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A crustal thrust system in an intracratonic tectonic environment

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Abstract—An intracratonic thrust belt, developed during the early Carboniferous in central Australia, deformed the Amadeus Basin and its basement, the Arunta Block. This belt is characterized by a marked structural asymmetry (vergence) and by the deposition of a thick molasse basin on the foreland. A review of existing field data shows that décollement tectonics produced folding, thrusting, faulting and back-faulting of the sedimentary sequence. Thin-skinned tectonics extend into the basement to produce recumbent folds and têtes plongeantes of nappe structures rooted in steeply dipping mylonite zones of greenschist to amphibolite grade. Minimum horizontal shortening displacements are 50–100 km resulting in a 50–70% contraction of the upper part of the basement. The structures and shortening are best explained by a crustal duplex, characterized by a crustal-scale thrust system, i.e. a sole thrust and imbricate faults, responsible for an isostatic bending of the underthrust slab. The observed Bouguer anomaly profiles support this crustal model. The dynamic evolution of this thrust belt on the scale of the crust is of thin-skin type.

INTRODUCTION

IN THE last two decades, geological and geophysical studies of orogenic belts have largely been concerned with deformation at plate boundaries. Considerable progress in the understanding of mountain-building processes has resulted from understanding oceanic subduction and continent-continent collision (see Smith 1981 and Hsü 1982). However, another type of orogenic activity exists, away from the continental margins, in intracratonic tectonic environments (the term 'intracratonic' is preferred here because of the ambiguity of the term 'intracontinental' that may characterize the late stages of collision-related orogens). This type of tectonic activity is poorly documented (Turcotte 1982). The present paper is a contribution to the description and tectonic interpretation of such intracratonic deformations.

The case history is taken from central Australia, where a late Palaeozoic orogeny (the Alice Springs Orogeny) is responsible for the deformation of an intracratonic sedimentary basin (the Amadeus Basin) and its metamorphic basement (the Arunta Block) (Fig. 1). Thrust tectonics have been recognized for a long time along the northern edge of the Amadeus Basin (Forman *et al.* 1967), where the basement/cover relation has been studied (Marjoribanks 1976a, Shaw *et al.* 1979, Shaw & Wells 1983). However, since the pioneering work by Forman & Shaw (1973), little has been done to describe the entire orogenic belt in terms of crustal deformation. Recent work carried out by the author on the high strain zones of the Arunta basement has allowed recognition of geometrical and kinematic frameworks from which a dynamic evolution can be proposed. Therefore, the aims of the paper are:

(i) to show that the structures encountered in both the sedimentary basin to the south and the basement rocks to the north form part of an integrated structural history and can be interpreted in terms of a crustal thrust system and

(ii) to state the tectonic implications this interpretation has on intracratonic deformation on a crustal scale.

After a brief description of the regional geology, a review of existing structural data is presented in the form of a comprehensive structural sketch map of the exposed late Palaeozoic structures. This compiled surface geology is the basis for constructed interpretative cross-sections across the Amadeus Basin and the Arunta Block, which allow the shortening to be estimated. A new model based on a crustal thrust system is then proposed to account for the observed structures and shortening. It is shown that a dynamic evolution can also be inferred from the observed geometries and kinematic trajectories. Finally, a qualitative test of the crustal model is performed using existing geophysical data.

MAJOR GEOLOGICAL FEATURES IN CENTRAL AUSTRALIA (900–300 Ma)

The Tectonic Map of Australia (Geological Society of Australia 1971), from which the central Australian geology is simplified in Fig. 1, shows E–W elongate outcrops of alternating metamorphic complexes and sedimentary basins. The metamorphic rocks are exposed in two blocks: the Arunta Block to the north, and the Musgrave Block to the south (Rutland 1976). There, lower to middle Proterozoic igneous and sedimentary rocks have been metamorphosed to the amphibolite and granulite facies during a complex middle Proterozoic tectonometamorphic event (see Mathur & Shaw 1982). The resulting continental crust seems to have been stabilized by 900 Ma and subsequently constituted the source as well as the basement for the sedimentary

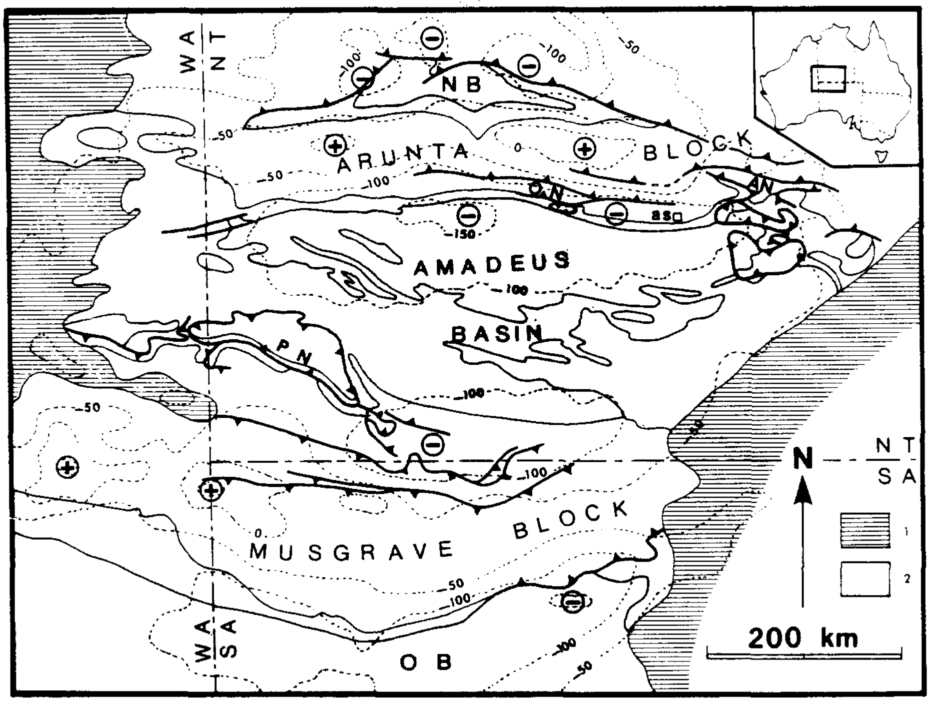


Fig. 1. Tectonic map of entral Australia (modified after The Tectonic Map of Australia and New Guinea, GSA, 1976). The Gravity Map of Australia (BMR, 1976) is superposed and shows highs (+) and lows (−). (1) Post-Carboniferous sediments; (2) Upper Proterozoic and Palaeozoic sediments; the metamorphic complexes are left blank. AN, Arltunga Nappe Complex; NB, Ngalia Basin; OB, Officer Basin; PN, Petermann Ranges Nappe Complex; AS, Alice Springs; NT, Northern Territory; SA, South Australia; WA, Western Australia.

sequences now preserved in three basins: from north to south, the Ngalia, Amadeus and Officer Basins (Fig. 1). In these sedimentary basins, Upper Proterozoic shallow marine sediments, remarkably well correlated throughout central Australia (Preiss & Forbes 1981), are unconformably overlain by a Palaeozoic sequence. The Amadeus Basin can be structurally divided into two basins separated by an E–W basement high.

(1) To the south, the Upper Proterozoic Adelaidean sequences are about 5 km thick and have been strongly deformed along the northern edge of the Musgrave Block during the Petermann Orogeny, 600 Ma ago (Forman 1966). As a result, extensive nappe structures are developed, the basement floor is dipping to the south, and a thick molasse basin (up to 10 km thick in some places) was deposited on the foreland.

(2) To the north, the Upper Proterozoic sequences are overlain by a Palaeozoic sequence with no major angular unconformity. The northern basin has an E–W extent of 600 km and a width of 150 km (Fig. 1); it deepens to the north to reach a maximum thickness of 13 km near its northern edge; this dip of the basement floor to the north is associated with an increase in the negative value of the Bouguer anomaly (Fig. 1). My interest is focused on this northern part of the basin.

A detailed stratigraphy of the Amadeus Basin is reviewed in Wells *et al.* (1970) and a simplified stratigraphic column of the Upper Proterozoic and Palaeozoic sediments is presented in Table 1. The points relevant to the scope of this study are summarized below.

(i) All the sediments were deposited in a shallow marine or terrestrial environment in an intracratonic basin. The tectonic setting of this basin is discussed by Lambeck (1983).

(ii) The Bitter Springs Formation (Table 1), characterized by siltstone, laminated dolomite, limestone and

Table 1. Simplified stratigraphy of the north Amadeus Basin (from Wells *et al.*, 1970)

Thickness (m) (maxi)	Formation	Dominant rock-type	Age
4000	Pertnjara Group	Coarse sandstone, conglomerate	Devono-Carboniferous
1000	Mereenie Sandstone	Sandstone	Siluro-Devonian
2000	Larapinta Group	Sandstone, siltstone	Ordovician
2500	Pertaoorta Group	Limestone, dolomite	Cambrian
2000	Pertatataka Fm.	Siltstone, limestone	
500	Areyonga Fm.	Siltstone, sandstone	
1000	Bitter Springs Fm.	Dolomite, limestone	Upper Proterozoic
500	Heavitree Quartzite	Quartzite, coarse sandstone	900 Ma?
	Arunta Block	Metamorphics	Lower and Middle Proterozoic

evaporite acted as a décollement horizon (Wells *et al.* 1965) during the tectonic event of the Alice Springs Orogeny. Locally, Cambrian evaporites can also be used as an upper décollement surface (Forman 1971).

(iii) Coarse-grained sediments (pebbly sandstone and conglomerate) especially well exposed along the northern edge of the Amadeus Basin were deposited during the Devono-Carboniferous (Jones 1972) and are referred to as the Pertnjara Group (Table 1); towards the top of this formation, a thick (>3 km in places) piedmont conglomerate, the Brewer Conglomerate, typically represents a synorogenic deposit.

The end of the widespread shallow marine sedimentation is marked by a major tectonic event, the Alice Springs Orogeny (Forman *et al.* 1967). Nappe structures, cored with basement rocks of the Arunta Block, were emplaced from the north to the south and were thrust over the Amadeus Basin. The nappes are particularly well exposed in the Ormiston Nappe Complex and the Arltunga Nappe Complex (Fig. 1). Dating of high strain zones in the basement rocks and/or lower part of the cover (431–322 Ma, K–Ar, Stewart 1971; 335–312 Ma, Rb–Sr, Armstrong & Stewart 1975; 510–330 Ma, Ar–Ar, Allen & Stubbs 1982) confirms that deformation in the Amadeus Basin is coeval with deformation of the basement. In the next section, a more precise description of the structures produced in the Amadeus Basin and the Arunta Block is presented.

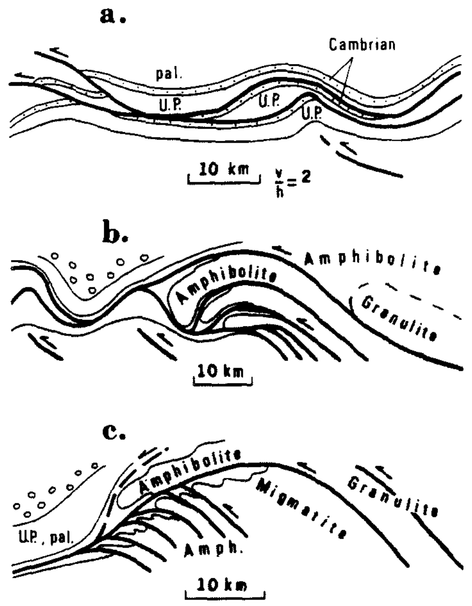


Fig. 2. Thin-skinned tectonics of the northern margin of the Amadeus Basin: (a) duplex structure showing the two major nappes, the Phillipson and Todd River Nappes, situation Fig. 3 (modified from Wells *et al.* 1970); (b) 'têtes plongeantes' at the Arltunga Nappe Complex (modified from Forman 1971); (c) 'têtes plongeantes' at the Ormiston Nappe Complex (modified after Marjoribanks 1976a).

STRUCTURAL RELATIONS

A review of published regional structural relations for the 450 km strike-length of the North Amadeus Basin and South Arunta Block is shown in Fig. 3, together with the author's mapping of structures and kinematic trajectories (i.e. mylonitic lineations) in the central part of the map (see caption). The structures in the basin and the basement are described below in modern thrust tectonics nomenclature. The shortening characteristics deduced from the constructed cross-sections (Fig. 4) are summarized in Table 2.

Structures in the north Amadeus Basin

The structures developed in the north Amadeus Basin are (1) open folds, (2) duplex structures, (3) back faults and back folds and (4) 'têtes plongeantes' (plunging noses) of nappe structures. Each of these particular structures is described below.

Open folds. E–W trending open folds (Fig. 3) with wide, box-shaped synclines and tight, narrow and frequently faulted anticlines (see Fig. 3) characterize the map pattern of the north Amadeus Basin (Wells *et al.* 1970). These features are typical of décollement tectonics as seen in the Jura or the Appalachians. This observation is further supported by magnetic and seismic surveys which show that the basement-cover contact is smooth, flat and not folded nor faulted (Froelich & Krieg 1969, Wells *et al.* 1970). The folds have a typical wavelength of 15–30 km (Fig. 3) and can be traced axially for considerable distances (up to 300 km).

Duplex structures. In the north-eastern part of the basin, the décollement surface in the Bitter Springs Formation passes upwards into the Cambrian unit (Forman 1971). A ramp effect is responsible for the observed duplex structure (Fig. 2a). Two klippen of the uppermost

Table 2. Shortening characteristics. L_0 and L_1, respectively refer to the initial length and the current length of the upper part of the basement. Contraction is first calculated for the deformed belt only, then for the belt and foreland. The southern margin of the foreland is arbitrarily taken at the flexure of the basin floor and/or at the site of back faulting in the basin (see cross-sections Fig. 4)

	Shortening (km) $L_0 - L_1$	Belt only Contraction ratio L_1/L_0	Belt only Contraction % $\frac{L_0 - L_1}{L_0} \times 100$	Belt and Foreland Contraction ratio L_1/L_0	Belt and Foreland Contraction % $\frac{L_0 - L_1}{L_0} \times 100$
Section AA'	43	0.49	51	0.72	28
Section BB'	74	0.42	58	0.51	49
Section CC'	52	0.44	56	0.62	38
Section DD'	85	0.29	71	0.56	44

nappe (the Phillipson Nappe) are now preserved (Fig. 3) above the Todd River Nappe (Wells *et al.* 1970, p. 152). The sense of transport of these nappes is from the north to the south as indicated by the vergence of the folds and the slickenside lineations on the thrust planes. Using the Areyonga Formation (Table 1) situated above the décollement surface as a structural marker, we can show that the duplex structure is responsible for a 70 km N–S shortening of the Upper Proterozoic sequence (Section DD′, Fig. 4). The thin horizon of Areyonga Formation or, when non-existent, the base of the Pertaoorta Formation (Table 1) is drawn on the structural map (dotted line) and related cross-sections in Figs. 3 and 4, respectively.

Back faults and back folds. Back-folding and back-faulting (Butler 1982) are developed along a continuous E–W trend that marks the southern edge of the thick molasse basin and the southern limit of the duplex structure (Fig. 3). The south-dipping faults or north-verging folds deform the sedimentary pile and do not affect the basement (see 'open folds' section). The back-thrusts steepen upwards; they are responsible for slight northward movements. This mechanism is common in fold and thrust belts and has been studied experimentally (Davis *et al.* 1983, Dahlen *et al.* in press). Here, the location of the back-thrusts and back-faults may be controlled by the sedimentary or tectonic thickening respectively produced by the deposition of synorogenic sediments or the emplacement of nappe structures.

Têtes plongeantes. The French term 'tête plongeante' is preferred to describe the plunging noses of nappe structures exposed along the northern margin of the Amadeus Basin (Figs. 2b & c). They are downward-facing synforms composed of a crystalline basement core usually surrounded by the thin Heavitree Quartzite (Table 1), resting on the Bitter Springs Formation (Forman 1971). Such structures are similar to those described in the southern zone of the Pyrenees (Choukroune & Séguret 1973, fig. 6). In the Arltunga Nappe Complex, three superposed 'têtes plongeantes' are exposed (Fig. 2b). The largest one has a basement core of 7 km across strike and its footwall thrust has recorded a displacement of 24 km to the south (Forman 1971). The 'têtes plongeantes' are situated on the top of basement-cored recumbent folds. Similar geometries are found in the Ormiston Nappe Complex (Marjoribanks 1976a) (Fig. 2c) and the Blatherskite Nappe (Stewart 1967). As the Heavitree Quartzite is stratigraphically situated below the major glide horizons, it appears to be rigidly deformed with the basement and therefore has recorded the shortening of the upper part of the basement; this feature will be used later in the paper.

Structures in the Arunta Block

The crystalline basement is mainly composed of micaceous schists and quartzo-feldspathic and mafic gneisses of the amphibolite and granulite facies. These rocks are characterized by a strong foliation and a complex geometry resulting form the middle Proterozoic orogenies (see Shaw & Stewart 1975). The structures associated wtih the Alice Springs Orogeny in the basement rocks are mainly restricted to cataclasite, mylonite and phyllonite zones. No regional schistosity is to be noted and a strong foliation is concentrated in narrow zones (up to 5 km) of intense deformation and recrystallization under retrogressive conditions (up to amphibolite facies of metamorphism). The major zones are reported on the map (Fig. 3) but narrow zones (cm to m scale) are ubiquitous. The mylonite zones are commonly E–W striking and are steeply dipping to the north (>45°) (Fig. 3). They form an anastomosing map pattern and can be traced for several tens or hundreds of kilometres. Map spacing between the major mylonite zones across strike varies from 3 to 20 km and averages a value of 10 km.

Within the deformed zones, a strong mylonitic lineation, which represents the direction of plastic flow, lies in the foliation plane. It is usually steeply plunging to the north with an orientation tranverse to the belt (Fig. 3). Detailed work (Teyssier 1983, in prep.) in the Redbank Deformed Zone (Fig. 3) has shown that sense of shear as deduced from the microstructures is from the north to the south across the north dipping mylonitic planes, parallel to the north trending mylonitic lineation. This is in good agreement with outcrop relations where rocks of higher grade of metamorphism are found to the north of the zone. No detailed microstructural work has been done on the other major deformed zones but scattered observations have confirmed that southward displacements consistently uplifted the northern blocks. In general, rocks of a higher grade of metamorphism are found progressively northward. Besides this, retrogressive reactions within the deformed zones show higher grades of metamorphism northwards. Cataclasite zones (characterized by brittle deformation) are common along the southern edge of the basement whereas only ductile deformation occurs in the northern deformed zones. Pseudotachylite has been found in quartzo-feldspathic gneisses exposed along the Charles River Fault (Fig. 3) (S. White, pers. comm.). Pseudotachylite

Fig. 3. Structural sketch map of the North Amadeus Basin and South Arunta Block. Key: (1) thrust faults (dip <45°); (2) reverse faults (dip >45°); (3) trace of open folds; (4) pseudotachylite zones; (5) stretching lineations and plunges; (6) Heavitree Quartzite; (7) Areyonga Formation. Data in the Amadeus Basin are from Wells *et al.* (1970) and Forman (1971); data in the Arunta Block from BMR (1969a) and Marjoribanks (1974) for the west of longitude 133° and BMR (1969b, 1983), for the east of longitude 134°30′. Basement rocks are shaded and the Pertnjara Group (Table 1) map contour is limited by a hatched line in the Amadeus Basin.

Fig. 4. Cross-sections of the North Amadeus Basin–South Arunta Block (located in Fig. 3); dashed lines are interpretive. Section BB′ extends to the Ngalia Basin to the north (for location, see Fig. 1). Structures in the Ngalia Basin are from Wells *et al.* (1972) and controlled by seismic profiles. Labels A–H refer to individual thrust sheets or horses (see text).

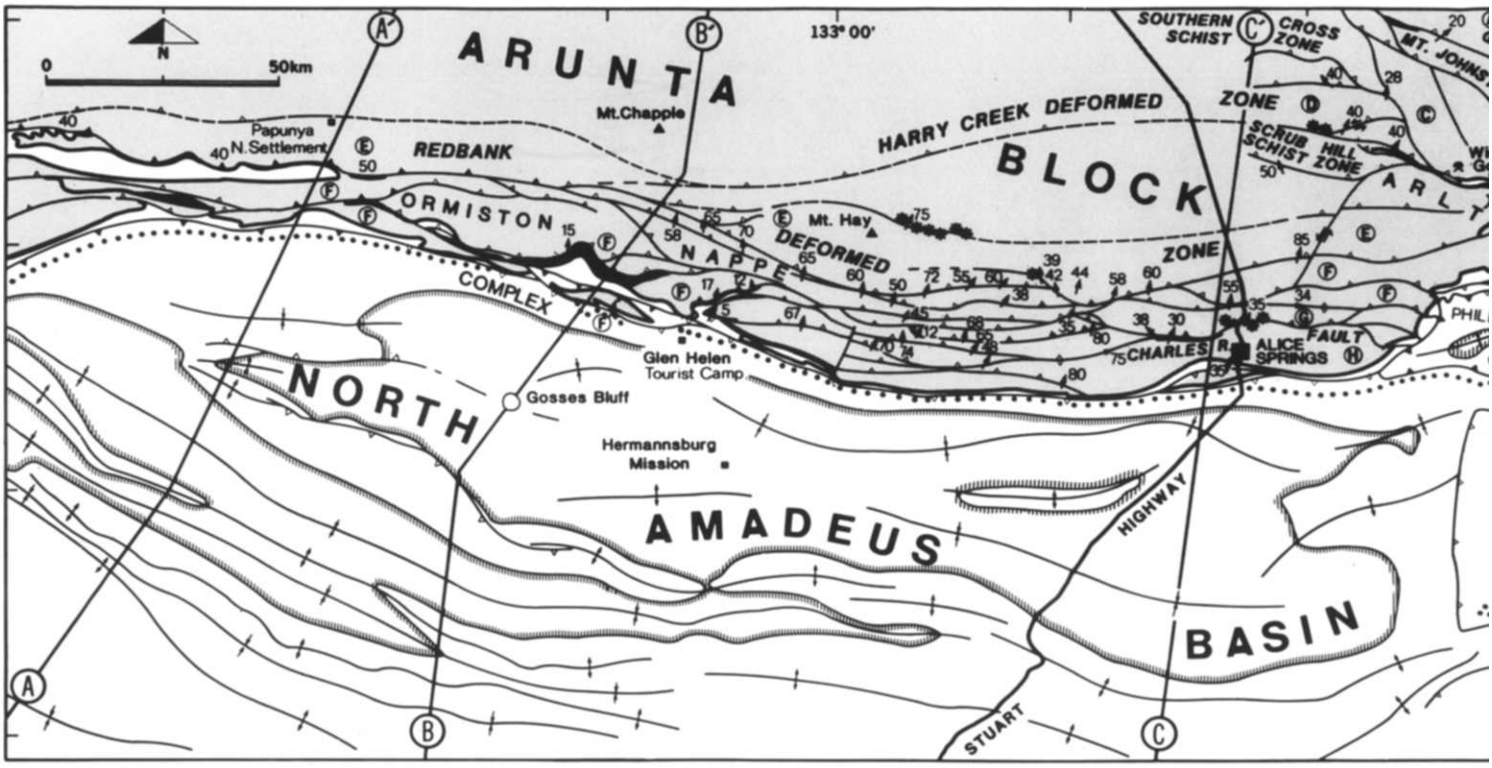

ARUNTA
BLOCK
HARRY CREEK DEFORMED ZONE
REDBANK
ORMISTON NAPPE COMPLEX
DEFORMED ZONE
Mt. Hay
Mt.Chapple
Papunya N. Settlement
SOUTHERN SCHIST
CROSS ZONE
SCRUB HILL SCHIST ZONE
MT. JOHNS
133° 00'
50km
Glen Helen Tourist Camp
Gosses Bluff
Hermannsburg Mission
NORTH AMADEUS BASIN
CHARLES R.
ALICE SPRINGS
FAULT
STUART HIGHWAY

FIG.3

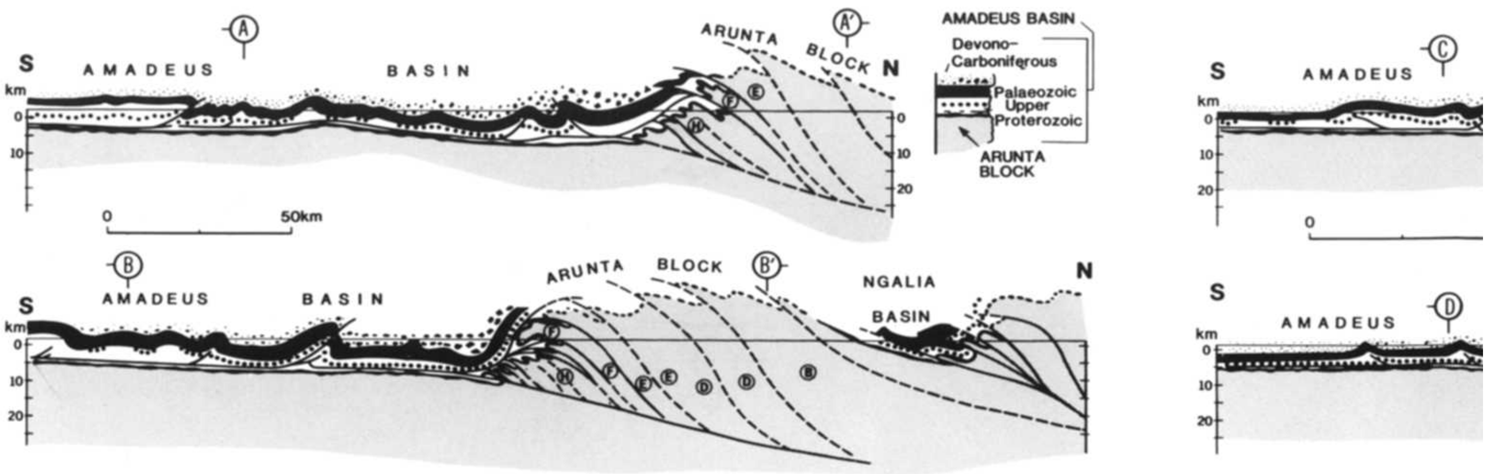
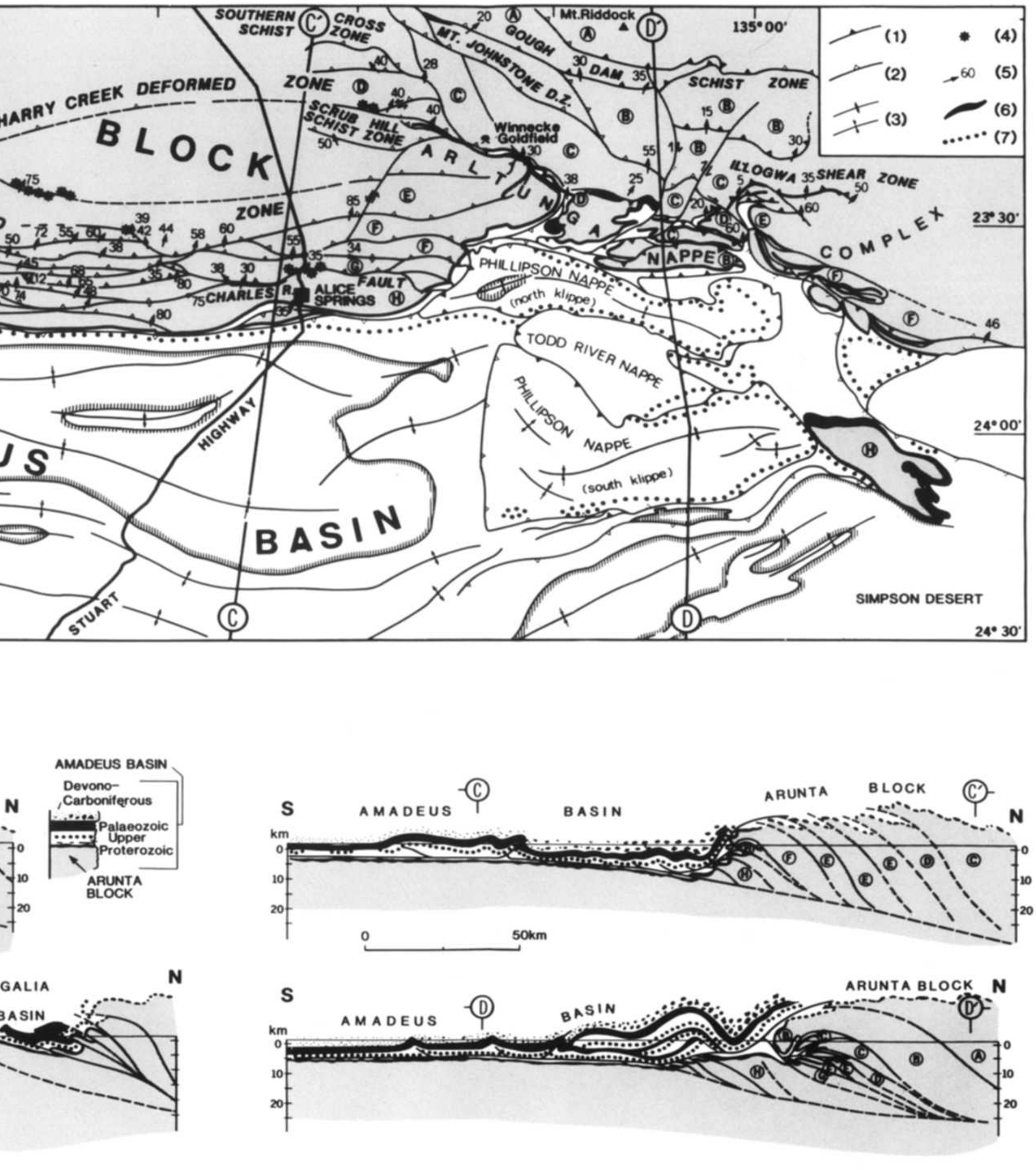

S AMADEUS BASIN
ARUNTA BLOCK N
km
50km
AMADEUS BASIN
Devono-Carboniferous
Palaeozoic
Upper Proterozoic
ARUNTA BLOCK
S AMADEUS BASIN
ARUNTA BLOCK
NGALIA BASIN N
S AMADEUS

FIG.4



SOUTHERN SCHIST
CROSS ZONE
Mt.Riddock
135° 00'
HARRY CREEK DEFORMED
ZONE
BLOCK
MT. JOHNSTONE D.Z.
GOUGH DAM
SCHIST ZONE
SCRUB HILL SCHIST ZONE
Winnecke Goldfield
ARLTUNGA
ILLOGWA SHEAR ZONE
COMPLEX
NAPPE
23° 30'
CHARLES R.
ALICE SPRINGS
FAULT
PHILLIPSON NAPPE
(north klippe)
TODD RIVER NAPPE
PHILLIPSON NAPPE
(south klippe)
HIGHWAY
STUART
BASIN
24° 00'
SIMPSON DESERT
24° 30'
(1)
(2)
(3)
(4)
(5)
(6)
(7)
AMADEUS BASIN
Devono-Carboniferous
Palaeozoic
Upper Proterozoic
ARUNTA BLOCK
S
N
km
AMADEUS
BASIN
ARUNTA
BLOCK
0
50km
GALIA
BASIN
ARUNTA BLOCK

is extensively developed to the north of the Redbank Deformed Zone (Teyssier 1983) but is restricted to the dry, quartz poor, mafic granulites. As a first approximation, these observations suggest that the active deformed zones were migrating southward, resulting in the uplift of the older (no more active) zones situated to the north. However, late seismic movements may be recorded along some of the northernmost zones as indicated by the presence of pseudotachylite in the Harry Creek Deformed Zone (Fig. 3) (Allen 1979).

An important point that emerges from the above descriptions is that the bulk N–S direction of movement along the deformed zones in the basement is subparallel to the bulk direction of transport along the thrusts in the Amadeus Basin; the general sense of movement is from the north to the south, except along the back faults in the Amadeus Basin.

Shortening estimation

As pointed out earlier in the paper, a peculiarity of this basement-cover system is that a sedimentary horizon, the Heavitree Quartzite, stratigraphically situated below the décollement surface of the Bitter Springs Formation (Table 1), is therefore not detached and is deformed in a contiguous manner with the basement. The macroscopic structure of the Heavitree Quartzite in the different cross-sections can be used to establish the minimum shortening. Finite strain studies of the Heavitree Quartzite (Yar Kahn 1972, Marjoribanks 1976b, Wilkie 1979) have shown that strain is heterogeneous and concentrated in narrow zones of deformation. Assuming that strain has not significantly affected the bulk length of the Heavitree Quartzite, and that the cross-sections (Fig. 4) are drawn parallel to the direction of movement on the thrust planes (and of maximum shortening of the folds), a minimum shortening of 50–100 km can be measured in the central and eastern part of the thrust belt (Table 2). These shortenings are associated with a contraction of 50–70% (a stretch of 0.3–0.5) of the upper crust across the width of the belt, where faulting and folding occur. If applied to the belt and its foreland (i.e. the width of the thick molasse basin added to the width of the deformed zone), the bulk contraction is substantially less, i.e. 30–50% (stretch 0.5–0.7) (see Table 2). It is suggested that this localized shortening and the relatively weak contraction on the scale of the thrust belt may be characteristic of intracratonic crustal deformations.

OVERTHRUST MODEL: A DISCUSSION

Some major points in the above description constrain the structural model proposed in this paper.

Detachment and thin-skinned tectonics. Geometries related to thin-skinned tectonics have been demonstrated in the Amadeus Basin. The têtes plongeantes further represent an extension of this thin-skinned thrust system to the north and we have established that the upper part of the basement has recorded considerable shortening (Figs. 3 and 4, Table 2).

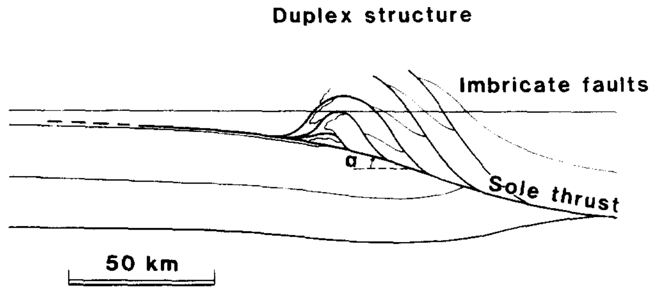


Fig. 5. Simplified overthrust model based on a crustal thrust-system geometry; α is approximately 15°; sole thrust and imbricate faults form a crustal antiformal stack towards the foreland; compare to cross-sections in Fig. 4 and see text for discussion.

Shear zones within the basement. There are similarities between the narrow, steeply dipping mylonitic zones of the Arunta Block and classical root zones (e.g. Burchfiel & Livingstone 1967, Boyer & Elliott 1982). Considerable displacements may have taken place along these north dipping zones as rocks of granulite facies (Figs. 2b & c) are exposed to the north of the Redbank Deformed Zone and to the north of the Arltunga Nappe Complex (Forman & Shaw 1973). Although it is argued that much uplift occurred before the deposition of the Heavitree Quartzite (Marjoribanks 1974, Shaw *et al.* 1984), the lack of precise estimation and the intensity of the Palaeozoic reactivation strongly suggest that faulting on the scale of the crust occurred during the Alice Springs Orogeny. Therefore, I propose as a working hypothesis to integrate the field observations into a unified model based on thrust system geometry (Fig. 5). This new model is extensively described and discussed in the following sections.

Description of the model

It is proposed here that the thrust system is composed of a sole thrust and a number of branching imbricate faults (Fig. 5).

Sole thrust. The sole thrust has a gentle dip of about 15° to the north and joins the décollement surface of the base of the sedimentary pile with the base of the crust, some 100 km further north. This dip is high compared to crustal-scale thrusts in the Rocky Mountains or Appalachians (Brewer *et al.* 1981) but is similar to the dip of the major thrust fault which bounds the Wind River Range in Wyoming, U.S.A. (Oliver 1980, COCORP seismic profile, fig. 10.10). In central Australia, the sole thrust is not exposed but several arguments in favour of such a structure can be put forward.

(i) The dip of the basin floor to the north reflects a flexuring of the underthrust lithosphere during the orogenic evolution, as it is associated with the deposition of a thick molasse-type basin.

(ii) The scale of the thrust system implies the participation of the whole crust.

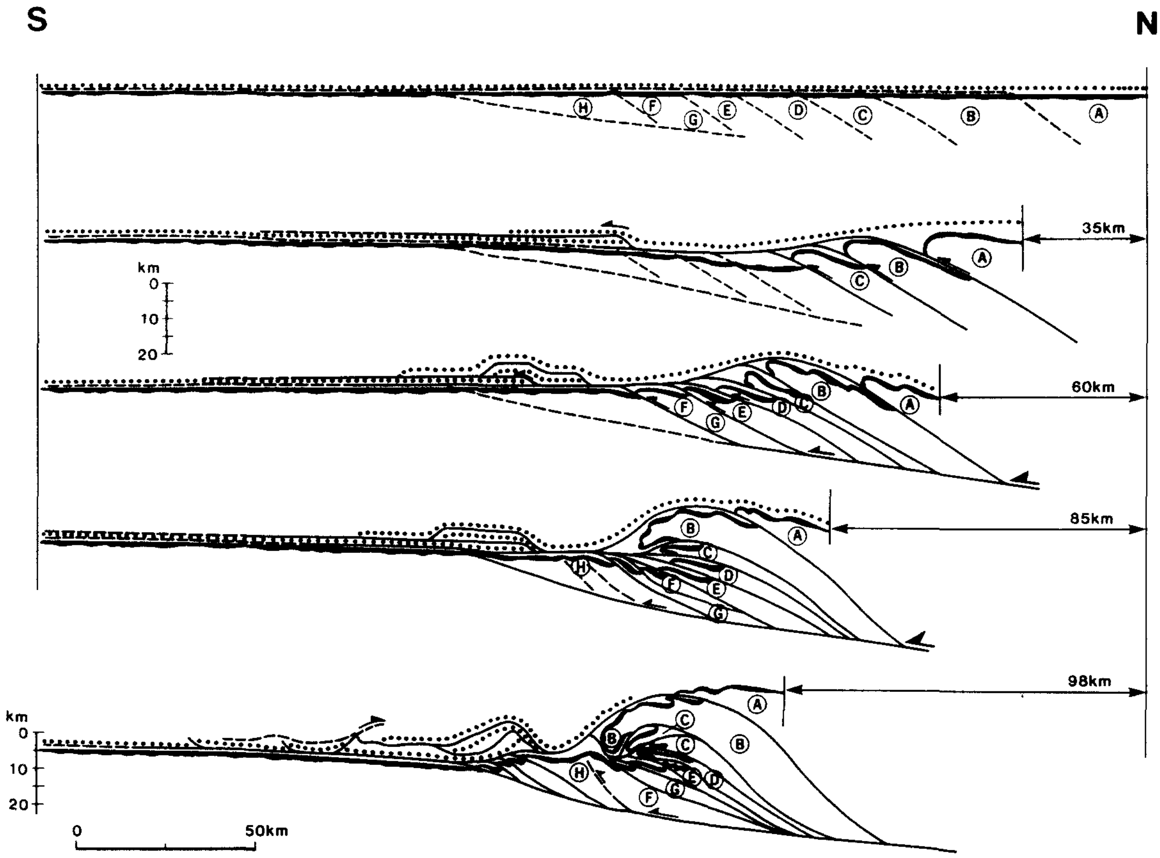


Fig. 6. Tectonic evolution of the section DD′ (Fig. 4) during the Late Devonian–Early Carboniferous; see text for discussion. Dotted line, Areyonga Formation.

(iii) Such low-angle shear zones have been previously proposed in Precambrian basement (see Butler & Coward 1984, Coward 1984).

(iv) Low-angle thrust faults have been recognized elsewhere by deep seismic reflection profiling (COCORP group, Brewer *et al.* 1981); note that such low-angle thrust faults have been recognized in the north of the Ngalia Basin (Section BB′, Fig. 4) (Wells *et al.* 1972).

It is proposed that discrete movements on all the steeply dipping faults are accumulated on the northern part of the sole thrust. Note that the displacement along the sole thrust progressively decreases towards the foreland and may be nil at its southern tip. Shear strain is expected to increase considerably from south to north on this surface.

Imbricate faults. In the basement to the north, the shear zones form a duplex structure composed of hinterland dipping imbricate faults (Fig. 4). They separate eight major thrust sheets (or horses) as indicated on the map and the cross-section (see labels A–H). An important point has to be emphasized: note that sections AA′, BB′ and CC′ are characterized by steeply dipping shear zones whereas the section DD′ shows more shallowly dipping shear zones. This difference may reflect the overall structural features of the Upper Arunta Block prior to the Alice Springs Orogeny. To the west of Alice Springs, large-scale E–W upright folds are extensively developed resulting in the presence of large areas of steeply dipping foliation and compositional layering. Pre-existing E–W oriented zones of weakness such as the complex multiply deformed Redbank Deformed Zone and Harry Creek Deformed Zone (Fig. 3) were broad zones of steeply dipping foliation before the imprint of the Alice Springs Orogeny; the Harry Creek Deformed Zone was active as a transcurrent fault during the middle Proterozoic (Allen & Black 1979) and the Redbank Deformed Zone is thought to have been involved in a long overthrusting history (see for example Shaw *et al.* 1984). In contrast, the foliation in the Harts Range (around Mt. Riddock in the north-east of the map, Fig. 3) outlines a broad domal structure characterized by a near horizontal fabric. Thus, during the Alice Springs Orogeny, it would appear that more vertical movement has taken place to the west of Alice Springs because of the re-utilization of older steeply dipping weak zones of the basement. The concept of idealized homogeneous basement may not be sufficient in such a study, and the structural characteristics of this basement may have to be taken into account.

To summarize, the thrust system envisaged in this section affects the whole crust, is responsible for a minimum horizontal shortening of 50–100 km, and its geometry is strongly dependent on the deep Precambrian structures of the basement.

Dynamic evolution

Having set the structural features and built a model that accounts for the observed geometries, it is possible

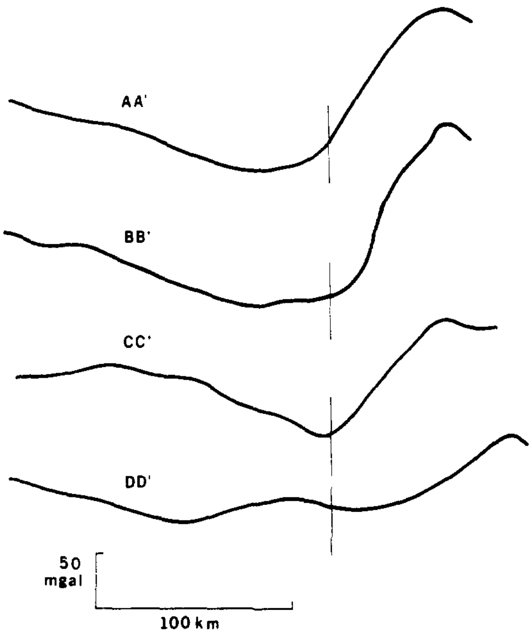


Fig. 7. Bouguer gravity anomaly profiles corresponding to the cross-sections in Fig. 4; vertical marker is the map boundary basin/basement.

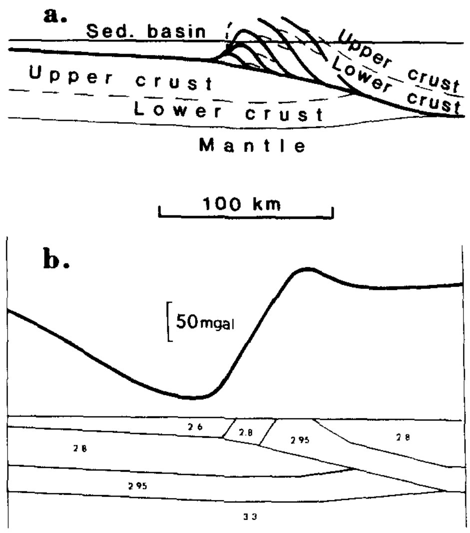


Fig. 8. (a) Crustal model. (b) Bouguer gravity anomalies calculated from the crustal model; the gravity anomaly profile has been calculated using a gravity 2D program (Campbell 1984); see text for discussion.

to establish a time sequence of faulting (Boyer & Elliott 1982) in both the basin and the crystalline basement. An attempt at such a tectonic reconstruction is outlined in Fig. 6, where the cross section DD′ (Fig. 4) is restored to its assumed original geometry. This is achieved by measuring the length of the Heavitree Quartzite horizon within each thrust sheet or horse (A–H). This technique gives us the loci of the intersections of the thrust faults with the upper basement at the time of the first increments of deformation. In the absence of good stratigraphic markers within the basement rocks, the initial dip of the thrust faults cannot be measured and the cross-section is therefore not balanced (Boyer & Elliott 1982, Elliott 1983) on the scale of the crust. In the development of the thrust belt, the formation of the duplex structure in the basin and the relative timing of faulting in the basement are included. Folding of early thrusts occurs when lower thrusts are activated. In a general way, faulting in the crust occurs through time from the hinterland to the foreland as proposed in most fold and thrust belts (see Boyer & Elliott 1982), as is produced experimentally (Davis *et al.* 1983). This result supports the idea that crustal-scale tectonics may have mechanical similarities with thin-skin tectonics (Coward 1983, 1984).

Test of the model—geophysical data

A test of the deep structure proposed in the overthrust model would be to compare the Bouguer gravity anomalies recorded in central Australia and the theoretical Bouguer anomalies calculated from the model.

Observed Bouguer gravity anomalies. One of the most striking features of the Australian map of Bouguer gravity anomalies (Bureau of Mineral Resources 1976) is situated in central Australia. Here gradients of the order of 3 mgal km^{-1} are observed between the north of the Amadeus Basin and the Arunta Block. Four profiles (Fig. 7) have been drawn respectively parallel to the geological cross-sections AA′, BB′, CC′ and DD′ of Fig. 4. A peculiarity of these profiles is the decrease of the values of the Bouguer anomaly from −50, −100 down to −150 mgal in the basin and a rapid increase to positive values on a distance a short as 50 km across the South Arunta Block. This feature has been extensively discussed. Forman & Shaw (1973) and Mathur (1976) argued for an important step on the Moho which would be much shallower beneath the Arunta Block than it is below the sedimentary basin; Anfiloff & Shaw (1973) and Wellman (1978) favoured density heterogeneities in the crust above a flat Moho. In more recent papers, Lambeck (1983, 1984) supports the idea of large vertical variations of the Moho discontinuity.

Calculated Bouguer gravity anomalies. The two-dimensional model of crustal structure (Fig. 8) is built using the following constraints: (i) a two layered model characterizes the crust; densities and thickness for the upper and lower crust and the sedimentary rocks have been chosen after Mathur (1976); (ii) the crust is characterized by a duplex structure responsible for a total shortening of the order of 100 km; (iii) the model is not far from isostatic equilibrium and (iv) the basin floor is dipping to the north (field data). It is argued that this last point is a result of subsurface loading introduced by the duplex structure (Fig. 8a). This flexure is responsible for a typical gravity anomaly profile as reported from the Alps, the Appalachians and the Himalaya (Karner & Watts 1983, Lyon-Caen & Molnar 1983).

It can be seen in Fig. 8(b) that the calculated Bouguer gravity anomaly profile has a similar asymmetry and amplitude as the observed anomaly profile.

Teleseismic travel time anomalies. In a recent paper, Lambeck & Penney (1984) present a range of teleseismic travel time anomalies through central Australia and argue that the observed anomalies reflect a shallow Moho below the south Arunta Block as opposed to a deep Moho below the Amadeus Basin; the amplitude of the variation could be as great as 20 km. In the present model, the Moho does not show this variation, but dense rocks of the lower crust, in which high seismic velocities are expected, form a thick pile below the Arunta Block as a result of a large-scale duplex structure. This interpretation may be an alternative to explain the travel time anomalies.

In summary, the present model, although oversimplified, is potentially capable of explaining the gravity-anomaly profiles. Such a crustal structure is responsible for a flexure of the underthrust elastic lithosphere (Karner & Watts 1983) by subsurface loading (intracrustal thrust system). As a consequence of the crustal flexure, a major geological process takes place which is the deposition of a thick piedmont type immature sedimentary sequence on the foreland of the evolving thrust belt. A deep seismic reflection profile is needed to verify this structural model.

TECTONIC IMPLICATIONS

Applicability of the structural model

It is believed that the case of the north Amadeus Basin is not isolated and that the model developed in this paper can apply to other orogenic zones. The Petermann Ranges situated to the south of the Amadeus Basin (Fig. 1) are characterized by 600 Ma old structures of which the broad geometrical relationships are similar to those of the present model. There, the exposed sedimentary rocks have recorded a medium-pressure metamorphism associated with a strong schistosity (Forman 1966), and low-angle faults are exposed (Woodroffe Thrust) in the basement.

Furthermore, this kind of intracratonic structural setting may help to characterize the evolution of even older (Middle Proterozoic) orogenies in central Australia. Here, shallow marine and terrestrial sediments have been strongly deformed and metamorphosed during horizontal tectonic movements.

The causes of the compressive forces

A major problem associated with intracratonic deformation lies in the causes of the horizontal compressive forces. Stress in the continental elastic lithosphere may be related to collisional orogenic activity at the plate margins. For instance, large-scale strike-slip movements develop in the Eurasian plate as a response to the India–Eurasia collision (Molnar & Tapponnier 1975). High-angle reverse faulting in the Ancestral Rocky Mountains is thought to be related to collision in the southern part of the Appalachians (Kluth & Coney 1981). However, collision is not necessary to build up horizontal compressional forces in the continental crust. A compressional state characterizes the Andes for a distance of 700 km to the east of the Peru trench (Stauder 1975). This observation led Burchfiel (1980) to propose that, by analogy, the Colorado–Wyoming structural province, although situated 1000 km from the plate boundary, may be treated as an effect of subduction of oceanic lithosphere. There, the Laramide uplift in the Wind River Range is the result of movements along a crustal-scale low-angle thrust (Brewer *et al.* 1981) comparable to that described in the present model (see also Rutland 1973, p. 1027 and 1981, p. 19). These examples show that large intraplate horizontal movements can exist at a considerable distance from the cause of the compressive forces.

To the north and the south of the present Australian continent, no plate boundary-related orogen is reported at the end of the Palaeozoic. However, the central Australian case is not isolated. In cratonic Australia, reverse faulting is reported from the north of the Ngalia Basin and the south of the Wiso Basin in Northern Territory and from the north of the Officer Basin in South Australia. Most importantly, a N–S shortening of 100–150 km, coeval with the Alice Springs Orogeny, has been recently suggested in eastern Australia by Powell (1984). Then, a large part of the Australian continent could have been involved in a N–S shortening of which the cause is still uncertain. Duff & Langworthy (1974) suggested that a rapid variation in the drift rate of the large Gondwanide plate could have had intraplate repercussions.

An alternative to these plate-tectonic models has been recently proposed by Lambeck (1983, 1984). Lambeck has developed an original model for the formation of intracratonic basins, based on a large-scale warping of the viscoelastic lithosphere under compression over a long period of time; this evolution leads to gravitational instabilities of which the ultimate stage is the orogeny. Although this model provides an interesting working hypothesis for the formation of intracratonic basins in central Australia, it is argued that the large shortening recorded along the north Amadeus Basin cannot be explained by simple isostatic re-equilibration.

CONCLUSIONS

(1) The overthrust model proposed in this paper is characterized by a sole thrust and a complex set of steeply dipping shear zones that may have reactivated older zones of weakness in the crust; this thrust system is responsible for the observed 50–100 km of minimum relative horizontal displacement and 50–70% localized contraction in a compressional regime. Contraction on the scale of the thrust belt would yield values of 30–50% only, which could be characteristic of intracratonic crustal deformations.

(2) The overthrusting crust created a flexure of the overthrust elastic lithosphere, coeval with the deposition

of a thick molasse basin. The gravity data support this hypothesis.

(3) The tectonic evolution of this thrust belt on the scale of the crust is mechanically similar to the evolution of thin-skin tectonic environments.

(4) The resulting intracratonic tectonic activity recorded in central Australia is a major feature of the crustal deformation during the late Palaeozoic in Australia; it is characterized by a thick piedmont-type basin, a marked structural asymmetry, no regional schistosity (on the exposed levels) but an intense reactivation of a cold (i.e. rigid) crust within narrow (up to 5 km wide) high strain zones.

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