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Sedimentary Geology 141–142 (2001) 79–94

Sedimentary Geology

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Development of the Archaean Mallina Basin, Pilbara Craton, northwestern Australia; a study of detrital and inherited zircon ages

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Accepted 19 January 2001

Abstract

SHRIMP U–Pb zircon dates are combined with an examination of the age distribution patterns and provenance of both detrital zircons and of zircon xenocrysts in granites to investigate the development of the Archaean Mallina Basin, in the granite–greenstone terrain of the Pilbara Craton, northwestern Australia. The oldest dated components of the basin are c. 3010 Ma volcaniclastic rocks in the western part of the area. New data indicate that siliciclastic turbidites that dominate the southern and eastern part of the basin were deposited at or after c. 2970 Ma but before c. 2955 Ma. Linking both the detrital zircon populations as well as zircon xenocrysts from granites that intruded the Mallina Basin to well-dated areas of the Pilbara granite–greenstone terrane indicates that the sediment was derived from the south, north, northwest, and east. The basin probably evolved primarily in an intracontinental setting between two elevated land masses to the southeast and northwest. Most of the rocks within the basin were folded before intrusion of granites, the oldest of which has been dated at 2954 ± 4 Ma. Evidence of a second depositional cycle is provided by a maximum depositional age of 2941 ± 9 Ma, indicated by a detrital zircon population from a sample of wacke from the southeast part of the Mallina Basin. This second depositional phase may have been related to renewed extension, and recycling of sedimentary rocks within the basin.

Keywords: Archaean basin evolution; Detrital zircon geochronology; Magmatism; Pilbara Craton

1. Introduction

The Mallina Basin is a key tectonic component of the granite–greenstone terrane of the Archaean Pilbara Craton, in northwestern Australia (Fig. 1). The basin developed over the boundary between the East Pilbara granite–greenstone terrane, where greenstone deposition was dominantly before c. 3240 Ma, and the West Pilbara granite–greenstone terrane, in which the greenstone sequences accumulated after c. 3270 Ma but before c. 3010 Ma (Smithies et al., 1999; Van Kranendonk et al., in preparation). Formation of the basin was a response to the tectonic regime that juxtaposed the eastern and western terranes, and so determining the nature of that tectonic regime first requires an understanding of the geological evolution of the basin.

The location and nature of the northern boundary of the basin, as well as the age of the basin, have been disputed. Particular controversy has focussed on how the siliciclastic turbidite sequences that form the Mallina Formation and underlying Constantine

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PII: S0037-0738(01)00069-0

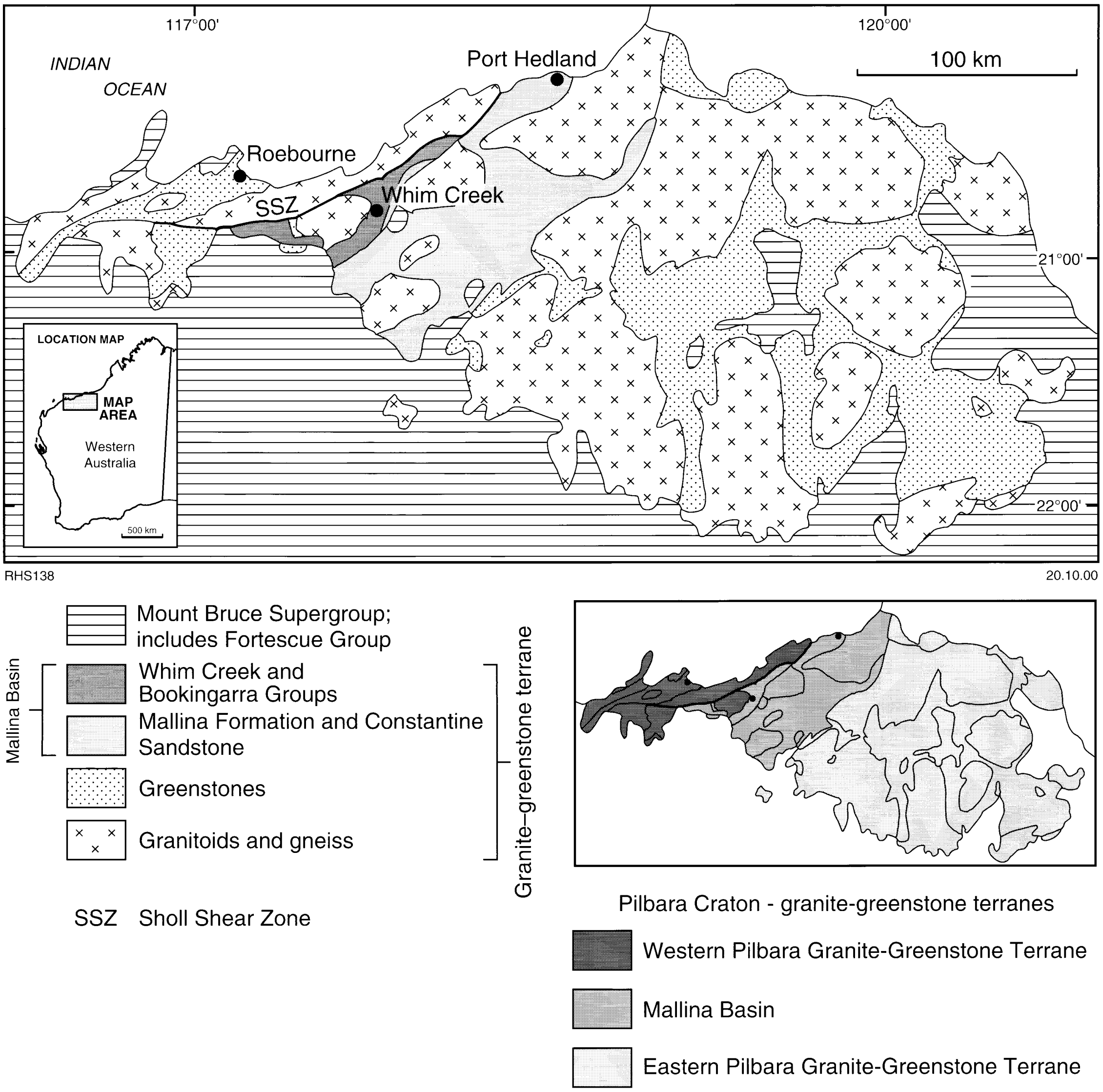

Fig. 1. Regional geological map showing the granite–greenstone terrain of the Archaean Pilbara Craton and the tectonic subdivisions.

Sandstone, in the south and east, relate to the volcaniclastic sequence that forms the Whim Creek Group, in the northwest (Fig. 2).

Fitton et al. (1975) and Horwitz (1979, 1990) considered that the Loudens Fault, which forms the contact between the Whim Creek Group and the Mallina Formation, was a minor and late feature that separates two facies equivalent successions. Hickman (1977, 1983) argued that the Mallina Formation formed basement to the Whim Creek Group.

Barley (1987), Krapez (1993), Eriksson et al. (1994) and Krapez and Eisenlohr (1998) argued that the Loudens Fault was a domain boundary across which no genetic correlations could be made. According to these authors, the Whim Creek Group accumulated in a c. 2990 Ma pull-apart basin. The Mallina Basin was thought to contain only the Mallina Formation and Constantine Sandstone, and was inferred to have accumulated in a hybrid retro-arc and remnant-ocean basin. It was estimated to have formed between

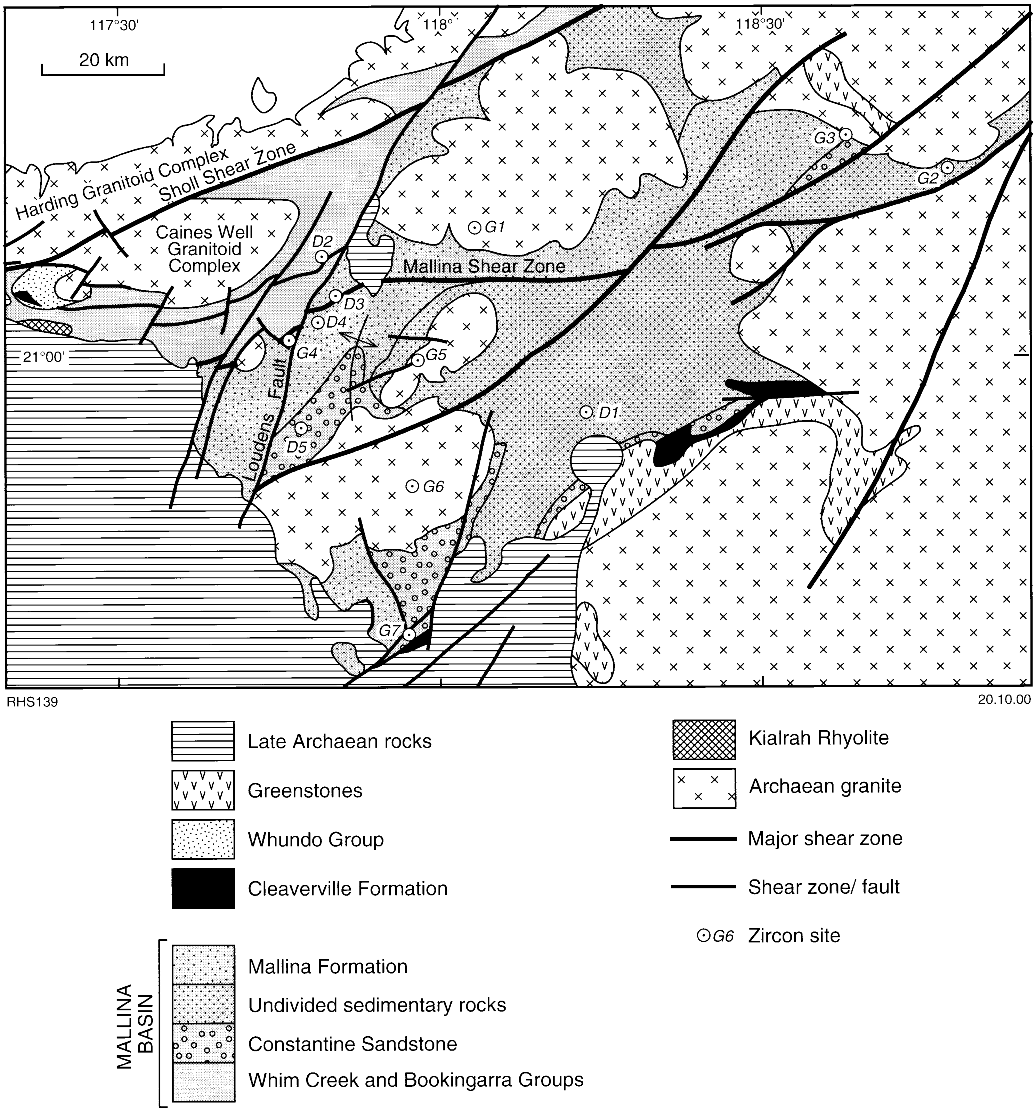

Fig. 2. Local geological map of the Mallina Basin showing the sites sampled for detrital (D1-5) and xenocrystic (G1-6) zircons (D1 = GSWA 142188, Egina Well; D2 = GSWA 142949, Whim Creek; D3 = GSWA 142942, Croydon Well; D4 = GSWA 118969, May Bore; D5 = GSWA 142943, Croydon Homestead; G1 = GSWA 142889, Portree Granitoid Complex; G2 = GSWA 142935, Wallareenya Granodiorite; G3 = GSWA 142934, intrusion at Florrie Well; G4 = GSWA 160498, Geemas Well stock; G5 = GSWA 118967, Peawah Granodiorite; G6 = GSWA 141877, Satirist Granite; G7 = GSWA 142945, Jigimining Pool dyke).

3090 and 3045 Ma, as a result of eastward subduction of oceanic crust towards the Pilbara Craton (Krapez and Eisenlohr, 1998).

Smithies et al. (1999), however, suggested that the outcrop extent of the Whim Creek Group was bounded by two independent fault sets which do not define a pull-apart structure. None of these faults was thought to preserve compelling evidence of a domain boundary.

Smithies et al. (1999) presented SHRIMP U–Pb zircon dates on detrital zircon grains extracted from a clastic sedimentary rock of the Mallina Formation. Most grains gave ages older than c. 3140 Ma, but three out of 31 concordant or near-concordant analyses gave a combined age of 2997 ± 20 Ma, interpreted as corresponding to a maximum age of deposition for the host sediment. Similarly, 3 out of 27 analyses obtained on detrital zircon grains from a volcanolithic sandstone in the basement to the Mallina Basin, provided an interpreted maximum age for host sediment deposition of 3016 ± 13 Ma. A pumiceous volcaniclastic rock at the base of the Whim Creek Group gave an age of 3009 ± 4 Ma, similar to the maximum depositional age from the Mallina Formation. This led Smithies et al. (1999) to support the earlier arguments of Fitton et al. (1975) and Horwitz (1979, 1990), that the Mallina Formation and Whim Creek Group were simply facies equivalents within the same Mallina Basin. Huston et al. (2000) modified this hypothesis slightly in concluding that the Whim Creek Group probably records a slightly earlier phase of development of the Mallina Basin, but showed at least partial stratigraphic equivalence with the Constantine Sandstone and Mallina Formation.

In the present study, new geochronological results (Nelson, 2000) obtained on sedimentary rock samples from the Mallina Basin are presented. These are combined with earlier geochronological results, including those obtained on zircon xenocryst populations in late intrusive granites (Fig. 2), to investigate basin evolution and provenance of the sedimentary rocks. We also discuss how the magmatic history of the Mallina Basin also places additional constraints on basin evolution.

2. Regional setting

The East Pilbara granite–greenstone terrane consists of large domal granitoid complexes, mantled by belts of tightly folded volcano-sedimentary greenstone successions and evolved between c. 3600 and 2850 Ma (Nelson et al., 1999). The West Pilbara granite–greenstone terrane is characterised by a northeast-trending structural trend, bisected by the east-trending Sholl Shear Zone (Fig. 1). Here, the oldest greenstones were deposited to the north of the shear zone between c. 3270 and 3250 Ma (Hickman, 1997 and references therein; Smith et al., 1998). To the south of the Sholl Shear Zone, the c. 3120 Ma (Horwitz and Pidgeon, 1993; Nelson, 1997) Whundo Group (Hickman 1997) containing mafic to felsic volcanic rocks, is unconformably overlain by 3020–3015 Ma (Nelson, 1997) banded iron-formation of the Cleaverville Formation.

The southeastern margin of the Mallina Basin is marked by an unconformity on a unit of chert, which is interpreted to belong to the Cleaverville Formation (see below), and on older greenstones of the East Pilbara granite–greenstone terrane. The northern margin of the basin is a faulted unconformity between the rocks of the Whim Creek Group and older rocks of the Whundo Group, the Cleaverville Formation and the oldest phase of the Caines Well Granitoid Complex. The latter complex evolved between c. 3100 Ma and 2925 Ma, with c. 2990 Ma granites comprising the volumetrically major part of the complex (Nelson, 1997, 2000).

The Mallina Basin includes siliciclastic rocks of the Constantine Sandstone and Mallina Formation, which Hickman (1977) and Eriksson (1982) considered to be of turbiditic origin, and rocks of the Whim Creek greenstone belt, which form the northwestern portion of the basin (Fig. 2). Fitton et al. (1975) placed the bulk of the stratigraphic succession of the Whim Creek greenstone belt into the Whim Creek Group. Pike and Cas (in preparation) present evidence that this succession represents two distinct, upward deepening cycles, separated by a disconformity that accounts for up to 40 m.y., and refer to these two sequences as the (redefined) Whim Creek Group and the overlying Bookingarra Group. In the discussion below, all references to the Whim Creek Group are to the redefined succession of Pike and Cas (in preparation).

3. Local geology

3.1. The Mallina basin

The geology of the Mallina Basin has been described by Smithies et al. (1999) and Huston et al. (2000). The preserved portion of the basin extends in a northeasterly direction for over 150 km (Fig. 1). Historically, the rocks in the south and east of the basin have been assigned to the Mallina Formation, comprising interbedded, well-graded, fine- to medium-grained wacke and shale, and the underlying Constantine Sandstone, comprising medium- to coarse-grained, poorly sorted subarkose to wacke, locally with thick conglomerate layers (e.g. Fitton et al., 1975; Hickman, 1990). Both units were probably deposited on a submarine fan (e.g. Hickman, 1977; Eriksson, 1982). The Mallina Formation is typically a fine-grained facies that probably reflects generally low rates of sediment supply whereas the coarse-grained Constantine Sandstone typically reflects generally higher rates of sediment supply. Fine- and coarse-grained facies are locally interbedded throughout the succession and such units may be difficult to assign to either the Constantine Sandstone or the Mallina Formation. The only clearly volcanic rocks so far identified are thin units of basalt and high-Mg basalt flows that occur within the stratigraphically lower to middle portion of the succession, within rocks that appear transitional between those of the Constantine Sandstone and those of the Mallina Formation. Significantly, these volcanic rocks show many compositional similarities to basalts of the Louden Volcanics, within the Bookingarra Group (R. H. Smithies, unpublished data).

The base of the Mallina Basin is best exposed in the southeast, where a chert-cobble conglomerate within the Constantine Sandstone unconformably overlies a basement chert unit. A maximum depositional age of 3016 ± 13 Ma was obtained from the U–Pb analysis of detrital zircons from a sample of volcanolithic sandstone (GSWA 142842) taken from beds located conformably beneath the basement chert (Nelson, 1998; Smithies et al., 1999). This age is consistent with a correlation of the chert with the Cleaverville Formation exposed further to the northwest.

Rocks of the Mallina Basin have been folded during three deformation events (Smithies, 1998; Smithies et al., 1999) (Fig. 3). The first event resulted in open east-trending folds, which are poorly preserved. The second event produced large north- to northeast-trending folds that have exposed the Constantine Sandstone in their cores. The third deformation event resulted in the dominant east–northeast structural fabric of the region. Numerous east–northeast shear zones are thought to reflect reactivation of early basin-developing faults within the basement, with dominantly south-side up movement (Smithies, 1999). The largest of these is the Mallina Shear Zone, which locally juxtaposes slivers of Constantine Sandstone against the Mallina Formation. Constantine Sandstone is not exposed to the north of this shear zone.

A number of granites have intruded the Mallina Basin (Fig. 2) and have been dated at between 2931 ± 5 and 2954 ± 4 Ma (Fig. 3). Those emplaced between c. 2955 and 2945 Ma belong to the Pilbara high-Mg diorite suite or are alkali-granites of the Portree Granitoid Complex. Rocks of both the suite and the complex have been studied in detail by Smithies and Champion (2000), and are high-temperature intrusions, with at least those of the Pilbara high-Mg diorite suite being of mantle origin. Intrusions of the high-Mg diorite suite are virtually confined to the Mallina Basin, where they define a belt that extends for 150 km, parallel to the long axis of the preserved basin. The c. 2955–2945 Ma granites have truncated structures related to the second phase of deformation but are affected by the third phase. For example, the Peawah Granodiorite (G5 in Fig. 2), dated at 2945 ± 4 Ma, has intruded into and across the major D_2 Croydon Anticline, indicating that D_2 occurred prior to this time. The geochemically identical Wallareenya Granodiorite (G2 in Fig. 2), dated at 2954 ± 5 Ma, is also undeformed by D_2, suggesting that this deformation event pre-dates 2954 Ma.

Younger granites, that intruded the sedimentary rocks of the Mallina Basin between c. 2940 and 2930 Ma, are early- to syn-tectonic with respect to the third phase of deformation (Smithies, 1998) and represent remelting of earlier crust (Champion and Smithies, 1998). Intrusion of these granites was concentrated along the southern margin of the Mallina Basin, and systematically decreased in both age and abundance further to the southeast (Smithies and Champion, 2000).

A population of four detrital zircons obtained from a wacke within the southeastern part of the Mallina Basin (GSWA 142188) indicates a maximum depositional age of 2941 ± 9 Ma (Nelson, 1999). Rocks in this area have been folded during the third phase of deformation. These detrital zircons may suggest the presence of an unrecognised unconformity and a late second depositional cycle (Fig. 3) that post-dated emplacement of the c. 2955–2945 Ma granites but pre-dated intrusion of the early- to syn-tectonic, c. 2940–2930 Ma, granites (see below).

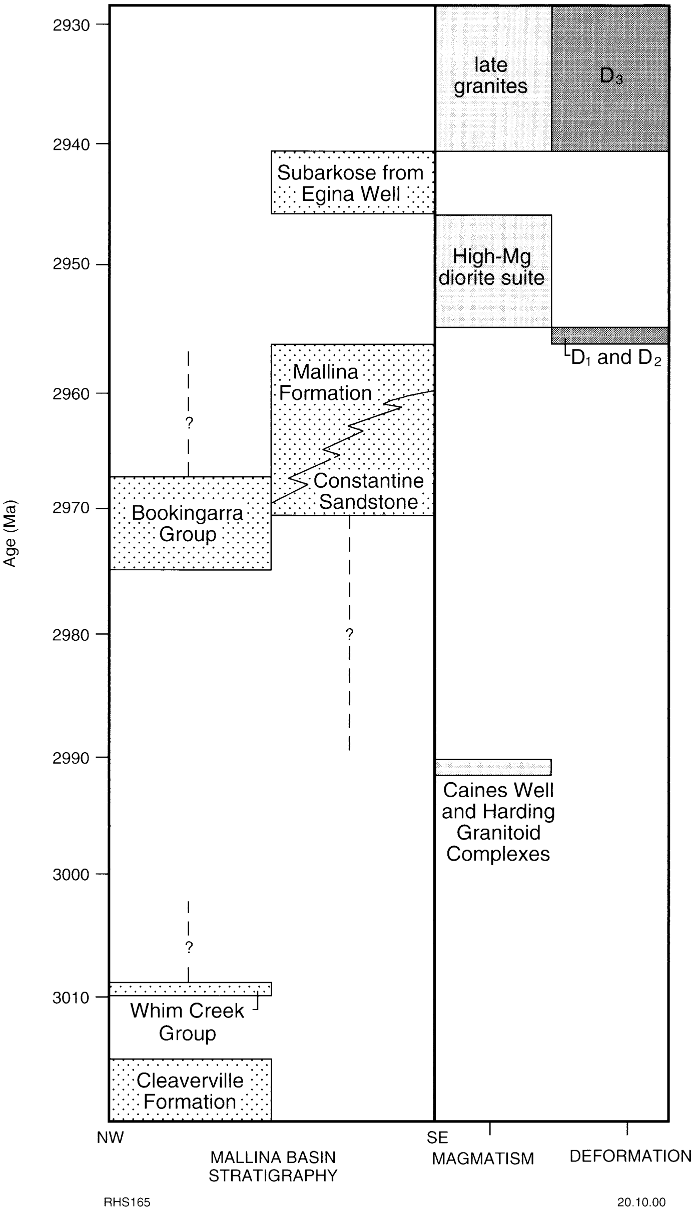

Fig. 3. Schematic diagram showing the stratigraphy of the Mallina Basin and the timing of magmatic and deformation events.

3.2. The Whim Creek greenstone belt

The Whim Creek greenstone belt forms the northwestern part of the Mallina Basin (Fig. 2) and includes rocks of the Whim Creek Group and the overlying Bookingarra Group (Pike and Cas, in preparation) (Fig. 3). However, all contacts between these rocks and those of the Mallina Formation and Constantine Sandstone are faulted, either along the Mallina Shear Zone or the northeast-trending Loudens Fault (Fig. 2).

The Whim Creek Group contains a complex association of approximately coeval felsic to mafic volcanic, intrusive and volcaniclastic rocks (Pike and Cas, in preparation) that have been dated at 3009 ± 4

(Nelson, 1998). Abundant juvenile volcaniclastic material was deposited by turbidity currents and debris flows, with limited palaeocurrent data suggesting a source to the south. These rocks are interleaved with subaqueous basaltic lavas and breccia, and the entire succession is intruded by a voluminous, synsedimentary, dacitic-rhyodacitic sill that includes apophyses into the overlying volcaniclastic rocks (Pike and Cas, in preparation).

The Bookingarra Group contains abundant volcaniclastic material derived from the underlying Whim Creek Group and shows an upward increase in nonvolcanogenic siliciclastic material (Pike and Cas, in preparation) and a concomitant decrease in grain size, culminating in the deposition of the Rushall Slate. The Rushall Slate is overlain by locally spinifex-textured and variolitic high-Mg basalts, which Hickman (1977) subdivided into the Louden Volcanics and the Mount Negri Volcanics. Contacts between the basalts and the volcaniclastic and siliciclastic rocks are generally conformable (Smithies, 1998) or a low angle unconformity (Hickman, 1997). However, Pike and Cas (in preparation) recognised peperite-like contacts, where basalts have locally intruded unlithified sedimentary material, indicating that basaltic volcanism and clastic deposition in the Bookingarra Group overlapped in time. Limited palaeocurrent data, including trough cross-beds and clast imbrication, indicate derivation of the Bookingarra Group from a northerly source (Pike and Cas, in preparation).

In the southwestern part of the belt, a rhyolite unit (the Kialrah Rhyolite; Hickman, 1997) either overlies, or has intruded the Louden Volcanics. Dating of zircons from a sample of this rhyolite indicated a maximum age of 2975 ± 4 Ma (Nelson, 1999). This date also provides a maximum age for the Louden Volcanics.

4. New U–Pb zircon data

4.1. SHRIMP U–Pb zircon geochronology

Photomicrographs of selected detrital zircons from clastic sedimentary rocks discussed in this study are shown in Fig. 4. Many of the zircon grains extracted from these metasedimentary rock samples are subrounded or have rounded terminations, and most show fine surface pitting which is commonly more intensive near acute surface terminations (see, for example, Fig. 4(b) and (d)). These features are consistent with detrital transport of these zircon grains prior to incorporation within the host sedimentary rock. Fig. 5 displays concordia plots for 3 metasandstone samples from the Mallina Basin (142942 from Croydon Well, 142943 from Croydon Homestead and 142949 from near Whim Creek). Table 1 provides sample details. For full analytical results and details of analytical procedure see Nelson (1997, 1998, 1999, 2000).

4.2. Inherited zircons from granites

Seven granites that have intruded either or both the Constantine Sandstone and Mallina Formation contain populations of concordant or near-concordant zircons with ages that are older than the crystallisation age of the granites (Nelson, 1997, 1998, 1999, 2000). Localities of the granites, which range in age between 2954 and 2935 Ma, are given in Table 1 and shown in Fig. 2 (G1 to G7) and the dates obtained from these inherited zircons are summarised in Table 1 and displayed in Fig. 6.

All of the five granites adjacent to, or to the north of, the Mallina Shear Zone contain c. 3030–3010 Ma zircons and four of those granites have a bimodal population that includes c. 2970 Ma zircons (Fig. 6). The Portree Granite (G1 in Fig. 2), in particular, contains abundant c. 2980–2970 Ma zircons. Of these five granites, only the granodiorite at Geemas Well (G4 in Fig. 2) contains zircons (one) older than c. 3020 Ma.

Two granites that have intruded sedimentary rocks of the southern part of the Mallina Basin do not contain c. 2970 Ma or c. 3030–3010 Ma zircons (Fig. 6). Inherited zircons in these rocks are considerably older with those in the Jigimining porphyry (GSWA 142945; G7 in Fig. 2) ranging between c. 3200 and 3160 Ma.

4.3. Detrital zircons

The age populations of detrital zircons from four clastic rocks from the Mallina Basin are summarised in Table 1 and are displayed in Fig. 6. Only analyses that are within 5% of concordia have been used.

Sample 142188, from near Egina Well in the

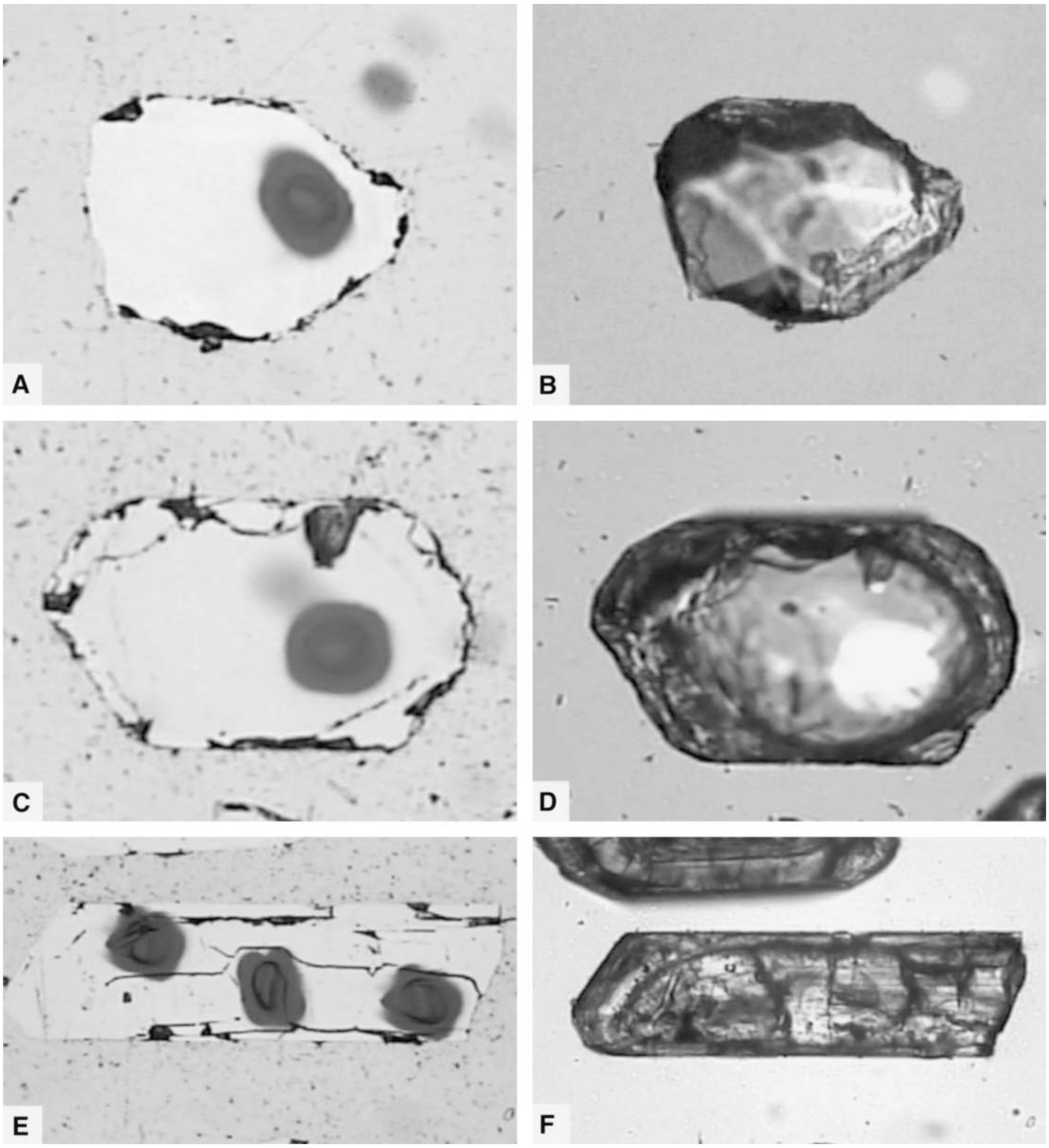

Fig. 4. Photomicrographs of detrital zircons from the samples discussed in this study (width of each photomicrograph is 250 μm). (a) Reflected light image of grain 20 from sample 142942: weakly metamorphosed subarkose, Croydon Well. SHRIMP analysis pits, surrounded by dark haloes caused by pre-analysis rastering of the surface with the primary beam, are clearly visible. (b) Transmitted light image of grain 20 from sample 142942: weakly metamorphosed subarkose, Croydon Well. Pitting due to abrasion during detrital transport is evident on the acute part of the surface of this grain. (c) Reflected light image, showing the ion microprobe analysis pit, of grain 13 from 142949: weakly metamorphosed arkose, Whim Creek (Bookingarra Group). (d) Transmitted light image of grain 13 from 142949: weakly metamorphosed arkose, Whim Creek. Pitting due to abrasion during detrital transport is evident on the surface of this grain. (e) Reflected light image of grain 18 from sample 142188: weakly metamorphosed subarkose, Egina Well. Three analysis pits are evident on the polished surface of this grain. (f) Transmitted light image of grain 18 from sample 142188: weakly metamorphosed subarkose, Egina Well. The surfaces at the terminations of this grain are pitted due to abrasion during detrital transport.

southeast of the Mallina Basin (D1 in Fig. 2), was of a weakly graded, poorly sorted, medium-grained subarkose bed within an interval of generally well graded wacke and shale and was presumed to be of Mallina Formation. The youngest zircons from this sample provided a population of four concordant and near-concordant analyses between 2950–2930 Ma, with a combined age of 2941 ± 9 Ma. This age is interpreted as a maximum depositional age for the host sedimentary rock. The sample, therefore, cannot be from the Mallina Formation as this formation was folded during D_2, prior to the intrusion of granites, the oldest of which has been dated at 2954 ± 4 Ma (Nelson, 1999). The maximum age for deposition of the Egina Well sample, indicated by its youngest detrital zircon population, postdates that folding event. This suggests that an unconformity may be present within the basin, marking deposition after c. 2945 Ma. The subarkose from Egina Well has been folded during D_3, which was accompanied by further granite intrusion between c. 2940 and 2930 Ma (Smithies, 1998), effectively constraining this late depositional cycle to the period between c. 2945 and c. 2940 Ma. Furthermore, the remaining detrital zircons within

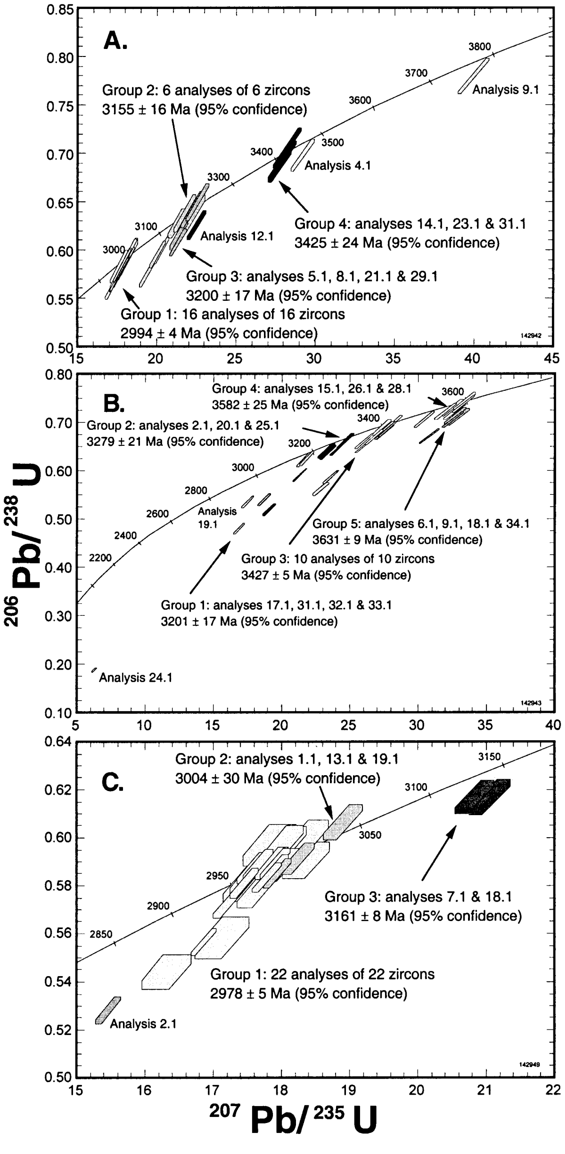

Fig. 5. Concordia diagrams for samples from the Mallina Basin. (a) 142942: weakly metamorphosed subarkose, Croydon Well. Thirty-two analyses were obtained from 32 zircons. All analyses are concordant or slightly discordant, with the discordance pattern consistent with a single recent episode of radiogenic-Pb redistribution. Sixteen concordant and near-concordant analyses (1.1, 2.1, 3.1, 7.1, 13.1, 15.1, 16.1, 17.1, 18.1, 20.1, 22.1, 24.2, 26.2, 27.1, 28.1 and 32.1) have ^{207}Pb/^{206}Pb ratios defining a single population and indicating a weighted mean date of 2994 ± 4 Ma (chi-squared = 0.72). This date provides a maximum time of deposition for the metasandstone. Apart from analysis 9.1, for which a source is currently not known within Western Australia, the remaining analyses indicate ^{207}Pb/^{206}Pb dates consistent with derivation of these detrital zirons from the eastern (Group 4 and analysis 4.1) and western parts of the Pilbara Craton (see Fig. 6). (b) 142943: weakly metamorphosed subarkose, Croydon Homestead. Thirty-five analyses were obtained from 35 zircons. All analyses are concordant to highly discordant, with the discordance patterns consistent with several episodes, including a single recent episode, of radiogenic-Pb redistribution. Four concordant and highly discordant analyses (17.1, 31.1, 32.1 and 33.1) have ^{207}Pb/^{206}Pb ratios defining a single population and indicating a weighted mean date of 3201 ± 17 Ma (chi-squared = 0.89). This date provides a maximum time of deposition for the metasandstone. The remaining analyses (apart from discordant analyses 19.1 and 24.1) indicate ^{207}Pb/^{206}Pb dates consistent with derivation of these detrital zircons from the eastern part of the Pilbara Craton. (c) 142949: weakly metamorphosed arkose, Whim Creek (Bookingarra Group). Twenty-eight analyses were obtained from 28 zircons. The analyses range from concordant to highly discordant, with the discordance pattern consistent with several episodes, including one recent episode, of radiogenic-Pb loss. Twenty-two analyses of 22 zircons, including many that are concordant, have ^{207}Pb/^{206}Pb ratios defining a single population and indicating a weighted mean date of 2978 ± 5 Ma (chi-squared = 1.54). This date provides a maximum time for deposition of the metasandstone. The remaining older analyses of Groups 2 and 3 are interpreted to be of detrital zircons possibly derived from the western part of the Pilbara Craton. Highly discordant analysis 2.1 is interpreted to have lost radiogenic Pb during a disturbance episode.

Table 1
Sample details and summary of SHRIMP U–Pb zircon results

GSWA sample no.	Sample name	Location	Reference in Fig. 2	Lithology	Intrusive or maximum depositional age (Ma)[a]	Number of zircons analysed[b]		Source of data
						Total	In age groups (Ma)[c]	
142188	Egina Well	118°14′47″ E 21°05′27″ S	D1	Medium-grained subarkose	2941 ± 9	23	4 ~ 2930–2950	Nelson (1999)
142949	Whim Creek (Bookingarra Group)	117°49′59″ E 20°52′34″ S	D2	Coarse-grained arkose	2978 ± 5	27	11 ~ 2980–2960 12 ~ 2990–2980 2 ~ 3020 2 ~ 3150	Nelson (2000)
142942	Croydon Well (Constantine Sandstone)	117°51′23″ E 20°55′51″ S	D3	Medium- to coarse-grained subarkose	2994 ± 4	31	15 ~ 2990 3 ~ 3150–3130 4 ~ 3190 1 ~ 3230–3250 4 ~ 3440–3400	Nelson (2000)
118969	May Bore (Mallina Formation)	117°50′35″ E 20°57′12″ S	D4	Fine-grained arkose to lithic arkose	2997 ± 20	25	2 ~ 2990 3 ~ 3150-3130 6 ~ 3190 5 ~ 3230–3250 6 ~ 3440–3400	Nelson (1997)
142943	Croydon Homestead (Constantine Sandstone)	117°48′25″ E 21°07′17″ S	D5	Medium- to coarse-grained subarkose	3201 ± 17	26	2 ~ 3190 4 ~ 3300–3260 11 ~ 3440–3400 8 ~ 3640–3570	Nelson (2000)
142889	Portree Granitoid Complex	118°04′04″ E 20°49′51″ S	G1	Alkali granite	1946 ± 6	11	6 ~ 2946 6 ~ 2975 1 ~ 3030	Nelson (1999)
142935	Wallareenya Homestead	118°48′56″ E 20°44′45″ S	G2	High-Mg diorite suite	2954 ± 4	25	24 ~ 2954 1 ~ 3015	Nelson (2000)
142934	Florrie Well	118°38′20″ E 20°41′01″ S	G3	Late granite	2941 ± 4	17	13 ~ 2941 4 ~ 3020	Nelson (2000)
160498	Geemas Well	117°56′28″ E 20°59′16″ S	G4	High-Mg diorite suite	2945 ± 6	16	12 ~ 2945 2 ~ 2970 1 ~ 3030	Nelson (2000)
118967	Peawah Granodiorite	117°59′29″ E 20°59′19″ S	G5	High-Mg diorite suite	2948 ± 5	13	11 ~ 2948 1 ~ 2970 1 ~ 3010	Nelson (1997)
141977	Satirist Granite	117°58′52″ E 21°12′10″ S	G6	Late granite	2931 ± 5	15	14 ~ 2931 1 ~ 3240	Nelson (1998)
142945	Jigimining Pool	117°56′05″ E 21°27′55″ S	G7	Late granite	2946 ± 20	14	3 ~ 2946 10 ~ 3180	Nelson (2000)
Other samples mentioned in text								
141936	Whim Creek Group	117°31′21″ E 20°57′43″ S		Rhyodacitic pumiceous volcaniclastic	3009 ± 4	22	20 ~ 3010 2 ~ 3150	Nelson (1998)
144261	Kialrah Rhyolite	117°21′08″ E		Rhyolite	≤ 2975	28	2 ~ 2945 16 ~ 2975	Nelson (1998)

[a] Errors are given at $t\sigma$ (where t is Fisher's t) or 95% confidence. For details of analytical procedures and full data tables see Nelson (2000).

[b] Only includes analyses that lie within 5% of concordia.

[c] Numbers of zircon analyses within the given age range.

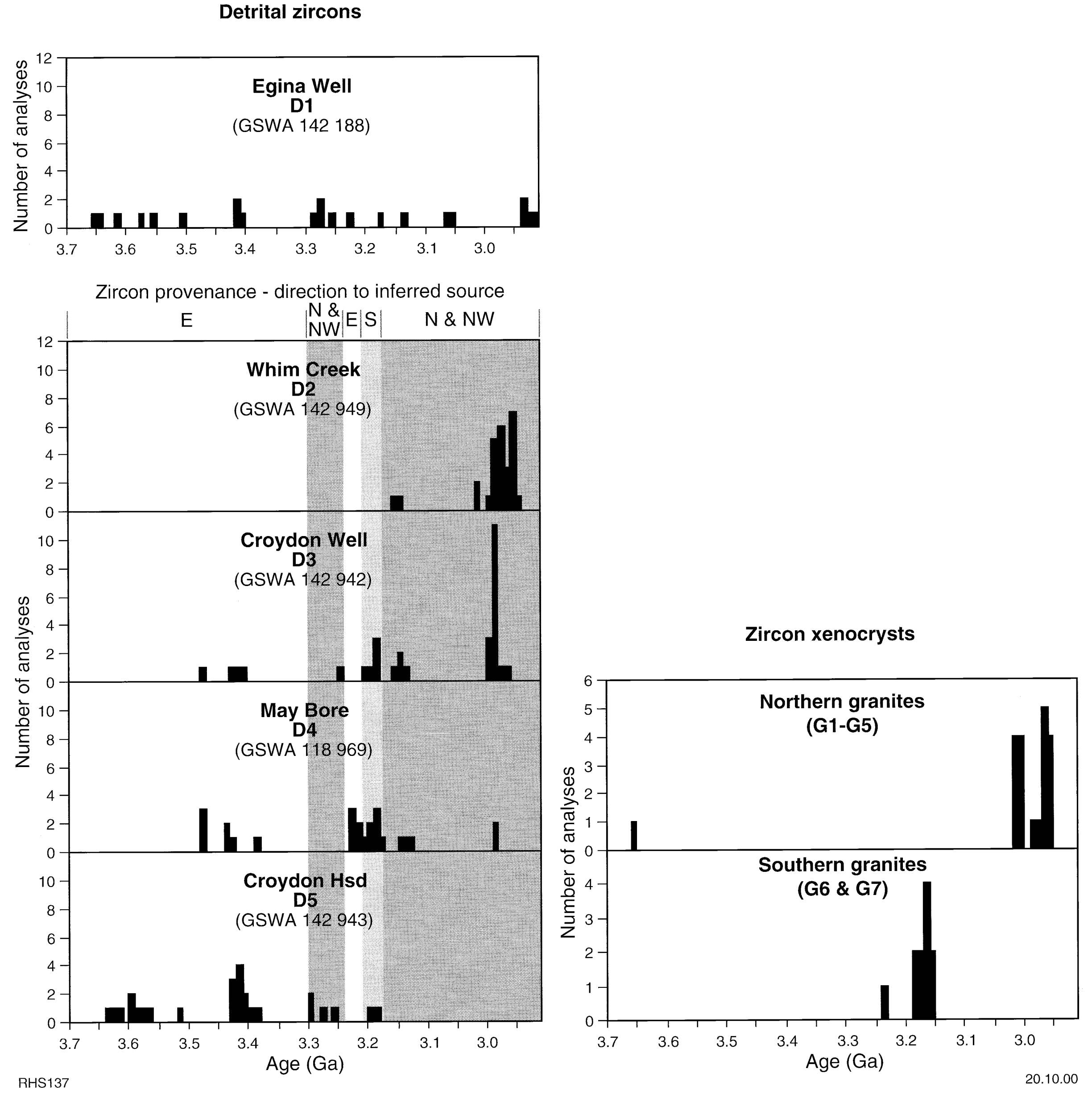

Fig. 6. Age distribution histograms for samples discussed in the text (see Fig. 2 and Table 1 for sampling localities). Samples D2 to D5 have been ordered to reflect a north (D2) to south (D5) traverse through the Mallina Basin. The various shades on figures for D2–D5 show the interpreted provenance of zircon populations, based upon current knowledge of age distributions within the Pilbara Craton, and suggest a major contribution of detritus from the eastern and north and northwestern parts of the craton. All zircon analyses used are within 5% of concordia.

this sample do not fall into distinct age groups but rather, show a wide scatter of ages spanning the ranges shown by detrital zircon populations from the other siliciclastic samples from the Mallina Basin (see below). This is consistent with the Egina Well sample having been derived via reworking of the Mallina Formation and Constantine Sandstone.

The remaining three samples, taken from sites south of the Mallina Shear Zone, have been ordered in Fig. 6 from northern most (Croydon well; D3 in Fig. 2) to southern most (Croydon Homestead; D5 in Fig. 2). The sample from near Croydon Well (GSWA 142942) is of a massive to weakly graded, medium- to coarse-grained subarkose of the Constantine Sandstone which has been juxtaposed against rocks of the Mallina Formation, along the Mallina Shear Zone. The sample taken from near May Bore (GSWA 118969; D4 in Fig. 2), about 3 km to the southwest of the Croydon Well sampling site, is a fine-grained, poorly sorted wacke, from a generally well graded sequence within the Mallina Formation. A third sample, of Constantine Sandstone, was taken from Croydon Homestead (GSWA 142943), about 19 km south of the May Bore sampling site, and was of an outcrop of massive to very weakly graded, locally planar laminated, medium- to coarse-grained subarkose.

Fig. 6 shows that there is a general younging of the entire detrital zircon population northwards. The samples from the Constantine Sandstone and the Mallina Formation (D3, D4 and D5) all contain zircon populations dated at c. 3440–3400 Ma and c. 3190 Ma. The samples from Croydon Well (D3) and May Bore (D4) contain populations at c. 3250–3230, c. 3150–3130 Ma and c. 2990 Ma, with the latter age dominating the zircon population within the sample from Croydon Well. The sample from Croydon Homestead (D5) in the south contains populations at c. 3640–3570 Ma and 3300–3260 Ma.

Although we have insufficient palaeocurrent data to provide an independent assessment of sediment transport directions, we have interpreted the provenance of the zircon populations, in Fig. 6, based upon current knowledge of age distributions within the Pilbara Craton. Detritus interpreted to have been derived from the south, north, northwest and east is present in all samples, with a progressive northerly increase in the contribution of detritus from an inferred north and northwesterly source. Only a minor component of the zircon population from the Constantine Sandstone at Croydon Well can be interpreted to have come from sources to the south, southwest and east of the Mallina Basin. Placing the May Bore and Croydon Well samples into a stratigraphic, rather than geographic, context allows speculation that, at least in the northern part of the Mallina Basin, the contribution of detrital material derived from the north and northwest decreased with decreasing age, as the Mallina Basin developed.

5. Age differences between inherited and detrital zircons

A comparison of the detrital zircons within the sedimentary rocks of the Mallina Basin with the inherited zircons within the granites that have intruded the basin (Fig. 6) shows virtually no age similarities. The c. 2970 Ma zircons in four of the five granites that have intruded the northern part of the Mallina Basin have only a single detrital equivalent, in the Constantine Sandstone at Croydon Well, whereas the inherited 3030–3010 Ma zircons have no detrital equivalents. Conversely, apart from a single c. 3660 Ma inherited zircon from a granodiorite at Geemas Well and some c. 3230–3160 Ma zircons in the granite from the southern part of the basin, zircons older than c. 3030 Ma are not present in these granites.

The c. 2970 Ma and 3030–3010 Ma zircons must be derived from rocks that are the same age as, or older than, the clastic rocks into which the granites intruded. These older rocks either did not contribute large amounts of sediment to the basin, were poor in zircon or contributed sediment only to the stratigraphically lower (and unstudied), portion of the basin. The c. 3030–3010 Ma ages are only known from rocks of the Cleaverville Formation, the Whim Creek Group (e.g. GSWA 141936- Table 1), and from granites that intrude the West Pilbara Granite-Greenstone Terrane, particularly in regions close to the Sholl Shear Zone (Fig. 2). The c. 2970 Ma ages are so far restricted to the Kialrah Rhyolite in the southwestern part of the Whim Creek greenstone belt, and to the Harding Granitoid Complex within the West Pilbara granite–greenstone terrane (Fig. 2).

The c. 2970 Ma zircons may be from a regionally extensive, felsic sill complex — unseen yet with a northeasterly extent of over 140 km — that intruded the basement to the Mallina Basin, during or after formation of that basin. A more reasonable interpretation, however, is that the c. 2970 Ma inherited zircons were sequestered from clastic rocks in the lower parts of the basin, and that this date represents a maximum age for deposition of those parts of the Constantine Sandstone. This date is significantly younger than previous estimates of 3015 Ma (Smithies et al., 1999), or c. 2990 Ma as suggested by the main detrital zircon population from the Croydon Well sample.

6. Ages from the Whim Creek greenstone belt

Krapez and Eisenlohr (1998) argued that the Mallina Basin was significantly older than, and evolved independently from, the Whim Creek greenstone belt, but was subsequently juxtaposed along the Loudens Fault. Fitton et al. (1975), Horwitz (1979, 1990) and Smithies et al. (1999), however, argued that there has been no significant strike-slip movement along this fault, and that the Whim Creek greenstone belt simply represents a northwestern component of the Mallina Basin.

The Whim Creek Group has been well dated at 3009 ± 9 Ma (Nelson, 1998; Smithies et al. 1999). For the disconformably overlying Bookingarra Group, the Kialrah Rhyolite either overlies or has intruded the Louden Volcanics and so the maximum depositional age of 2975 ± 4 Ma for the rhyolite also provides a maximum age for deposition of the Louden Volcanics. Sulphide mineralisation within the Rushall Slate has a Pb isotope model age of c. 2950 Ma (Huston et al., 2000), which may provide a minimum depositional age for the Bookingarra Group. Nelson (2000) presented the ages of detrital zircons from a sample of metasandstone (GSWA 142949) conformably beneath the mineralised horizon within the Bookingarra Group (Figs. 2 and 6 and Table 1). Four age populations, at c. 3150, 3020, 2990–2980 and 2980–2960 Ma, were found. The youngest zircon population provides a maximum depositional age for the sandstone of c. 2975 Ma. This is consistent with the maximum age of 2975 ± 4 Ma obtained from the Kialrah Rhyolite which stratigraphically overlies the metasandstone.

These data also indicate that the Whim Creek Group was deposited before deposition of the Constantine Sandstone and Mallina Formation (Fig. 3). The depositional age range for the Bookingarra Group, however, is between c. 2975 and c. 2950 Ma, and is similar to that for the Constantine Sandstone and Mallina Formation (Fig. 3).

Another important feature of the detrital zircon population from the Bookingarra Group is that the age populations match a combination of those found as xenocrysts in intrusive granites and those detrital populations within the northern-most sample of the basal Constantine Sandstone (Croydon Well): i.e. they closely match populations expected to be within the lowest part of the Mallina Basin. Thus, the combined sediment provenance of both the Bookingarra Group and the Constantine Sandstone and Mallina Formation is identical, strongly suggesting that they evolved over a similar period and within the same region.

If the c. 2950 Ma Pb isotope model age for mineralisation in the Bookingarra Group dates syngenetic mineralisation, then deposition of those rocks may conceivably have post-dated that of the Constantine Sandstone and Mallina Formation, since the latter formations were folded by c. 2950 Ma. Deposition of the Bookingarra Group may then correlate with the late recycling of the Constantine Sandstone and Mallina Formation, and renewed deposition, inferred from young detrital zircons from the Egina Well sample.

The preferred interpretation, however, is that the sandstone sampled from the Bookingarra Group is a stratigraphic equivalent of the Constantine Sandstone. Both the Constantine Sandstone in the northern part of the Mallina Basin and the sandstone sample from the Bookingarra Group contain abundant c. 2990 Ma zircons (Table 1, Fig. 6). While the c. 2990 Ma phase of the nearby Caines Well Granitoid Complex is possibly too close to the site of deposition to be a viable source for these zircons, c. 2990 Ma granites also occur in the Harding Granitoid Complex (Fig. 2), and indicate regional granite emplacement to the north and west of the Mallina Basin. This is consistent with the limited palaeocurrent data from the siliciclastic portion of the Bookingarra Group, which indicates a granitic source to the north (Pike and Cas, in preparation). The detrital zircon data from the May Bore (Mallina Formation) sample and from the stratigraphically lower Croydon Well (Constantine Sandstone) sample also provide evidence than the contribution of young detrital material derived from the north and northwest decreased with decreasing age (Fig. 6), or as the Mallina Basin developed. Consequently, we interpret the sandstone sampled from the Bookingarra Group to be from a stratigraphically lower part of the Mallina Basin, and to be a partial equivalent of the Constantine Sandstone. If this is the case, then the Louden Volcanics, in the Bookingarra Group, may correlate with geochemically similar basaltic flow units within the lower parts of the Mallina Basin, to the south.

There is no reason to infer that the Bookingarra Group evolved independently of the Constantine Sandstone and Mallina Formation, and this is consistent with the absence of evidence for any significant strike-slip movement along the Loudens Fault (Smithies et al., 1999). The simplest interpretation of all the available data is that the Whim Creek Group, Bookingarra Group, Constantine Sandstone and Mallina Formation are part of a single depositional basin-the Mallina Basin- or a series of sequential basins, or both.

7. Summary and conclusions

The Mallina Basin represents a late stage in the geological evolution of the granite-greenstone terrane of the Archaean Pilbara Craton and developed over the boundary between the West Pilbara granite–greenstone terrane and the East Pilbara granite–greenstone terrane. The ages of detrital zircons within the Mallina Basin, the ages of inherited (xenocrystic) zircons in granites that have intruded this basin, the intrusive ages of the granites and the ages of deformation events, allow an assessment of the temporal relationships between basin evolution, magmatism and tectonism. The new geochronological and zircon provenance results support the conclusions of Fitton et al. (1975), Horwitz (1979, 1990), Smithies et al. (1999) and Huston et al. (2000), that the evolution of the Whim Creek Group, Bookingarra Group, Constantine Sandstone and the Mallina Formation were closely linked.

The Whim Creek Group was deposited in the northwestern part of the Mallina Basin at c. 3010 Ma, on rocks that are c. 3020–3015 Ma and older. The southern margin of the Mallina Basin also overlies a c. 3015 Ma chert unit and it is possible that stratigraphically equivalent rocks underlie the entire basin. There is no evidence from outcrop or from the ages of zircon xenocrysts in granites, that the rocks of the Whim Creek Group were deposited in the southern part of the Mallina Basin. The Whim Creek Group was confined to the northwestern part of the early Mallina Basin. Although the volcaniclastic succession of the Whim Creek Group is bimodal in character, regional geological interpretations of the northwestern and central parts of the Pilbara Craton (e.g. Krapez and Eisenlohr, 1998; Van Kranendonk, in preparation) have not invoked subduction at c. 3010 Ma, and the tectonic setting of the Whim Creek Group remains unclear.

New estimates suggest that the maximum depositional age of the overlying Constantine Sandstone and the Mallina Formation is probably younger than c. 2990 Ma, and possibly younger than c. 2970 Ma, rather than the previous estimate of c. 3015 Ma (Smithies et al., 1999). The Bookingarra Group was deposited in the northern part of the Mallina Basin at the same time, or slightly before, deposition of the Constantine Sandstone, deriving most of its detritus from the underlying Whim Creek Group and from c. 2990 Ma granites exposed to the northwest.

Populations of detrital zircons and of zircon xenocryst in late granites that have intruded the rocks of the Mallina Basin can be linked to specific regions outside the Mallina Basin that have characteristic age ranges. These allow the identification of likely sources of detritus to the south, north and northwest, and east. This indicates that the basin evolved primarily between two elevated land masses the eastern and western granite–greenstone terranes. Material inferred to have been derived from the south and east dominates in the southern part of the basin but decreases systematically in abundance to the north. In the northern part of the basin, material inferred to have been derived from the south and east also increases in abundance with decreasing depositional age, possibly indicating differential uplift of the East Pilbara granite–greenstone terrane with respect to the West Pilbara granite–greenstone terrane. This would be consistent with dominantly south-side up movement shown by major reactivated basin faults such as the Mallina Shear Zone (Fig. 2). Again, regional geological interpretations of the northwestern and central parts of the Pilbara Craton (e.g. Krapez and Eisenlohr, 1998; Smithies and Champion, 2000; Van Kranendonk, in preparation) have not invoked subduction between c. 2990 and c. 2950 Ma, and so there is no suggestion that the Mallina Basin evolved at or near an active plate margin. We tentatively suggest that the basin evolved in an intracontinental rift setting (e.g. Smithies et al., 1999; Smithies and Champion, 2000) and that subsequent deformation (D_2) was a far-field result of collision along the margins of the Pilbara Craton.

Most rocks of the preserved basin were folded during D_2 and subsequently intruded by granites between c. 2955 and 2945 Ma. A zircon population with an age as young as 2941 ± 9 Ma suggests that some rocks preserved in the Egina Well region (D1 in Fig. 2) were deposited during or following emplacement of these granites, but before D_3 folding which is dated by intrusion of early- to syn-tectonic granites at between c. 2940 and 2930 Ma. According to Smithies and Champion (2000), the c. 2955–2945 Ma high-Mg diorite suite of granites intrudes zones of active dilation along major basin-parallel faults, suggesting that emplacement was controlled by extensional reactivation of structures related to the earlier evolution of the Mallina Basin. Thus the late-stage evolution of the Mallina Basin involves:

- east–west to southeast–northwest compression and folding (D_2);
- erosion of the uplifted landmass;
- renewed extension associated with intrusion of high temperature, mantle-derived c. 2955–2945 Ma granites (Smithies and Champion, 2000);
- post-2945 but pre-2940 Ma recycling of Mallina Basin sedimentary rocks;
- intrusion of voluminous c. 2940–2930 Ma, crustally derived granites, into and adjacent to the Mallina Basin, during south-southeast to north-northwest compression (D_3).

Smithies and Champion (2000) speculate that this c. 2955–2930 Ma cycle of extension (rifting) accompanied by high-temperature magmatism, subsequent sedimentation, followed by voluminous crustally-derived magmatism was related either to local lithospheric detachment-delamination or to a small mantle plume beneath the Mallina Basin.

Acknowledgements

The authors thank A. Hickman, D. Huston and M. Van Kranendonk for numerous discussions. Reviews by O. Catuneanu, P. Eriksson, A. Hickman, D. Martin, A. Thorne and I. Tyler greatly improved the manuscript. T. Veale and S. Urbini are thanked for drafting the figures. RHS and DRN publish with the permission of the Director of the Geological Survey of Western Australia. This paper represents a contribution to the National Geoscience Mapping Accord (NGMA), Pilbara Craton Project, between the Geological Survey of Western Australia (GSWA) and the Australian Geological Survey Organization (AGSO).

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