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Geomorphology of pit gnammas in southwestern Australia

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Most granite rock outcrops in the Wheatbelt and Goldfields have numerous shallow pan gnammas generally on the flattish upper parts of the dome, but some rocks have single or a few deep pit gnammas often on the lower flanks. The classic pit gnamma is subcircular in plan, hemispherical in profile and formed by weathering of homogeneous granite. This and minor variations account for about 60% of the 80 pit gnammas studied in the Wheatbelt and Goldfields. Previous studies suggest depth is greater than width or about half of width in pit gnammas, but 76% of the study gnammas had a D:W ratio between 0.2 and 1.0, still much greater than in pan gnammas.Because of the influence of preferential weathering along joints, and because some have been formed by running water, some pit gnammas are of unusual shape and profile, so that 10 types are recognised: hemispherical (two varieties), cylindrical, canoe, trough, underground shelf, flask, lotic potholes and plunge pool (two varieties). Most have a distinctive plan and profile and some have characteristic locations on a rock or distinctive morphometrics. Two further types of pit gnammas, armchair hollows and pipe gnammas, are known in Australia but not in the study area.

KEYWORDS: canoe gnammas, evorsion, granite outcrops, joints, pan gnammas, pit gammas, rock basins, weathering

INTRODUCTION

Gnammas, or rock holes, occur commonly on granite outcrops in the southwest of Western Australia (Pinder *et al*. 2000). They are of two basic types: pan gnammas are of diverse shape in plan, shallow, flat-floored and seasonally filled with water while pit gnammas are typically subcircular in plan, have a depth to diameter ratio exceeding 0.2, and contain water for longer periods (Twidale & Vidal Romani 2005; this study). Pan gnammas are far more common than pit gnammas but it is the pits that are of human interest because of their value as water sources in a dry and inhospitable countryside (Bayly 2011). These days, local councils and tourist authorities in South and Western Australia have marked the presence of some with signage so that the public is aware of them and their significance, more so than for pan gnammas. Unfortunately, to protect the public from their own folly, many larger ones have been filled in or covered (e.g. at War Rock, via Morewa and the Moningarin Gnammas via Cadoux), so reducing opportunities for study.

Indigenous Australians have long been familiar with these natural water-storage pits in Australia's desert regions where they were vital to their survival (Bayly 1999). The Nyungar people used the anglicised 'gnamma' to describe the rock hole and its retained water, if any (Bayly 2002a, 2011). Hence the term 'gnamma hole' is a tautology and though widely used, is incorrect. The first scientific references to them were by Ormerod (1859) on granitic rock holes in England and Hartt (1870) on similar holes in Brazil. In Australia, early miners in the Goldfields soon realised their value and perhaps the earliest record of this is Göczel's diagram of a pit gnamma in the first annual report of the Western Australian Department of Mines (Göczel 1894). Thereafter there were many skirmishes between local Aborigines and the new explorers, miners and pastorialists over the water in the gnammas (Bayly 2002a,b, 2011; Carnegie 1898). The location of gnammas often determined the route of early European tracks (e.g. the Holland track to Coolgardie: Underwood & Elliott 2002) and sometimes the location of early homesteads (e.g. the Wattoning Homestead north of the present day Mukinbudin: Anon 2013). An early scientific paper on gnammas by Maclaren (1912) explained their origin by initial flaking due to insolation thus forming a hollow, and then weathering of the granite by the collected water, and the importance of hardening of the orifice by mineralisation and hence slowing of its widening. Other early publications to mention gnammas in Western Australia include Woodward (1912, 1916), Talbot (1912) and Jutson (1934).

The word 'gnamma' is now widely used by scientists, both locally (Twidale 1971) and also overseas (Domínguez-Villar & Jennings 2008), applying it to depressions in rock both of the pan and pit types, usually in granite. It is the pits that have a utilitarian value (Bayly 2011) so most lay people think of deeper rock hollows when the word gnamma is mentioned. The mode of origin of pit gnammas intrigued many authors. A very early explanation in England proposed that rock hollows were the work of Druids and in Australia indigenous people often claim ancestral beings dug them out in the 'dreamtime.' An example is the row of five pit gnammas 14 km north of Trayning; according to signage at the site they are attributed to Nyimgarn, the echnida, digging pits as he migrated south from Ninghan Station and Lake Moore.

Gnamma formation is a three-stage process: initiation of a depression, breakup of the rock, and finally evacuation of the debris. Apparently initial depressions have many causes ranging from insolation causing flaking, to breakdown of crystalline irregularies, to lichen attack and to subaerial weathering by attack of acid groundwater on bedrock granite (Twidale & Corbin

1963). Proposals for mechanisms of rock breakup include the continual role of insolation and attack of xenoliths, the direct action of wind and running water, and glacial ice. Majority opinion (Twidale & Corbin 1968; Twidale & Romani Vidal 2005) supports the weathering of bedrock granite by alternate wetting and drying. Excavation of weathered material is by wind or in solution or by human interference (Twidale & Romani Vidal 2005). These processes form a basic shape of a roundish, hemispherical basin, supposedly deeper than wide. Magnification of weathering along joints leads to the formation of elongated 'canoe'-type gnammas (Twidale & Corbin 1963). Observations incidental to the study of the biology of 80 gnammas in southwestern Western Australia (B V Timms in prep.) suggests that many local gnammas do not fit these descriptions and may have originated by geomorphic processes that differ from those described in the literature.

The aim of the present study is to describe the geomorphology of these 80 pit gnammas and prepare a classification of them. Particular attention is given to structural parameters and possible modes of origin.

METHODS

Pit gnammas are uncommon compared with pan gnammas. They occur singly or in very small numbers on just a small proportion of the numerous granite outcrops across southwestern Western Australia. While quite a number were easily located via roadside signage (e.g. the five gnammas 14 km north of Trayning), the locations of many were brought to the attention of the author by local enthusiasts at Beacon, Mukinbudin, Hyden and Norseman, and by colleagues. Thus those in the study tend to be clumped around those townships (Figure 1; Appendix 1).

Most gnammas were visited four to five times in 2010–2012, associated with limnological studies (B V Timms in prep.), so many were seen full, in various stages of filling, and also when dry. Length, width at right angles to the length, and depth were measured with varying degrees of accuracy: depth to the nearest centimetre, and length and width varying between centimetre for small gnammas with distinct rims, to 50 cm for large round gnammas with sloping edges (e.g. Beringbooding North with a recorded diameter of 12 m, the estimation confounded by lack of a rim and no observation of its water line when overflowing). In most cases the depth measured was of necessity to the surface of bottom sediment, and hence the measurement is not the true depth of the rock hole. The few exceptions were those gnammas freshly cleaned of their soft infill (indicated in Appendix 1). Lengths and widths were also often difficult to determine exactly, especially where the edge was sloping; a good guide was the full water level, but taking care not to include situations where there was shallow flooding of the surrounding rock. For elongated gnammas width was measured at a few places to get an average value which was important in volume calculations. Another inaccuracy occurred when the rim overhung underlying cavities. Such cavities were most developed in gnammas on a major vertical joint so that the joint was perhaps excavated in some cases up to 50 cm below the rim; this is not recorded in the measurements in Appendix 1. Another even greater measurement problem was presented in those gnammas where a deep horizontal joint had been hollowed underground (Wattoning and Horse Collar Gnammas: Appendix 1): it was impossible to measure these underground dimensions, so that the values recorded are of the visible cavity.

Volumes for most gnammas were calculated assuming the basin shape was a 3D parabola and using the formula

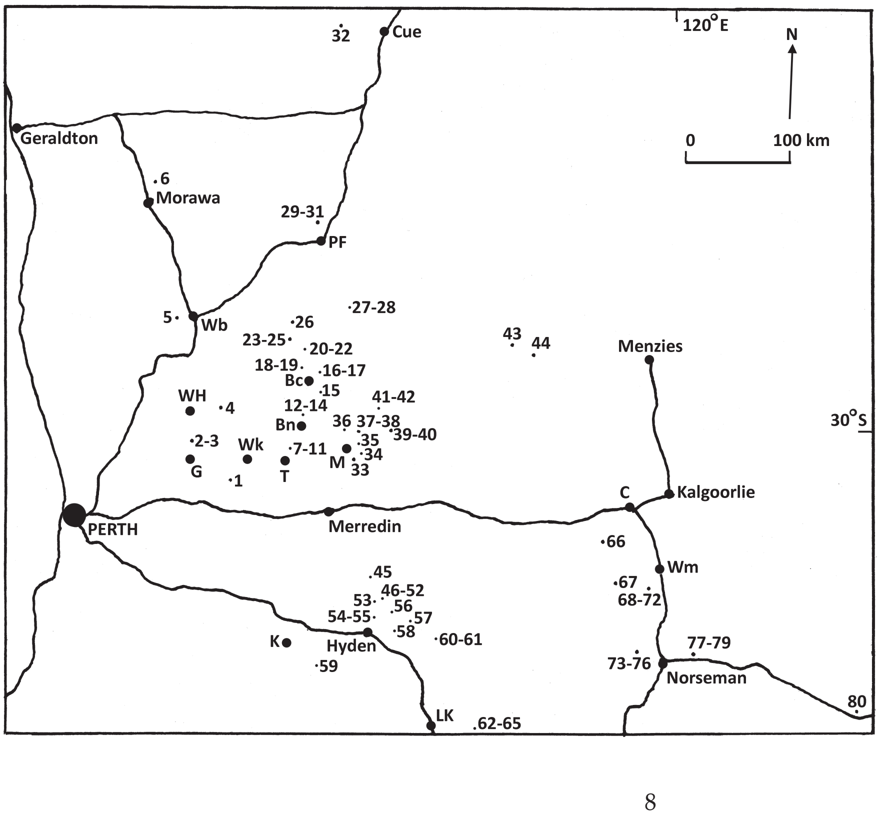


Figure 1 Map of the study area in the Wheatbelt and adjacent Goldfields showing the location of the 80 pit gnammas as listed in Appendix 1, associated major roads and towns. C, Coolgardie; Bc, Beacon; Bn, Bencubbin; G, Goomalling; K, Kulin; LK, Lake King; M, Mukinbudin; PF, Paynes Find; T, Trayning; Wb, Wubin; WH, Wongan Hills; Wk, Wyalkatchem; Wm, Widgiemooltha.

$V = d^2h\pi/8$ where V is volume, d is mean diameter and h is depth. For those with a near-rectangular shape or triangular profile (most type 3 and 4 gnammas, see Appendix 1) the formulae $V = lwh$ was used where l is length, w is width, h is height for near-rectangular gnammas, with $V=lwh/2$ for triangular gnammas.

The position of each gnamma on a granite outcrop was noted, particularly whether on the flattish top, the slide slopes or on the lower flattish flanks. Each gnamma was photographed, including when dry in most cases, thus providing images when later analysing shapes and possible origins (Figure 2).

RESULTS

The gnammas varied in mean diameter from 0.19 to 12 m and in depth from 24 to 300 cm (Appendix 1). The majority of gnammas were 1.0–2.5 m in mean diameter (Figure 3a) and 50–100 cm deep (Figure 3b). The 12 m-diameter gnamma on Beringbooding Rock, and the 3.8 m-deep gnamma at Cadigan are exceptional, though there is an even larger gnammas on Jindarra Rock North of Elachbutting Rock (W Bayly pers. comm. 2010) and on King Rock via Hyden (Twidale & Vidal Romani 2005). True depths are probably greater than indicated as many gnammas had more than a few centimetres of sediment at the bottom. As indicated in Appendix 1, some were cleaned out during the study, so it is only for most of these that the true depth is known (though the Bullamanya pits were impossible to clean out completely without mechanical assistance). The depth:width ratio was 0.57 (95% confidence limits via Fieller's Theorem 0.26 – 0.88) a figure which would be somewhat higher if the true depth of each hollow was known, but still not greater than 1 in most cases.

While most gnammas are of the hemispherical to parabolic pit shape, not all are circular in plan and with smooth and even rims (Figures 2, 5). Many have rims interrupted by minor joints and laminations up to 10 cm deep around the rim and bending with it and extending to some depth within the hollow. Some of these laminations are incomplete, mainly above the usual water line. An example is Quanta Cutting Gnamma. In some the sides are vertical (e.g. Cadigan Mid and South Gnammas), in many the sides tend to be steep (60–80^o), but in others side slopes are moderate at 20-30^o (e.g. the Willogyne Gnammas). The sides may be smooth, but minutely rough revealing individual grains in the rock, or rough at a greater scale of many centimetres because they are interrupted by joints and attendant missing or protruding blocks.

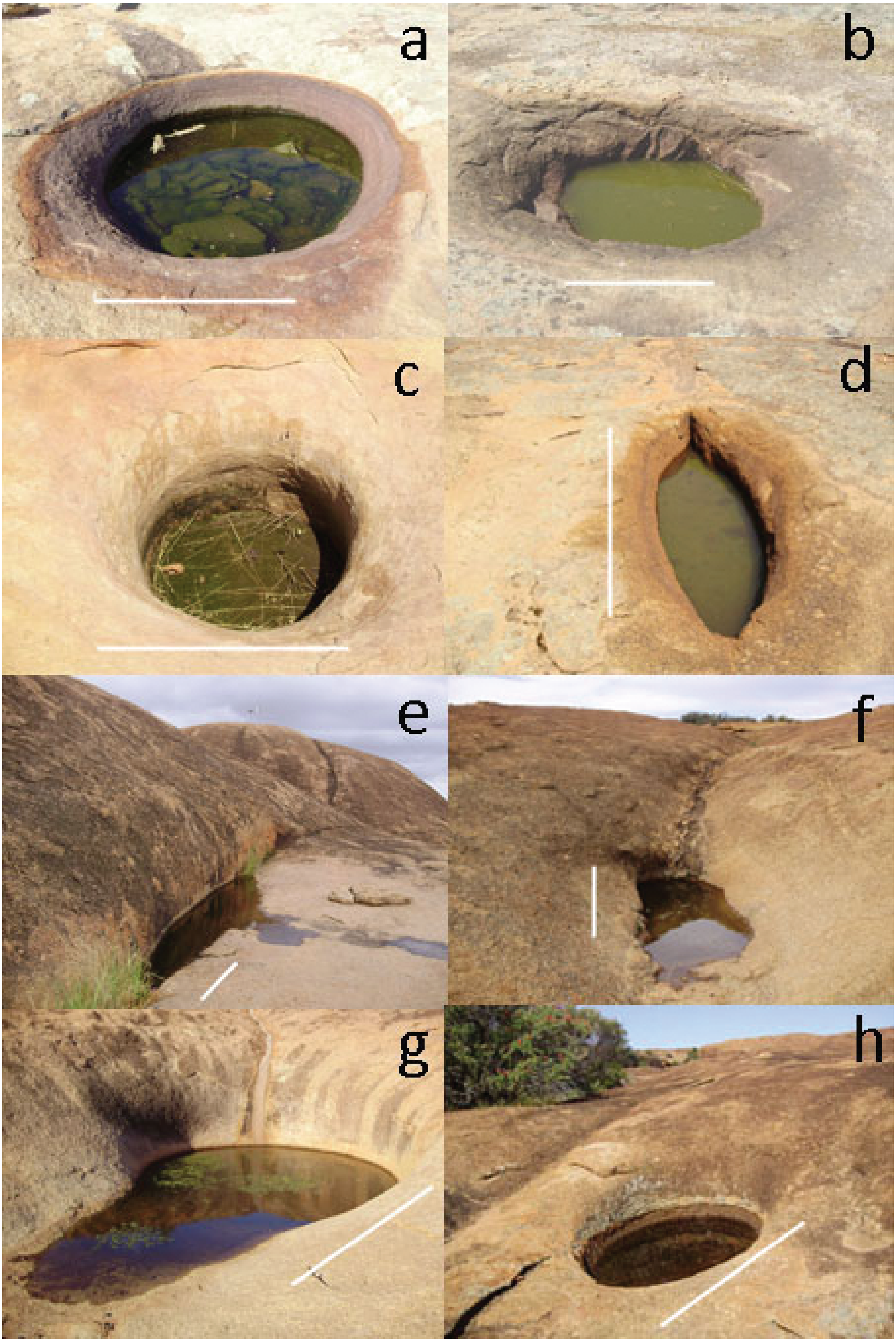
Quite a few gnammas lie on major vertical joints. These usually influence their shape, so that they are elongated along the joint but often narrowing at each end to give an overall 'canoe' shape in plan. Many of these are undercut along the joint, at least at one end. Also, most tend to have vertical sides (e.g. Trayning Far Northwest Gnamma: Figure 2d), though those of Twine Scrub Gnamma has steep parabolic sides, and the Granite Creek Gnamma has a hemispherical cross-section. A few gnammas are also elongated along a major joint, but the joint has not been enlarged, so that the cross-section is triangular (e.g. Higgensville North Gnamma) or in the cases of the War Gnamma and Balladonia Gnamma vertical on one side (Figure 2e).

Rarely a pit gnamma is wider underneath than on the surface. This can occur in homogeneous rock, in which the only known case in the present study is the small flask shaped gnamma on Lillian Stokes Rock (Stokes Far South Gnamma). In two cases the underground expansion is along a horizontal joint 24 cm (Horse Collar Gnamma) to 100 cm (Wattoning Gnamma) from the surface. In both cases the horizontal extent of the cavity is unknown, but at least 50 cm on one side of Wattoning Gnamma and probably much bigger in the case of Horse Collar, as it was known in the early days to water stock without drying, despite its visible small volume (R Trenorden pers. comm. 2010)

All of the above pit gnammas occur on flattish rock surfaces either at the base of elevated exposures of granite or on sheets of granite exposed at ground level, and significantly are not associated with waterways. However there are two groups of gnammas on waterways, which often occur on the steeper slopes of granite exposures. The first group lie on larger waterways often utilising a major joint that has been eroded a little. Examples on Isoetes, Roe and Cave Rocks are elongated, steep sided and in profile are deep upstream and shallow downstream. The Twine Far North pit gnamma is somewhat different as it is at the base of the rock outcrop and on a joint scarcely enlarged though it is deeper upstream. The second group superficially resemble the common roundish pit gnammas with steep sides, but they lie on waterways at the bottom of a steep slope. Like the first group some are deeper rearwards and have shallower overflow lips (both Bullamanya North and South Gnammas, and Yanneymooning Gnamma: Figure 2h), but two are steep-sided round holes with even floors (Twine North and Bullamanya Upper North). Four are on watercourses active after rain, but the waterway has changed course at Yanneymooning and now does not flow through the gnamma.

DISCUSSION

Pits due to the physical and/or chemical weathering on exposed rock surfaces are common in many parts of the world and in many types of rocks (Twidale & Corbin 1963; Twidale & Vidal Romani 2005). Numerous terms are used to describe them, some of local validity and restricted to particular types and others such 'weathering pits' more universal and descriptive. The most common rocks attacked are sandstones (Netoff *et al.* 1995; Chan *et al.* 2005) and granites (Twidale 1971; Domínguez-Villar *et al.* 2009). Studies often classify subtypes based on their physical shape and on the processes forming them. For instance Netoff *et al.* (1995) recognised shallow pans, deeper bowls and cylinders, and armchairs in sandstone in southeastern Utah. Weathering hollows in granites are often called gnammas (see above) and the shallow pan types have been studied in Western Australia (Pinder *et al.* 2000; Timms 2012a, b and references therein), Chile (Domínguez-Villar 2006), Portugal (Domínguez-Villar *et al.* 2009), Spain (Vidal Romani 1983) and USA (Domínguez-Villar & Jennings 2008) among other places. The deeper pit gnammas are less common and litttle studied.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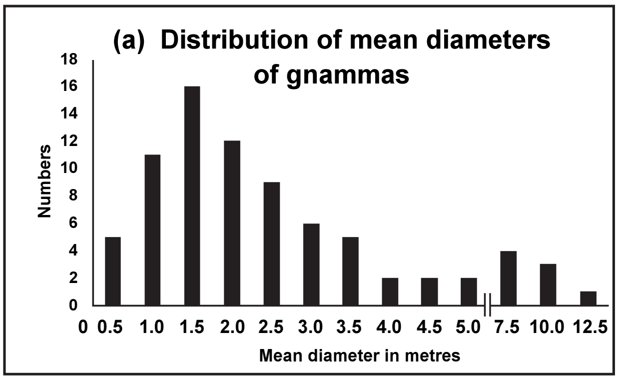

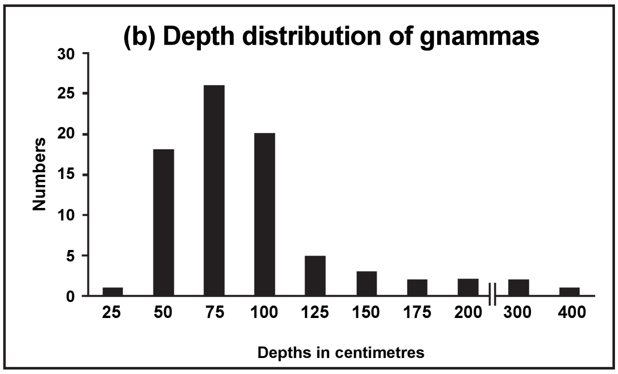

Figure 3 (a) Frequency distribution of mean diameters of the 80 pit gnammas; note most size intervals in 0.5 m steps, but last three in 2.5 m steps. (b) Frequency distribution of the depths of the 80 pit gnammas; note most depth intervals in 25 cm steps, but last two in 1.0 m steps.

A pit gnamma is defined by Twidale & Cobbin (1963) as a rock hollow elliptical or circular in plan and semicircular in cross-section with a large depth relative to the maximum diameter. In contrast, pan gnammas have flat floors and a small depth:diameter ratio. This ratio has only been partly quantified, with a value of D:W >1 suggested for pits by Twidale & Corbin (1963) and a ratio of ~0.5 by Twidale & Vidal Romani (2005). It is not clear if the diameter these authors used was the maximum or mean, though probably not the minimum. Morphometrics of the present set of pit gnammas suggest that if the mean diameter is used, 12.5% qualify by the first ratio and 36.25% by the second ratio. Twidale & Corbin's ratio was apparently based on two pit gnammas on Pildappa Rock South Australia, but these have actual ratios of 0.27 and 0.20 (B V Timms unpubl. data), so that perceptions by eye are tricked. Their ratio is obviously too restrictive, and even that given by Twidale & Vidal Romani (2005) is not very helpful. From the present study, 44% of gnammas have a ratio between 0.2 and 0.4, and 76% a ratio between 0.2 and 1.0 (Figure 4), with a mean of 0.57. A ratio of D:W >0.2 fits the data much better and still distinguishes pits from pans, in that pan gnammas have ratios <0.1 [Dominguez-Villar et al. 2009; 0.026 for 100 pan gnammas on 10 rocks in the Western Australian Wheatbelt (B V Timms unpubl. data)]. Even this lower value of 0.2 excludes 12.5% of present gnammas, though most of these would qualify if the true rock basin depth was available and used. At the other end of the scale five gnammas have values >2 (Figure 4); all have small diameters and deep cylindrical pits thus distinguishing them from other pit gnammas (see below).

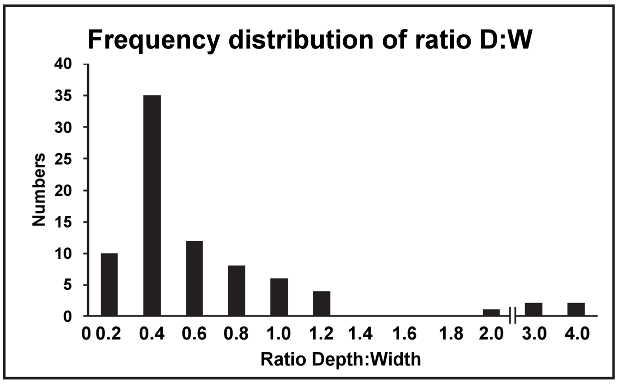

Figure 4 Frequency distribution of depth:width ratios; note most intervals in 0.2 steps, but last two in 1.0 steps.

Table 1 Types of pit gnammas and their frequency percentage.

Type	Name	Description	Percentage
1a	Hemispherical	Hemispherically shaped, no microlayering or joint control	21.25
1b	Hemispherical	Hemispherically shaped, with layering and/or minor joint influence	30.00
2	Cylindrical	Cylindrical due to dominant vertical solution	11.25
3	Canoe	Elongated 'canoe' shape, due to major joint control	17.50
4	Trough	Sitting along a major joint between two rock blocks	5.00
5a	Underground shelf	Expanded depthwise at a lower horizontal joint	2.50
5b	Flask	Expanded depthwise in homogenous rock	1.25
6	Lotic potholes	Eversion trench along a waterway	5.00
7a	Plunge pool	Plunge pool on a water course, presently active	5.00
7b	Plunge pool	Plunge pool on a previous water course, now inactive	1.25

◀ **Figure 2** Representative pit gnammas. (a) Type 1a, Dingo Rock Gnamma; note infilled rocks to prevent human visitors drowning but lizards falling in drown. (b) Type 1b, Oak Flat West Gnamma. (c) Type 2, Cadigan Middle Gnamma. (d) Type 3, Far North West Gnamma of the Trayning Group. (e) Type 4, Trough gnamma on Balladonia Rock. (f) Type 6, Pothole Gnamma on Isoetes Rock. (g) Type 7a, Northern Pit Gnamma on Bullamanya Rock. (h) Type 7b, pit gnamma on Yanneymooning Rock. Scale bars 2 m along length of gnamma.

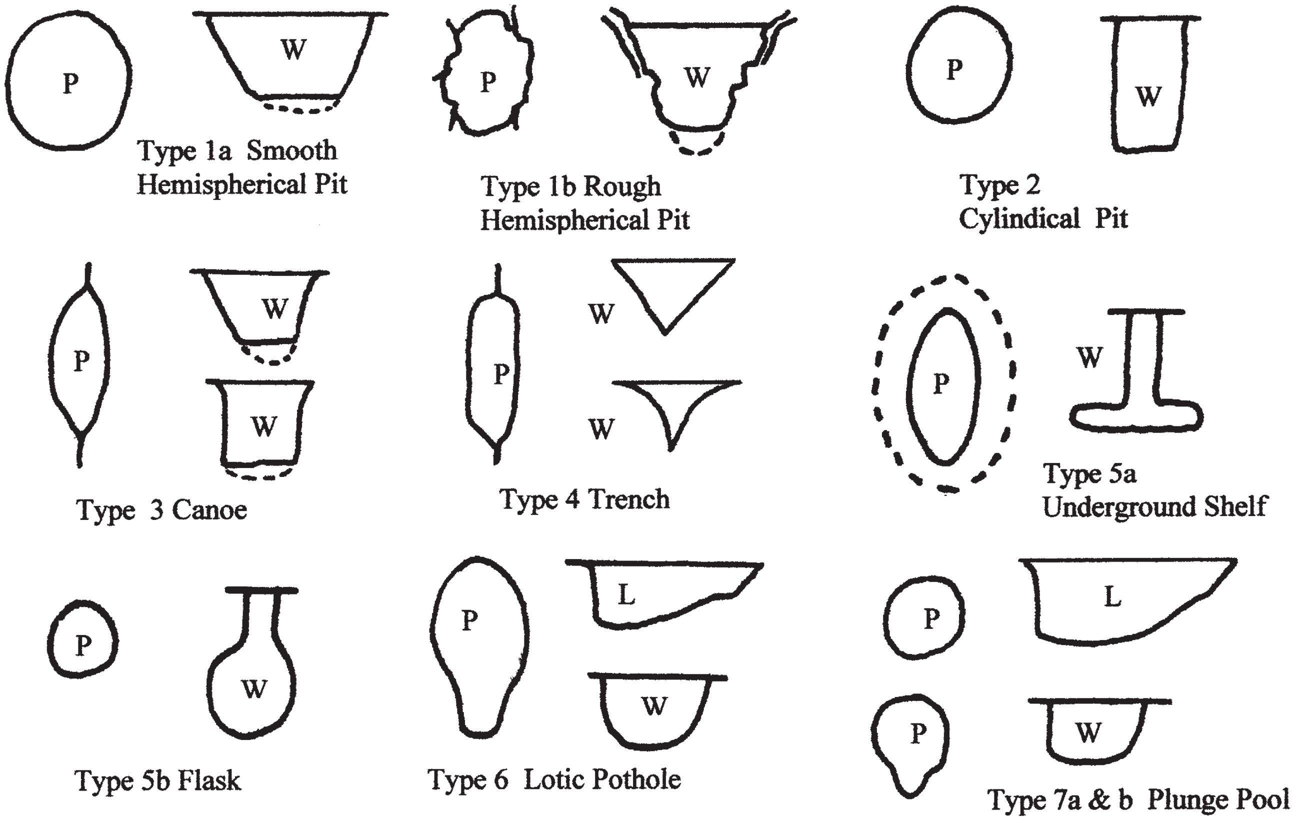

Figure 5 Conceptual profile diagrams of the various types of pit gnammas. L, length; P, plan; W, width; dashed lines are for rock surfaces not seen at ground level.

Many pit gnammas have a hemispherical pit shape and can be accounted for by rock solution subequally horizontally and vertically (Twidale & Corbin 1963; Twidale & Bourne 1976; Twidale & Vidal Romani 2005). This assumes the gnamma fills to about capacity each time it rains and the rock substrate is homogeneous. If there are joints, weathering will be preferential along them, and if the pit collects only a little water in most years it is possible the pit may deepen vertically, though this may be inhibited by accumulated bottom sediment if clayey. However, if sediment is dominated by organics, bottom weathering may be enhanced by contact with carbonic acids. In those pits which have been excavated (Appendix 1) there was no evidence of clay, just organics plus grus. For pits in sandstone, one problem restricting depth is the difficulty in removing weathered sand grains from the base (Netoff *et al.* 1995; D Netoff pers. comm. 2013), although wind is an important eroding factor in shallow pits. It is assumed pits in granite lose most of their rock in solution (Twidale & Corbin 1963) though many have an accumulation of grus and organics on the bottom. This sediment can remain unless indigenous people clean out pit gnammas due to their importance as water reservoirs (D McKellar pers. comm. 1996). With no restriction to natural deepening processes, gnammas on Australian granites have become relatively common, but still sparsely distributed.

Most pit gnammas are modified from the classical profile either horizontally or vertically (see above) and some are due to other processes. The situation is thus more complex than envisioned by Twidale & Corbin (1963) and Twidale & Vidal Romani (2005), with 10 types being recognised in this study (Figures 2, 5; Table 1). The first (Type 1a; Figure 2a) is the hemispherical pit (alias 'pudding-basin-shaped pit') in homogeneous granite due totally to rock weathering by stagnant acid water, as explained by Twidale & Cobbin (1963). It has a hemispheric profile because of equal weathering in all directions. More often than not the horizontal and/or vertical profile is uneven because of minor joints intersecting the basin, these being preferentially attacked by solution; this is Type 1b (Figure 2b), both being recognised by Twidale & Cobbin (1963) though not differentiated in this way. This second group may not be due totally to solution of homogeneous granite, crystal by crystal, but could be assisted by pre-existing abnormalities in crystallisation (e.g. xenoliths in the rock: Twidale 1971) these being more prone to weathering, or in some large gnammas such as Beringbooding North pre-existing sagging in the curvilinear joints of the rock outcrop could define a hollow that is then enlarged by weathering. Many must be exposed to the sun's radiation for long dry periods since there are thin laminations at their rims bending down to depths, such laminations being a feature of the surface of many granite outcrops and generally secondary and due to insolation (Twidale & Vidal Romani 2005). Together these two types account for 51.25% of the present study group (Table 1), which fits the perception of pit gnammas usually being circular and hemispherical in section.

A few pit gnammas (Type 3; Figures 2c, 5) have almost vertical sides all around and are often deeper than wide, with D:W>2 (see above). All are in homogeneous rock: five (Stokes Far North and Far South, Twine

Borehole, Forestiana North and South) are very small, two Karroun pits are bigger, with D:W <1, while the two Cadigan pits are widest and deepest, being in a massive granite layer. All have a small catchment so that perhaps most rarely fill, meaning the little water they do catch weathers the basal rock rather than the shallower rock, which weathers only when the gnamma is full. This would apply to Stokes Far North and Far South, Twine Borehole and the two Karroun pits, all of which were never seen more than half full; others were usually found full or nearly full of water. In the case of the Forestiana pits this is because they now receive overflow water from adjacent pan gnammas, and the Cadigan pits now reach down to a horizontal joint and associated underground springs (R Sache pers. comm. 2011). There is no indication in any of these examples of spiral grooving in the walls due to vortices of water entering forcefully as described by Twidale & Vidal Romani (2005). There is however an unstudied pit gnamma, now usually dry, of this nature on the western side of Victoria Rock; unlike the others it receives considerable volumes of water via overland flow. This cylindrical type is the one illustrated by Göczel (1894), perhaps reflecting that he thought this shape was typical.

It is possible there are more gnammas of Type 3 in the Wheatbelt but they are covered over or filled in, an indication of the danger of steep-sided pits to tourists. One is on Dingo Rock and included in this study, but classified as a hemispherical pit (Type 1a) because the bottom is filled with large rocks and hence not observable in detail. Others covered with a framework and wire mesh occur at Jibebring Rocks, via Wubin, at Moningarin, via Cadoux and at Buldania Rocks via Norseman.

A more common modification of the basic pit gnamma characteristics occurs when they lie on a major joint (Type 3; Figures 2d, 5). Weathering is preferential along the joint so that they are elongated and usually 'canoe' shaped (Twidale & Cobbin 1963). The side walls are narrow, and parabolic or vertical, but rarely a low-angle hemisphere, thus showing the importance of preferential weathering along the joint. Twine Scrub pit has narrow parabolic sides, Trayning Far North pit has wider parabolic sides, Cadigan North pit has vertical sides, and the War pit has the north side vertical and the south side almost a hemisphere. Another feature of these canoe pits is undercutting at one or both ends along the joint. This may extend the length under the rim by 20–50 cm. These canoes are the third most common type (17.5 %; Table 1), and together with above other types account for 82.5% of all pit gnammas.

Four gnammas lie *on* joints between granitic masses, rather than *in* the joints like canoe gnammas, and distinct enough to be considered as Type 4 (Figure 5). Rock weathering has been minimal, so that lateral profiles are triangular or even convex on each side. The Wondoning Hill pit has slightly concave sides, indicating some weathering, the two Higgensville North pits have a triangular profile and the Balladonia pit (Figure 2e) has one side vertical and the other convex. It is possible these are incipient canoe pit gnammas (Type 3), weathering to the usual profile being slower because of infrequent filling.

Three gnammas are expanded underground, two guided by horizontal joints (Type 5a; Figure 5), and one flask shaped formed in homogeneous granite (Type 5b; Figure 5). Both Type 5a pits are in essence canoe gnammas (torpedo shape on surface, vertical walls leading to a flat floor), but their downward weathering has encountered a horizontal joint and this has been enlarged to create an underground cavern. The flask gnamma (Type 5b) would have started as a Type 2 cylindrical gnamma, but further weathering underground has enlarged it to a wider base below a narrower neck. Both of these types are due to special circumstances. Maclaren's (1912) view that gnammas are typically flask shape is not supported by this study.

The last nine gnammas look like other gnammas, the lotic potholes (Type 6; Figure 5) look like blunt canoes, and the plunge pools (Types 7a and 7b; Figure 5) look like cylindrical gnammas, although neither are formed by rock solution, but by moving water and its bedload. Most examples of both types have uneven bottom profiles in that they are deeper at the rear than at the overflow. Also generally both types lie on the steeper slopes of rock outcrops or near their base under a steep slope. Type 6 pits lie on a distinct stream, usually along a joint (Figure 2f), while Type 7a pits lie on an intermittent flow pathway (Figure 2g). The Yanneymooning pit (Type 7b; Figure 2h) is unusual in that it has the character of Type 7a, but is not presently on a waterway. However, there are indications upslope of a past waterway, so it is suggested it is a fossil plunge pool. As such, neither type has been reported on rock outcrops before in Australia. It could be argued that neither are gnammas in that they are not due to rock solution, but by flowing water. However both occur in granite outcrops along with other gnamma types, both are relatively deep and retain water for long periods Furthermore they contain similar aquatic invertebrates as in other pit gnammas, though diversity is severely restricted in the lotic potholes, no doubt due to occasional fast throughflows (B V Timms in prep.).

Each of these 10 types is distinguishable in plan and/or profile (Figure 5) and sometimes by their position on a granite outcrop or their D:W ratio. There are two basic modes of origin: chemical weathering and removal of rock in solution, and rock corrasion due to erosion by running water and its bedload. Types 1–5 owe their origin to rock weathering, each a minor variation on the theme championed by Twidale & Corbin (1963). Types 6 and 7 are unusual, though of course typical of many waterholes on stream courses on hard homogeneous substrates

There are at least two other types of Australian deep gnammas not encountered in this study. One is the armchair hollow, generally on side slopes of an exposed rock outcrop. Two examples are illustrated in Bayly (2011 p. 50, 53), and Twidale & Corbin (1963) provided a picture and two diagrams. These have a steep rear and side walls, and either a flat floor (and hence maybe a type of pan gnamma) or a deeper pit. According to Twidale & Corbin (1963) they develop by loss of the indurated surface and then asymmetrical weathering of the exposed rock to perhaps form a cavern. These authors then proposed that the rear and side walls are smoothed by water washing downslope. This may be so, but based on the my observations of Victorian gnammas, the hollow formed may be caused by differential weathering because of crystalline imperfections. Clearly more study is needed on armchair gnammas. While some armchairs occur in the study area (e.g. on the Humps: Twidale 1971) I could not find any with a pit holding water.

The second type of pit gnamma occurs in desert topography generally in lateritic rocks further east of the Wheatbelt and Goldfields in the Victoria and Gibson Deserts. It has been termed a pipe gnamma (Bayly *et al.* 2011) because most are narrow deep pits (D:W>>1) and claimed to be formed by dominantly vertical weathering. Walls are rough due to included rock pieces in the laterite, and not smooth as in most granitic pit gnammas. Hence they are similar in structure to the present Type 2 cylindrical gnammas, but are not in granite and have particularly high D:W ratios. Further study of them is needed.

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APPENDIX 1 LOCATION, SIZE AND TYPE OF PIT GAMMAS

No	Name	Nearest town	Coordinates	Width (m)	Depth (cm)	Ratio D:W	Volume (m^3)	Type
1	Derdibin[a]	Wyalkatchem	31°20'25"S, 117°20'04"E	5.5 x 3.5	~300	0.66?	23.86	1b
2	Oak Flat East	Goomalling	31°08'20"S, 116°52'49"E	2.5 x 2.1	80	0.35	1.66	1b
3	Oak Flat West	Goomalling	31°08'21"S, 116°52'46"E	2.6 x 2.1	90	0.38	1.95	1b
4	Dingo	Wongan Hills	30°51'43"S, 116°58'28"E	2.7 x 2.0	67	0.29	1.39	1a
5	Miamoon	Wubin	30°09'08"S, 116°28'45"E	~3.5 x 3.3	40	0.11	1.82	1b
6	War	Morawa	29°04'37"S, 115°59'51"E	6.4 x 3.2	120	0.25	9.60[e]	3
7	Trayning Far Southwest	Trayning	30°59'29"S, 117°50'46"E	2.8 x 2.8	105	0.37	3.23	1b/3
8	Trayning Southwest	Trayning	30°59'29"S, 117°50'46"E	1.6 x 1.1	85	0.63	0.61	1b/3
9	Trayning Mid[a]	Trayning	30°59'29"S, 117°50'47"E	1.3 x 1.0[b]	~100[b]	0.87	0.52	1b/3
10	Trayning Northeast	Trayning	30°59'28"S, 117°50'47"E	2.7 x 1.3[b]	95[b]	0.48	2.56[d]	3
11	Trayning Far Northeast	Trayning	30°59'28"S, 117°50'47"E	2.3 x 0.8	60	0.39	0.82[d]	3
12	Cadigan South[a]	Bencubbin	30°46'54"S, 117°52'22"E	1.15 x 1.05	230	2.09	1.09	2
13	Cadigan Mid[a]	Bencubbin	30°46'54"S, 117°52'22"E	1.7 x 1.7	380	2.23	4.31	2
14	Cadigan North[c]	Bencubbin	30°46'53"S, 117°52'22"E	0.95 x 0.5	65	0.89	0.10	3
15	Wondoning Hill	Beacon	30°34'36"S, 118°04'43"E	3.2 x 1.4	49	0.21	0. 94[e]	4
16	Alkiri South	Beacon	30°23'59"S, 117°55'54"E	2.8 x 1.5	50	0.23	0.91	1a
17	Alkiri North[c]	Beacon	30°23'59"S, 117°55'54"E	0.9 x 0.85	92	1.05	0.28	1a
18	Yellari South	Beacon	30°19'44"S, 117°49'58"E	3.7 x 3.1	135	0.40	6.12	1b
19	Yellari North	Beacon	30°19'44"S, 117°49'58"E	0.8 x 0.8[b]	48[b]	0.60	0.12	1b
20	Herndermoning South	Beacon	30°15'23"S, 116°58'29"E	3.6 x 3.5	80	0.22	3.96	1b
21	Herndermoning North	Beacon	30°15'23"S, 116°58'29"E	1.3 x 1.25	57	0.36	0.45	1b
22	Granite Creek	Beacon	30°14'20"S, 117°49'08"E	4.6 x 1.1	56	0.20	1.41[e]	3
23	Washington South	Beacon	30°09'06"S, 117°34'41"E	~12 x 8[b]	115[b]	0.12	45.16	1a
24	Washington Northwest[c]	Beacon	30°08'52"S, 117°34'46"E	2.1 x 1.0	58	0.37	0.17	1a
25	Washington Northeast[c]	Beacon	30°08'57"S, 117°34'41"E	1.5 x 1.1	38	0.29	0.25	1a
26	Remlap North[a]	Beacon	30°02'04"S, 117°37'50"E	4.7 x 3.8	105	0.25	7.45	1a
27	Karroun Hill South	Beacon	29°59'43"S, 118°10'44"E	1.25 x 1.2	85	0.50	0.69	2
28	Karroun Hill North	Beacon	29°59'43"S, 118°10'44"E	1.5 x 1.45	87	0.74	0.59	2
29	Bullamanya South[a]	Paynes Find	29°09'53"S, 117°39'36"E	2.5 x 2.3	60	0.25	1.36	7a
30	Bullamanya North[a]	Paynes Find	29°09'52"S, 117°39'36"E	3.8 x 3.1	72	0.21	3.36	7a
31	Bullamanya Upper[a]	Paynes Find	29°09'51"S, 117°39'37"E	1.5 x 1.2	55	0.39	0.41	7a
32	Walga	Cue	27°24'09"S, 117°27'48"E	2.5 x 1.4	95	0.49	1.42	1b
33	Weira	Mukinbudin	30°59'54"S, 118°23'13"E	8.5 x 5.0	150	0.22	26.84	1b
34	Isoetes	Mukinbudin	30°54'11"S, 118°33'20"E	2.7 x 0.8	53	0.30	0.20	6
35	Quanta Cutting	Mukinbudin	30°51'49"S, 118°25'46"E	6.5 x 4.8	90	0.16	11.28	1b
36	Wattoning	Mukinbudin	30°46'11"S, 118°11'14"E	1.5 x 0.45	105	1.08	0.35	5a/3
37	Willogyne South	Mukinbudin	30°45'59"S, 118°16'27"E	8.5 x 5.5	80	0.10	15.39	1b
38	Willogyne North	Mukinbudin	30°45'59"S, 118°16'27"E	5.5 x 4.5	145	0.29	14.24	1b
39	Yanneymooning	Mukinbudin	30°43'04"S, 118°33'24"E	1.9 x 1.0	53	0.37	0.44	7b
40	Melancobbing	Mukinbudin	30°40'12"S, 118°32'21"E	~8.0 x 8.0	90	0.11	22.62	1b
41	Beringbooding Southwest	Mukinbudin	30°33'38"S, 118°29'35"E	7.25 x 4.5	175	0.30	7.55	1a
42	Beringbooding North	Mukinbudin	30°33'31"S, 118°29'42"E	12.0 x 12.0	>200	0.22?	>110.00	1b
43	Old Rainey	Menzies	29°43'24"S, 119°37'42"E	2.4 x 1.9	45	0.82	0.21	1b
44	Johnson	Menzies	29°48'11"S, 119°49'29"E	2.05 x 1.0	88	0.80	0.83[d]	3
45	Roe	Mt Walker	31°59'37"S, 118°48'40"E	3.8 x 1.2	62	0.25	1.52	6
46	Twine Far North	Mt Walker	32°06'26"S, 118°57'22"E	4.6 x 2.2	46	0.63	0.14	6
47	Twine North	Mt Walker	32°06'34"S, 118°57'27"E	1.05 x 1.0	85	0.83	0.35	7a
48	Twine Mid	Mt Walker	32°06'51"S, 118°57'27"E	2.8 x 1.8	95	0.41	4.05	1a/3
49	Twine Shrub[a]	Mt Walker	32°06'53"S, 118°57'27"E	2.5 x 1.4	195	1.00	2.91	3
50	Twine Southeast[a]	Mt Walker	32°06'53"S, 118°57'28"E	2.7 x 1.45	80	0.39	2.70[d]	3
51	Twine Southwest[a]	Mt Walker	32°06'53"S, 118°57'27"E	2.5 x 1.8[b]	57[b]	1.03	0.27	1a/3
52	Twine Borehole	Mt Walker	32°06'53"S, 118°57'27"E	0.85 x 0.5	31	0.50	0.06	2
53	Anderson	Hyden	32°10'12"S, 118°51'26"E	1.2 x 1.2	38	0.21	0.32	1a
54	Humps North	Hyden	32°18'41"S, 118°57'37"E	1.7 x 1.7[b]	76[b]	0.45	0.86	1a
55	Humps South	Hyden	32°18'46"S, 118°57'38"E	1.0 x 0.6	100	1.20	0.50[d]	3
56	Meeking[c]	Hyden	32°12'53"S, 119°05'04"E	1.05 x 0.6	55	0.67	0.15	1b
57	Wheelers[c]	Hyden	32°19'59"S, 119°17'10"E	0.5 x 0.45	42	0.88	0.04	1a
58	Baohm	Hyden	32°21'34"S, 119°12'02"E	1.5 x 1.15	64	0.48	0.44	1b
59	Horse Collar	Kulin	32°48'04"S, 118°23'34"E	1.5 x 0.75	50	0.24	0.44?	5a/3
60	Forestiana South[c]	Hyden	32°24'42"S, 119°12'03"E	0.5 x 0.4	84	1.86	0.07	2
61	Forestiana North	Hyden	32°24'42"S, 119°12'03"E	1.0 x 0.3	34	0.52	0.06	2
62	Lilian Stokes Far South[a]	Lake King	33°04'06"S, 120°05'49"E	0.20 x 0.18	66	3.47	0.01	5b
63	Lilian Stokes South	Lake King	33°04'06"S, 120°05'49"E	1.6 x 1.0[b]	58[b]	0.38	0.45	1a
64	Lilian Stokes North	Lake King	33°04'06"S, 120°05'49"E	1.2 x 0.9[b]	40[b]	0.17	0.38	1a

APPENDIX 1 (cont.)

No	Name	Nearest town	Coordinates	Width (m)	Depth (cm)	Ratio D:W	Volume (m^3)	Type
65	Lilian Stokes Far North[a]	Lake King	33°04'06"S, 120°05'49"E	0.25 x 0.2	70	3.11	0.01	2
66	Victoria Rock	Coolgardie	31°17'37"S, 120°51'48"E	1.8 x 1.45	61	0.38	1.72	1b
67	Cave Rock	Widgiemooltha	31°39'40"S, 121°13'38"E	1.4 x 0.9	56	0.49	0.29	6
68	Higgensville Far North	Norseman	31°44'41"S, 121°34'08"E	~15.0 x 5.0	160	0.16	60.00[e]	4
69	Higgensville North	Norseman	31°44'41"S, 121°34'08"E	6.5 x 1.9	30	0.16	1.85[e]	4
70	Higgensville Mid	Norseman	31°44'41"S, 121°34'08"E	2.7 x 1.1	50	0.26	1.21[d]	3
71	Higgensville South	Norseman	31°44'41"S, 121°34'08"E	1.3 x 0.5	60	0.67	0.27[d]	3
72	Higgensville Southwest[c]	Norseman	31°44'41"S, 121°34'07"E	1.65 x 0.55	50	0.43	0.33[d]	3
73	Theatre Far North	Norseman	32°08'23"S, 121°33'23"E	4.6 x 3.1[b]	54[b]	0.16	3.14	1b
74	Theatre North	Norseman	32°08'23"S, 121°33'23"E	0.6 x 0.4	30	0.60	0.05[d]	3
75	Theatre South[c]	Norseman	32°08'24"S, 121°33'22"E	0.95 x 0.45	45	0.64	0.14[d]	3
76	Theatre Far South	Norseman	32°08'25"S, 121°33'22"E	2.7 x 2.6	65	0.25	1.79	1b
77	Buldania East	Norseman	32°07'56"S, 120°55'38"E	2.7 x 2.6	90	0.34	2.48	1a
78	Buldania South	Norseman	32°07'56"S, 120°55'38"E	2.05 x 1.1	44	0.28	0.43	1a
79	Buldania West	Norseman	32°07'56"S, 120°55'37"E	3.0 x 2.5	67	0.24	1.99	1a
80	Balladonia[a]	Norseman	32°27'41"S, 123°51'48"E	6.3 x 0.45	65	0.19	1.13[e]	4

[a] cleaned out in 2010 summer.

[b] floods to greater area and depth.

[c] capped.

[d] rectangular formula used for volume calculation.

[e] triangular profile formula used for volume calculation.