-----	-----
BFBB	251.2	72.4	16.0	5.8	41	186.4	66.2	16.0	5.8	27.6	112.3	57.7	61.8	138.1	48.6
BFBC	222.2	85.1	46.4	3.2	44	243.7	65.1	46.5	3.2	27.9	139.8	80.3	32.9	100.5	47.1
BFBA	311.6	87.3	67.8	11.2	4	277.9	77.8	67.9	11.2	17.0	142.9	84.5	15.9	123.1	66.7
BFBF	236.4	74.6	51.6	4.9	18	56.7	79.7	51.6	4.9	34.2	117.6	60.7	9.0	163.9	70.0
BFBG	221.0	78.5	43.0	5.9	15	67.1	73.1	43.0	5.9	36.4	129.2	67.9	6.5	175.8	58.7
AFBH-K	273.0	71.1	50.2	6.2	12	187.5	70.7	22.6	9.3	15.3	11.7	55.6	55.3	139.9	54.9
<b><u>Bulgonunna Volcanic Group, dacitic-rhyolitic association (previously Cv)</u></b>															
BFBE	218.6	76.0	100.6	4.8	10	242.4	53.3	100.6	4.8	40.0	125.8	63.5	33.8	84.6	33.8
AFBA-G,BFBD	204.7	77.0	277.7	1.3	46	269.8	68.8	277.7	1.3	42.5	133.4	65.3	16.3	107.5	52.2
<b><u>Star of Hope Formation volcanics (previously CIs<sub>1</sub>)</u></b>															
BFBH	143.4	80.7	39.0	4.7	25	217.0	72.2	40.2	4.6	34.6	160.2	71.9	44.5	120.1	57.3 <sup>4</sup>
<b>B) FEATHERBED VOLCANICS<sup>5</sup></b>															
BBFA	201.8	74.3	30.9	3.9	44	-----	-----	-----	-----	43.5	129.9	60.6	-----	-----	-----
(BBFB)	175.5	62.2	27.3	5.0	32	-----	-----	-----	-----	63.4	151.9	43.4	-----	-----	-----) <sup>4</sup>
BBFC	213.2	69.7	24.8	6.2	23	-----	-----	-----	-----	45.6	117.2	53.4	-----	-----	-----
BBFD	179.0	78.1	19.0	5.4	39	-----	-----	-----	-----	40.1	145.4	67.2	-----	-----	-----
(BBFD)	161.3	73.2	195.3	6.6	4	-----	-----	-----	-----	46.2	158.8	58.8	-----	-----	-----) <sup>6</sup>
<b>C) LIZZIE CREEK VOLCANICS AND CARMILA BEDS<sup>2</sup></b>															
AFLA-D	186.6	80.9	57.6	4.6	18	163.0	76.3	29.7	6.5	38.2	145.1	72.2	45.0	158.1	64.0
<b>D) SILVER HILLS VOLCANICS<sup>2</sup></b>															
ADSA-D	220.2	67.7	28.4	7.0	16	247.5	55.5	28.5	7.0	48.9	109.1	50.6	31.2	86.6	36.0
ADSE-H	275.5	63.2	-----	-----	3	279.0	35.9	-----	-----	12.2	100.8	44.7	2.8N	98.7	36.2

- <sup>1)</sup> Harder of two related components (C<sub>21</sub>, C<sub>2n</sub>), see text.  
<sup>2)</sup> Late Carboniferous-Early Permian overprint magnetization.  
<sup>3)</sup> Post-Cv granitoids, age relationship with Cb sequence uncertain.  
<sup>4)</sup> Probably Late Carboniferous-Early Permian primary magnetization.  
<sup>5)</sup> Suspect, could be a (R-polarity) Late Cretaceous overprint.  
<sup>6)</sup> Very hard C<sub>2n</sub> component of rare occurrence.

TABLE 4: MEAN DIRECTIONS, COMPONENT C3, PRIMARY MAGNETIZATIONS

SITE	IN SITU					BEDDING CORRECTED					SOUTH POLE POSITIONS					
	DECL	INCL	K	$\alpha 95$	N	DECL	INCL	K	$\alpha 95$		IN SITU LAT (°S)	LONG (°E)	PALLAT (°S)	BEDDING CORRECTED LAT (°S)	LONG (°E)	PALLAT (°S)
<b>A) BULGONUNNA VOLCANIC FIELD</b>																
<u>Bulgonunna Volcanic Group, rhyolite dominated association (previously Cb)</u>																
BFBF	336.9	18.3	13.1	15.9	8	343.8	12.0	13.1	15.9		52.3	287.8	9.4	58.8	294.6	6.1 <sup>1</sup>
<u>Bulgonunna Volcanic Group, dacitic-rhyolitic association (previously Cv)</u>																
(BFBE	182.8	-1.3	----	----	2	181.0	-7.8	----	----		68.5	334.8	0.7	65.4	329.4	3.9) <sup>2</sup>
(AFBA-G, BFBF)	341.2	-1.0	----	----	4	343.1	-17.4	----	----		62.7	282.4	0.4N	69.9	270.4	8.9) <sup>2</sup>
(AFBA-G, BFBF)	119.0	-0.1	----	----	4	118.5	19.7	----	----		27.0	248.3	0.1	30.1	247.2	10.2) <sup>2</sup>
<u>Star of Hope Formation volcanics (previously CIs,)</u>																
BFBH	352.3	-3.0	13.8	18.7	6	352.4	2.6	14.3	18.4		69.4	304.6	1.5	66.9	307.5	1.3 <sup>3</sup>
<b>C) LIZZIE CREEK VOLCANICS AND CARMILA BEDS</b>																
<u>Carmila Beds</u>																
(AFCA-D	257.2	40.3	5.5	28.4	7	251.7	64.9	5.5	28.4		19.0	76.6	23.0	26.9	101.6	46.9) <sup>4</sup>
<b>D) SILVER HILLS VOLCANICS</b>																
ADSA-D	197.3	15.8	76.1	5.3	11	202.3	14.1	76.2	5.3		67.4	17.3	8.0	63.1	23.8	7.2 <sup>3</sup>
(ADSE-H	206.5	14.3	----	----	2	221.5	7.0	----	----		60.1	30.0	7.3	53.9	29.4	3.5) <sup>3</sup>

<sup>1)</sup> Suspect, looks like Early Carboniferous direction which is not acceptable according to present stratigraphic constraints.

<sup>2)</sup> Suspect, very badly defined and may not be realistic. Looks like Late Devonian-Early Carboniferous direction.

<sup>3)</sup> Late Devonian-Early Carboniferous primary magnetization.

<sup>4)</sup> Possibly Early-Middle Permian primary magnetization.

TABLE 5: MEAN DIRECTIONS, COMPONENT C3, VARIOUS OVERPRINTS

SITE	IN SITU					BEDDING CORRECTED				SOUTH POLE POSITIONS					
	DECL	INCL	K	$\alpha 95$	N	DECL	INCL	K	$\alpha 95$	IN SITU LAT (°S)	LONG (°E)	PALLAT (°S)	BEDDING CORRECTED LAT (°S)	LONG (°E)	PALLAT (°S)
<b>A) BULGONUNNA VOLCANIC FIELD</b>															
<u>Bulgounna Volcanic Group, rhyolite-dominated association (previously Cb)</u>															
AFGA-B	93.4	-80.8	23.2	19.5	4	-----	-----	-----	-----	18.6	128.3	72.1	-----	-----	1
<u>Star of Hope Formation volcanics (previously Cls.)</u>															
BFBH	325.0	-48.4	40.2	12.2	5	346.9	-47.6	40.2	12.2	57.2	214.5	29.4	75.6	202.2	28.7 <sup>2</sup>
<b>B) FEATHERBED VOLCANICS</b>															
BBFA	237.4	17.2	79.4	4.5	14	-----	-----	-----	-----	33.6	53.9	8.8	-----	-----	3
BBFC	219.7	6.6	97.2	9.4	4	-----	-----	-----	-----	48.7	39.8	3.3	-----	-----	3
BBFC	215.6	17.8	70.1	14.8	3	-----	-----	-----	-----	54.5	46.4	9.1	-----	-----	3
BBFA	119.9	67.9	66.7	8.3	6	-----	-----	-----	-----	31.7	184.3	51.0	-----	-----	4
BBFB	110.4	0.8	5.8	57.0	3	-----	-----	-----	-----	19.6	240.4	0.4	-----	-----	5
BBFD	196.1	-48.9	508.9	3.0	6	-----	-----	-----	-----	40.6N	163.4	29.8N	-----	-----	5
BBFD	273.3	-21.7	3.3	39.8	7	-----	-----	-----	-----	6.4	225.1	11.3N	-----	-----	5
BBFD	112.0	-46.5	199.8	18.8	2	-----	-----	-----	-----	10.4N	88.4	27.7N	-----	-----	5
<b>C) LIZZIE CREEK VOLCANICS AND CARMILA BEDS</b>															
<u>Lizzie Creek Volcanics</u>															
AFLA-D	184.9	37.4	46.8	18.2	3	-----	-----	-----	-----	85.4	63.6	20.9	-----	-----	6
<u>Carmila Beds</u>															
AFCA-D	190.5	3.6	31.0	12.2	6	186.0	13.5	28.2	12.8	69.0	358.1	1.8	75.5	352.7	6.9 <sup>7</sup>
(AFCA-D	222.7	-55.6	8.5	33.5	4	236.5	-28.5	8.5	33.5	20.7	4.1	36.2	24.2	30.2	15.2) <sup>8</sup>
<b>D) SILVER HILLS VOLCANICS</b>															
ADSE-H	284.8	-53.5	30.5	7.0	15	288.0	-80.9	30.5	7.0	24.4	208.8	34.1	17.4	151.6	83.1 <sup>9</sup>

- 1) Normal polarity, post-Kiaman overprint, presumably of Middle-Late Permian age.
- 2) Possible Middle to Late Carboniferous overprint (~320 Ma). Early Tertiary overprint seems less likely.
- 3) Expected Devonian-Carboniferous direction, not acceptable according to age dating
- 4) Possible Permo-Triassic or Jurassic-Cretaceous overprint.
- 5) Spurious direction, uncertain interpretation.
- 6) Reverse polarity Recent-Tertiary overprint?
- 7) Suspect, looks like Late Devonian-Early Carboniferous direction, which is in disagreement with Early Permian stratigraphic control.
- 8) Aberrant, may not mean anything.
- 9) Normal polarity, post-Kiaman overprint, Permo-Triassic, not sure whether bedding correction should be applied.

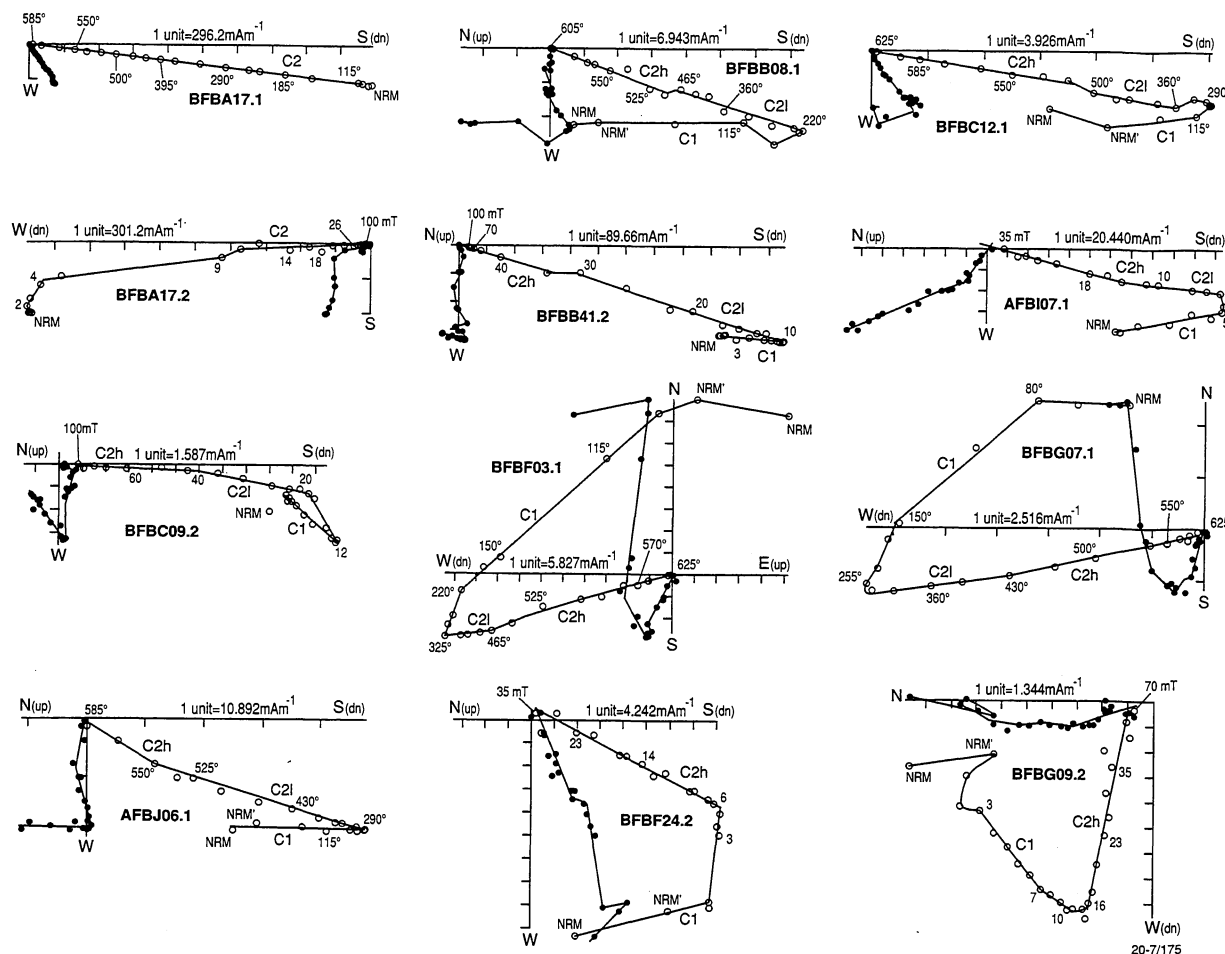


Fig.4A

Figure 4. Zijderveld (1967) plots of representative specimens during thermal and alternating field demagnetization. The orthogonal projections are shown in geographic (field) coordinates, uncorrected for tilting. The circles indicate successive positions of the end-points of the resultant magnetization vector during progressive demagnetization. Open circles indicate projections on the vertical east-west or vertical north-south plane, and solid circles indicate projections on the horizontal plane. Numbers denote successive peak field values in mT or  $^{\circ}\text{C}$ . C1, C2<sub>l</sub>, C2<sub>h</sub>, and C3 indicate the three component groups as discussed in the text. C2<sub>l</sub> and C2<sub>h</sub> represent the predominant Late Carboniferous-Early Permian overprint, or primary component, of lower or higher blocking temperature range respectively. C1, is the less pervasive overprint component of Recent, Tertiary or Late Cretaceous origin. C3, is a primary magnetization component or spurious component of unclear interpretation. The Zijderveld plots are grouped by volcanic field (A: Bulgonunna Volcanic Field; B: Featherbed Volcanics; C: Lizzie Creek Volcanics and Carmila Beds; and D: Silver Hills Volcanics) and by formation (A1: Cb sequence; A2: Cv sequence [AFGA,AFGB post-Cv granitoids]; A3 C1s<sub>l</sub> sequence; C1: Lizzie Creek Volcanics; C2: Carmila Beds). See text for description of component notation. R (after component notation) = reverse polarity component, ctd = partial enlargement as indicated by shaded box.

## Magnetic fabric results

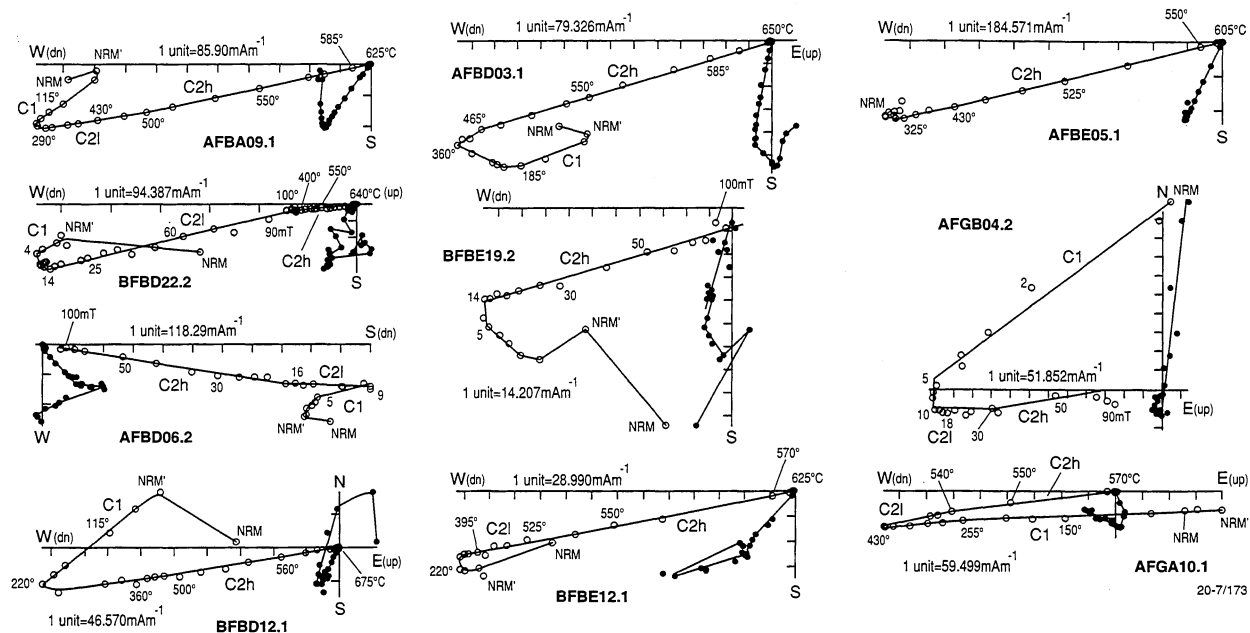


Fig.4A2, caption on page 27.

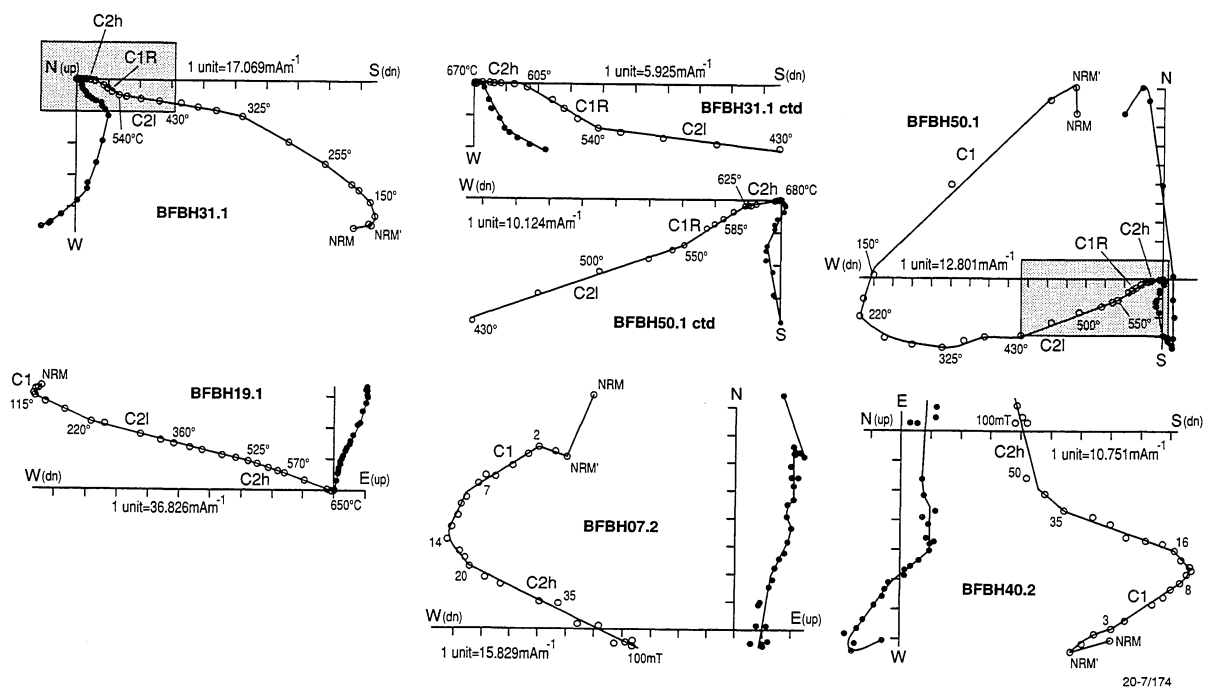


Fig.4A3, caption on page 27.

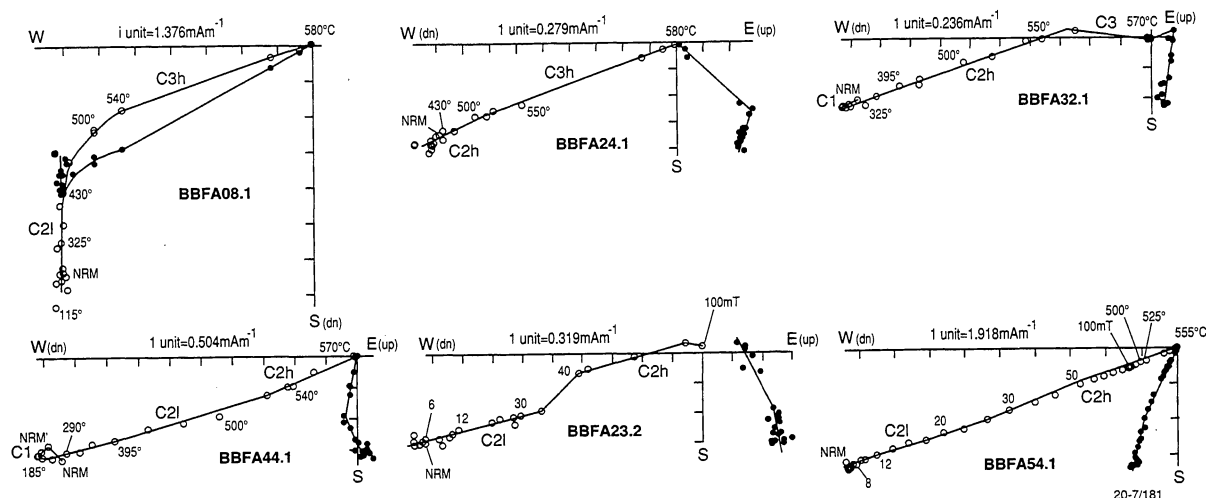


Fig.4B1, caption on page 27.

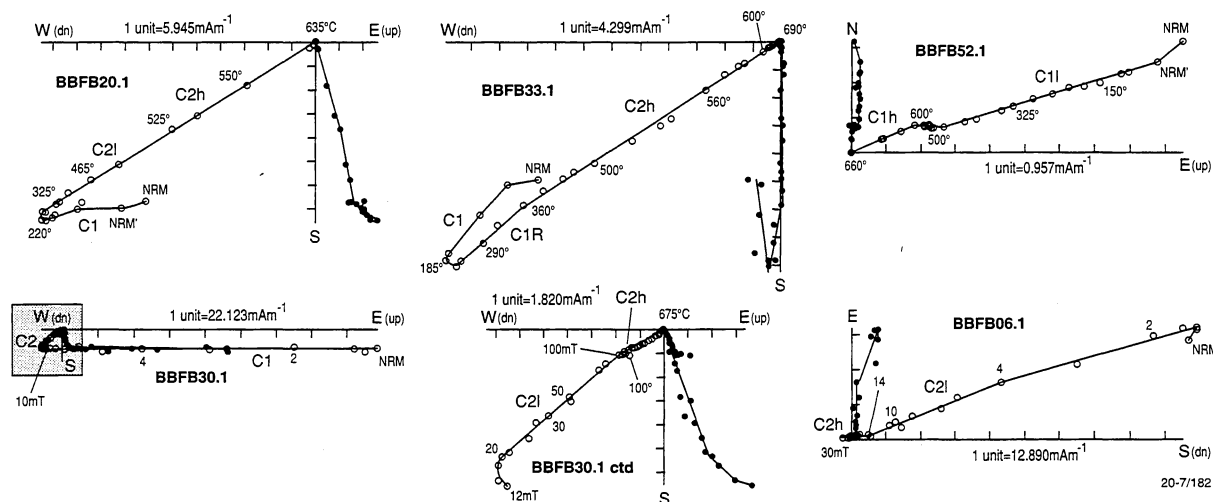


Fig.4B2, caption on page 27.

### Description of parameters

The magnetic fabric studies carried out here are based on measurements of the anisotropy of low-field magnetic susceptibility (for a general description of the method, see Aubourg et al., 1993 and references therein). Briefly, the susceptibility of a rock is characterized by a susceptibility ellipsoid, along the 3 principal axes of which, the susceptibility has a maximum, intermediate, or minimum value ( $K_{\max}$ ,  $K_{\text{int}}$  and  $K_{\min}$  respectively). Anisotropy is defined as  $K_{\max}/K_{\min}$ . Fabrics are described as having magnetic foliation (planar structures) or magnetic lineations (linear structures). With magnetic foliation, we have  $K_{\max} \approx K_{\text{int}}$  and  $K_{\text{int}} > K_{\min}$  so the ellipsoid is oblate (flattened), and the direction of  $K_{\min}$  is a pole to the foliation plane which contains  $K_{\max}$  and  $K_{\text{int}}$ . Hence magnetic foliation is defined by  $K_{\text{int}}/K_{\min}$ . With magnetic lineation  $K_{\max} > K_{\text{int}} \approx K_{\min}$ , so the ellipsoid is prolate (elongated). Hence magnetic lineation is defined by  $K_{\max}/K_{\text{int}}$ .

## Magnetic fabric results

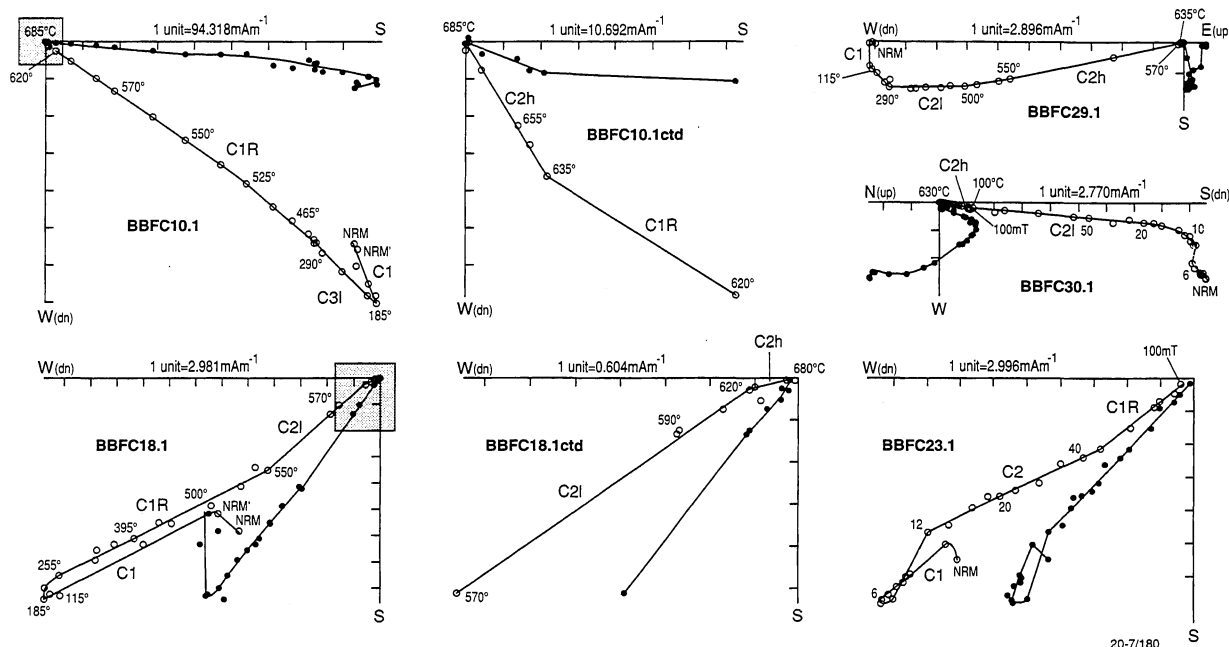


Fig.4B3, caption on page 27.

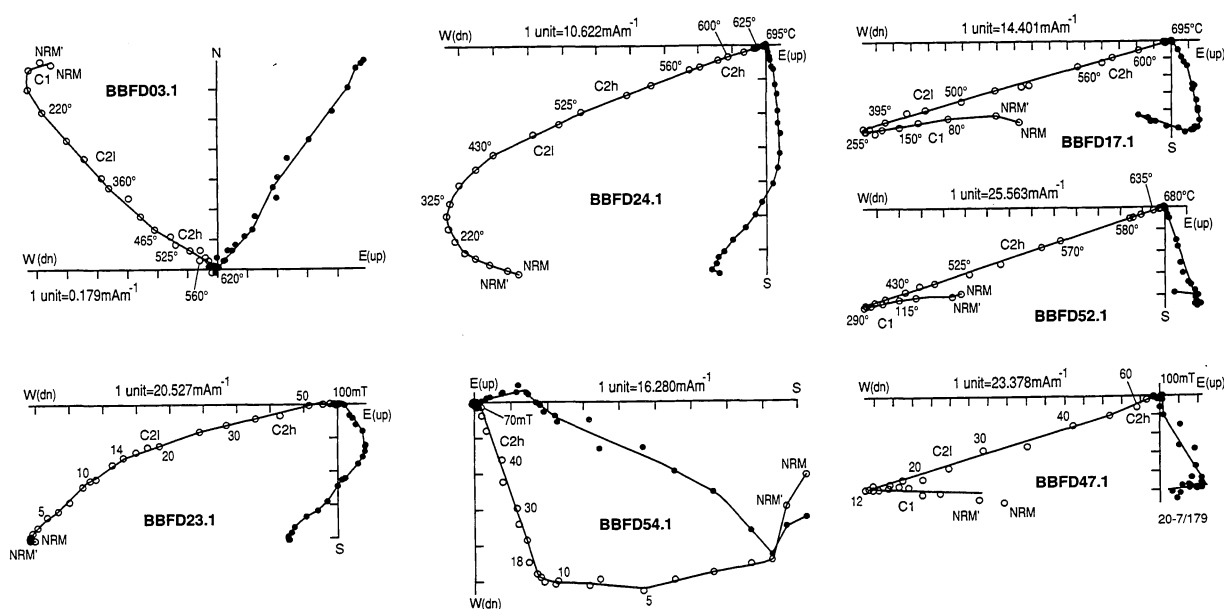


Fig.4B4, caption on page 27.

### A) Bulgonunna Volcanic Field

The anisotropy, though well defined, was generally less than 2% to 3% (see Table 6). The ellipsoids were generally oblate, characterized by planar structures rather than by lineations.

#### Planar structures:

Analysis of the  $K_{\min}$ -axes proved to be very instructive. Consistent patterns were observed throughout the Smedley Dacite sites (location 6, Fig.7A1), Arundel Rhyolite sites (location 3, Fig.7A2;



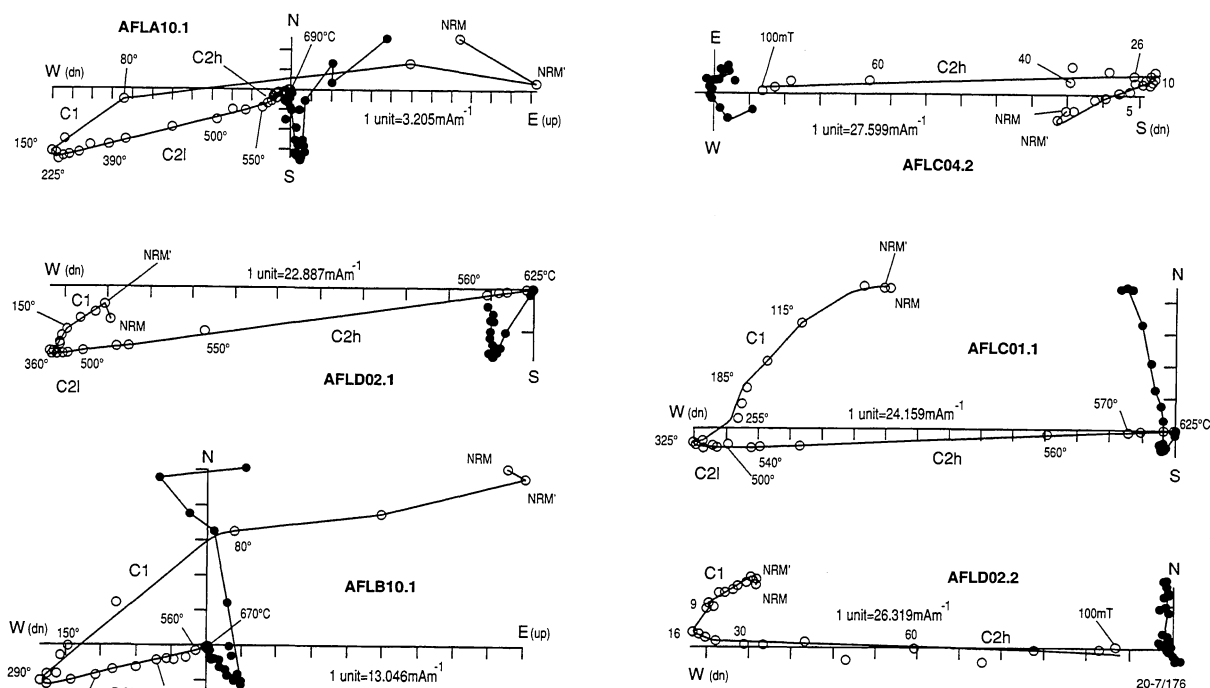


Fig.4C1, caption on page 27.

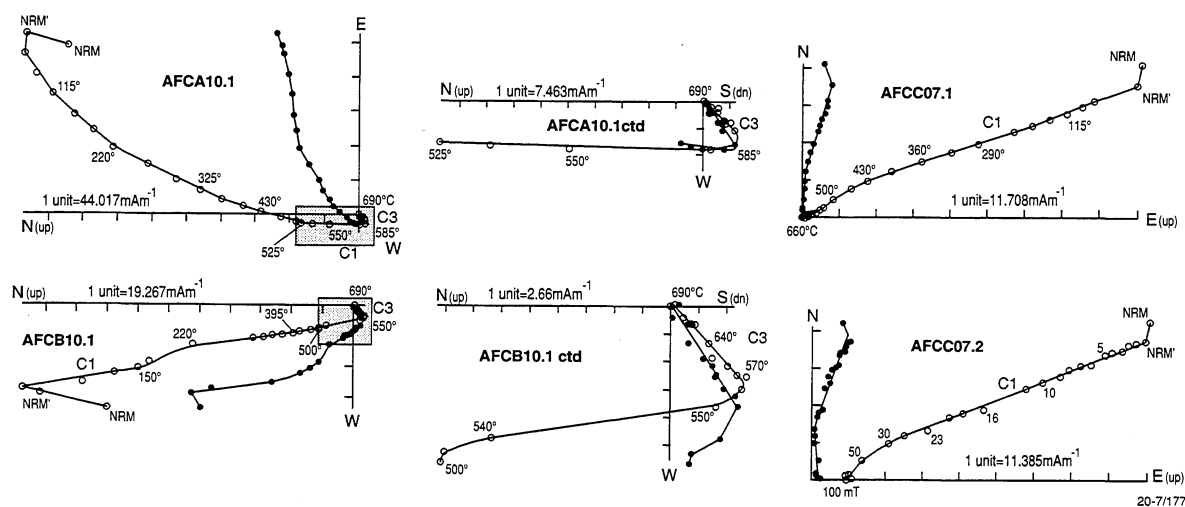


Fig.4C2, caption on page 27.

location 4 [BFBG], Fig.7A3), and some sites in rhyolitic ignimbrites associated with the Locharwood Rhyolite (Cb<sub>4</sub> [Oversby et al., 1991], location 5). The planar structures indicated by the  $K_{\min}$ -axes, as poles to those planes, generally do not relate to any observed bedding information. However, the strike of these consistent planar structures seems to relate to the surface trace of nearby major fault zones (see figures 2A and 7). The Smedley Dacite (location 6), for example, shows a particularly revealing pattern. The degree of magnetic foliation increases, from a distal 1%-2% to a more proximal 4% (Table 6), the closer the sampling sites are to the major NE-SW oriented fault zone that has been mapped directly to the north of the location. It seems reasonable, therefore, to interpret the

## Magnetic fabric results

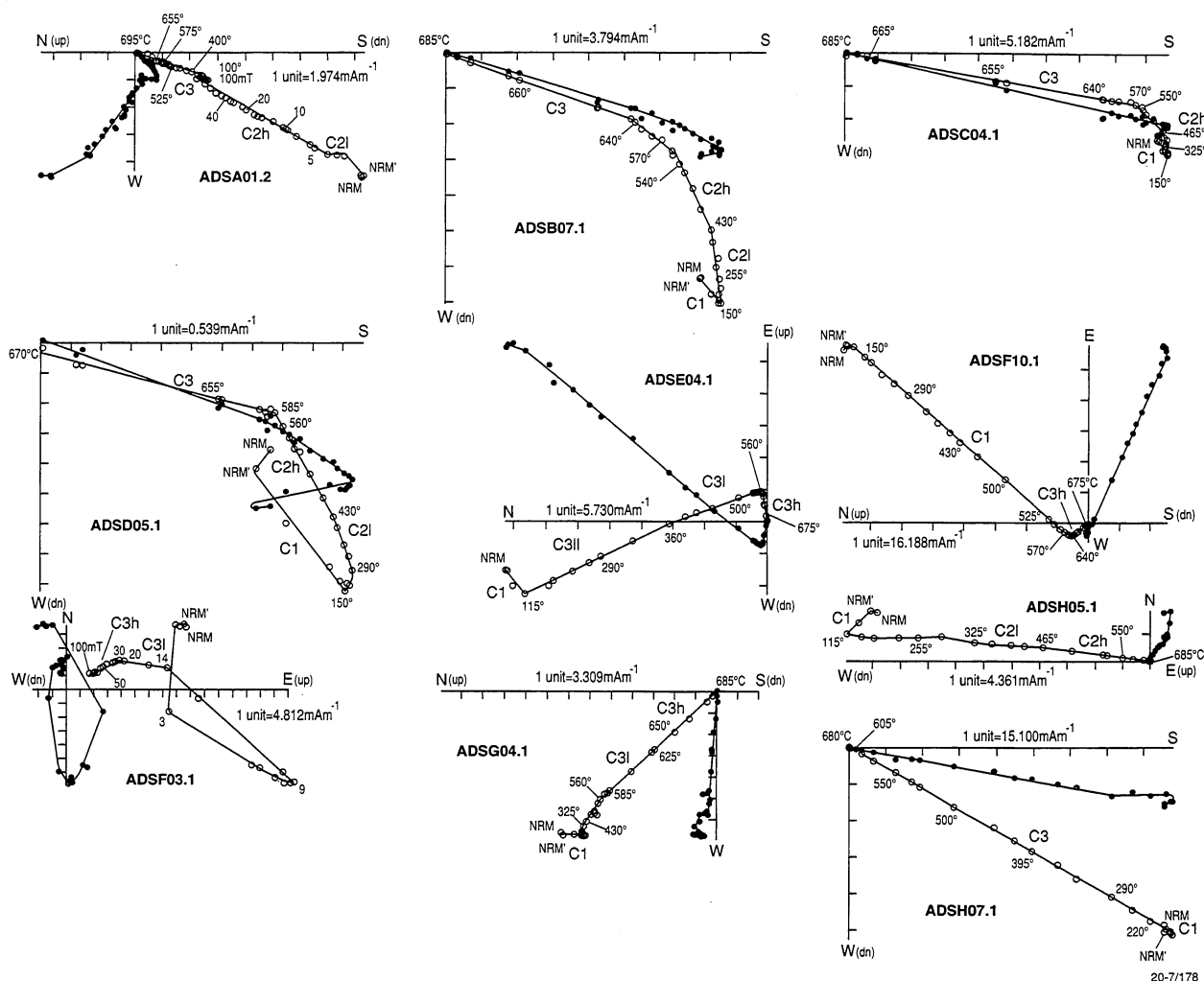


Fig.4D, caption on page 27.

Fig.5A opposite page.

Figure 5. Normalized curves showing the decay of remanent magnetization during alternating field or thermal demagnetization of representative samples, grouped by volcanic field and by formation (see caption to figure 4). The data displayed do not necessarily correspond to specimens illustrated in figures 4A-D.

### A) Bulgonunna Volcanic Field

#### Thermal demagnetization:

Cb: 1=BFBA41.1; 2=BFBA03.1; 3=BFBF16.1; 4=BFBG15.1; 5=BFBB08.1; 6=BFBC08.2; 7=BFBG01.1; 8=AFBJ06.1; 9=BFBB51.1; 10=BFBC44.1; 11=AFBH10.1

Cv: 12=AFBF10.1; 13=BFBE01.1; 14=BFBD20.1; 15=AFGA04.1; 16=AFGB04.1 (AFGA and AFGB samples are from granitoids of post-Cv origin and unclear relationship with the Cb sequence. Note that the granitoids have been grouped with the Cb sequence throughout tables and text).

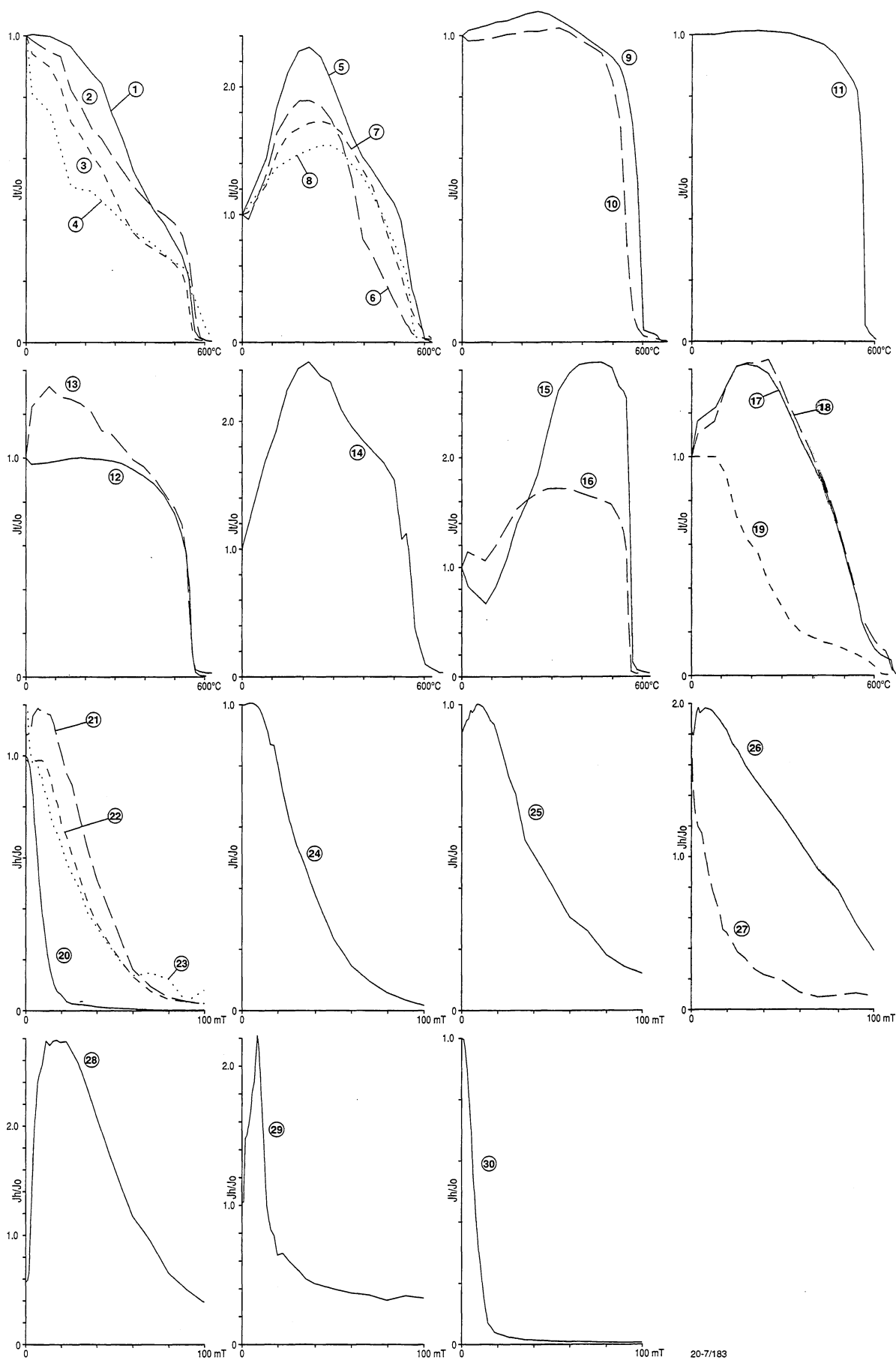
Cls<sub>1</sub>: 17=BFBH01.1; 18=BFBH21.1; 19=BFBH51.1

#### AF-demagnetization:

Cb: 20=BFBA49.2; 21=BFBB17.2; 22=BFBC40.2; 23=BFBF17.2; 24=AFBH30.1

Cv: 25=AFBA03.2; 26=BFBD22.2; 27=BFBE01.2; 28=AFGA04.2 (see above).

Cls<sub>1</sub>: 29=BFBH24.2; 30=BFBH51.2



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## Magnetic fabric results

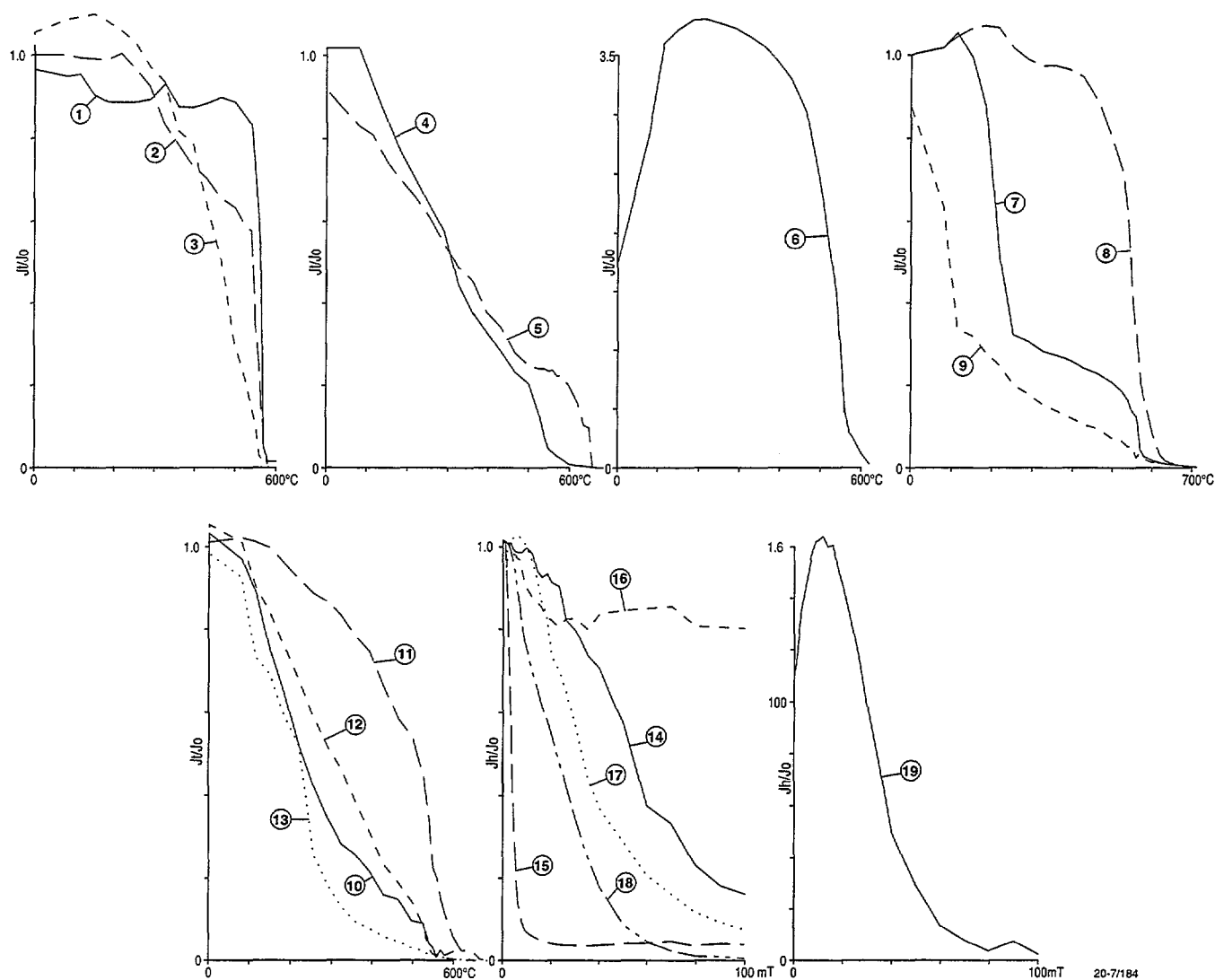


Fig.5B

### Fig.5 ctd. B) Featherbed Volcanics

#### Thermal demagnetization:

1=BBFA01.1; 2=BBFA37.1; 3=BBFA42.1; 4=BBFB13.1; 5=BBFB52.1; 6=BBFB04.1; 7=BBFC04.1; 8=BBFC09.1;  
9=BBFC36.1; 10=BBFD01.1; 11=BBFD22.1; 12=BBFD25.1; 13=BBFD57.1

#### AF-demagnetization:

14=BBFA39.1; 15=BBFB46.1; 16=BBFB55.1; 17=BBFC13.2; 18=BBFD23.1; 19=BBFD47.1

### C1) Lizzie Creek Volcanics

Thermal demagnetization: 1=AFLA01.1; 2=AFLC01.1

AF-demagnetization: 7=AFLC04.2

### C2) Carmila Beds

Thermal demagnetization: 3=AFCA06.1; 4=AFCC04.1; 5=AFCD01.1; 6=AFCB05.1

AF-demagnetization: 8=AFCC07.2; 9=AFCB02.2

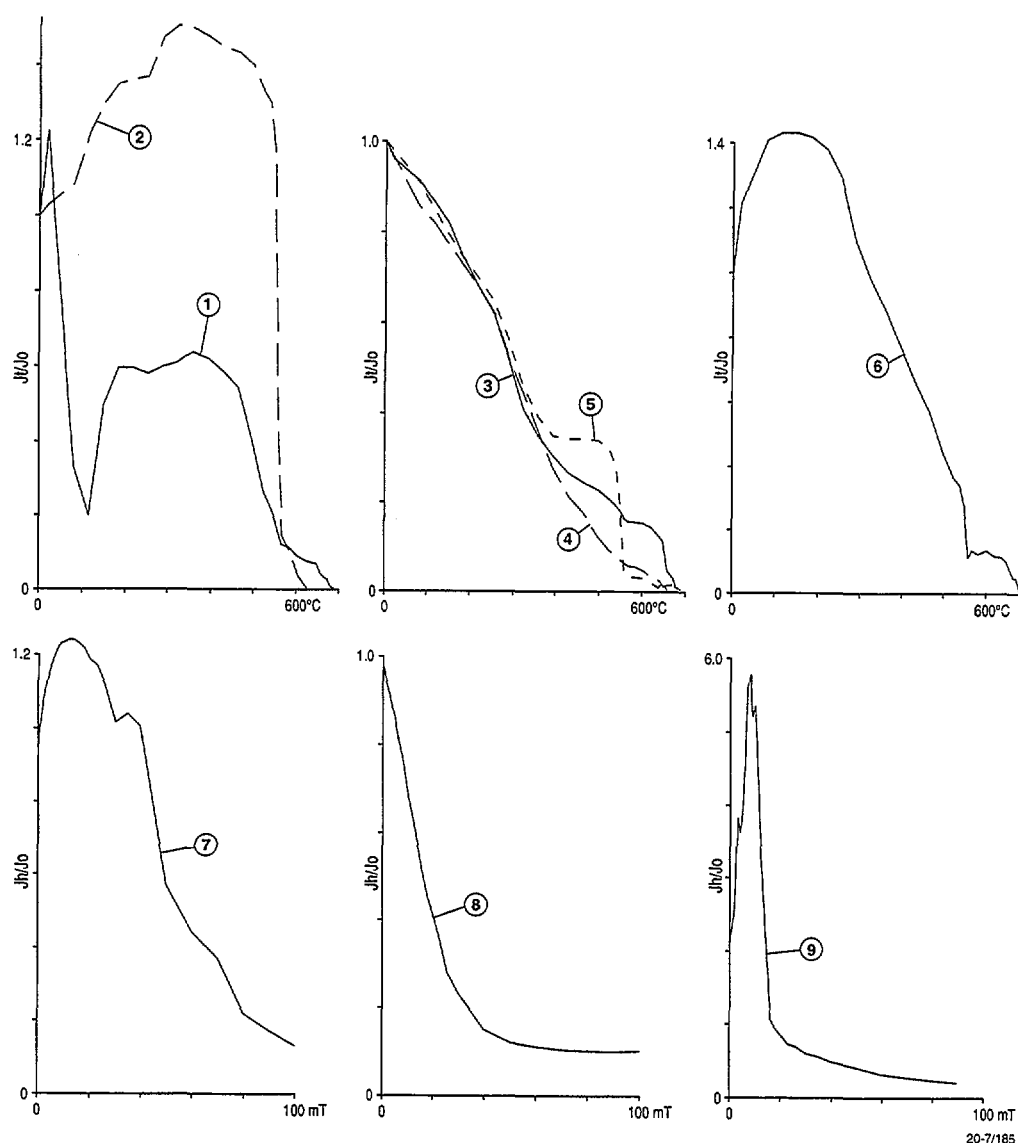


Fig.5C

magnetic foliation structures at these four localities as a secondary fabric, related to nearby major fault structures. Such planar structures are not obvious in the field nor in thin-sections. Magnetic fabric studies of these ignimbrites may thus provide a sensitive indicator of secondary fabrics, which cannot otherwise be measured and which are indicative not only of the surface trace but also for the general dip of causative fault zones.

At the above mentioned four localities, the observed dip of bedding and the interpreted dip of the nearby fault zones show a similar azimuth, with dip of the bedding far less than dip of the fault zones if the plane of magnetic foliation is taken to be indicative for the fault plane (Figs.7A1-A3). It may be speculated, therefore, that tilting of the beds is directly related to the faulting mechanism, i.e. an extensional environment with cauldron-type collapse.

## Magnetic fabric results

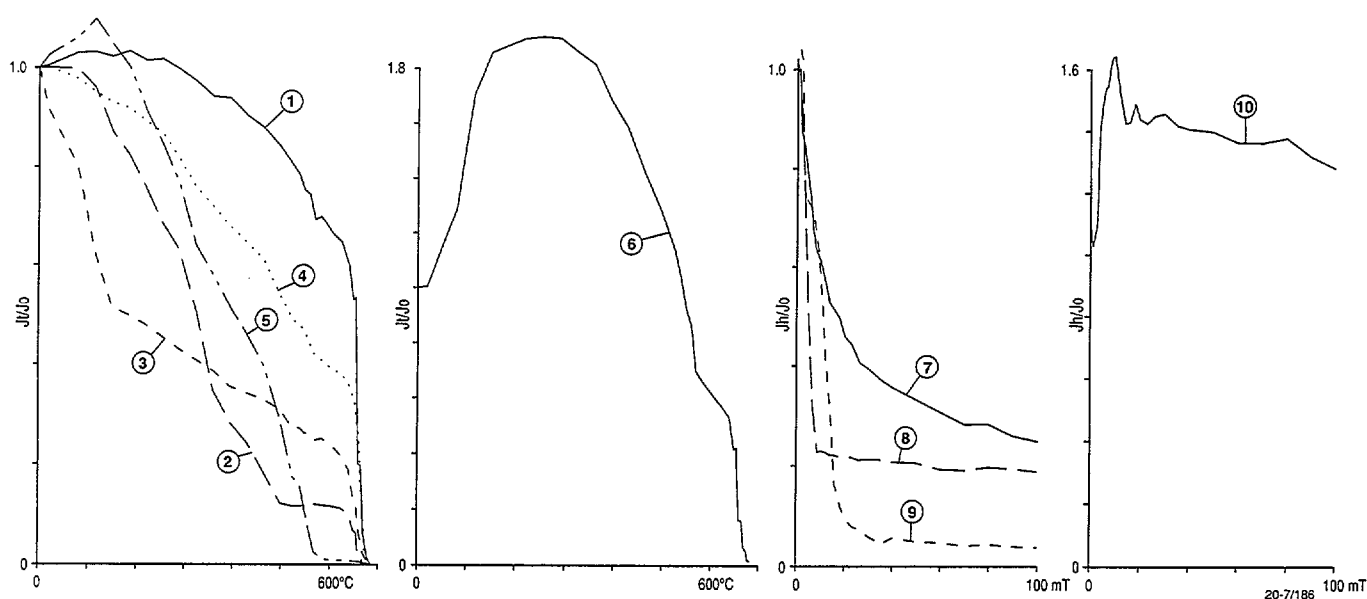


Fig.5D

### Fig.5 ctd. D) Silver Hills Volcanics

#### Thermal demagnetization:

1=ADSB01.1; 2=ADSE04.1; 3=ADSF04.1; 4=ADSG07.1; 5=ADSH05.1; 6=ADSA03.1

#### AF-demagnetization:

7=ADSA01.2; 8=ADSE04.2; 9=ADSH06.2; 10=ADSB10.2

A few of the localities showed a magnetic foliation pattern that is consistent with observed eutaxitic foliation, which is often used to determine bedding. For the BFBF sites at location 4 (Fig.2A, Table 1) there was very good agreement with the top surfaces of well-developed, columnar-jointed blocks containing rather steep eutaxitic foliation (Fig.7A4). However, this columnar structure and eutaxitic and magnetic foliation are of a local nature only, and not representative for regional dips of the ignimbrite sheet as a whole. One of the two BFBE sites at location 3, however, did show good correlation with eutaxitic foliation of the sheet. The nine BFBC sites at location 2 showed a particularly interesting development of magnetic fabric in progressing from the basal to the topmost site in this massive sheet. Upwards through the upper part of the sheet, the magnetic fabric plane progressively approached the observed eutaxitic foliation, with virtual agreement in the top site (Fig.7A5). This is to be expected for a cooling massive sheet whose unconsolidated interior undergoes rheomorphic movements simultaneously with solidification of its top surface. In terms of bedding determination, it is preferable to use the top of a regionally-massive or locally-ponded flow because the effect of any possible interference with the eutaxitic foliation recording primary bedding due to draping over existing topography would be minimized or non-existent. The observed good agreement between the magnetic foliation and bedding in this top site is therefore gratifying.

#### Linear structures:

The magnetic lineation was low, generally less than 1% and never more than 2%. Interpretation of magnetic lineation in terms of flow transport proved feasible only for those few sites

whose magnetic foliation agrees with bedding. Of these limited sites, a single site at location 3 (BFBE) and the top site at location 2 (Fig.7A5) showed an insignificant magnetic lineation (less than 1%). The four sites in the Arundel Rhyolite at location 4 (BFBF sites, Fig.7A4) show a more instructive pattern. Two of the sites show a pronounced lineation, close to 2%, whereas the two other sites show a far less-developed lineation. Corrected to the palaeo-horizontal, the pronounced  $K_{\max}$ -axes for the former two sites show a west-southwesterly orientation. This suggests an east-northeast to west-southwest transport axis. Regional mapping indicates that the eruptive centre(s) of the Arundel Rhyolite was (were) located directly beneath the main outcrop area, rather than peripheral to or outside it. Since location 4 is in a near-peripheral southwest position with respect to the main outcrop area, a flow direction to the west-southwest is the more likely. The few significant magnetic lineation observations, however, do not allow any in-depth conclusion to be drawn on regional transport patterns, let alone on the location of eruptive centres.

#### B) Featherbed Volcanics

Susceptibility anisotropy was generally well-defined, and ranged between 2% and 6% (Table 6). It was characterized by prolate ellipsoids with a more pronounced lineation rather than a foliation. The  $K_{\max}$ -axes were generally subvertical. This is surprising for subhorizontal flows. If not due to possible shape effects, this suggests an inverse fabric in which the  $K_{\max}$  rather than the  $K_{\min}$ -axis is perpendicular to the bedding plane (Rochette, 1988; Aubourg, 1990; Aubourg et al., 1993). Locations 9 (BBFA, Fig.7B3) and 10 (BBFB, Fig.7B1) show rather tight distributions of  $K_{\max}$ -axes about the vertical, with a more dispersed distribution for location 12 (BBFD, Fig.7B2). The latter site's magnetic fabric may be related to a nearby north-south oriented fault zone. Thus only a few sites showed  $K_{\max}$ -axes that were substantially off vertical. These were location 10 (BBFB41-48, Fig.7B1) and location 12 (BBFD49-56, Fig.7B2).

Application of an ad-hoc tilt correction to the site mean remanence direction for component  $C2_h$  for individual sites, based on the angular discrepancy between the  $K_{\max}$ -axis and the vertical, would lead to better agreement between them and the overall mean direction for this Late Carboniferous-Early Permian component for some sites (location 10, BBFB09-16, Fig.7B1; location 12, BBFD25-32, Fig.7B2), but not for others (location 9, BBFA33-40, Fig.7B3; location 10, BBFB41-48, Fig.7B1). Clearly, there is no convincing rationale to single out and apply such a tilt correction to the palaeomagnetic results from these last three sites merely on the basis of magnetic fabric data.

Location 11 (BBFC01-40, Fig.7B4), in contrast, shows a magnetic fabric pattern with  $K_{\max}$ -axes (lower hemisphere projection!) that are consistently offset towards the west. A tilt correction in this case, for sites 1, 3 and 5 particularly, would result in better agreement of remanence directions for the Late Carboniferous-Early Permian component ( $C2_h$ ) with the overall result, but the correction has not been applied.

Location 12 (Fig.7B2) shows a discrepantly oriented magnetic fabric for site 7 (BBFD49-56;  $K_{\max}$ -axis directed to the southwest and shallow) that may be related to a nearby major north-south oriented fault zone. This fabric may be of secondary origin, but its acquisition apparently has not affected the remanence direction for the Late Carboniferous-Early Permian component ( $C2_h$ ) which is in agreement with the overall result for this locality.

## Magnetic fabric results

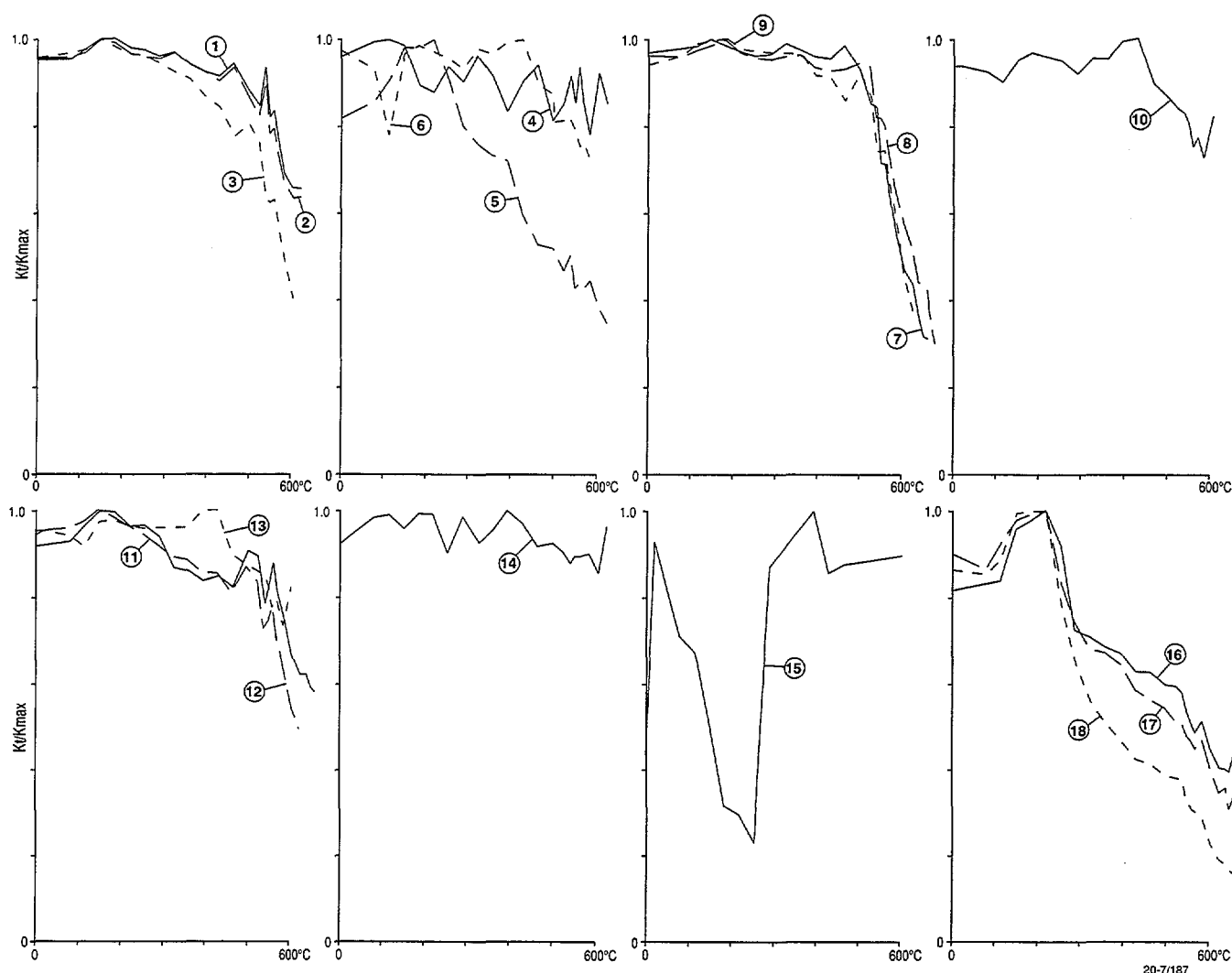


Fig.6A

Figure 6. Normalized curves showing changes in bulk susceptibility upon thermal demagnetization of representative samples, grouped by volcanic field and by formation (see caption to figure 4).

### A) Bulgonunna Volcanic Field

Cb: 1=BFBA41.1; 2=BFBA03.1; 3=BFBF16.1; 4=BFBB08.1; 5=BFBC08.2; 6=BFBG01.1; 7=BFBB51.1; 8=BFBC44.1; 9=BFBF17.1; 10=AFBH10.1

Cv: 11=BFBE01.1; 12=BFBD20.1; 13=AFBF10.1; 14=AFGA04.1; 15=AFGB04.1 (see note on post-Cv granitoids in the captions to figure 5).

Cls: 16=BFBH01.1; 17=BFBH21.1; 18=BFBH51.1

### B) Featherbed Volcanics

1=BBFA01.1; 2=BBFA37.1; 3=BBFA42.1; 4=BBFB13.1; 5=BBFB52.1; 6=BBFB04.1; 7=BBFD01.1; 8=BBFD22.1; 9=BBFD25.1; 10=BBFD57.1

### C1) Lizzie Creek Volcanics

1=AFLA01.1; 2=AFLC01.1

### C2) Carmila Beds

3=AFCA06.1; 4=AFCC04.1; 5=AFCD01.1; 6=AFCB05.1

### D) Silver Hills Volcanics

7=ADSA03.1; 8=ADSB01.1; 9=ADSE04.1; 10=ADSF04.1



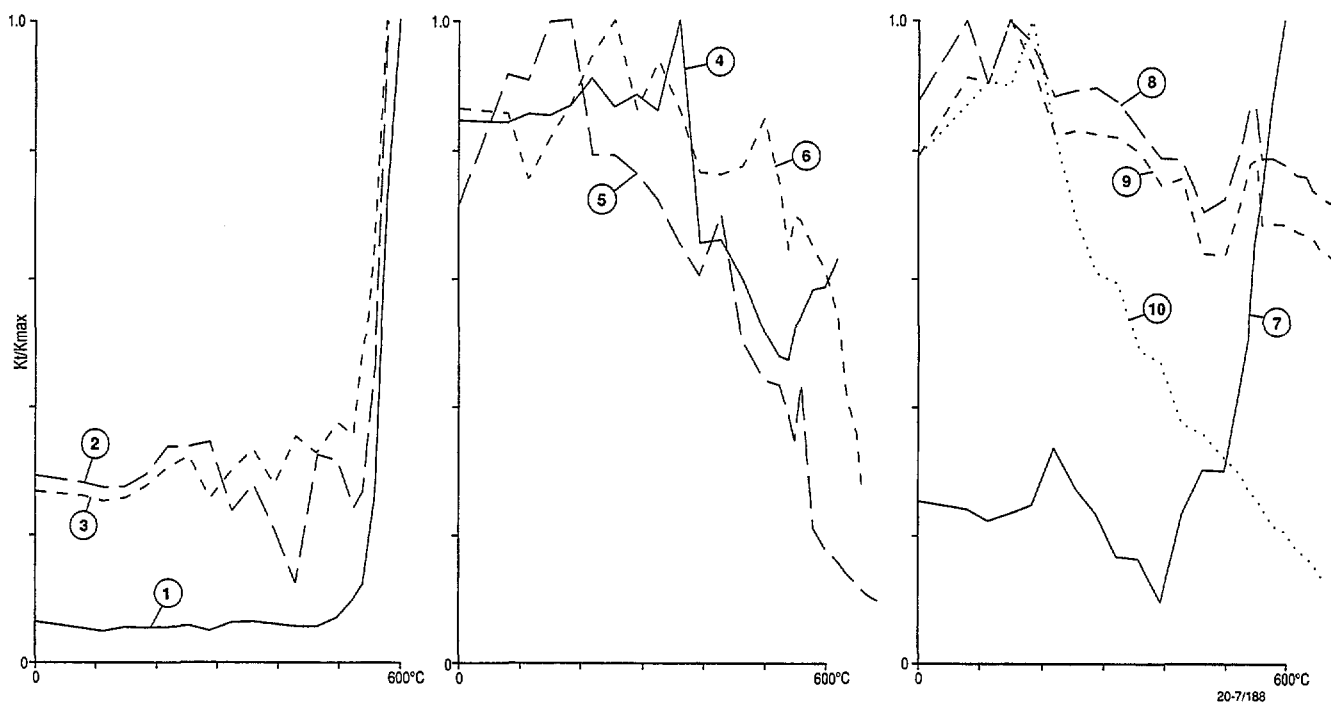


Fig.6B

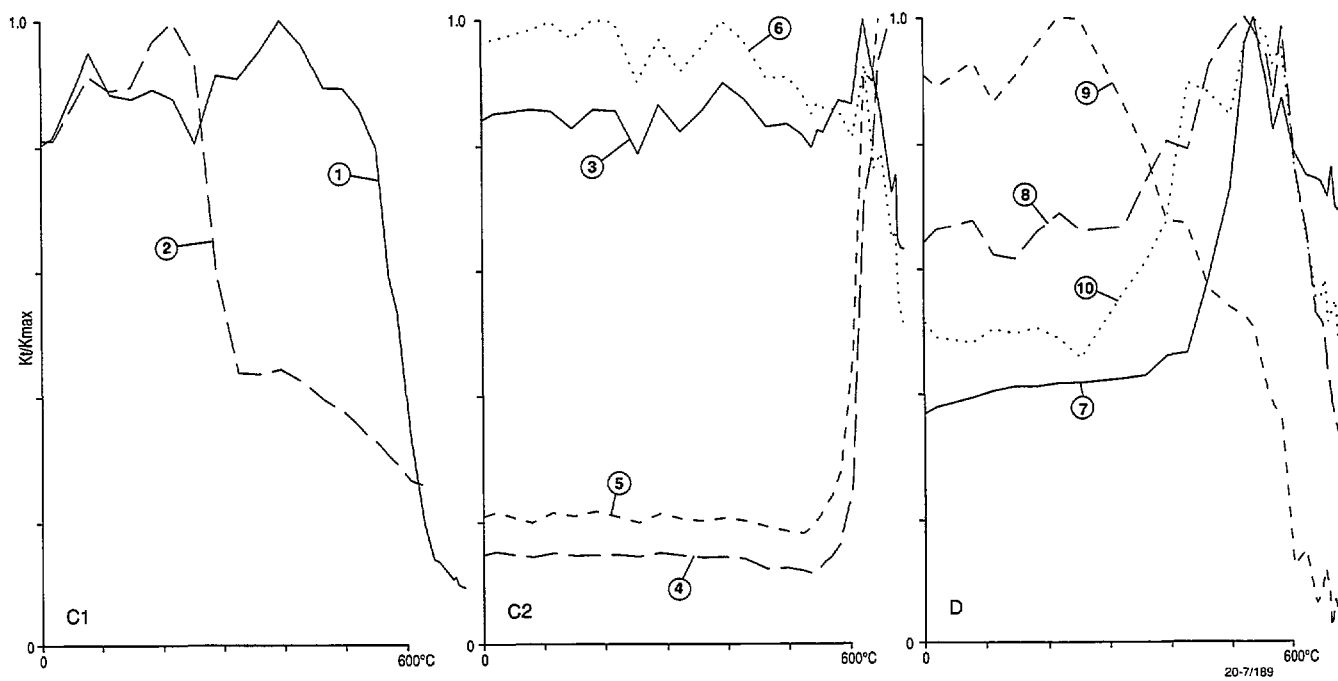


Fig.6C,D

TABLE 6: MAGNETIC FABRIC RESULTS

SITE <sup>1</sup>	POLE TO BEDDING		N	DEC	K <sub>max</sub>	INC	DEC	K <sub>int</sub>	INC	DEC	K <sub>min</sub>	INC	ANIS% <sup>2</sup>	LIN% <sup>2</sup>	FOL% <sup>2</sup>	T <sup>3</sup>	PROL <sup>3</sup>	BULK SUSC <sup>4</sup>
A) BULGONUNNA VOLCANIC FIELD <u>rhyolite-dominated association (previously Cb)</u>																		
LOCATION 1																		
1= BFBB01-08	321.6	66.6	10	81.6	66.7	197.7	10.8	291.8	20.5	3.11	2.47	0.62	-0.5953	1.0184	63.7795			
2= BFBB09-16	321.6	66.6	10	23.1	70.6	200.3	19.3	290.6	0.9	0.48	0.24	0.24	0.0028	1.0000	422.703			
3= BFBB17-24	321.6	66.6	10	181.6	51.1	78.2	10.6	340.1	36.9	2.31	1.28	1.02	-0.1165	1.0027	1127.60			
4= BFBB25-32	321.6	66.6	10	158.0	61.1	62.6	3.0	331.0	28.8	1.95	1.20	0.74	-0.2371	1.0046	1266.54			
5= BFBB33-40	321.6	66.6	10	138.3	59.9	355.1	24.9	257.5	15.8	1.37	0.94	0.42	-0.3757	1.0051	230.079			
6= BFBB41-48	321.6	66.6	10	143.2	42.0	277.3	37.7	28.4	25.0	1.76	1.14	0.61	-0.3050	1.0053	409.932			
7= BFBB49-56	321.6	66.6	10	164.1	39.0	259.8	7.0	358.3	50.2	2.32	1.30	1.01	-0.1279	1.0029	369.741			
8= BFBB57-64	321.6	66.6	10	350.1	38.8	229.8	32.1	113.9	34.8	1.33	0.72	0.60	-0.0943	1.0012	600.476			
9= BFBB65-72	321.6	66.6	10	352.9	8.2	84.4	10.1	224.4	76.9	1.50	1.00	0.50	-0.3343	1.0050	1793.94			
LOCATION 2																		
1= BFBC01-08	68.9	69.5	10	196.6	37.1	294.2	9.9	36.8	51.1	1.54	0.59	0.95	0.2332	0.9964	8.05689			
2= BFBC09-16	68.9	69.5	10	47.2	87.3	214.2	2.6	304.2	0.6	2.59	0.74	1.84	0.4226	0.9892	34.2471			
3= BFBC17-24	68.9	69.5	10	264.0	30.1	11.7	27.7	135.8	46.9	2.40	0.11	2.29	0.9058	0.9787	831.824			
4= BFBC25-32	68.9	69.5	10	114.5	28.7	20.7	6.9	278.5	60.4	2.92	0.97	1.93	0.3283	0.9906	292.607			
5= BFBC33-40	68.9	69.5	10	351.3	22.9	81.7	0.9	173.9	67.1	2.03	0.38	1.65	0.6243	0.9875	434.821			
6= BFBC41-48	68.9	69.5	10	310.8	34.8	46.9	8.6	148.7	53.8	2.18	0.81	1.36	0.2545	0.9945	305.187			
7= BFBC49-56	68.9	69.5	10	342.6	20.1	250.3	6.4	143.4	68.6	1.47	0.56	0.90	0.2336	0.9966	1052.51			
8= BFBC57-64	68.9	69.5	10	347.8	13.9	252.4	21.0	108.9	64.5	2.50	0.34	2.16	0.7256	0.9822	1262.66			
9= BFBC65-72	68.9	69.5	10	174.5	2.2	265.6	25.8	80.0	64.1	3.41	0.03	3.37	0.9797	0.9677	1383.76			
LOCATION 3																		
1= BFBA01-08	89.2	80.0	10	208.3	32.4	318.2	28.2	79.9	44.4	3.37	0.84	2.51	0.4957	0.9837	1723.79			
2= BFBA09-16	89.2	80.0	10	176.9	10.8	280.2	50.4	78.4	37.6	1.77	0.30	1.46	0.6551	0.9886	1510.58			
3= BFBA17-24	89.2	80.0	10	326.1	33.1	207.0	36.7	84.3	35.9	1.56	0.66	0.90	0.1542	0.9976	2051.75			
4= BFBA25-32	89.2	80.0	10	307.6	36.5	197.6	24.8	81.8	43.3	2.16	0.76	1.39	0.2937	0.9937	2105.84			
5= BFBA33-40	89.2	80.0	10	298.3	42.9	188.5	20.0	80.6	40.4	1.56	0.76	0.80	0.0243	0.9996	1925.47			
6= BFBA41-48	89.2	80.0	10	310.8	35.1	208.4	16.9	97.3	49.9	1.66	0.91	0.75	-0.0926	1.0015	2104.56			
7= BFBA49-56	89.2	80.0	10	201.1	27.9	316.4	39.0	86.3	38.4	2.71	0.71	1.98	0.4665	0.9876	2191.80			
LOCATION 4																		
1= BFBF01-08	149.7	42.5 <sup>5</sup>	10	296.4	41.7	42.0	16.8	148.6	43.5	2.48	0.08	2.41	0.9375	0.9773	1716.36			
2= BFBF09-16	149.7	42.5 <sup>5</sup>	10	257.7	16.7	4.1	43.4	152.1	41.9	4.08	1.73	2.31	0.1421	0.9943	2345.19			
3= BFBF17-24	149.7	42.5 <sup>5</sup>	10	248.6	21.8	3.2	46.2	141.9	35.7	1.88	0.75	1.12	0.1987	0.9963	1552.22			
4= BFBF25-32	149.7	42.5 <sup>5</sup>	10	245.7	20.5	348.2	30.1	126.8	52.3	3.61	1.76	1.82	0.0167	0.9994	1462.67			

TABLE 6 ctd  
MAGNETIC FABRIC RESULTS

SITE <sup>1</sup>	POLE TO BEDDING		N	DEC	K <sub>max</sub>	INC	DEC	K <sub>int</sub>	INC	DEC	K <sub>min</sub>	INC	ANISX <sup>2</sup>	LINX <sup>2</sup>	FOLX <sup>2</sup>	T <sup>3</sup>	PROL <sup>3</sup>	BULK SUSC <sup>4</sup>
LOCATION 4																		
1= BFBG01-08	236.5	62.3	10	51.2	65.2	149.6	3.9	241.4	24.4	4.89	2.15	2.68	0.1068	0.9949	41.0544			
2= BFBG09-16	236.5	62.3	10	133.7	64.8	353.2	20.0	257.7	14.7	3.98	1.24	2.71	0.3698	0.9857	205.468			
3= BFBG17-24	236.5	62.3	10	136.6	72.6	333.5	16.7	242.0	4.8	5.24	3.81	1.38	-0.4646	1.0240	93.6831			
LOCATION 5																		
1= AFBH01-10	320.6	52.8	4	72.9	42.6	201.5	34.1	313.0	28.4	2.91	1.21	1.68	0.1613	0.9954	2058.19			
2= AFBH01-10	320.6	52.8	6	62.9	49.5	219.5	38.1	318.9	11.7	2.32	0.37	1.94	0.6763	0.9846	3255.29			
3= AFBH01-10	325.5	69.2	5	86.4	8.0	351.5	31.3	189.1	57.5	7.94	1.48	6.36	0.6147	0.9541	196.769			
4= AFBH01-10	284.4	82.7	7	334.7	51.1	217.8	20.0	114.8	31.7	1.05	0.43	0.62	0.1809	0.9981	2365.58			
LOCATION 8 <sup>5</sup>																		
1= AFGA01-10	Unknown		10	238.1	82.1	95.2	6.3	4.7	4.7	3.26	2.46	0.78	-0.5165	1.0167	10230.2			
2= AFGH01-10	Unknown		10	335.1	68.8	199.1	15.6	105.1	14.0	1.80	0.73	1.06	0.1826	0.9968	13542.4			
<u>Dacitic-rhyolitic association, previously Cv</u>																		
LOCATION 3																		
1= BFBE01-10	77.0	65.2	10	316.7	15.5	220.9	20.1	81.6	64.2	1.94	0.36	1.57	0.6244	0.9881	4334.22			
2= BFBE11-20	77.0	65.2	10	306.4	59.7	130.3	30.2	39.3	1.7	1.20	0.76	0.44	-0.2693	1.0032	4332.03			
LOCATION 6 <sup>7</sup>																		
1= BFBD21-30	127.1	70.0	10	307.0	58.4	43.5	4.0	135.9	31.3	4.07	1.26	2.77	0.3712	0.9853	3905.82			
2= BFBD11-20	127.1	70.0	10	317.3	65.1	227.3	0.0	137.2	24.9	3.75	2.23	1.48	-0.1985	1.0073	4083.41			
3= BFBD01-10	127.1	70.0	10	353.4	54.4	244.2	13.2	145.7	32.4	1.67	0.41	1.25	0.5014	0.9917	4446.15			
4= AFBH01-10	127.1	70.0	10	4.9	67.6	226.7	17.1	132.3	14.0	1.56	0.96	0.59	-0.2413	1.0037	3651.35			
5= AFBH01-10	127.1	70.0	10	27.9	68.8	237.7	18.6	144.4	9.8	1.72	0.30	1.42	0.6480	0.9890	5031.05			
6= AFBH01-10	127.1	70.0	10	357.3	80.5	226.1	6.3	135.3	7.1	1.27	0.56	0.71	0.1223	0.9985	4965.63			
7= AFBH01-10	127.1	70.0	10	355.6	71.6	237.4	8.9	144.8	15.9	1.27	0.43	0.84	0.3244	0.9959	5438.44			
8= AFBH01-10	127.1	70.0	10	248.5	42.0	20.5	36.6	132.1	26.3	2.22	1.20	1.01	-0.0817	1.0018	5011.71			
9= AFBH01-10	127.1	70.0	10	226.5	59.7	24.4	28.4	119.7	9.6	1.25	0.81	0.43	-0.3032	1.0038	6183.90			
10=AFBG01-10	127.1	70.0	10	11.3	84.2	216.0	5.3	125.8	2.4	2.72	1.08	1.62	0.1977	0.9947	4449.54			

TABLE 6 ctd  
MAGNETIC FABRIC RESULTS

SITE <sup>1</sup>	POLE TO BEDDING		N	DEC	K <sub>max</sub>	INC	DEC	K <sub>int</sub>	INC	DEC	K <sub>min</sub>	INC	ANIS% <sup>2</sup>	LIN% <sup>2</sup>	FOL% <sup>2</sup>	T <sup>3</sup>	PROL <sup>3</sup>	BULK SUSC <sup>4</sup>
<u>Star of Hope Formation volcanics (previously Cls.)</u>																		
<b>LOCATION 7</b>																		
1= BFBH01-10	63.7	70.6	10	123.4	85.6	344.5	3.3	254.4	2.9	0.90	0.58	0.32	-0.2890	1.0026	592.921			
2= BFBH11-20	63.7	70.6	10	4.0	80.5	217.1	8.0	126.3	5.1	3.47	2.93	0.53	-0.6913	1.0239	92.3628			
3= BFBH21-30	63.7	70.6	10	65.4	79.5	309.0	4.7	218.3	9.3	1.95	1.11	0.83	-0.1456	1.0028	247.764			
4= BFBH31-40	73.9	74.2	10	127.4	76.6	247.3	6.8	338.7	11.5	2.48	0.45	2.01	0.6306	0.9847	148.147			
5= BFBH41-50	73.9	74.2	10	124.5	56.7	350.1	24.7	250.0	20.8	1.00	0.59	0.40	-0.1842	1.0018	724.053			
6= BFBH51-60	73.9	74.2	10	7.3	84.2	133.6	3.5	223.9	4.7	1.71	1.19	0.52	-0.3921	1.0067	1135.28			
<b>B) FEATHERBED VOLCANICS</b>																		
<b>LOCATION 9</b>																		
1= BBFA01-08			10	220.8	86.1	18.7	3.6	108.8	1.4	4.73	3.56	1.13	-0.5126	1.0240	21.3609			
2= BBFA09-16			10	211.9	84.3	27.4	5.6	117.4	0.4	3.91	3.63	0.27	-0.8576	1.0335	21.5885			
3= BBFA17-24			10	218.4	86.4	49.8	3.6	319.7	0.7	3.61	3.18	0.41	-0.7667	1.0276	8.71744			
4= BBFA25-32			10	21.5	85.2	266.2	2.1	176.0	4.3	4.84	4.24	0.57	-0.0057	1.0365	8.14679			
5= BBFA33-40			10	102.3	64.3	309.5	23.1	215.0	10.5	1.62	0.96	0.65	-0.1933	1.0031	11.1608			
6= BBFA41-48			10	290.2	82.0	61.8	5.3	152.3	6.0	3.82	3.16	0.64	-0.6589	1.0250	20.3244			
7= BBFA49-56			10	117.6	86.9	226.8	1.0	316.8	2.9	3.93	3.70	0.22	-0.8837	1.0347	21.6043			
8= BBFA57-64			10	301.7	81.9	40.5	1.2	130.6	8.0	3.39	3.07	0.31	-0.8143	1.0275	21.9234			
<b>LOCATION 10</b>																		
1= BBFB01-08			10	80.6	84.8	341.7	0.8	251.6	5.2	2.56	2.29	0.26	-0.7926	1.0202	46.2450			
2= BBFB09-16			10	308.2	78.5	60.9	4.5	151.7	10.6	1.05	0.89	0.16	-0.6881	1.0072	428.225			
3= BBFB17-24			10	197.2	69.1	322.7	12.5	56.4	16.5	2.31	2.09	0.22	-0.8063	1.0186	138.765			
4= BBFB25-32			10	253.7	81.9	357.5	1.9	87.7	7.9	2.39	2.30	0.09	-0.9271	1.0221	154.733			
5= BBFB33-40			10	248.4	80.6	134.1	3.9	43.5	8.5	3.26	2.59	0.66	-0.5912	1.0192	87.0664			
6= BBFB41-48			10	270.3	40.6	54.6	43.5	163.3	18.8	1.30	0.64	0.66	0.0132	0.9998	748.854			
7= BBFB49-56			10	152.9	84.0	308.8	5.5	39.0	2.4	3.86	3.49	0.36	-0.8094	1.0312	21.1754			
8= BBFB57-64			10	351.3	64.1	57.4	5.8	150.2	25.1	5.77	0.65	5.08	0.7688	0.9578	44.3697			
<b>LOCATION 11</b>																		
1= BBFC01-08			10	346.4	55.0	100.0	15.7	199.5	30.4	1.22	0.95	0.27	-0.5614	1.0069	518.738			
2= BBFC09-16			10	325.5	70.6	89.8	11.2	183.0	15.6	1.21	1.03	0.17	-0.7121	1.0086	2022.29			
3= BBFC17-24			10	247.7	61.4	155.4	1.2	64.7	28.6	1.75	1.09	0.65	-0.2479	1.0043	246.747			
4= BBFC25-32			10	315.4	81.9	86.5	5.4	177.0	6.1	2.88	2.49	0.38	-0.7343	1.0210	35.9698			
5= BBFC33-40			10	311.0	72.9	133.0	17.1	42.8	0.5	6.06	5.04	0.97	-0.6710	1.0403	7.00789			

TABLE 6 ctd  
MAGNETIC FABRIC RESULTS

SITE <sup>1</sup>	POLE TO BEDDING	N	DEC $K_{max}$	INC	DEC $K_{int}$	INC	DEC $K_{min}$	INC	ANIS% <sup>2</sup>	LIN% <sup>2</sup>	FOL% <sup>2</sup>	T <sup>3</sup>	PROL <sup>3</sup>	BULK SUSC <sup>4</sup>
<b>LOCATION 12</b>														
1= BBFD01-08		10	41.1	76.0	190.5	12.1	282.5	6.9	3.79	3.35	0.42	-0.7730	1.0292	11.1259
2= BBFD09-16		10	358.7	74.7	154.7	14.1	246.2	6.0	4.27	2.30	1.93	-0.0850	1.0036	10.5559
3= BBFD17-24		10	53.2	76.5	212.8	12.6	303.8	4.6	5.01	1.35	3.62	0.4529	0.9781	144.410
4= BBFD25-32		10	205.7	68.2	9.3	21.0	101.4	5.6	2.39	0.81	1.57	0.3213	0.9924	505.883
5= BBFD33-40		10	22.8	76.4	213.5	13.3	122.9	2.4	2.49	0.98	1.50	0.2061	0.9949	563.734
6= BBFD41-48		10	289.5	73.0	35.5	4.8	126.9	16.2	3.07	1.50	1.55	0.0167	0.9995	576.216
7= BBFD49-56		10	236.0	34.5	352.8	33.2	113.5	38.0	2.71	1.56	1.14	-0.1548	1.0041	580.567
8= BBFD57-64		10	166.2	74.9	330.3	14.5	61.3	4.0	2.26	1.75	0.50	-0.5521	1.0124	311.209

<sup>1)</sup> Site numbers refer to figure 7.

<sup>2)</sup> Anis% =  $(K_{max}/K_{min}-1)*100$ ; Linearity L =  $K_{max}/K_{min}$ , Lin% =  $(L-1)*100$ ; Foliation F =  $K_{int}/K_{min}$ , Fol% =  $(F-1)*100$ .

<sup>3)</sup> Prolate ellipsoid (linear fabric), L/F > 1.0; oblate ellipsoid (planar fabric) L/F < 1.0.

Shape parameter T =  $2\log F/\log P - 1$  (Degree of anisotropy P =  $K_{max}/K_{min}$ ).

<sup>4)</sup> Bulk susceptibility in Gauss.cm<sup>3</sup>/Oersted.

<sup>5)</sup> Local observation, based on well-developed columnar jointing. Regional bedding is different, see BFEG sites (pole: 236.5°/62.3°).

<sup>6)</sup> Post-Cv granitoids, age relationship with Cb sequence uncertain.

<sup>7)</sup> Sites listed on profile from NE to SW.

## Magnetic fabric results

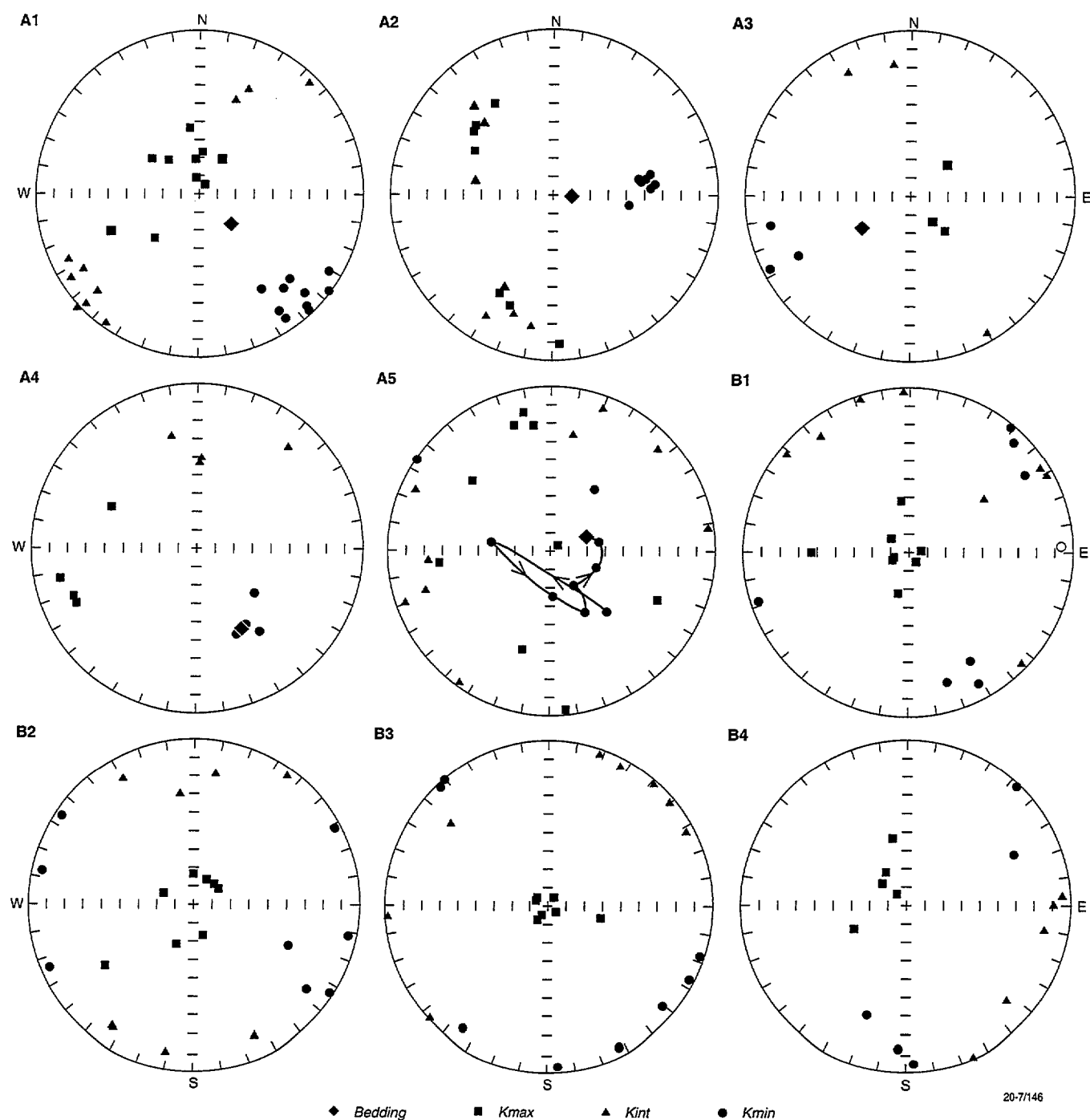


Fig.7

Figure 7. Magnetic fabric analysis. Principal susceptibility axes for mean anisotropy ellipsoids for individual sites (Table 6) shown for various sampled locations in the Bulgonunna Volcanic Field and the Featherbed Volcanics. Equal area projection, lower hemisphere only. Diamond: pole to regional bedding; square:  $K_{\max}$ -axis; triangle:  $K_{\text{int}}$ -axis; circle:  $K_{\min}$ -axis. Numbers refer to sites labeled in table 6. A = Bulgonunna Volcanic Field: A1 = Cv, location 6 (AFBA-G,BFBD, "Dam Dacite"); A2 = Cb, location 3; A3 = Cb, location 4 (BFBA-G,BFBD sites); A4 = Cb, location 4 (BFBF sites: local bedding as determined from columnar structures); A5 = Cb, location 2. B = Featherbed Volcanics: B1 = location 10; B2 = location 12; B3 = location 9; B4 = location 11.

## INTERPRETATION OF REMANENCE RESULTS

The directions of remanence determined in this study are interpreted mainly through comparison of their pole positions with representative APWPs for Australia. These comprise Idnurm's (1985) pole path for the late Mesozoic-Cenozoic (Fig.8, Table 7), and two alternative pole paths for the late Palaeozoic (see Klootwijk and Giddings, 1988a) which represent current, but divergent, views. On the one hand (Fig.9A, Table 8) we have the view expressed by Schmidt et al. (1986, 1987, 1990), Li et al. (1989, 1990, 1991a,b), and Thrupp et al. (1991); on the other hand we have the view (Fig.9B, Table 9) of Klootwijk (1987, 1988), and Klootwijk and Giddings (1988b). Musgrave's (1989) Cenozoic pole path could have been included in this comparison. Although the methodology used in constructing Musgrave's path has come in for criticism (Idnurm, 1990), the pole path is broadly similar to Idnurm's (1985) path and its inclusion would have added a level of detail to the discussion that is beyond the scope of this Record. For the latter reason no comparison is made with pole paths based on Gondwana-wide palaeomagnetic datasets or on palaeoclimatic or other datasets.

As a brief overview of the interpretation presented, comparison of the data presented here with Klootwijk and Giddings' version of the late Palaeozoic APWP (Fig.9B) and Idnurm's late Mesozoic-Cenozoic APWP (Fig.8) indicates: (a) component C1 (Table 2, also C<sub>1i</sub> and C<sub>1h</sub> in diagrams) represents a Recent field, Early Tertiary, or Late Cretaceous overprint; (b) component C2 (also C<sub>2i</sub> and C<sub>2h</sub>, Table 3A, 3B) represents Late Carboniferous-Early Permian widespread remagnetization (Smedley Dacite, Star of Hope Formation volcanics, Lizzie Creek Volcanics, Silver Hills Volcanics), a probable primary magnetization (Featherbed Volcanics), and a syn-sagging primary component acquired during extrusion (Pyramid Range and Arundel Rhyolites); and (c) component C3 (also C<sub>3i</sub> and C<sub>3h</sub> in diagrams) represents a primary magnetization (Table 4) of Late Devonian-Early Carboniferous age (Silver Hills Volcanics, Star of Hope Formation volcanics) or of Early Permian age (Carmila Beds), reverse polarity overprints (Table 5) of late Mesozoic-Cenozoic age, and diverse components of widely different interpretation or unclear, possible composite, origin (Table 5).

### Component C1

#### *Bulgonunna Volcanic Field:*

C1-components (includes C<sub>1i</sub>, C<sub>1h</sub>, C<sub>1r</sub>) from the different locations show a somewhat elongated distribution of pole positions (Fig.10A, Table 2). Comparison of these C1 pole positions with Idnurm's (1985) APWP (Fig.8) demonstrates that the pole positions vary from (i) close to the Late Tertiary part of the APWP (Locations: 4,8), to (ii) close to the present-day geomagnetic south pole (Locations: 3,5,7), to (iii) close to the Early Tertiary part of the APWP (Locations: 1,2,3,6). Groupings (i) and (ii) may therefore represent overprints of Recent (ii) or Late Tertiary age (i) and be of viscous origin (ii). Grouping (iii) of pole positions may indicate the effects of Early Tertiary weathering episodes observed in the Eromanga Basin (Idnurm and Senior, 1978), overprints associated with Early Tertiary spreading in the Coral Sea-Tasman Sea region (Weissel and Hayes, 1977; Weissel and Watts, 1979; Veevers, 1984; Veevers et al., 1991), or prolonged activity of hydrothermal systems that may have been already active during the Carboniferous tectonism of the Tasman Orogenic System.

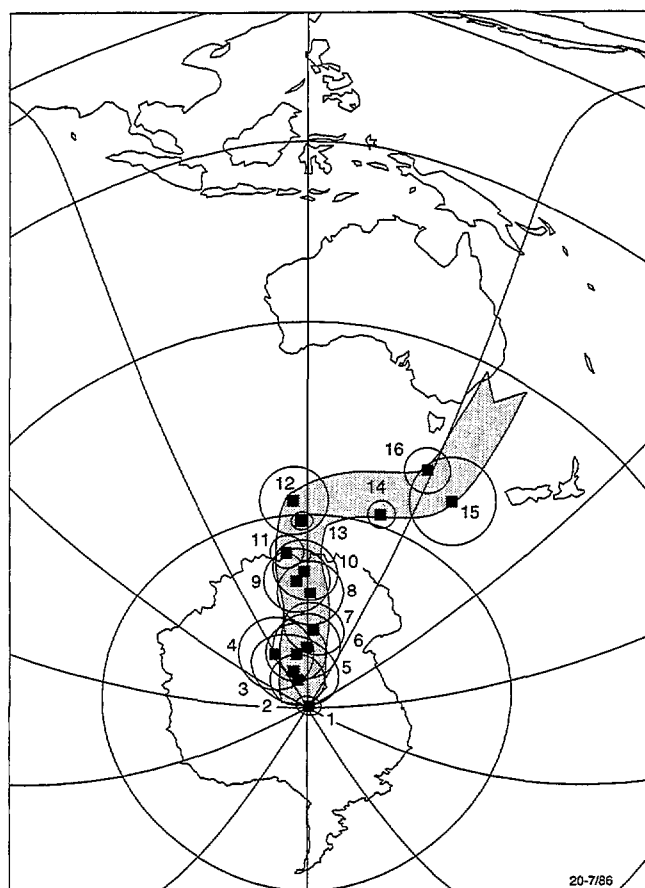


Figure 8. Tertiary and Late Cretaceous apparent polar wander path after Idnurm (1985). Aitoff projection. See Table 7 for data.

#### *Featherbed Volcanics:*

Interpretations for the C1 component are equally diverse. Pole positions for locations 9, 10 and 11 (BBFA, BBFB and BBFC) are spread between the pole position for the Late Cretaceous overprint, so widespread throughout the Tasman Sea board of southeastern Australia, and the present-day geomagnetic south pole (cf. Table 2, Figs.8,10B). The directions and magnetic characteristics of this component (Appendix B) do not suggest a present-day viscous origin, and a Late Cretaceous overprint origin is thus most likely. The occurrence of such an overprint beyond the obvious northern boundary of the Tasman Sea in which seafloor spreading started ~96 Ma ago (Veevers et al.,1991), and notably also further cratonward, suggests that parts of northeastern Australia could have experienced hydrothermal and possibly tectonic effects associated with the early or pre-rifting phases of the rifting process in the Tasman Sea, or more probably associated with incipient rifting in the Coral Sea. Preliminary fission track data from northeastern Queensland (A.Gleadow, pers. comm.,1992) seem to reflect the latter. Dual occurrence of this component direction at location 10 (BBFB), in a softer and in a very hard magnetic phase, and the non-discrete nature of the thermal demagnetization spectra (Fig.5B), indicates a chemical origin and suggests hydrothermal effects.

The harder reverse polarity component observed at location 11 (BBFC) falls on the middle



TABLE 7: AUSTRALIAN LATE MESOZOIC AND CENOZOIC POLE POSITIONS (Fig.8)

No	Formation	Age Ma	South Pole Position		A <sub>95</sub> (°)	Ref
			Long (°E)	Lat (°S)		
1	Holocene lake sed.	0.005	144.6	89.4	1.5	1
2	Newer volcanics	~3	100.9	85.4	4.0	2
3	Newer volcanics/ Werriko Lst.	2.9	103.6	83.2	6.2	1
4	Springfield basin	----	90.5	80.4	5.6	3
5	Perth basin	----	108.8	81.2	4.5	4
6	Sequence 2	----	119.2	80.4	<5	1
7	Glenample Fm./ Port Campbell Lst.	12	123.5	77.2	4.2	1
8	Sequence 3	----	121.4	72.1	<5	1
9	Sequence 1	----	115.3	70.1	<5	1
10	Point Addis Lst.	26	118.7	68.4	4.8	1
11	Browns Creek Clay	43?	112.5	65.5	2.5	2
12	Morney profile	----	116.2	57.8	5.2	1
13	North Rankin 1	58	118.4	61.7	---	1
14	Late Cretaceous overprint	----	141.8	58.2	2.1	5
15	100 Ma	100	157.6	51.7	6.7	6
16	Otway group	110-115	148.7	48.9	3.6	1

- 1) Idnurm (1985).
- 2) Idnurm (pers. comm., 1989).
- 3) Schmidt (1976).
- 4) Schmidt and Embleton (1976).
- 5) Mean from Patonga Claystone (Embleton, 1981), Hornsby Breccia (Embleton, 1981), Gordon Sub-Group (Staples and Klootwijk, 1981), and Brisbane Tuff (Robertson, 1963).
- 6) Embleton (1981).

Tertiary part of the Australian APWP (cf. Figs.8,10B,Table 2), and can be dated as such. The origin of the soft component at location 12 (BBFD) is more ambivalent. Its pole position (Fig.10B) is not far off the Late Cretaceous (~100 Ma) part of the Australian APWP, but is also close to the segment of Triassic-Early Jurassic age, which is also a time of extension off the northeastern margin of cratonic Australia.

#### *Lizzie Creek Volcanics, Carmila Beds, and Silver Hills Volcanics*

Pole positions for the C1-components are grouped about the present-day geomagnetic south pole (locations 13,15, and 16: AFLA-D,ADSA-D,ADSE-H) and the pole position for the Late Cretaceous overprint (location 14: AFCA-D) (cf. Table 2, Figs.8,10C). The former pole positions represent components with soft magnetic characteristics and most likely represent components of viscous origin. The latter pole position is based on a magnetically-harder component, and may well represent acquisition of a Late Cretaceous overprint by the coastal Carmila Beds of the successor sequence to the Proserpine terrane similar to the above interpretation for the Featherbed Volcanics.

#### **Component C2**

##### *Bulgonunna Volcanic Field:*

The hard southwesterly and steep downward-directed component C2<sub>h</sub> is very predominant in the Bulgonunna Volcanic Field. The directions are much better concentrated "in situ" than corrected

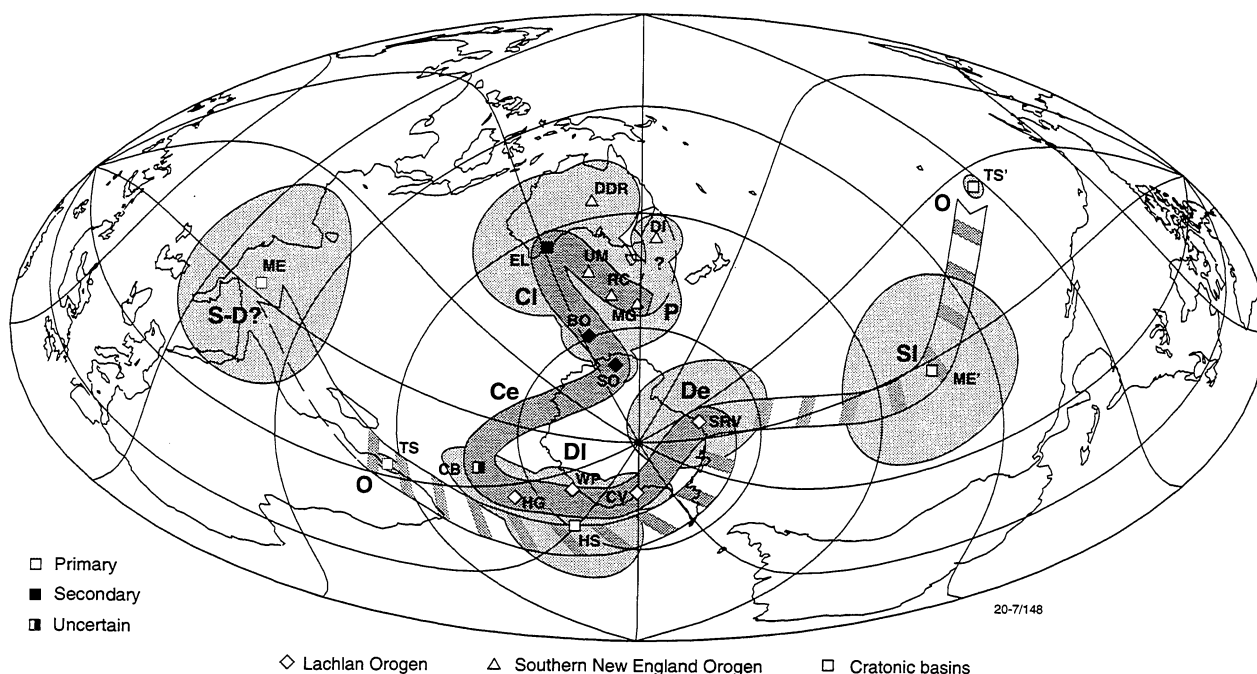


Fig.9A

Figure 9. Generalized versions of the late Palaeozoic apparent polar wander path: A) SLP-path proposed by members of the palaeomagnetic groups from CSIRO and UWA (after Schmidt et al.,1986,1987,1990; Li et al.,1989,1990,1991a,1991b; Thrupp et al.,1991). Two possibilities are shown for the pre-Devonian part of the APWP. The one illustrated shows the generally accepted polarities for the Mereenie Sandstone (ME) and Tumblagooda Sandstone (TS). The other is based on antipoles of ME and TS and requires that the path linking poles older than SRV comes in from the east (as shown); B) KG-path proposed by members of the AGSO palaeomagnetic group (after Klootwijk,1988; Klootwijk and Giddings,1988b). Oblique Aitoff projection. See tables 8 (SLP-path) and 9 (KG-path) for data and pole acronyms. Plotted poles have been restricted to results with  $\alpha_{95}$  or  $A_{95}$  values less than  $20^\circ$ . Period key: O = Ordovician; S = Silurian; D = Devonian; C = Carboniferous; P = Permian; e = early; m = middle; l = late.

for bedding (Fig.11A1-4, Table 10). Application of McFadden's (1990) fold test to all data regardless of formation, however, is inconclusive, although we note that the correlation is very much weaker for the *in situ* position. The results strongly indicate a secondary or synfolding origin for this component. This suggestion can be qualified by separate analysis of results for the individual sequences of the Pyramid and Arundel Rhyolites, the Smedley Dacite and the Star of Hope Formation volcanics.

Pole positions for the  $C_{2h}$  component from the two synclinal structures sampled in the Bulgonunna Volcanics, that is from the Pyramid Range (Pyramid Rhyolite, locations 1,2) and from the Myall-Coopers Creek area (Arundel Rhyolite, locations 3,4), cross-over during correction for bedding (Fig.11A2) and show a negative foldtest (Table 10). This indicates an extrusion-related, syn-sagging, or possibly syntectonic, origin for this component in the Cb sequence. Most likely, acquisition of this component occurred during sagging and accumulation upon extrusion (cf. earlier discussed AMS results). Strong support for this interpretation is shown by the even more marked cross-over upon unfolding of the softer  $C_{2l}$ -component (Fig.11A3), which most probably was acquired at a slightly

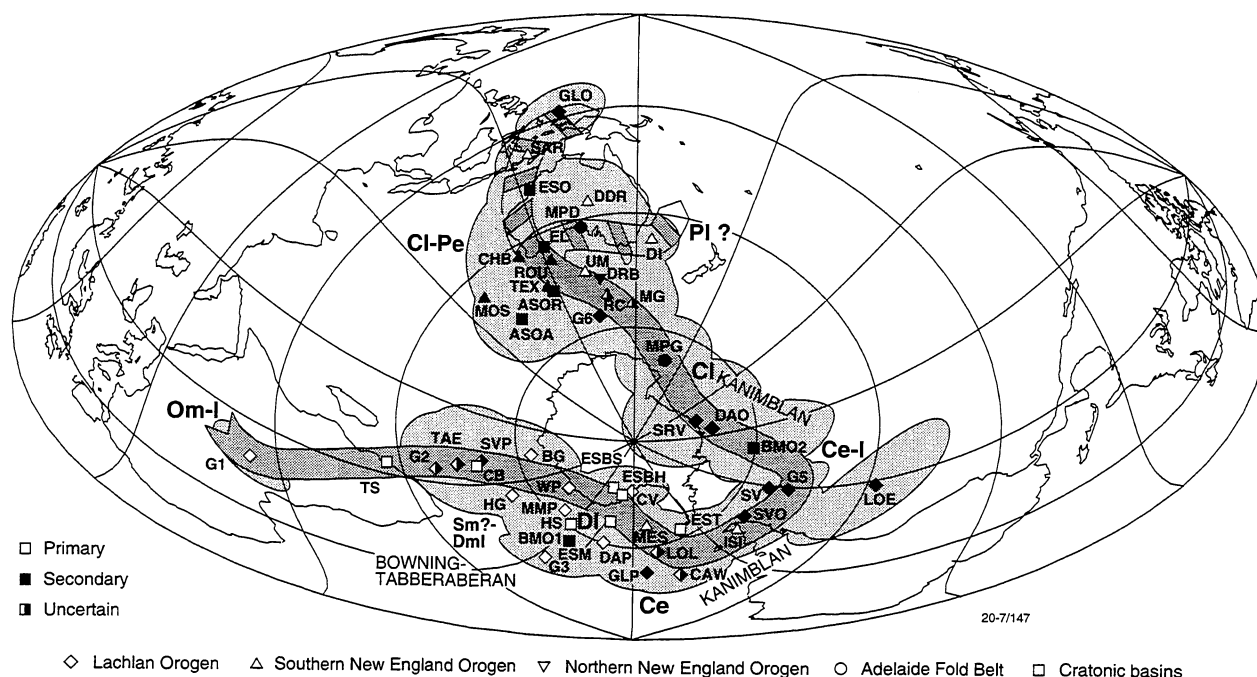


Fig.9B

later stage in the sagging process. Alternatively, these components ( $C_{2i}, C_{2h}$ ) could have been acquired during a subsequent post-extrusion folding phase, that on the grounds of the pole position's relation to the APWP is still of Late Carboniferous-Early Permian age. Occurrence of such a phase can only be inferred tentatively from the geological record of the region.

Results from the four unnamed ( $Cb_4$ , Oversby et al., 1991) flows at location 5 (AFBH-AFBK) also suggest a greater dispersion of directions after correction for bedding (Table 3B), but additional bulk demagnetization results are needed to substantiate the statistical significance of this observation with a proper foldtest. The flows have been hornfelsed by the nearby and eastward-adjacent granitoid Cug (Fig. 2A, Oversby et al., 1991) which is regarded as broadly co-magmatic with, but to slightly postdate extrusion of, the  $Cb$  volcanics. This suggests that for these location 5 flows, component  $C_2$  is post-extrusional rather than primary in origin.

Results for the only two locations of the Smedley Dacite ("Dam ignimbrite", previously  $Cv_d$ ; Locations 3, 6) that have been studied, clearly disperse after unfolding (Fig. 11A4). This indicates a secondary post-tectonic origin for component  $C_{2h}$  in this  $Cv$  sequence. McFadden's (1990) foldtest is strongly indicative for a negative foldtest, but requires more data (Table 10). Bedding control for location 3 (BFBE) is well-established from local eutaxitic foliation observations. There is less stringent bedding control, however, for the Smedley Dacite at the sampling sites below the dam (location 6), but the few local eutaxitic foliation observations that could be made are in good agreement with more numerous and regionally consistent bedding observations in the vicinity. Magnetic fabric studies on the Smedley Dacite failed to provide additional bedding control. Instead they showed the predominance of a secondary fabric that is probably related to the nearby major NE-SW fault zone

TABLE 8: SLP-PATH  
SELECTED AUSTRALIAN POLE POSITIONS (Refs:1,2,3)

middle-late Palaeozoic (Fig. 9A)

Acron	Formation	Magn. Age	Site Lat,Long (°S,°E)	DIRECTION					Field/ Bedding	SOUTH POLE POSITION						Ref
				Decl (°)	Incl (°)	K	$\alpha_{95}$ (°)	N(sam)		Lat (°S)	Long (°E)	Pallat (°S)	dp (°)	dm (°)	A <sub>95</sub> (°)	
<u>Southeast Australia</u>																
SRV	Snowy River Volcanics	E Devonian	37.5,148.3	340.1	-59.2	----	9.7	10	B	74.3	222.7	40.0	10.9	14.5		4
CV	Comerong Volc.	M-L Devonian	35.5,150.0	0.4	-38.7	38.8	7.2	11	B	76.9	330.7	21.9	5.1	8.6		5
WP	Worange Pt. Fm	L Devonian	~37.1,150.0	16.8	-38.1	10.4	7.4	(40)	B	70.8	19.7	22.0			7.1	6
HG	Hervey Group	L Dev - E Carb	33.3,148.5	29.2	-19.3	13.8	15.5	8	B	54.4	24.1	9.9	8.4	16.2		7
SO*	Snowy River Volc. overpr	M Carbon?	37.5,148.3	10.5	-72.3	----	3.2	(77)	F	68.7	132.5	57.5	5.0	5.7		4
BO*	Buchan Cave Lst. overpr	M Carbon?	37.5,148.3	17.4	-74.0	----	2.5	(64)	F	64.7	127.9	60.2	4.0	4.5		4
MG	Main Glacial Stage	L Carbon	~32.6,151.6	185	79	----	6	5	*	53	149	69.5			11	8
RC	Rocky Creek Conglomerate	L Carbon	~29.9,150.3	200	78	----	9	8	B	52	138	66.1			17	8
UM	Upper Marine Latites	L Permian	~34.6,150.8	232	81	----	6	11	F/B	46	136	74.0			15	9
DI	Dundee Ignimbr. (Bolivia Rhyod)	L Permian	~29.2,152.0	163.5	86.0	----	3.3	13	F	36.9 (21.6)	154.8 149.6	---- 82.0) <sup>b</sup>	6.5	6.5		10
DDR	Dundee Rhyodac.	L Permian	~29.5,151.8	281.5	82.8	----	6	19	F	25.8 (31.3)	136.3 168.1	---- 75.8	12 11.5	13 11.7) <sup>b</sup>		10
<u>Cratonic Australia</u>																
TS	Tumblagooda Sst	Ordovician	~27.7,114.2	69.6	-36.1		3	6	B	26.7	33.7	20.0	2	3		11
ME <sup>c</sup>	Mereenie Sst	Sil - Devonian	~24.0,132.0	----	----	----	----	6	B	15.7	242.7	21.1			23.7	12
HS	Hermannsburg Sst./Ooraminna Sst. mb.	M-L Devonian	24.2,132.3/ 23.7,134.3	----	----	----	----	3	B	61.0	0.9	3.8			15.6	12
CB	Canning Basin Lst. overprint?	L Dev - E Carb?	~18.0,125.0	42.7	-28.9	61.6	7.8	7	B	49.1	38.0	15.4	4.7	8.6		13
EL	Mount Eclipse Sst. overprint	~320 Ma	~22.3,131.3	215.5	82.6	14.3	10.1	16	B(part)	33.8	121.2	75.4	19.2	19.7		14

1) Schmidt et al., 1990; 2) Powell et al., 1990; 3) Li et al., 1990; 4) Schmidt et al., 1987; 5) Schmidt et al., 1986; 6) Thrupp et al., 1991;

7) Li et al., 1988; 8) Irving, 1966; 9) Irving and Parry, 1963; 10) Lackie 1988; 11) Schmidt and Embleton, 1990; 12) Li et al., 1991a;

13) Hurley and Van der Voo, 1987; 14) Li et al., 1989.

<sup>a</sup>) Not included in table 9, possibly a Late Cretaceous-Tertiary overprint. <sup>b</sup>) Recalculated.

<sup>c</sup>) Not included in figures 9B and 12, excessive uncertainty.

TABLE 9: KG-PATH  
SELECTED AUSTRALIAN POLE POSITIONS  
middle - late Palaeozoic (Fig.9B)

Acron	Formation	Magn. Age	Site Lat, long (°S, °E)	DIRECTION					Field/ Bedding	SOUTH POLE POSITION						Ref
				Decl (°)	Incl (°)	K	$\alpha_{95}$ (°)	N(sam)		Lat (°S)	Long (°E)	Pallat (°S)	dp (°)	dm (°)	A <sub>95</sub> (°)	
<u>Tasman Orogen</u>																
G1	Cowra Trough/ Molong High	M-L Ordovician	~33.7, 148.8	251.1	-55.5	57.1	6.1	3	B	6.1N	19.1	36.4N	6.2	8.7		15
G2	- same -	E-M Silurian	~33.0, 148.8	45.9	-8.3	37.8	8.5	4	B	38.2	34.6	4.2	4.3	8.6		15
G3	- same -	M-L Silurian	~33.0, 148.8	19.1	10.2	28.6	9.2	4	B	47.3	357.5	5.1N	4.7	9.3		15
SVP	Silurian Volc primary?	M-L Silurian	~35.3, 149.1	----	----	----	----	6	B	50.4	39.8	15.9			14.9	17
MMP	Mugga Mugga Porphyry	L Sil-E Dev	35.1, 148.8	----	----	----	----	----	B	63.2	7.9	13.1			7	15
BG	Bowning Group	E Devonian	34.8, 149.8	28	-42	36.8	10	7	B	64	45	24.2	7.5	12.3		16
TAE	Taemas Basin	M Devonian	34.9, 148.8	----	----	----	----	6	B	44.2	37.8	10.9			13.5	17
CV	Comerong Volc.	M-L Devonian	35.5, 150.0	0.4	-38.7	38.8	7.2	11	B	76.9	330.7	21.9	5.1	8.6		5*
HG	Hervey Group	M Dev - E Carb	33.3, 148.5	29.2	-19.3	13.8	15.5	8	B	54.4	24.1	9.9	8.4	16.2		7*
WP	Worrange Pt. Fm	L Devonian	~37.1, 150.0	16.8	-38.1	10.4	7.4	(40)	B	70.8	19.7	22.0			7.1	6*
DAP	Dandenong Volc. prim?	L Devonian	~37.8, 145.3	----	----	----	----	3	B	60.1	343.8	9.1			9.9	17
LOL	Lochiel Fm. overprint?	L Dev - E Carb?	37.2, 149.8	----	----	----	----	(48)	B	58	320	5.5			7	16
CAW	Catoombal Gr. overprint?	L Dev - E Carb?	~32.7, 148.8	171	-14	33	10	13	B	49 (49.3)	312 315	----- 7.1N	----- 5.2	----- 10.2) <sup>1</sup>		18
MES	Merlewood Fm.	E-M? Carbon	~31.3, 150.7	356.6	-15.4	----	8.8	(51)	B	66.6	322.5	7.8	5	9		20
GLP	Goodradigbee Lst. overprint	E-M? Carbon	35.2, 148.7	357.7	4.9	13.6	10.7	(15)	B	52.3	324.9	2.5N	5.4	10.8		17
ISI	Isismurra Fm.	M Carbon	32.1, 151.1	337.0	-3.5	11.7	18.4	7	B	52.7	290.9	1.8	9.2	18.4		17
SVO	Silurian Volc overprint?	M Carbon?	~35.3, 149.1	----	----	----	----	16	F?	54.1	285.4	7.0			7.8	17
SV	Silurian Volc overprint	M Carbon?	34.8, 148.8	329	-22	18.4	10	13	F/B?	54	271	11.4	5.6	10.6		16
G4 <sup>2</sup>	Cowra Trough/ Molong High overpr?	M Carbon?	~32.6, 149.0	320.9	-24.4	11.2	28.7	4	B	44.0 (49.2)	253.2 258.8	----- 12.8	17.3 16.5	32.1 30.7) <sup>1</sup>		15
G5	Cowra Trough/ Molong High overpr?	M Carbon?	~33.0, 148.8	325.7	-12.8	26.7	9.5	8	F	50.4 (48.6)	272.5 271.0	----- 6.5	5.0 4.9	9.8 9.7) <sup>1</sup>		15
LOE	Lochiel Fm. overprint?	M Carbon?	37.1, 149.9	311	10	---	18.5	5	B	28	272	5.0N	9.5	18.7		19

TABLE 9: KG-PATH ctd.

Acron	Formation	Magn. Age	Site Lat,Long (°S,°E)	DIRECTION					Field/ Bedding	SOUTH POLE POSITION						Ref
				Decl (°)	Incl (°)	K	$\alpha_{95}$ (°)	N(sam)		Lat (°S)	Long (°E)	Pallat (°S)	dp (°)	dm (°)	A <sub>95</sub> (°)	
<u>Tasman Orogen ctd.</u>																
DAO	Dandenong Volc overpr?	M Carbon?	~37.8,145.3	----	----	----	----	9	B	70.9	234.2	35.7			8.1	17
SRV	Snowy River Volc. overpr?	M Carbon?	37.5,148.3	340.1	-59.2	----	9.7	10	B	74.3	222.7	40.0	10.9	14.5		4**
MPG	Radium Ridge gran. breccias	M Carbon?	30.2,139.3	163.1	66.2	19.2	7.7	(20)	B	65.7	165.1	51.1			11.5	21
MG	Main Glacial	L Carbon	~32.6,151.6	185	79	----	6	5	B	53	149	69.5			11	8*
RC	Rocky Creek Conglomerate	L Carbon	~29.9,150.3	200	78	----	9	8	B	52	138	66.1			17	8*
UM	Upper Marine	L Permian	~34.6,150.8	232	81	----	6	11	F/B	46	136	74.0			15	9*
ROU	Rouchel reg. overprint	L Carb-E Perm?	~32.1,151.1	247.9	77.1	15.3	14.6	8	F	38.0	121.8	65.4	25.4	27.2		17
TEX	Texas Block overprint	L Carb-E Perm?	~28.7,151.1	231.0	73.3	40.8	9.6	7	F	43.7	117.9	59.0	15.4	17.1		17
CHB	Coffs Harbour Block overpr	L Carb-E Perm?	~29.7,153.3	253.3	71.2	61.6	9.8	5	F	33.4	113.1	55.8	15.0	17.2		17
DRB	Dotswood Red Beds overpr	L Carb-E Perm?	19.8,146.4	195.1	75.1	17.4	8.2	(19)	F/B	46.1	135.6	62.0	13.7	15.0		22
MPD	Radium Ridge Diamictite	L Carb-E Perm?	30.2,139.3	248.2	87.2	19.6	4.2	(62)	F	33.1	133.9	84.6			6.9	21
MOS	Merlewood Fm. overprint	L Carb-E Perm?	~31.3,150.7	247.8	64.3	----	1.3	(30)	F	36.4	97.5	46.1	1.7	2.1		20
G6	Cowra Trough/ Molong High	Pal - Mesoz?	~33.0,148.8	20.6	-76.5	74.9	6.4	6	F	56.6	132.8	64.4	11.1	11.9		15
SAR	Alum Rocks	E Permian	28.5,151.7	304.1	70.1	53.4	2.4	(66)	B	5.6	122.5	54.1	3.6	4.1		23
GLO	Goodradigbee Lst. ovrpr.	E-M Permian?	35.1,148.7	334.5	67.2	32.2	6	(19)	F	2.0N	132.6	50.0	8.3	10.0		17
DI	Dundee Ignimbr. (Bolivia Rhyod)	L Permian	~29.2,152.0	163.5	86.0	----	3.3	13	F	36.9 (21.6)	154.8 149.6	---- 82.0) <sup>1</sup>	6.5	6.5		10*
DDR	Dundee Rhyodac. Monzonite	L Permian	~29.5,151.8	281.5	82.8	---	6	19	F	25.8 (31.3)	136.3 168.1	---- 75.8	12 11.5	13 11.7) <sup>1</sup>		10*

Results additional to table 8, results not accepted by the "SLP" authors for inclusion into their compiled paths:

15) Goleby, 1980; 16) Luck, 1973; 17) Klootwijk, unpublished preliminary results; 18) Williamson and Robertson, 1976; 19) Embleton and Shepherd, 1977; 20) Schmidt, 1988; 21) Idnurm and Heinrich (1993); 22) Chamalaun, 1968; 23) Aubourg et al., 1992; 24) Camacho et al., 1991; 25) Klootwijk, 1980; 26) Ripperdan and Kirschvink, 1992.

TABLE 9: KG-PATH ctd.

Acron	Formation	Magn. Age	Site Lat, Long (°S, °E)	DIRECTION					Field/ Bedding	SOUTH POLE POSITION						Ref
				Decl (°)	Incl (°)	K	$\alpha_{95}$ (°)	N(sam)		Lat (°S)	Long (°E)	Pallat (°S)	dp (°)	dm (°)	A <sub>95</sub> (°)	
<u>Cratonic Australia</u>																
BMP <sup>3</sup>	Chatsworth Lst/ Ninmaroo Fm.	Cambro-Ord	22.6, 140.3	274.5	4.3	6.7	7.4	64	B	3.1N	54.1	2.2	3.7 <sup>1</sup>	7.4 <sup>1</sup>		26
TS	Tumblagooda Sst	Ordovician	~27.7, 114.2	69.6	-36.1	----	3	6	B	26.7	33.7	20.0	2	3		11*
ME <sup>2</sup>	Mereenie Sst	Sil - Devonian	~24.4, 132.3	----	----	----	----	6	B	15.7	242.7	21.1			23.7	12*
HS	Hermannsburg Sst./Ooraminna Sst. mb.	M-L Devonian	24.2, 132.3/ 23.7, 134.3	----	----	----	----	3	B	61.0	0.9	3.8			15.6	12*
CB	Canning Basin Lst.	L Devonian	~18.0, 125.0	42.7	-28.9	61.6	7.8	7	B	49.1	38.0	15.4	4.7	8.6		13*
BMO1	Chatsworth Lst/ Ninmaroo Fm. overpr	L Devonian?	22.6, 140.3	199.9	-7.5	10.7	11.4	17	B	57.2	359.3	3.8N	5.7 <sup>1</sup>	11.5 <sup>1</sup>		27
ESBH	Mt Eclipse Sst. base-hard	L Dev-E Carb	~22.2, 131.2	187.4	17.6	50.9	8.5	7	B	75.0	340.6	9.0	4.6	8.5		17
ESBS	Mt Eclipse Sst. base-soft	L Dev-E Carb	~22.2, 131.2	189.0	22.2	41.4	9.5	7	B	76.3	351.5	11.5	5.3	10.1		17
ESM	Mt Eclipse Sst. middle	L Dev-E Carb	~22.2, 131.2	192.2	4.7	39.6	12.3	5	B	66.9	343.5	2.4	6.2	12.3		17
EST	Mt Eclipse Sst. top	L Dev-E Carb	~22.2, 131.2	178.0	-10.1	42.2	8.6	8	B	62.6	306.8	5.1N	4.4	8.7		17
BMO2	Chatsworth Lst/ Ninmaroo Fm. overpr	M Carbon	22.6, 140.3	333.5	-17.7	10.7	15.5	8	B	59.9 (61.2)	256.2 254.1	----	17.2 8.3	32.6 16.1 <sup>1</sup>		26
EL	Mount Eclipse Sst. overprint	~320 Ma	~22.3, 131.3	215.5	82.6	14.3	10.1	16	B(part)	33.8	121.2	75.4	19.2	19.7		14*
ESO	Mt Eclipse Sst. overprint	L Carb-E Perm?	~22.2, 131.2	297.5	85.2	27.2	5.5	26	B	17.6	122.2	80.5	10.8	10.9		17
KDS <sup>2</sup>	Kulgera Dyke Swarm overpr	L Carb-E Perm?	~25.9, 133.1	----	----	----	----	(13)	F	30	138	84.0			23.8	24
ASOA	ASO overprint Areyonga	L Carb-E Perm?	24.1, 132.3	217.5	72	10.5	7.7	(36)	B	47.5	102.6	57.0	11.9	13.6		25
ASOR	ASO overprint Ross River	L Carb-E Perm?	23.6, 134.5	206.5	76.5	14	2.9	(178)	B	45.8	118.1	64.5	5.0	5.4		25

<sup>1</sup>) Recalculated.

<sup>2</sup>) Not shown in figure 9B, excessive error.

<sup>3</sup>) Not shown in figure 9B, outside period of main interest.

<sup>\*</sup>) Results also used in table 8.

<sup>\*\*</sup>) As above, but with a different interpretation for the age of magnetization.

<sup>3\*</sup>) Li et al., 1990; <sup>4\*\*</sup>) Schmidt et al., 1987; <sup>5\*</sup>) Schmidt et al., 1986; <sup>6\*</sup>) Thrupp et al., 1991; <sup>7\*</sup>) Li et al., 1988; <sup>8\*</sup>) Irving, 1966;

<sup>9\*</sup>) Irving and Parry, 1963; <sup>10\*</sup>) Lackie 1988; <sup>11\*</sup>) Schmidt and Embleton, 1990; <sup>12\*</sup>) Li et al., 1991a; <sup>13\*</sup>) Hurley and Van der Voo, 1987; <sup>14\*</sup>) Li et al., 1989.

### *Interpretation of remanence results*

(Fig.7A1). The presence of this acquired fabric at location 6 provides circumstantial support for the interpreted secondary origin of component C2. Magnetic fabric results for the other studied Smedley Dacite location 3 (Cv<sub>d</sub>, BFBE), however, are puzzling. This location is close to a nearby N-S aligned fault zone. Although the local Cb sequence (Arundel Rhyolite) showed an obviously acquired fabric (Fig.7A2), the Smedley Dacite (Cv<sub>d</sub>) sequence did not. This dichotomy in fabric patterns is puzzling and does not add to our interpretation of a secondary origin for component C2<sub>h</sub> in both Cv<sub>d</sub> locations. Additional palaeomagnetic data from other units of the Cv sequence with clear bedding control are needed in order to arrive at a **statistically significant** negative foldtest.

The Star of Hope Formation volcanics have been studied at only one location (Location 7), in a sequence with uniform bedding (Fig.2A). This does not allow for a foldtest. Component C2<sub>h</sub>, with its steep downward direction, can be interpreted definitively as a secondary component, because the equatorial direction of component C3, for the age of the volcanics, is in full agreement with the Late Devonian-Early Carboniferous APWP and is therefore definitely of primary origin (Fig.11A5). Comparison of components C2<sub>i</sub> and C2<sub>h</sub> for the Cv<sub>d</sub> and Star of Hope Formation volcanics shows an inconclusive foldtest (Table 10). There is slightly better agreement between the *in situ* Cv<sub>d</sub> results and the bedding-corrected Star of Hope Formation volcanics result than with the latter *in situ* result (Fig.11A4). The implication of this observation is not clear. The considerable spread in C2-component pole positions for the Bulgonunna Volcanic Field, the Featherbed Volcanics, and the Lizzie Creek Volcanics suggests that it may merely reflect local, mainly post-folding acquisition at different times during a period of considerable movement of the pole across Australia's southern margin (Figs.11,12). Alternatively, it is possible that the Star of Hope Formation volcanics component C2 may have been acquired during a Late Cretaceous (~100 Ma) overprint phase related to the nearby basaltic plug. The occurrence of this component in both a magnetite phase and a hematite phase suggests a (thermo-)chemical origin, probably due to hydrothermal activity.

#### *Featherbed Volcanics:*

The *in situ* pole positions for component C2<sub>h</sub> of the Featherbed Volcanics locations are in good agreement with the *in situ* pole positions for component C2<sub>h</sub> in the two Cv<sub>d</sub> locations of the Bulgonunna Volcanic Field (Fig.11B2), but not with their tilt-corrected pole positions. This strongly supports our earlier conclusion for an overprint origin for component C2 in the Cv<sub>d</sub> locations. Regional mapping (D.MacKenzie, pers. comm.,1988) has indicated that the sampled Featherbed Volcanics ignimbrites are subhorizontal. The origin of component C2 in these flows, therefore, cannot be tested using a fold test. However, available Rb/Sr ages for the sampled Featherbed Volcanics range between 305 Ma and 280 Ma, and overlap with the U-Pb (SHRIMP) zircon age range of 305-290 Ma (Black,1993) for the Cb and Cv sequences of the Bulgonunna Volcanic Field. The location of the Featherbed Volcanics poles on the Late Carboniferous to Early Permian segment of the APWP, in conjunction with the geochronological data, allows us therefore to interpret the Featherbed Volcanics results as a **primary** Late Carboniferous-Early Permian component.

#### *Lizzie Creek Volcanics, Carmila Beds, and Silver Hills Volcanics:*

The mean direction for the four Lizzie Creek Volcanics sites shows some dispersion after correction for bedding (Fig.11C). This observation is based on limited results only and, pending the results of bulk demagnetization studies, does not warrant any firm conclusion on the origin of component C2. A secondary origin seems the more likely in view of the increase in dispersion after



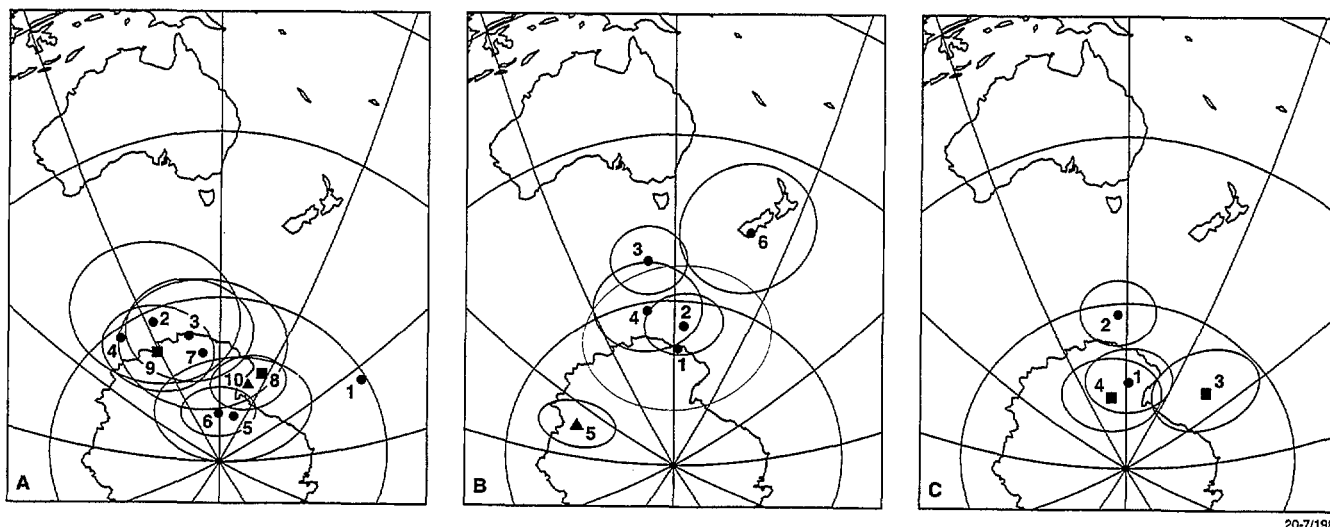


Figure 10. Some selected pole positions for component C1 determined at the various locations (see Table 2). Compare with Idnurm's late Mesozoic-Cenozoic APWP (Fig.8). The pole positions are shown on the same global projection as shown in figure 8, but without the pole path in order to avoid cluttering. The pole positions are grouped by volcanic field (A-C) and by formation (see caption to figure 4), and are shown in field coordinates. Plotted pole positions are identified by a number which corresponds in the legend to the given site acronym and, in brackets, the formation acronym or component acronym, and location number.

**A) Bulgonunna Volcanic Field:**

C1 components for Cb (solid circles), Cv (solid squares) and Cls<sub>i</sub> (solid triangle) sequences: 1=AFGA,AFGB (post-Cv granitoids, relation with Cb unclear, 8), 2=BFBB (Cb,1), 3=BFBC (Cb,2), 4=BFBA (Cb,3), 5=BFBF (Cb,4), 6=BFBG (Cb,4), 7=AFBH-AFBK (Cb,5), 8=BFBE (Cv,3), 9=AFBA-AFBG,BFBD (Cv,6), 10=BFBH (Cls<sub>i</sub>,7).

**B) Featherbed Volcanics:**

Normal polarity components indicated by solid circles, reverse polarity component by solid triangle. 1=BBFA (9), 2=BBFB (10), 3=BBFB (Cl<sub>h</sub>,10), 4=BBFC (11), 5=BBFC (Cl<sub>r</sub>,11), 6=BBFD (12).

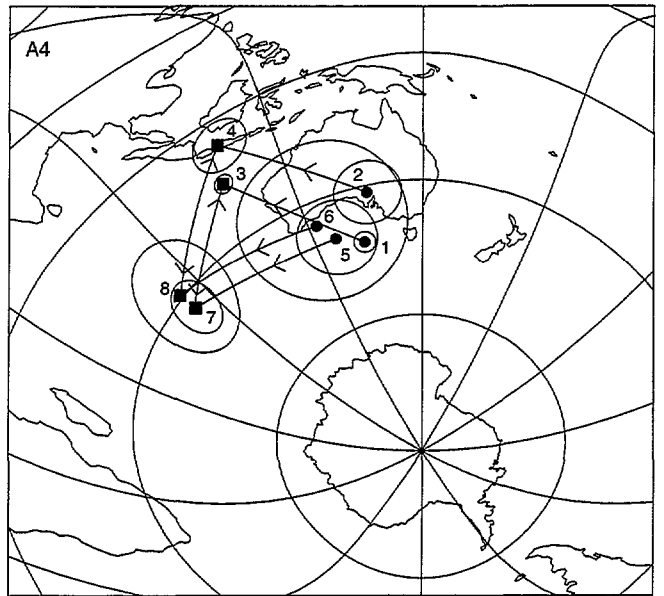
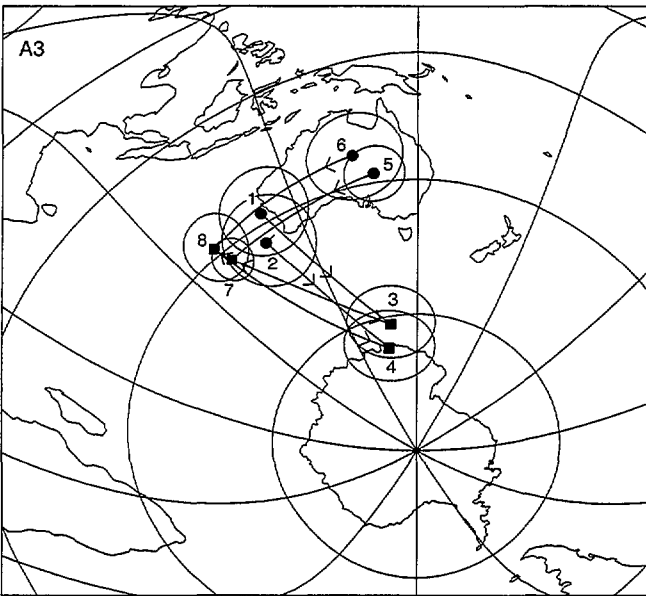
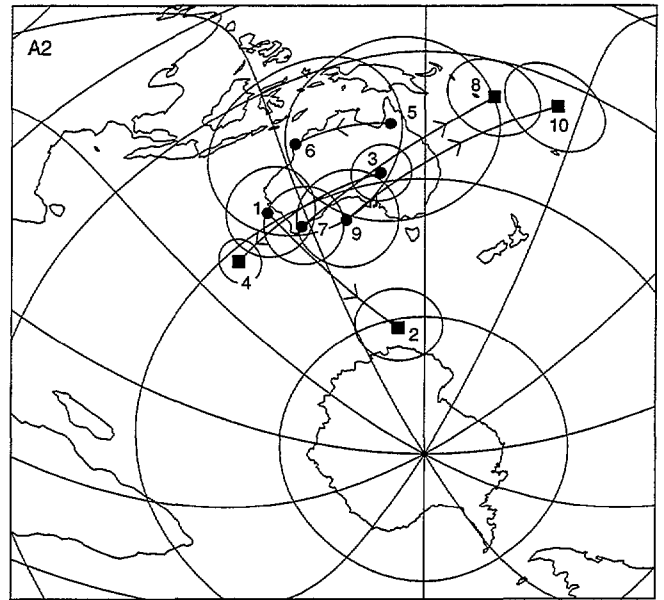
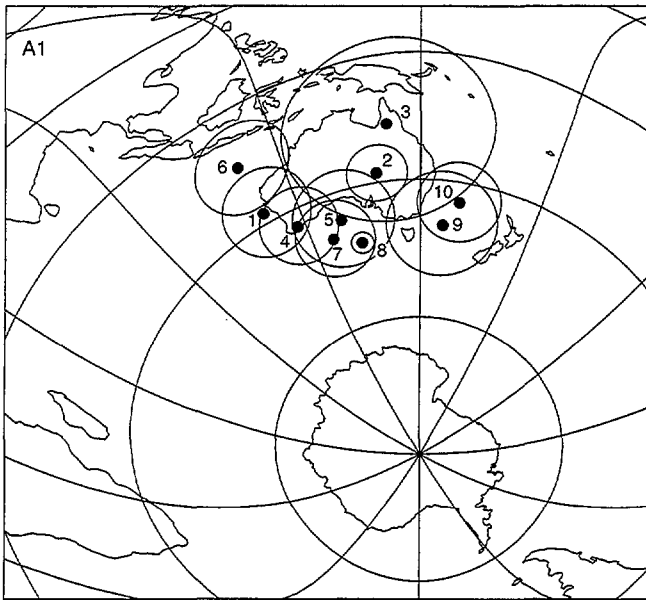
**C) Lizzie Creek Volcanics, Carmila Beds, and Silver Hills Volcanics:**

Lizzie Creek Volcanics and Carmila Beds results indicated by solid circles, Silver Hills Volcanics by solid squares. 1=AFLA-AFLD (13,14), 2=AFCA-AFCD (15,16), 3=ADSA-ADSD (17), 4=ADSE-ADSH (18).

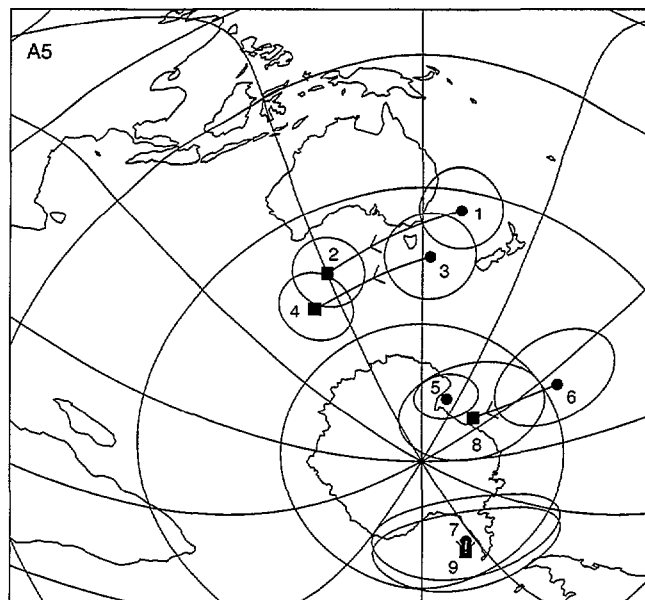
correction for bedding, but a primary origin cannot be excluded. The Lizzie Creek Volcanics have palaeontological indicating an Early Permian age. However, Murray (1983) proposed a Middle Permian age on the basis of marine Fauna II beds at the top of the sequence, and the pole positions lie close to this segment of the APWP (cf. Figs.9B,11C,12).

Results for the Early Permian Carmila Beds are poorly defined (Fig.11C), and do not warrant any firm conclusion. The bedding corrected result seems in better agreement with the *in situ* results for component C2 in the Bulgonunna Volcanic Field. Therefore, pending further data, a primary origin (C3, Table 4) seems the slightly more likely option for this Carmila Beds result.

Palaeontological control on the age of the Lizzie Creek Volcanics and Carmila Beds may provide important additional constraints on the acquisition age of component C2, and further palaeomagnetic studies are planned.



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Component C2 is also distinctly present as an overprint in the Silver Hills Volcanics of the southern Drummond Basin (Fig.11D). This observation further underlines the regional, if not wider, extent of this overprint component.

### **Component C3**

#### *Primary components:*

There is surprisingly little evidence throughout the studied volcanic fields, other than the younger Featherbed Volcanics, for primary magnetization components. This indicates the pervasiveness and severity of the Late Carboniferous-Early Permian overprint mechanism.

Only some C3-component results for the Star of Hope Formation volcanics (Location 7, Fig.11A5) and for one of the two Silver Hills Volcanics locations (Location 17, Fig.11D) can be interpreted with confidence as primary components acquired during the Late Devonian-Early Carboniferous. The stratigraphic relationship of the Star of Hope Formation volcanics and the Silver Hills Volcanics has not been established from field evidence, but the former (Early to Middle? Carboniferous) are presumed to postdate the latter (Late Devonian-Early Carboniferous). Pole positions for the primary components in both units are far apart, with the difference mainly in divergent declinations. Assuming the absence of differential movement between the sampling locations in the northern (Star of Hope Formation volcanics) and southern part (Silver Hills

Figure 11. Some selected pole positions for components C2 and C3 determined at the various locations (see Tables 3-5). Compare with the late Palaeozoic KG-path (Fig.9B). The pole positions are shown on the same global projection as shown in figure 9B, but without the KG-path in order to avoid cluttering. The pole positions are grouped by volcanic field (A-D) and by formation (see caption to figure 4), and are shown in field coordinates (F) and/or in geographic coordinates (B, bedding corrected) as indicated in the legend. Plotted pole positions are identified by a number which corresponds in the legend to the given site acronym and, in brackets, the formation acronym or component acronym, and location number. Circles (squares) represent field (bedding) corrected results.

#### **A) Bulgonunna Volcanic Field:**

A1= C<sub>2h</sub> components (F) for the Cb, Cv and Cls<sub>i</sub> sequences; 1=BFBB (Cb,1), 2=BFBC (Cb,2), 3=BFBA (Cb,3), 4=BFBF (Cb,4), 5=BFBG (Cb,4), 6=BFBH-BK (Cb,5), 7=BFBE (Cv,3), 8=AFGA-GH,BFBD ("Dam ignimbrite",Cv,6), 9=AFGA-GB (post-Cv granitoids,8), 10=BFBH (Cls<sub>i</sub>,7).

A2= C<sub>2h</sub> components (F,B) for Cb sequence, locations 1-4, note the cross-over of pole positions during correction for tilting implying a syn-magmatic origin; 1=2=BFBB (Cb,F=B,1), 3=4=BFBC (Cb,F=B,2), 5=6=BFBA (Cb,F=B,3), 7=8=BFBF (Cb,F=B,4), 9=10=BFBG (Cb,F=B,4).

A3= C<sub>2i</sub> and C<sub>2h</sub> components (F,B) for location 1 and 2 (Pyramid Range) of the Cb sequence. Note that the bedding-corrected pole positions for C<sub>2i</sub> show greater separation than those for C<sub>2h</sub>, as expected for components acquired during a later stage in the cooling/sagging process; 1=3=BFBB (C<sub>2i</sub>,F=B,1), 2=4=BFBB (C<sub>2i</sub>,F=B,1), 5=7=BFBC (C<sub>2h</sub>,F=B,2), 6=8=BFBC (C<sub>2i</sub>,F=B,2).

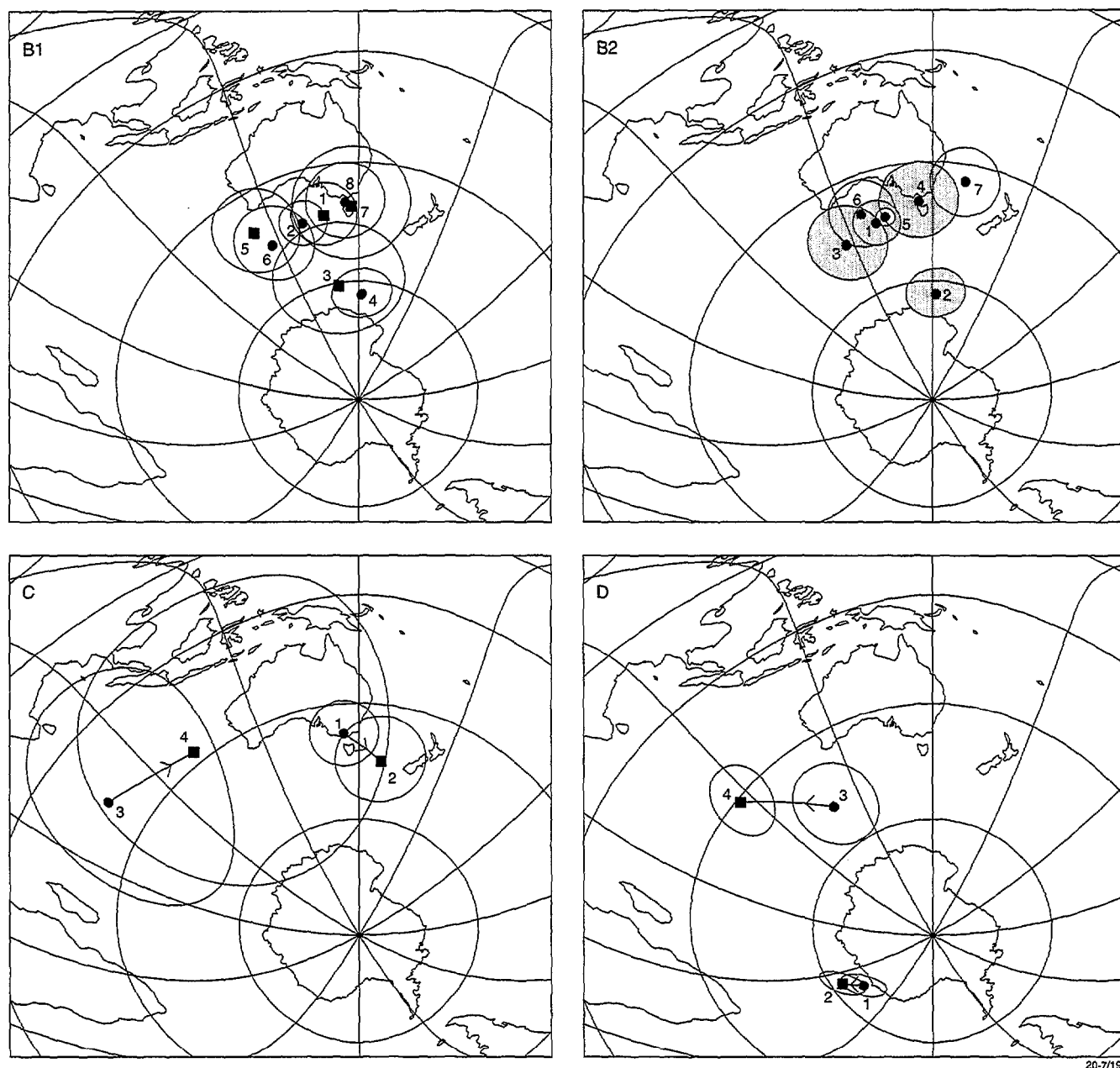
A4= C<sub>1i</sub> and C<sub>2h</sub> components (F,B) for the Cv<sub>d</sub> sequence (Smedley Dacite). The two sets of pole positions separate upon correction for tilting, suggesting a secondary origin. However, bedding is not well-constrained for the "Dam ignimbrite" (location 6) and it is possible that the dispersion is just an artifact resulting from an incorrectly determined attitude for the ignimbrite unit. Note that the tilt corrected pole positions for C<sub>2i</sub> show greater separation than those for C<sub>2h</sub>, as expected for components acquired during a later stage in the deformation processes; 1=3= AFGA-GH,BFBD ("Dam ignimbrite",C<sub>2h</sub>,F=B,6), 2=4= AFGA-GH,BFBD("Dam ignimbrite",C<sub>2i</sub>,F=B,6), 5=7=BFBE(C<sub>2h</sub>,F=B,3), 6=8=BFBE(C<sub>2i</sub>,F=B,3).

A5= Cls<sub>i</sub> sequence (Star of Hope Formation volcanics; BFBH,1), C<sub>1</sub>, C<sub>2i</sub> and C<sub>2h</sub>, and C3 (C3o= overprint, C3= primary) components; 1=2= (C<sub>2h</sub>,F=B), 3=4= (C<sub>2i</sub>,F=B), 5= (C<sub>1</sub>), 6=8= (C3o,F=B), 7=9= (C3,F=B).

TABLE 10: FOLD TEST RESULTS (McFadden, 1990)  
LATE CARBONIFEROUS-EARLY PERMIAN OVERPRINT COMPONENT C2,  
BULGONUNNA VOLCANIC FIELD

IN SITU								UNFOLDED (100%)						
FORMATION/ TEST SITES	N	DECL	INCL	K	$\alpha_{95}$	SCOS1(95%-99%) <sup>1</sup> SCOS2	CORREL?	DECL	INCL	K	$\alpha_{95}$	SCOS1(95%-99%) SCOS2	CORREL?	
Cb+Cv <sub>1</sub> +Cls <sub>1</sub> <sup>2</sup> (AFBA-G/BFBD, BFBA, BFBB, BFBC, BFBE, BFBF, BFBG,BFBH, [AFBH-K excluded])	8	222.9	80.6	100.0	5.6	4.96(3.30/4.56) 5.18	YES>99% YES>99%	238.2	78.5	16.72	14.0	6.70(3.30/4.56) 6.65	YES>99% YES>99%	<sup>3)</sup> <sup>3)</sup>
Ch <sup>2</sup> (BFBA, BFBB, BFBC, BFBF, BFBG)	5	239.7	80.2	114.7	7.2	2.48(2.61/3.57) 2.44	NO NO	276.1	80.3	13.83	21.3	4.67(2.61/3.57) 4.73	YES>99% YES>99%	<sup>4)</sup> <sup>4)</sup>
Cv <sub>d</sub> <sup>2</sup> (AFBA-G/BFBD, BFBE)	2	211.9	76.6	1151	7.4	0.03(1.70/1.94) 0.46	NO NO	252.7	61.7	32.74	45.1	0.74(1.70/1.94) 1.97	NO YES>99%	<sup>5)</sup> <sup>6)</sup>
Cv <sub>d</sub> +Cls <sub>1</sub> <sup>2</sup> (AFBA-G/BFBD, BFBE, BFBH)	3	195.9	79.5	108.6	11.9	0.32(2.08/2.66) 0.05	NO NO	246.9	66.3	36.29	20.8	0.53(2.08/2.66) 2.47	NO YES>95%	<sup>5)</sup> <sup>4)</sup>

<sup>1)</sup> SCOS1 and SCOS2 represent the sum of the direction cosines ( $\zeta_1$  and  $\zeta_2$ ) for the two definitions of McFadden's fold test. The values between brackets indicate the critical values for rejection or acceptance of the null hypothesis.  
<sup>2)</sup> Previous nomenclature (Oversby et al., 1991, 1993).  
<sup>3)</sup> Correlation with the tectonics in both the in situ and unfolded state, the correlation being stronger in the unfolded case.  
<sup>4)</sup> Negative foldtest, magnetization acquired in situ.  
<sup>5)</sup> Inconclusive foldtest.  
<sup>6)</sup> Indication for negative fold test, but N<5, the recommended number of observations (McFadden, 1990).



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Fig.11 ctd. **B) Featherbed Volcanics:**

B1=  $C_{2l}$  and  $C_{2h}$  components for locations 9-12, all in field coordinates (F); 1,2= BBFA ( $C_{2l}, C_{2h}$ , 9), 3,4= BBFB ( $C_{2l}, C_{2h}$ , 10), 5,6= BBFC ( $C_{2l}, C_{2h}$ , 11), 7,8= BBFD ( $C_{2l}, C_{2h}$ , 12).

B2= Comparison of pole positions ( $C_{2h}$  component) for locations 9-12 of the Featherbed Volcanics and for the Cv and Cls sequences of the Bulgonunna Volcanic Field, all in field coordinates (F); 1= BBFA (9), 2= BBFB (10), 3= BBFC (11), 4= BBFD (12), 5= AFGA-GH, BFBD ("Dam ignimbrite", Cv, 6), 6= BFBE (Cv, 3), 7= BFBH (Cls, 7).

**C) Lizzie Creek Volcanics and Carmila Beds:**

$C_{2h}$  and  $C_3$  components in field and bedding coordinates (F $\Rightarrow$ B); 1=2= AFLA-LD ( $C_{2h}$ , F $\Rightarrow$ B, 13+14), 3=4= AFCA-CD ( $C_3$ , F $\Rightarrow$ B, 15+16).

**D) Silver Hills Volcanics:**

$C_{2h}$  and  $C_3$  components in field and bedding coordinates (F $\Rightarrow$ B); 1=2= ADSA-SD ( $C_3$ , F $\Rightarrow$ B, 17), 3=4= ADSA-SD ( $C_{2h}$ , F $\Rightarrow$ B, 17).

### *Interpretation of remanence results*

Volcanics) of the Drummond Basin, the stratigraphic relationship between both units can be constrained from comparison of their pole positions with the two alternative late Palaeozoic APWP's for Australia (Figs.9,11,12). Comparison with the APWP following Schmidt, Li, Powell and coworkers from the CSIRO and UWA groups (SLP-path, Fig.9A,12), would suggest the Silver Hills Volcanics to be not only younger than the Star of Hope Formation volcanics, but would also suggest Early to Late Devonian ages rather than the Late Devonian to Early Carboniferous ages concluded from field evidence. Comparison with the alternative APWP proposed by Klootwijk and Giddings from the AGSO group (KG-path, Fig.9B,12), however, confirms the Star of Hope Formation volcanics to be younger than the Silver Hills Volcanics and supports the previously concluded ages.

### *Components of uncertain origin:*

The Star of Hope Formation volcanics show another overprint which is ill-defined and which, after correction for bedding, falls on the (mid-Carboniferous) Kanimblan part of the KG-path (Fig.11A5), close to pole positions of secondary origin for the Dandenong Volcanics (Klootwijk, unpublished data), the Mount Painter uraniferous breccias (Idnurm and Heinrich,1993), and the Snowy River Volcanics (Schmidt et al.,1987) as presumed in the KG-path (Klootwijk,1988; Klootwijk and Giddings,1998a,1993). This component could possibly be related to hydrothermal events in the Drummond Basin, for which K-Ar ages of around 330-300 Ma have been obtained (Ewers et al.,1990; Ewers et al.,1993). Such hydrothermal activity could have been triggered during the Visean by the Australia-wide tectonic effects of the Kanimblan Orogeny. This tectonism could be related to a period of large-scale southward movement of Eastern Gondwana. Conjugate movement of Western Gondwana at the northwestern Gondwana/Laurussia antipode is exemplified by the Late Visean onset of the main Variscan/Alleghenian/Mauritanian orogenic phase (Ziegler,1984,1988; Hatcher et al.,1989).

The interpretation and significance of the south-south-westerly and shallow downward components in Featherbed Volcanics locations 9 and 11 is uncertain. Pole positions (not illustrated) fall in the general Devonian-Carboniferous part of the SLP-path and on the Middle to Late Devonian part of the KG-path. Such older ages obviously conflict with stratigraphic constraints and with the latest Carboniferous-earliest Permian Rb-Sr ages for the Featherbed Volcanics.

## **CONSTRAINTS ON THE AGE OF THE Cv SEQUENCE**

The pervasive and severe "Kiaman" remagnetization identified in all units studied but the Featherbed Volcanics, highlights the underlying problem of the age of the Cv sequence in the Bulgonunna Volcanic Field. How can such severe remagnetization not manifest itself in the U-Pb (SHRIMP) zircon ages? Here we review evidence for the age of the Cv sequence and the bearing palaeomagnetic results have on it.

### **Field evidence:**

Extensive data gathering during three mapping seasons has shown the Cv sequence to be spatially associated with the Cb sequence within a 20 km wide belt trending southeast from the Burdekin River. There are, however, conspicuous contrasts in lithofacies and magma composition between the two sequences. Where they occur together, the Cv sequence is lower and generally

more intensely faulted and probably also folded than the Cb sequence (McPhie et al.,1990; Oversby et al.,1990). The Cv and the Cls<sub>i</sub>/DCv sequences likewise show superficially similar magma compositions, but the Cls<sub>i</sub>/DCv sequences contain a substantially higher volume of clastic volcanic and sedimentary components (Black et al.,1990), contain substantial mafics which are absent or rare in the Cv sequence (B.Oversby, pers. comm.,1993), and are generally more deformed (Oversby et al.,1990). Stratigraphic relationships concluded from accumulated field evidence were summarized by McPhie et al. (1990 [Fig.3]) in a schematic profile, which is reproduced in figure 3.

#### **U-Pb SHRIMP zircon dates:**

U-Pb (SHRIMP) zircon ages from a few selected Cb and Cv samples (Black,1993) show some important disagreements with McPhie et al's (1990) evolutionary scheme. This is demonstrated by the discordances between age and stratigraphic relationships highlighted in figure 3. The heavily faulted nature of the Bulgonunna Volcanic Field and the consequent absence of evident stratigraphic contacts between the various volcanic sequences do not allow, on the basis of currently available evidence, confirmation or denial of the interpretation of the SHRIMP ages. With no further field mapping planned, map compilation has proceeded on the basis of acceptance of the SHRIMP ages. This has led to considerable readjustment of the earlier perceived stratigraphic relationships. Foremost amongst these is the newly-promoted concept of time-juxtaposition and lateral interfingering of the Cb and Cv sequences, and the identification of two Cb and two Cv associations (not all studied palaeomagnetically). The justification for this procedure can be questioned on the following grounds: (i) it ignores observations for a higher degree of deformation in the Cv sequence than in the Cb sequence; (ii) regional evidence for palaeomagnetic overprinting and oxygen isotope depletion caused by widespread high-temperature hydrothermal activity that may have affected the stability of the isotopic systems; and (iii) the SHRIMP ages are dependent on the method of zircon selection and the statistical analysis of results which assumes a unimodal population of zircon crystals. An obvious test on the soundness of this assumption would be congruity or otherwise of the measured ages with clearcut stratigraphic relationships, but interpretation of field evidence has not been able to establish such relationships.

#### **Fluid inclusion and oxygen isotope data:**

Potassium-Argon dating of sericite alteration from prospects and sinters in the Bulgonunna Volcanic Field indicates the occurrence of multiple hydrothermal events between 330 Ma and 280 Ma. These events may have exploited the same controlling structures in some prospects (Ewers et al.,1993). Fluid inclusion studies at several of the prospects in the Conway area (Fig.2A) indicate mean temperatures for this hydrothermal activity of around 200-300°C, and up to 340°C (Ewers et al.,1990). Further evidence for widespread hydrothermal activity derives from the recent identification of an extensive area of  $\delta^{18}\text{O}$  whole-rock depletion (Ewers et al.,1991) throughout the Bulgonunna Volcanic Field. This depletion could have resulted either directly from high-temperature interaction of low  $\delta^{18}\text{O}$  meteoric fluids with a cooling volcanic pile or possibly deeper level heat source and indirectly from interaction of such heated fluids with rock sequences of sufficient permeability, or though the extrusion of low  $\delta^{18}\text{O}$  magmas (Ewers et al.,1993). The regional extent of the  $\delta^{18}\text{O}$ -depleted area suggests that direct or indirect hydrothermal interaction was most likely. This may have been facilitated by the high primary permeability of volcanics in the Bulgonunna Volcanic Field, and/or in the case of the Drummond Basin sequence the high permeability of the sedimentary units and the ample presence of subvertical fracture zones. This prolonged period of hydrothermal activity

**TABLE 11: KG-PATH ADDITION**  
**SELECTED POLE POSITIONS NE QUEENSLAND**  
middle - late Palaeozoic, this study (Fig.12)

Acron Table	Formation	Magn. Age	Site	DIRECTION					Field/ Bedding	SOUTH POLE POSITION					
			Lat,Long	Decl	Incl	K	$\alpha_{95}$	N(sam)		Lat	Long	Pallat	dp	dm	A <sub>95</sub>
			(°S,°E)	(°)	(°)		(°)			(°N)	(°E)	(°S)	(°)	(°)	(°)
<u>Northeastern Queensland, primary results</u>															
SHV	Silver Hills	L Dev-E Carb	23.5,147.5	202.3	14.1	76.2	5.3	(11)	B	-63.1	23.8	7.2	2.8	5.4	4
	Volcanics (ADSA-D)														
CLS	Star of Hope	E Carb	20.6,147.2	352.4	2.6	14.3	18.4	(6)	B	-66.9	307.5	1.3	9.2	18.4	4
	Fm. volcanics (BFBH)														
FBA	Featherbed	L Carb-E Perm	16.8,144.4	201.8	74.3	30.9	3.9	(44)	F	-43.5	129.9	60.6	6.4	7.1	3B
	Volc. (BBFA)														
FBC	Featherbed	L Carb-E Perm	17.3,145.0	213.2	69.7	24.8	6.2	(23)	F	-45.6	117.2	53.4	9.1	10.6	3B
	Volc. (BBFC)														
FBD	Featherbed	L Carb-E Perm	17.2,144.9	179.0	78.1	19.0	5.4	(39)	F	-40.1	145.4	67.2	9.6	10.2	3B
	Volc. (BBFD)														
<u>Northeastern Queensland, overprint results</u>															
CLS01	Star of Hope	M Carbon?	20.6,147.2	346.9	-47.6	40.2	12.2	(5)	B	-75.6	202.2	28.7	10.3	15.9	5
	Fm. overprint (BFBH)														
SHVO	Silver Hills	L Carb-E Perm?	23.5,147.5	220.2	67.7	28.4	7.0	(16)	F	-48.9	109.1	50.6	9.8	11.7	3B
	overprint (ADSA-D)														
CLS02	Star of Hope	L Carb-E Perm?	20.6,147.2	143.4	80.7	39.0	4.7	(25)	F	-34.6	160.2	71.9	8.7	9.1	3B
	Fm. overprint (BFBH)														
CV01	Cv-sequence	L Carb-E Perm?	20.6,147.1	204.7	77.0	277.7	1.3	(46)	F	-42.5	133.4	65.3	2.3	2.4	3B
	overprint (AFBA-G,BFBD)														
CV02	Cv-sequence	L Carb-E Perm?	20.7,147.1	218.6	76.0	100.6	4.8	(10)	F	-40.0	125.8	63.5	8.2	8.9	3B
	overprint (BFBE)														
LCVO	Lizzie Creek	E(M?) Permian	~20.5,147.7	186.6	80.9	57.6	4.6	(18)	F	-38.2	145.1	72.2	8.6	8.9	3B
	Volc. overpr.? (AFLA-D)														



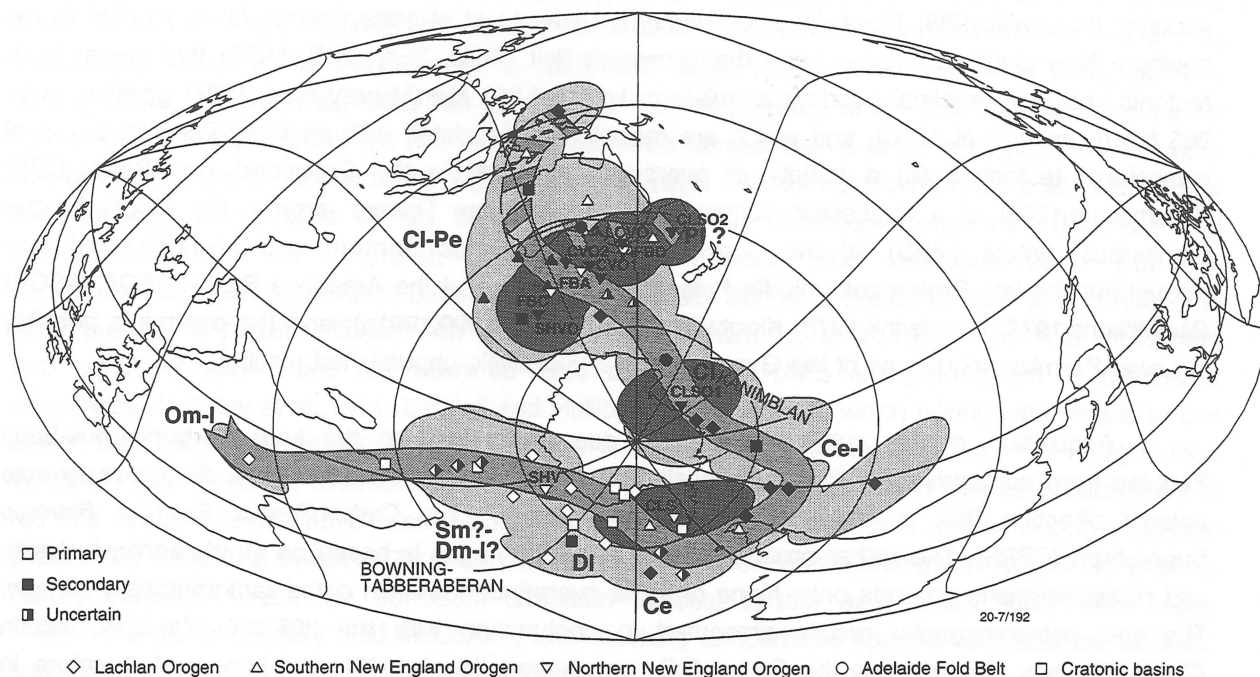


Figure 12. The late Palaeozoic KG-path (Fig.9B) upgraded with relevant pole positions from northeastern Queensland documented herein. The latter are distinguished by medium-shaded ellipses of confidence and acronyms as listed in table 11. For Period key see caption to figure 9.

at moderate to high temperatures, and the consequent pervasive alteration readily accounts for the observed, regionally-pervasive, magnetic overprinting present in the Star of Hope Formation volcanics (Cl<sub>s</sub>) and the Silver Hills Volcanics, and, according to the negative foldtest, the complete resetting of the magnetization in the Smedley Dacite (Cv<sub>d</sub>). Such spatial association of regions of  $\delta^{18}\text{O}$  depletion and magnetic alteration, that extends far beyond the zones of strong visible alteration, has been observed also in other epithermal districts (Criss et al., 1985). However, we note that the U-Pb (SHRIMP) ages are interpreted, in contrast, only in terms of totally-closed and unaffected isotopic systems (Black, 1993). It may be prudent, therefore, to test the stability of the U-Pb isotope system against the effect of moderate to high temperatures (thermo-chemical) acting over a prolonged time (thermo-viscous) which is characteristic of many regional hydrothermal systems. In view of theoretical studies that suggest there is a close relationship between the processes that govern the blocking temperature spectra of both magnetic and isotopic systems (York, 1978), such a test is an emerging imperative.

#### Magnetic constraints:

The *in situ* pole positions for overprint component C2<sub>h</sub> in the Smedley Dacite (Cv<sub>d</sub>: CVO1, CVO2), the Star of Hope Formation volcanics (Cl<sub>s</sub>: CLSO1, CLSO2), and the Silver Hills Volcanics (SHVO) (overprints in Table 11, Fig. 12) broadly agree with prevalent overprints of similar age observed elsewhere throughout wide regions of the Australian craton and TOS (Figs. 9A, B; Table 9). The latter overprints, likewise, are characterized by steep downward, southerly directions and uniquely reverse polarities. They have been observed as: (i) syn-tectonic secondary magnetizations

### *Constraints on the age of the Cv sequence*

in the Mt. Eclipse Sandstone (EL, ESO) of the Ngalia Basin that are of Late Carboniferous age or younger (Klootwijk, 1988; Klootwijk and Giddings, 1988a; Li et al., 1989, 1991b); (ii) overprints in the southern New England Orocline and the Tamworth Belt (ROU, TEX, CHB, MOS) that are of post-tectonic and post-oroclinal bending acquisition, i.e. post-300 Ma (Murray et al., 1987) possibly post-265 Ma (Korsch et al., 1990), and which are most likely associated with an Early Permian phase of extensional tectonics; (iii) a variety of overprints observed in the Dotswood Red Beds (DRB) (Chamalaun, 1968) of a successor sequence to the Charters Towers terrane, the Mount Painter uraniferous sinters (MPD) of the northern Flinders Ranges (Idnurm and Heinrich, 1993) and throughout the late Proterozoic-middle Palaeozoic sequence of the Amadeus Basin (ASOA, ASOR) (McWilliams, 1977; Kirschvink, 1978; Klootwijk, 1980; Li et al., 1990, 1991a); and (iv) overprints possibly in Lower Permian sequences of the Gympie terrane (Klootwijk, unpublished results).

Acquisition of this suite of overprints seems confined to the Late Carboniferous-Early Permian from comparison of their pole position with the APWP, and all have a distinctive reverse polarity direction that is characteristic for the "Kiaman", the Carboniferous Permian Reverse Superchron (CPRS). This rather broad range of acquisition ages is based on stratigraphic, tectonic, and palaeomagnetic grounds only. None of these overprints has been dated radiometrically till now. The new palaeomagnetic results presented in conjunction with the 305-290 Ma U-Pb zircon (SHRIMP) ages obtained for the Cb and Cv sequences (Black, 1993), are important therefore in allowing us to provide the first such direct radiometric constraints. These dates define the period of acquisition for the syn-sagging components in the Cb sequence (Table 3A, 3B), and also for the overprint components in the Smedley Dacite (Cv<sub>d</sub>), Star of Hope Formation volcanics (Cl<sub>s</sub>) and the Silver Hills Volcanics.

Acquisition of such "Kiaman" overprints is not confined to TOS or to those parts of the Australian craton that have been affected by late Palaeozoic remobilisation. During the late eighties it was recognized that "Kiaman" overprints are widely and dominantly present throughout the Hercynides and adjacent cratonic regions. In the Hercynides, the overprints have been recorded in: the Appalachian Fold Belt (Alleghenian orogenic phase) of western North America (e.g., Miller and Kent, 1988; McCabe et al., 1989; McCabe and Elmore, 1989; Van der Voo, 1988, 1989; Elmore and McCabe, 1991); the Variscan Fold Belt of central Western Europe (e.g., Courtillot et al., 1986; Edel, 1987; Edel and Coulon, 1987; Ruffet et al., 1992); and the Atlas and Mauritanides Fold Belts of Northwest Africa (e.g., Perrin and Prévot, 1988; Salmon et al., 1988a, 1988b; Aïfa et al., 1990; Henry et al., 1992). In the adjacent cratonic regions, the overprints are present in: the Baltic Shield (Smethurst, 1990; Torsvik and Trench, 1991; Perroud et al., 1992; Channell et al., 1992); the Russian Platform (Smethurst and Khramov, 1992); and the interior basins of North America (Lu et al., 1990; Sun et al., 1993). The overprints in the Hercynides are broadly dated as Late Carboniferous-Early Permian. Their older age limit of acquisition seems well-defined at 300 Ma (Edel, 1987; Miller and Kent, 1988; Salmon et al., 1988a, 1988b), but their younger age is less well-constrained, varying from Stephanian-Autunian (270 Ma) in the Variscan and Atlas Fold Belts (Edel, 1987; Aïfa et al., 1990) to as young as 240 Ma in the Northern Appalachians (Miller and Kent, 1988).

The remagnetizations are commonly attributed to hydrothermal activity. However, the relative importance of two mechanisms causing remagnetization - (thermo)chemical and thermoviscous - has been debated vigorously within the North American palaeomagnetic community for many years.

Remagnetization of the Appalachian sedimentary pile is assumed to be driven by craton-prograding fluids that have been tectonically expelled from overpressured sediments within the advancing Alleghenian thrust fronts (McCabe et al.,1983,1984; Oliver,1986,1990; Bethke and Marshak,1990; Deming,1992; Schedl et al.,1992; Sun et al.,1993). The temperature of the fluid front is fundamental to the relative importance of the two mechanisms. A consensus seems to be emerging which favours the predominance of chemical remagnetization, through the authigenic formation, at relative low temperatures, of hematite in red beds and magnetite in carbonate sequences (McCabe and Elmore,1989; Lu et al.,1990; Jackson,1990; Elmore and McCabe,1991; Suk et al.,1990a,1990b,1991,1992,1993; Saffer and McCabe,1992; Sun et al.,1993; Elmore et al.,1993). The latter process is possibly linked with potassic metasomatism (Lu et al.,1991). The fluid movement and remagnetization does not seem to have affected the U-Pb isotopic system in carbonate sequences (Halliday et al.,1991; DeWolf and Halliday,1991), which is worth noting with regard to our earlier discussion on the interpretation of the U-Pb (SHRIMP) zircon dates for the Bulgonunna Volcanic Field. However, thermochemical and thermoviscous remagnetization may be predominant in red bed sequences that have been exposed to more elevated temperatures and over longer periods (Kent,1985; Kent and Miller,1987). Identification of the predominant mechanism hinges on thermal history indicators such as: conodont alteration indices, apatite and zircon fission-track data,  $^{40}\text{Ar}/^{39}\text{Ar}$  data, secondary fluid inclusions, and blocking temperature spectra. Occurrence, severity, and mode of remagnetization seem dependent to a large extent on the presence of fluid conduits, which also control the occurrence of mineral plumbings that are deposited from expelled brines (Elmore et al.,1993). Prospects for the use of regional remagnetization as a sensitive prospecting tool have been recognized within the North American palaeomagnetic community and in the Australian community, but it has yet to be commercially developed.

## TECTONIC AND APWP IMPLICATIONS

The 305-290 Ma events recorded in the Bulgonunna Volcanic Field have to be considered in their proper geodynamic context. This period was one of highly intense tectonic activity of global extent that coincided, may be causally so, with the early part of the "Kiaman" Reverse Polarity Interval.

In the context of Gondwana's proto-Pacific margin, the "Bulgonunna" events coincided in time with a proposed large-scale, dextral wrench motion and with oroclinal deformation of the southern part of the New England Orogen. This part became decoupled from TOS along the Gogango-Baryulgil zone (Murray et al.,1987), or possibly the Mooki-Goondiwindi-Cracow-Eungella zone and its probable continuation in the Millaroo Fault zone (Harrington and Korsch,1985), was transported southward and underwent oroclinal bending. This large-scale displacement, and concomitant shortening by about 500 km, occurred between 310-300 Ma (Murray et al.,1987), or possibly slightly later at 280-265 Ma (Korsch et al.,1990). The latter timing is notably similar to the 286-267 Ma age bracket for dextral strike-slip movements interpreted for another section of the proto-Pacific margin of Gondwana, in the Argentinian Central Andes. Such a dextral movement system is concluded from palaeomagnetic evidence for late Early Permian clockwise rotations relative to the South American craton (Rapalini and Vilas,1991).

### *Tectonic and APWP implications*

Comparable dextral wrench motion occurred also at Gondwana's antipode, along the Gondwana-Laurussia contact in the Ural-Variscan-Mauritanides-Appalachian Orogenic System (Arthaud and Matte, 1977; Ziegler, 1984, 1986; Matte, 1986, 1991; Sacks and Secor, 1990). Occurrence of this dextral movement is generally no better constrained than between 300 Ma to possibly 270 Ma (Stephanian-Early Permian), but Sacks and Secor (1990) detail evidence from the Appalachians that date its onset at 273 Ma and continuation till at least 268 Ma. Concomitant shortening of the orogenic system is estimated at a minimal 600 km.

Other common characteristics of the New England and Variscan wrench systems are: (i) occurrence of an Early Permian tensional phase; (ii) systematic rejuvenation of isotopic systems in the internal metamorphic belts by thermal events (Variscides: about 340-330 Ma [Dallmeyer et al., 1992], about 330-290 Ma [Ziegler, 1984], about 380-280 Ma [Matte, 1991], and a later event at about 250 Ma [Arthaud and Matte, 1977]; New England: ~320 Ma and about 240 Ma in the Coffs Harbour sequence [Korsch, 1978; Graham and Korsch, 1985], and 255-250 Ma in the Nambucca Slate Belt [Leitch and McDougall, 1979]); (iii) comparable sizes of the affected regions (Variscides: 8000 km length by 1000 km width; TOS: at least 2000 km by 500 km); (iv) concomitant deformation in the interior of the plates; and (v) both wrench systems are characterized by oroclinal bending (Ibero-Armorican Arc, Texas-Coffs Harbour Orocline) which may have developed as mega-drag folds (Van der Linden, 1985). Such an origin has been advanced for the Texas-Coffs Harbour Orocline (Korsch and Harrington, 1987), but the Ibero-Armorican Arc is generally interpreted in terms of a Himalayan-type indentation model (Lefort, 1983; Matte, 1986, 1991).

We thus have two comparable and contemporaneous deformational systems operating along antipodal parts of Gondwana's margin. Clearly the common driving factor is the movement pattern of the Gondwana supercontinent. Palaeomagnetic constraints on Gondwana's movement during the late Palaeozoic rely heavily on Australian palaeomagnetic data. Interpretation of these data is under considerable dispute at present as demonstrated by the two widely different interpretations of the APWP (Fig. 9A,B). The main difference between the two APWPs resides in the shape of the Devonian-Carboniferous loop. This difference has a major impact on conclusions regarding Gondwana-Laurussia tectonic interaction.

The APWP advocated by Schmidt, Li, Powell and others (SLP-path) shows a westward loop, whereas the alternative APWP advocated by Klootwijk and Giddings (KG-path) shows an eastward loop. The SLP-path is based on the Y-path of Morel and Irving (1978), is well-publicized, and is currently the more widely accepted path (Schmidt et al., 1986, 1987; Hargraves et al., 1987; Van der Voo, 1988, 1989; Li et al., 1989, 1990, 1991a, 1991b; Ruffet et al., 1992). However, the main implication of the westward loop - the reopening of an oceanic basin between Gondwana and Laurussia during the (Middle?) Devonian- (Early?) Carboniferous is being increasingly criticized. This criticism hinges on the absence of evidence for, and contradictory evidence against, such an opening phase from such widely diverse sources as: faunal and floral similarities (Boucot and Gray, 1979; Van der Zwan, 1981; Young, 1987, 1990; Morzadec et al., 1988); palaeoclimatic and oceanic circulation interpretations (Heckel and Witzke, 1979; Copper, 1986); tectonic interpretations (Matte, 1986, 1991; Matte and Burg, 1986; Vai and Coccozza, 1986; Ziegler, 1988; Piqué, 1991; Piqué and Skehan, 1992); the Variscan flysch record (Franke and Engel, 1986); palaeogeographic reconstructions (Dineley, 1979; Carls, 1988; Blieck et al., 1988; Martinez-Catalan, 1990; Robardet et al., 1990; Paris and Robardet, 1990); Late

Devonian and Early Carboniferous lithospheric thickening in western Europe and northwestern Africa attributed to continental convergence and post-thickening Carboniferous granitoid emplacement (Lagarde et al.,1992); comparable evolution of presumed opposing margins (Rolet et al.,1986); and the implication of a regionally extensive, Early Mississippian hiatus in the Ouachita system for a Late Devonian to earliest Mississippian onset of tectonic activity attributed to convergence of Gondwana and Laurussia (Noble,1993).

The less publicized KG-path with its eastward Devono-Carboniferous loop, in contrast, advocates continuing Gondwana-Laurussia contact during the Devonian and Carboniferous. This APWP has recently gained support (see Klootwijk and Giddings,1993 [Fig.3]) from an APWP derived from different sources and based on lithological indicators for the late Palaeozoic climate (Scotese and Barrett,1990), and from an APWP based on reinterpretation of palaeomagnetic data in terms of Carboniferous overprints (Aïfa et al.,1990; Bachtadse and Briden,1991; Henry et al.,1992).

Irrespective of which Devono-Carboniferous APWP will prove to be the preferred option, both versions imply that Eastern Gondwana moved during the Carboniferous from equatorial to near polar latitudes. The occurrence of the main part of this movement is currently no better constrained palaeomagnetically than between extrusion of the basal ignimbrites of the Isismurra Formation and extrusion of the Paterson Volcanics (Klootwijk,1985). Palaeomagnetic studies in progress on the Carboniferous ignimbrite sequence of the Tamworth Belt, for which U-Pb (SHRIMP) age control is now available (Roberts et al.,1991a,1993), indicate that a phase of large-scale latitudinal and rotational movements - possibly an early northward movement followed by a large-scale southward movement - occurred between 345 Ma and about 330 Ma, or about 310 Ma (K-Ar age, Roberts et al., 1991b) if the characteristic magnetization of the Paterson Volcanics is of secondary origin. This large-scale movement may well be related causally with a major change in climatic conditions. This change has been observed not only in Eastern Gondwana (Veevers and Powell,1987; Powell and Veevers,1987), but also in various parts of Laurussia. In eastern Australia this climatic change has been related to the second of two major phases of faunal extinction (Roberts,1981). The original latest Visean to earliest Namurian date (Roberts,1981) for this change can now be revised on the basis of recent SHRIMP dates on ignimbrites from the Tamworth Belt (Roberts et al.,1993) to middle to late Visean (V2b-V3a to V3b). The climatic change is dated likewise as middle to late Visean in Laurussia and from global studies, Arundian in southern Great Britain, and middle Meramecian in western North America (Van der Zwan et al.,1985; Ross and Ross,1985; Wright,1988,1990; Witzke,1990; Vanstone,1991; Kelley and Raymond,1991; Smith and Dorobek,1993). Subsequent movement of Eastern Gondwana seems characterised by a slowdown in southward movement, but with continuing rotational movements during the remainder of the late Palaeozoic. The Late Carboniferous southward movement of Eastern Gondwana would result in a clockwise rotation of Gondwana. Consequently, the post-300 Ma part of Australia's (Gondwana's) APWP should reflect the counterclockwise rotational movement of Gondwana that resulted in the dextral wrench systems in the New England Orogen, the Variscides (Arthaud and Matte,1977; Ziegler,1986), and the Appalachians (Sacks and Secor,1990), bearing in mind that the form of the APWP also depends on the position of the rotation pole with respect to Gondwana. The new data do indeed contribute to a further definition of the latest Carboniferous-Permian segment of the Gondwanan APWP (compare figures 9 and 12), and provide support for the conventional west-to-east path to the south of Australia (Irving and Irving,1982; Li et al.,1991a), rather than the west-to-east path to the north of

Australia previously proposed by Klootwijk and Giddings (1988b).

## IMPLICATIONS FOR DATING

It is only during the past few years that palaeomagnetists have come to realize the global extent and pervasive nature of Permo-Carboniferous "Kiaman" overprinting and the far reaching implications for geodynamic interpretations. This revelation on temporality in the stability of the palaeomagnetic signal, may find no match in the assumption by a majority of geochronologists of permanency in the stability of zircon U-Pb systems. Is this assumption justified? The history of geochronology is marked by pitfalls in the assumed stability of other isotopic systems that have become apparent and accepted only after the accumulation of a mass of evidence to the contrary. The K-Ar and Rb-Sr methods have passed through this awareness stage, but is this so for the U-Pb method, and in particular the implementation by the RSES/AGSO group on the SHRIMP? Judgment by palaeomagnetists with no practical experience in U-Pb methods would be presumptuous. However, comparable time/temperature relationships seem to govern the stability of the palaeomagnetic and isotopic systems (York, 1978). The palaeomagnetic experience, therefore, may be helpful to geochronologists in focussing attention on possible problems. We list some critical observations.

(i) Palaeomagnetic studies on the Bulgonunna Volcanic Field have so far been unsuccessful in determining a primary magnetization component in the ignimbrites of the Cv sequence. There is thus, as yet, no decisive palaeomagnetic constraint on the crystallisation age of the Cv sequence.

(ii) Rockmagnetic analysis of widespread remagnetizations in the Appalachian Fold Belt and in the sedimentary basins on the North American craton has shown chemical remagnetization in low-temperature hydrothermal systems to be far more prevalent than thermochemical and thermoviscous remagnetization in moderate-temperature hydrothermal systems over prolonged periods. This may be no more than a reflection of the preferred selection for palaeomagnetic studies of rock sequences of low thermal maturation. Thermochemical and thermoviscous remagnetization mechanisms are favoured only for those few studied rock sequences with relatively high conodont alteration indices of around 3-4. Australian palaeomagnetic studies lack, as yet, the rockmagnetic analysis component which permits identification of the prevalent remagnetization mechanism. However, prevalence of thermochemical and possibly thermoviscous remagnetization is to be expected in the Bulgonunna Volcanic Field, where prospect-scale fluid inclusion data and regional-scale oxygen isotope data indicate that hydrothermal systems had temperatures around and in excess of 300°C. Whilst (thermo)chemical remagnetization may find its analogue in U-Pb systems as overgrown rims on otherwise unaffected zircon cores, thermoviscous remagnetization could be indicative of temperature/time relationships conducive to resetting of zircon cores.

(iii) "Kiaman" remagnetization occurred in widely different tectonic settings: thrustbelts in the Appalachians and the Mauritanides; shearbelts in the Variscides and TOS; and sedimentary basins in the interior of the Baltic, Russian, North American and Australian cratons. Oliver's (1986, 1990) hypothesis of craton-ward movement of an orogenic fluid front driven by tectonic dewatering of a thrustbelt, could also be applicable, but with modifications, to cratonic sedimentary basins and to

shearbelts. Occurrence of the "Kiaman" remagnetization throughout widely different tectonic regimes is suggestive of a common causative agency that is of subcrustal rather than supracrustal origin. Although we would argue that the base of the "Kiaman" Reverse Polarity Interval is currently undefined, it appears that the observed remagnetizations occurred near to its start. We speculate, therefore, that the liquid core hydrodynamic system that led to establishment of this unique and prolonged period of polarity stability, and the conjugate mantle convection system, together triggered enhanced lithosphere-wide, hydrothermal activity whose surface expression was facilitated in tectonically active regions. If so, we would expect the hydrothermal systems to be of higher temperature and active over prolonged periods, resulting in the necessary time and temperature conditions for thermochemical and thermoviscous remagnetization and for resetting of isotopic systems.

(iv) Palaeomagnetists have come to realize the dangers of the reinforcement syndrome. In the formative years of palaeomagnetism, it was common practice amongst palaeomagnetists to interpret a clustering of pole positions, for rock sequences that spanned considerable time intervals, in terms of periods of geodynamic stability when there was no detectable motion of the crust with respect to the pole ("quasistatic intervals"). Nowadays, however, interpretation in terms of widespread and prolonged remagnetization has become well-established as a more likely and realistic alternative.

It is presumptuous for palaeomagnetists to warn the isotope geochronology community on vigilance against the reinforcement syndrome. It may be perfectly acceptable practice for a geochronologist to interpret regionally consistent isotopic ages in terms of periods of widespread synchronous igneous activity (equivalent to the "quasistatic intervals" of the palaeomagnetist). We venture to question, however, whether there has been sufficient critical scrutiny of the stability of U-Pb zircon systems to be able to exclude, with confidence, alternative interpretations that may favour widespread resetting of isotopic systems (e.g. Rudnick and Williams, 1987; Zeitler, 1989; Lee et al., 1991; Lee and Sinha, 1992).

## CONCLUSIONS

Upper Palaeozoic ignimbrite sequences from volcanic fields in northeastern and eastern Queensland show three main magnetic components:

(i) A pervasive component C2 of latest Carboniferous-earliest Permian age. In the Bulgonunna Volcanic Field this component is of syn-sagging or possibly syn-tectonic origin in the Cb sequence (Late Carboniferous), and of post-tectonic origin in the Cv sequence (Late Carboniferous) and the Star of Hope Formation volcanics (Cl<sub>s</sub>, Early Carboniferous). In the Featherbed Volcanics (Late Carboniferous to Early Permian) the component is apparently of primary origin, although this could not be tested with a foldtest in the subhorizontal flows. The component is obviously of overprint origin in the Silver Hills Volcanics (Late Devonian to Early Carboniferous) and probably also in the Lizzie Creek Volcanics (Early [Middle?] Permian), but could represent a primary magnetization (C3) in the Carmila Beds (Early Permian).

(ii) A less pervasive, but still prominent, overprint component C1 of generally softer magnetic

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characteristics. This component is of Recent to Early Tertiary origin in the Bulgonunna Volcanic Field, the Lizzie Creek Volcanics, the Carmila Beds, and the Silver Hills Volcanics, and may have been acquired during the Late Cretaceous in the Featherbed Volcanics.

(iii) A component C3 which is of limited occurrence and represents a primary Late Devonian-Early Carboniferous magnetization in the Silver Hills Volcanics and an Early Carboniferous magnetization in the Star of Hope Formation volcanics (CIs), and magnetizations of uncertain origin. The relative age of the two primary magnetizations according to the KG-APWP confirms the *presumed* older age for the Silver Hills Volcanics.

Magnetic fabric studies of the Bulgonunna Volcanic Field generally show a low anisotropy of susceptibility of around 1% to 2%, characterized by oblate susceptibility ellipsoids with more pronounced foliation than lineation patterns. Some of the locations show consistent secondary magnetic fabric patterns. These seem related to nearby major fault zones and support foldtest arguments for a secondary origin of component C2, particularly in the Cv sequence. Only a few sites show a magnetic foliation that is in agreement with macroscopic bedding observations. The top of one of the massive Cb flows shows the best agreement. Lineation features show some consistency, but observations are too limited to establish general flow transport directions or to allow homing-in on eruptive centres (e.g. LaMarche and Froggatt, 1993).

Magnetic fabric results from the Featherbed Volcanics generally show prolate ellipsoids with subvertical  $K_{\max}$ -axes. The reason for this inverted fabric is not clear. The results support mapping evidence for a subhorizontal attitude of the flows at three of the four sampled locations.

The pervasive magnetic overprints of "Kiaman" signature in the northeastern Queensland volcanic provinces form part of a global pattern of overprints in orogenic zones of Hercynian age. Oxygen isotope data in the Bulgonunna Volcanic Field suggest there has been widespread hydrothermal activity at temperatures around and above 300°C. Although rockmagnetic evidence for the origin of the overprints in the Bulgonunna Volcanic Field has yet to be established, such temperatures suggest thermochemical and probably thermoviscous remagnetization as the more likely acquisition mechanisms. The pervasive nature of the "Kiaman" remagnetization and its thermochemical and probably thermoviscous modes of acquisition do pose the question as to what extent the isotopic systems have been affected by such hydrothermal activity, characterized as it is by moderate to high temperatures acting over a prolonged timespan, and in particular whether the 297 Ma U-Pb zircon (SHRIMP) age for the Cv sequence represents a crystallization age or an overprint age. In the absence of a primary magnetization component that constrains the crystallization age of the Cv sequence, our argument is largely circumstantial. We feel, nevertheless, that it warrants further testing of the stability of the U-Pb isotopic system in the Bulgonunna Volcanic Field. Whatever the outcome of such tests, the 305-290 Ma U-Pb ages observed for the Bulgonunna Volcanic Field represent the first isotopic dating of the "Kiaman" overprint.

## ACKNOWLEDGEMENTS

We cordially thank Brian Oversby, Doug MacKenzie and Greg Ewers (AGSO), and John Veevers (Macquarie University) for instructive discussions on suitable sampling locations and on the



### *Acknowledgements*

regional geology, and Brian Oversby in particular for guidance in the field. This paper benefitted from careful scrutiny and helpful comments by Brian Oversby, Doug MacKenzie, Greg Ewers, Russell Korsch, Mart Idnurm, Charlie Barton, David Denham and Phil MacFadden. The many text figures were drafted by Rex Bates with characteristic enthusiasm, dependability and care, and with only an occasional dig at the authors' seemingly endless stream of demands.

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## APPENDIX A: DESCRIPTION OF SAMPLED LOCATIONS

### A) BULGONUNNA VOLCANIC FIELD (FIG.2A)

#### Bulgonunna Volcanic Group, rhyolite-dominated association (previously Cb):

##### Location 1: BFBB: Pyramid Rhyolite

Northwestern limb of the NNE-SSW aligned synclinal structure at Pyramid Range. Nine sites (72 samples) were sampled over a 70 m stratigraphic interval through an ignimbrite sequence with a vesicular base and a more massive upper part. Some variable eutaxitic foliation was observed throughout the ignimbrite sequence, but overall bedding observations at the sampled sites are in good agreement with regional observations.

##### Location 2: BFBC: Pyramid Rhyolite

Northeastern limb of the Pyramid Range synclinal structure. Nine sites (72 samples) were sampled over a 90 m stratigraphic interval through an ignimbrite sequence; two lower sites in poorly-welded, greenish-white tabular units and the remaining sites in the thoroughly-welded, pinkish overlying sequence. Eutaxitic foliation shows a rather constant orientation which was particularly well-determined in the lower sites.

##### Location 3: BFBA: Arundel Rhyolite

Seven sites (56 samples) were sampled over the upper 40 m of an about 70 m thick massively-welded ignimbrite on the ridge directly south of Coopers Creek. This unit overlies a sampled Smedley Dacite flow (BFBE). Limited observations of eutaxitic foliation show local variations, but are in overall agreement with the attitude of the base of the sheet.

##### Location 4: BFBF,BFBG: Arundel Rhyolite

Sampled in two units near a powerline track, north of the road to "Myall Creek".

**BFBF:** Four sites (32 samples) were sampled in the lowermost part of the upper unit, in dark-grey, thoroughly-welded, quartz-rich ignimbrite. The unit shows well-developed columnar joints with variable attitudes ( $20^{\circ}$  to  $40^{\circ}$  dip). Local attitude at the BFBF sites ( $\sim 240^{\circ}/35^{\circ}\text{NW}$ ) differs from the overall bedding of the sheet, as determined from regional mapping observations ( $\sim 340^{\circ}/25^{\circ}\text{NE}$ ) and according to the underlying unit BFBG. The regional bedding estimate for the latter unit was used for tilt correction.

**BFBG:** Three sites (24 samples) were sampled over an about 20 m stratigraphic interval in the underlying clast-rich and less welded unit. Local eutaxitic foliation dips ( $\sim 325^{\circ}/25^{\circ}\text{NE}$ ) are in good agreement with overall bedding estimates from mapping.

##### Location 5: AFBH-AFBK

Four sites (40 samples) were sampled at four levels in un-named dark-blue and locally clast-rich ignimbrite associated with the Locharwood Rhyolite. The section was hornfelsed by the nearby, and possibly co-magmatic, granitoid with apophyses intruding into the sampled ignimbrite sequence. Eutaxitic foliation dips vary from  $50^{\circ}/37^{\circ}\text{SE}$  (AFBH,AFBI) to  $14^{\circ}/7^{\circ}\text{E}$  (AFBK).

#### Post-Cv granitoids:

##### Location 8: AFGA,AFGB

Two sites (10 samples each) were sampled, one site in a coarse-grained granodiorite (AFGA) that was intruded by a nearby dolerite dyke, and another site (AFGB) in a coarse-grained granodiorite with large dioritic xenoliths. These samples belong most probably to a suite of mafic-intermediate intrusives (Fig.2A), whose age is generally no better defined than Devonian-Carboniferous. Regional field relationships (B. Oversby, pers. comm.,1993) indicate that site AFGA, and presumably site AFGB, were sampled in a post-Cv granitoid that is intrusive into the Smedley Dacite ( $\text{Cv}_1$ , previously  $\text{Cvi}_3$  and  $\text{Cvi}_2$ ). The relationship with Cb cannot be reliably inferred. No tectonic control is available.

#### Bulgonunna Volcanic Group, dacitic-rhyolitic association (previously Cv):

##### Location 3: BFBE: Smedley Dacite

Two sites (20 samples) were sampled in the upper, heavily-jointed, part of the ignimbrite that outcrops in Coopers Creek, directly beneath the Arundel Rhyolite sampled at BFBA. Bedding was determined from limited local eutaxitic foliation observations ( $167^{\circ}/25^{\circ}\text{W}$ ), and is somewhat steeper than bedding estimates for the overlying Arundel Rhyolite (BFBA).

##### Location 6: AFBA-AFBG,BFBD: Smedley Dacite

This dacitic ignimbrite ("Dam ignimbrite" or "Dam dacite") was sampled in 10 sites (100 samples) at the Burdekin Falls dam, spread across the riverbed and its south wall, up to the exposed top of the unit. Bedding is constrained by only a few observations of eutaxitic foliation (B. Oversby, pers. comm.,1988), but is in agreement with regional mapping

estimates.

#### Volcanic member in the Star of Hope Formation (previously Cls):

##### Location 7: BFBH

Sampled near the track to the Glenroy outstation. Three sites (BFBH01-BFBH30) were taken from a dark purple-coloured and clast-rich dacitic ignimbrite-unit, exposed in humpback structures. The sites are close to a (Tertiary?) basalt plug which was not recognized during sampling. Another three sites (BFBH31-BFBH60) were taken from well-bedded clast-rich ignimbrite-units in a gully about 250 m to 400 m to the south of the above location. Bedding ( $154^{0}/19.5^{0}$ ) is well constrained by overlying bedded tuffs, the local topography, and based on contour mapping estimates (B. Oversby, pers. comm., 1992).

#### B) FEATHERBED VOLCANICS (FIG.2B)

##### Location 9: BBFA

Eight sites (64 samples) were sampled, in groups of two, from rhyolitic ignimbrites with Rb-Sr ages around 308 Ma. The sampled sites are spread along a profile that stretches between about 2 and 5 km to the east-south-east of the Nychum homestead; sites 1 to 6 on the south side of Elizabeth Creek, and sites 7 and 8 in a dyke-like outcrop cross-cutting Elizabeth Creek.

##### Location 10: BBFB

Eight sites (64 samples) were sampled from rhyolitic ignimbrites with Rb-Sr ages around 290 Ma, along the Walsh River between about 2 and 4 km east of Fisherman Waterhole. The sampled sites are close to a north-south trending fault zone with signs of ongoing hydrothermal activity (warm springs). Sites 1 to 6 were collected from unit Pff (D.Mackenzie, pers. comm., 1991) in the Walsh River bed, with sites 4 to 6 showing local signs of alteration (e.g. in particular along polygonal cracks at site 5). Sites 7 and 8 were collected in unit Pfc, at the base of a waterfall north of the Walsh River.

##### Location 11: BBFC

Five sites (40 samples) were sampled at the base of Eight Mile Mountain (site 1: vesicular ignimbrite), and about 2 km eastward along the nearby Dimbulah-Chillagoe road in red-purple welded tuff and pyroclastics (site 2), in a greenish-grey ignimbritic unit (sites 3 and 4), and in a rhyolitic dyke (site 5). The flat-lying rhyolitic ignimbrite at the top of Eight Mile Mountain has been dated using Rb-Sr methods at 303-305 Ma.

##### Location 12: BBFD

Eight sites (64 samples) were sampled north of the Walsh River, from about 3 to 7 km east of its confluence with Emu Creek. Sites 1 to 3 were sampled in coarsely-crystalline rhyolitic to rhyodacitic ignimbrite, probably belonging to unit Pfa1; site 3 at Flat Rock Waterhole and sites 1 and 2 about 1 km to the west. Sites 4 to 6 and probably site 7 were sampled in rhyolitic ignimbrite mapped as unit Pfa. Site 8 was sampled in a reddish rhyolitic ignimbrite, probably belonging to unit Cbr. Nearby rhyolitic ignimbrites, probably mapped as unit Pfa1, have been dated through Rb-Sr methods at 290 Ma.

#### C) LIZZIE CREEK VOLCANICS AND CARMILA BEDS (FIG.2C)

##### Lizzie Creek Volcanics:

##### Location 13: AFLA, AFLB

Two sites (20 samples) were sampled from two thin and rather loosely welded pyroclastic beds, which outcrop directly north of Strathmore Homestead. Bedding was well-determined from the sedimentary sequence.

##### Location 14: AFLC, AFLD

Two sites (20 samples) were sampled in a coarsely clast-rich welded tuff; site AFLC in the welded central part and site AFLD about 5 m upwards in the less welded top part. Bedding was well-determined from local flowbanding observations.

##### Carmila Beds:

##### Location 15: AFCA, AFCB

Two sites (20 samples) were sampled in dark-purple welded dacitic-andesitic tuffs in beach outcrops at Mt. Maria. Bedding was well-defined.

## *Appendix A*

### Location 16: AFCC,AFCD

Two sites (20 samples) were sampled in the fine-grained top (AFCC) and the coarser-grained basal part (AFCD) of a dark-purple welded pyroclastic flow, which is intersected by doleritic dykes. Bedding was well-defined.

### D) SILVER HILLS VOLCANICS (FIG.2D)

#### Location 17: ADSA-ADSD

Four sites (40 samples) were sampled in the type section at Spring Creek, to the west-south-west of the Silver Hills Homestead (Veevers et al.,1964a [Fig.10], noted as Spring Creek Homestead on the Rubyvale 1:100,000 topographic map). Four flow-banded rhyolite units were sampled over an about 40 m stratigraphic interval, downward from about 30 m below the contact between the Telemon Formation and the Silver Hills Volcanics. Bedding was well-determined from sediments in the overlying Telemon Formation.

#### Location 18: ADSE-ADSH

Four sites (40 samples) were sampled in rheomorphically-deformed flowbanded rhyolites at Red Mountain. Bedding was estimated from the general topographic surface of the unit, and is not well-constrained.

## APPENDIX B: DESCRIPTION OF DEMAGNETIZATION RESULTS (Figs.4-6)

Directional results are grouped and described in terms of three component types (C1, C2 and C3, see text).

Component C1 (Table 2), with occasionally a softer C1<sub>i</sub> and a harder C1<sub>h</sub> subcomponent, represents either a Recent field, an Early Tertiary, or a Late Cretaceous overprint.

Component C2, with a softer C2<sub>i</sub> (Table 3A) and a harder C2<sub>h</sub> (Table 3B) subcomponent, represents mainly a Late Carboniferous-Early Permian widespread remagnetization (Smedley Dacite, Star of Hope Formation volcanics, Lizzie Creek Volcanics, Silver Hills Volcanics), but also a probable primary magnetization (Featherbed Volcanics), or a syn-sagging primary component acquired during extrusion (Cb sequence, Pyramid Rhyolite and Arundel Rhyolite).

Component C3, with occasionally a softer C3<sub>i</sub> and a harder C3<sub>h</sub> subcomponent, represents either a primary magnetization (Table 4) of Late Devonian-Early Carboniferous age (Silver Hills Volcanics, Star of Hope Formation volcanics) and a possible primary magnetization in Early Permian age (Carmilla Beds), reversed polarity overprints (Table 5) of Late Cretaceous-Tertiary age, or diverse components of widely different interpretation, or unclear and possibly composite origin (Table 5).

In those cases where two subcomponents have been distinguished, particularly for component C2, the description concentrates on the demagnetization characteristics of the harder subcomponent. The softer subcomponent, with generally less distinctive characteristics and directionally more dispersed groupings, is described only in those cases where it has a predominant presence and/or an obvious interpretation.

**A) BULGONUNNA VOLCANIC FIELD**

Bulgonunna Volcanic Group, rhyolite-dominated association (previously Cb):

**Location 1: BFBB: Pyramid Rhyolite**

Two main components: a subdued soft Recent field component C1, generally removed at 200°C, and a predominant hard southwesterly to westerly downward directed component C2<sub>h</sub>, removed at 560°C to 680°C, with greatcircle-streaking of directions between components C1 and C2<sub>h</sub>. AF-demagnetization does not separate C1 as an entity, but C2<sub>h</sub> is eliminated between 40 mT (occasionally 20 mT) and 100 mT.

**Location 2: BFBC: Pyramid Rhyolite**

Two main components: a rather subdued soft Recent field component (C1), generally removed at 100°C to 300°C, and a predominant hard south-westerly and very steep downward-directed component C2<sub>h</sub>, removed at 550°C to 670°C. AF-demagnetization is only occasionally successful in the separation of C1 at 10 mT, and in the elimination of C2<sub>h</sub> over a wide range of AF-fields up to 100 mT.

**Location 3: BFBA: Arundel Rhyolite**

Well-determined component directions with rather dispersed directional groupings, possibly due to pronounced lightning effects on the sampled ridge. The two main components C1 and C2<sub>h</sub> can be identified but are not prominent. The rather hard Recent field component C1 is eliminated in a few of the samples at 400°C to 500°C, but cannot be separated during AF-treatment. Only AF-treatment between 20 mT and 100 mT was successful in separating the very steep westerly-directed component C2<sub>h</sub>.

**Location 4: BFBB: Arundel Rhyolite**

Two main components: a rather subdued soft Recent field component C1 eliminated at 200°C to 300°C and at very low AF-fields up to 10 mT, and a more pronounced south-westerly and very steep downward-directed component C2<sub>h</sub>, generally eliminated around 630°C and between 20 mT to 100 mT. Greatcircle-streaking between components C1 and C2<sub>h</sub>.

**Location 4: BFBB: Arundel Rhyolite**

Two components: a rather prominent but soft Recent field component C1 generally removed at 150°C to 250°C and at 10 mT to 20 mT, and a south-westerly, steep downward-directed component C2<sub>h</sub>, generally eliminated at 540°C to 630°C and between 20 mT to 100 mT. Slight greatcircle-streaking between C1 and C2<sub>h</sub>.

**Location 5: AFBH-AFBK**

One main component only: a southerly and steep downward-directed component C2<sub>h</sub> eliminated at 570°C to 630°C and generally between 20 mT to 100 mT.

## Appendix B

### Post-Cv granitoids:

#### Location 8: AFGA,AFGB

Two main components: a soft Recent field component C1 eliminated at about 200°C and at 10 mT, mainly present in site AFGB, and a harder south-easterly (sic!) and steep downward-directed component C2<sub>h</sub> eliminated between 560°C to 640°C and 20 mT to 100 mT. Site AFGA alone shows a third and soft northerly-to-easterly and very steep upward-directed component, more or less antipodal to C2<sub>h</sub>, which is eliminated at 250°C and at 20 mT.

### Bulgonunna Volcanic Group, dacitic-rhyolitic association (previously Cv):

#### Location 3: BFBE: Smedley Dacite

One predominant component only: a southerly and steep downward-directed component C2<sub>h</sub>, eliminated at 550°C to 630°C and between 15 mT to 100 mT.

#### Location 6: AFBA-AFBG,BFBD: Smedley Dacite

Two main components: a soft Recent field component C1, eliminated at 150°C to 250°C and at 10 mT, and a very predominant coherent southerly and very steep downward-directed component C2<sub>h</sub>, eliminated at 600°C to 630°C and between 10 mT to 100 mT.

### Volcanic member in the Star of Hope Formation (previously CIs):

#### Location 7: BFBH

Complex magnetization. The two predominant components are:

(i) a soft Recent field component C1 eliminated at 100°C to 250°C and at 10 mT, (ii) ~~two~~ southerly and steep downward-directed sub-components C2<sub>l</sub>,C2<sub>h</sub>. The softer one C2<sub>l</sub> is a magnetite-based component eliminated at about 540°C and occasionally at 10 mT to 20 mT, and the harder one C2<sub>h</sub> is a hematite-based component eliminated between 580°C and 680°C, and between 20 mT and 100 mT.

Far less dominant are: (iii) a normal polarity, northerly component of equatorial inclination and of presumed primary origin, with a rather variable blocking temperature range mainly below the Curie point of magnetite (~580°C); (iv) a reverse polarity Recent or Tertiary component which is eliminated at the very high end of the magnetite range between the softer C2<sub>l</sub>-component and the harder C2<sub>h</sub>-component, i.e. between 550°C and 570°C (occasionally up to 630°C); (v) scanty occurrence of north-westerly and moderate upward-directed components of a generally very soft nature, eliminated at 100°C and at 10 mT, but also with occurrences of a much harder nature.

## B) FEATHERBED VOLCANICS

#### Location 9: BBFA

Two main components: a rather subdued and soft Recent or possibly Early Tertiary component C1, eliminated at 4 mT and at 150°C, and a predominant and hard southerly to south-south-westerly, steep downward-dipping component C2<sub>h</sub>. The latter shows composite breakdown with a softer and slightly more southerly-directed component C2<sub>l</sub>, and is only broken down in isolation in samples from sites 4-8 between 40-100 mT and between 360°C and 570°C.

Sites 1-3 show different behaviour. (i) Sites 1-2 show a component C2<sub>h</sub>, broken down between 4 and 26 mT, and a south-westerly and moderate-shallow, downward-directed component C3<sub>h</sub> of harder characteristics, eliminated between 14 and 100 mT and between 460°C and 580°C. The origin of component C3<sub>h</sub> is not clear. Unrecognized tilting problems can be excluded because component C2<sub>h</sub> directions are similar to those in sites 4-8. Pole positions for this component fall on the general Devonian-Carboniferous segment of the SLP-path (Fig.9A), and on the Middle Devonian part of the KG-path (Fig.9B). Rb-Sr dates for these ignimbrites, however, indicate a latest Carboniferous age (280 Ma). (ii) Site 3, in contrast, shows a component C2<sub>h</sub> and an east-south-easterly and steep downward-directed component C3<sub>h</sub> of harder magnetic characteristics, eliminated at 430°C to 580°C. Component C3<sub>h</sub>, likewise, does not seem to reflect unrecognized tilting because component C2<sub>h</sub> directions from this site are comparable to other sites. The C3<sub>h</sub> pole position falls on the Jurassic-Cretaceous or possibly the Permo-Triassic part of the Australian APWP.

#### Location 10: BBFB

Results from this location differ from the other three locations (9,11,12), presumably due to sampling in the vicinity of a north-south fault zone which shows signs of ongoing hydrothermal activity (warm springs).

Sites 1-6 (Pff unit) show a predominant and soft Recent or Late Cretaceous-Early Tertiary component C1<sub>l</sub>, broken down between 120°C and 220°C and up to 10 mT. A harder component of very similar direction (C1<sub>h</sub>) is broken down in isolation between 430°C and 690°C and between 20 and 100 mT, but shows composite breakdown with another slightly more southerly directed component at lower °C/mT steps. Sites 7 and 8 (Pfc unit) show a rather hard component C1, broken down at up to 460°C-540°C and up to 100 mT, and a harder component C1<sub>h</sub> with a somewhat steeper downward and slightly more southerly direction, that is broken down between 600°C and 670°C but not during AF-demagnetization. Its



pole position approaches those for component C2 in the other three Featherbed Volcanics locations (9,11,12). Its normal polarity, however, makes it unlikely that this is a primary component of Late Carboniferous-Late Permian origin (Fig.11B2).

There are some observations of low inclination components of uncertain origin; a south-westerly component in sites 2,3 and 6 that is broken down between 10 and 50 mT, and an easterly component in site 5 that is broken down between 400°C and 640°C.

#### Location 11: BBFC

All five sites show the consistent, but not predominant, presence of a Recent or possibly Late Cretaceous-Early Tertiary component C1, eliminated generally at 10 mT (site 5 up to 100 mT) and at 150°C to 200°C. Sites 1-3 also show a harder to hard reverse polarity component C1<sub>r</sub>, eliminated between 10mT and 100 mT and between 450°C and 670°C (sites 1 and 3: 550°C to 570°C, site 2: 500°C to 620°C). This component is presumably of middle Tertiary origin (Fig.11B1), although comparison with the SLP APWP (Fig.9A) suggests a possible (Middle) Carboniferous origin.

All five sites show also a hard south-south-easterly and steep downward-dipping component C2<sub>h</sub>, presumably of Late Carboniferous-Early Permian primary origin. It is generally broken down between 500°C and 680°C (sites 1, 4 and 5: 550°C to 630°C; sites 2 and 3: generally 600°C to 680°C) and between 10mT and 100mT. Component C2<sub>h</sub> has a more westerly declination than comparable components for the other 3 locations. Magnetic fabric results (Fig.7B4) can be interpreted in terms of a slight westerly to north-westerly tilt of the sampled beds. Correction for such a tilt would give a more southerly direction which is in better agreement with the three other locations.

Site 1 also shows a component C3 with low to very low downward inclinations and southerly to south-south-westerly declinations. This direction occurs both as a soft subcomponent C3<sub>1</sub> broken down between 180°C to 360°C, and as a very hard component C3<sub>h</sub> broken down between 620°C and 715°C. The dual occurrence of this direction as both a soft and a very hard (hematite) component suggests a secondary origin. The location of its pole position on the Devonian-Carboniferous part of the SLP-path may be merely fortuitous.

#### Location 12: BBFD

Most of the sites (1-3,7, and 8) show the presence of a soft component C1 that is broken down at 12 mT and between 80°C and 290°C. It is not very consistent or predominant. Its inclination is steeper than the expected local field direction and its pole position is closer to the Late Cretaceous APWP segment (100 Ma: Figs.8,9,11B1) or possibly the Triassic/Jurassic part of the ill-defined Mesozoic APWP for Australia. Sites 3 and 7 alone show a few observations of a rather similar, but very hard, component broken down between 580°C and 695°C. It is possible that both components represent the same overprint residing in different magnetic phases or parts of the blocking temperature spectrum.

All sites show the presence of a Late Carboniferous-Early Permian component C2<sub>h</sub>, comparable to, but slightly eastward, of the components observed in locations 9-11 (Fig.11B2). This component is broken down either at the high end of the magnetite range (Sites 1 and 2: between 400°C and 560°C and between 10 mT and 100 mT), or mainly in the hematite range (Sites 3-8: between 580°C and 695°C and between 20 mT and 100 mT).

Sites 4 to 6 show some softer components C3 of spurious direction and unclear origin. A westerly and moderately upward component is eliminated in site 4 and 6 between 200°C and 560°C. Site 5 shows a southerly and moderately steep upward component, eliminated between 150°C and 550°C and at 12 mT. Sites 4 and 6 show a few occurrences of an easterly and moderately upward directed component, eliminated in the same temperature range (site 6), or up to the hematite blocking temperature range (site 4) and 100 mT. Site 5 was sampled on a ridge which showed deep weathering. Lightning and/or weathering could explain this southerly component and possibly also the easterly components of sites 4 and 6. The origin of the dispersed westerly component is not clear. It is not observed from pilot AF demagnetization data.

Magnetic fabric patterns for sites 1-3,5,6 and 8 have subvertical K<sub>max</sub>-axes (Fig.7B2), suggesting a subhorizontal attitude of the ignimbrite flows. The magnetic fabric axis and the Late Carboniferous-Early Permian component for site 4 are displaced westward from the main groupings, and an ad-hoc tilt correction may be justified. Site 7 shows an unusual magnetic fabric (Fig.7B2) which may be related to a nearby, and major, north-south oriented fault zone. The results for the Late Carboniferous-Early Permian component C2<sub>h</sub>, however, are in agreement with the overall result for this location.

### C) LIZZIE CREEK VOLCANICS AND CARMILA BEDS

#### Lizzie Creek Volcanics, Locations 13 and 14 combined: AFLA-AFLD

Two main components: a soft Recent field component C1 eliminated at 200°C to 300°C and in some samples at 10 mT, and a hard very steep downward and southerly directed component C2<sub>h</sub> eliminated at 580°C to 680°C and in sites AFLC-D between 20 mT and 100 mT. A reverse polarity Recent component C1<sub>r</sub> is sporadically present and is eliminated between 200°C and 650°C.

#### Carmila Beds, Locations 15 and 16 combined: AFCA-AFCD

A rather complex magnetization pattern, unlike the other locations described. Overprint component C2 has not been positively identified. All sites show a predominant component C1 of presumed Recent origin but with an inclination somewhat steeper than expected. This component is eliminated between 150°C and 550°C (occasionally 650°C in sites AFCC and AFCD) and over a wide range of AF-fields. There is a pronounced, but dispersed, streaking in the upper hemisphere over a NNW-SSE oriented greatcircle through this steeply upward-directed component. Three other groupings

## Appendix B

of directions can be distinguished. One grouping only can be interpreted at this stage as a physical reality. This is a poorly-constrained, westward and moderate downward-directed hard component  $C3_h$ , eliminated at  $570^{\circ}\text{C}$  to  $690^{\circ}\text{C}$  but not very effectively upon AF treatment.

### D) SILVER HILLS VOLCANICS

#### Location 17: ADSA-ADSD

Three main components: a soft Recent field component C1 removed at  $150^{\circ}\text{C}$  to  $200^{\circ}\text{C}$  (occasionally  $250^{\circ}\text{C}$ ) and less effectively at 10 mT; a south-westerly and steep downward-directed component  $C2_h$  eliminated in site ADSA at  $600^{\circ}\text{C}$  to  $680^{\circ}\text{C}$  and up to 100 mT, and in sites ADSB-D mainly at  $400^{\circ}\text{C}$  to  $570^{\circ}\text{C}$ ; and a hard southerly component C3 (or  $C3_h$ ) of very low inclination, restricted to sites ADSB-D and eliminated between  $570^{\circ}\text{C}$  and  $680^{\circ}\text{C}$ .

#### Location 18: ADSE-ADSH

Complex magnetization pattern with up to four components: a soft Recent field component C1 eliminated at  $150^{\circ}\text{C}$  to  $200^{\circ}\text{C}$ , and occasionally between 30 mT and 100 mT; a sporadic and not very significant occurrence of a steep downward and westerly directed component  $C2_h$  eliminated over a wide range of blocking temperatures and alternating fields; a sporadic occurrence of a rather hard southerly component of very low inclination C3 (or  $C3_h$ ) comparable to the component observed more prominently in the sites at location 17; and a prevalent moderate upward and westward-directed component C3 (or  $C3_h$ ) of hard magnetic characteristics mainly broken down between  $570^{\circ}\text{C}$  and  $680^{\circ}\text{C}$  and between 20 mT and 100 mT.