Department of Science, Information Technology and Innovation

Doongmabulla Galilee Springs Group

Hydrogeology and ecology

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Front Cover: Edgbaston Springs and a spring (imaginatively) called “New Big”. There is Spinifex in the foreground, free water in the mid-ground, with some scalding in front and the far right rear. Photo: Queensland Herbarium.

March 2017

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Overview

The springs at Doongmabulla form an isolated cluster of wetlands associated with the Carmichael River and its tributaries (Figure 1). They have been included within the Barcaldine Supergroup but are treated separately here because unlike the other springs in this supergroup they are associated with the Galilee Basin rather than the Eromanga Basin. Due to limitations in available data their source aquifer is ambiguous and unlike the other Barcaldine supergroup springs, depending on their source aquifer, they may be under threat from mining developments in the Galilee Basin.

The springs include relatively large spring wetlands and consist of 187 vents forming 160 separate wetlands (Figure 1; Table 1). The Doongmabulla Galilee Group springs are located on two properties, Doongmabulla and Labona. The springs occur near the confluence of the Carmichael River and Bimbah Creek, and downstream of this area. The following paragraphs provide a summary of the springs location, landscape position, morphology and known ecological values of the main springs in this group.

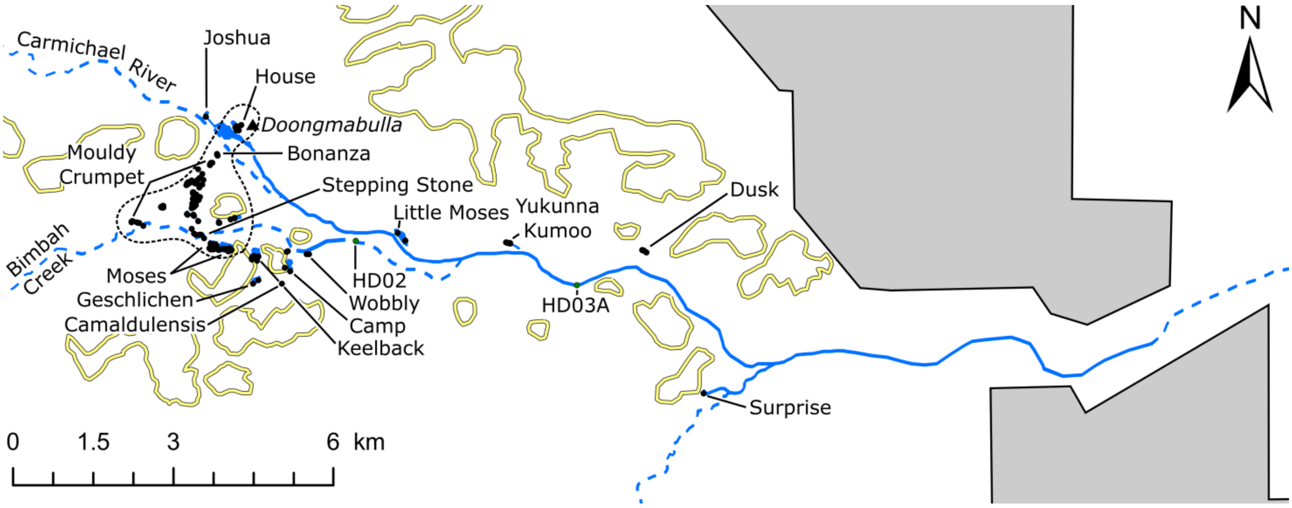

Figure 1. The Doongmabulla Springs at the small-scale; the location of two monitoring bores (HD02, HD03) and the approximate location of the proposed Carmichael Mine (Source: GHD, 2013a, p. 19). The permanent (solid) and impermanent (dashed) sections of the streams (blue lines) and the areas of outcropping sandstone (yellow lines) are identified. The dotted black line distinguishes springs with an unambiguous discharge character, i.e. discrete mounded vents on flat scalded ground not associated with sandstone outcrop.

Table 1. Summary of the status of the springs in the Doongmabulla springs at the complex, wetland and vent scale.

	Complex			Wetland		Vent	
	Active	Partially active	Inactive	Active	Inactive	Active	Inactive
Outcrop	1	0	0	11	0	13	0
Discharge	1	0	0	149	0	174	0

The House Springs comprise a cluster of small to medium-sized springs (64 to 6400 m^2) to the north of the junction of these streams just west of the Doongmabulla homestead. These are mounded vents in the middle of wetlands situated in flat topography.

Adjacent to the House Springs is the Joshua Spring. The area adjacent to the spring vent has been modified and a turkey nest dam with a pipe discharging a large flow of water through the dam wall (Figure 2). The outflow from Joshua Spring and the House Springs converge to provide the main discharge feeding the Carmichael River for a distance of approximately 20 km (Sam Cobb, pers. comm.). The vent of the massive Joshua Spring has not been located within the turkey nest where it occurs, and its precise character is difficult to determine. This spring excluded, the physical morphology of the vents and the topographic situation of the springs is variable and changes from the west to the east.

Figure 2. Joshua spring enclosed within a rectangular shaped ‘turkey nest’ in the foreground (left); the outflow pipe (right) is through the right-hand wall.

On the scalded plain between the Carmichael River and Bimbah Creek are a cluster of numerous small springs poignantly known as the Mouldy Crumpet group (Figure 3). These springs are mounded and occur on flat scalded ground, features typical of discharge springs. Despite their small size (generally less than < 100 m^2) these springs contain high concentrations of endemic species. The vents are mounded in the middle of the wetlands and are located on flat topography.

Figure 3. One of the large number of Mouldy Crumpet springs, north of Bimbah Creek.

South of these and amongst the channels of Bimbah Creek are the Stepping Stone Springs. The vents are mounded in the middle of the wetlands and are located on flat topography.

South of the confluence of the streams are small and large springs on a scalded area extending over 1.4 m, from the most westerly Moses Springs, to Keelback Springs, Geschlichen Spring (on a shallow side gully to the south) and Camp Spring (Figure 4). The large wetlands at Moses and Keelback Springs flow into permanent open ponds and channels within the bed of Bimbah Creek, but when evaporation reduces moisture in the regolith during drought times these channels do not discharge into the Carmichael River. A vent at the large Moses Spring was accurately measured at 0.5m above the edge of the wetland using a dumpy level in November 2014. This situation strongly suggests groundwater fed by artesian pressure through a vertical conduit, and all these features are characteristic of discharge springs elsewhere.

Figure 4. The main Camp Spring vent discharging from outcropping sandstone.

To the north of Camp Springs amidst the channels of Bimbah Creek is Bush Pig Trap Spring and to the south of Camp Spring on the edge of a belt of red-gums (Eucalyptus camaldulensis) is Camaldulensis Spring. On the side of a large water hole in Bimbah Creek are the Wobbly Springs, which contribute to the permanence of the water-hole.

On the bank of the Carmichael River south of Joshua Spring are the Bonanza Springs. Bonanza, Keelback, Geshlichen, Bush Pig Trap and Camaldulensis are not mounded but also occur in flat areas remote from outcrop, and are also almost certainly discharge springs with vertical conduits. Camp Spring has two vents, both emerging from sandstone rock at the base of outcrop (Figure 5), but unlike other outcrop springs to the east the vents are very discrete, indicative of discharge springs fed by pressurised artesian water.

Figure 5. Camp Spring looking west towards Keelback Springs, visible as a stand of dark-green paperbarks. Note the scalded areas around the springs characteristic of discharge springs. The vents are at the base of a low rise (visible in the middle of the photograph).

North of the Carmichael River and 1 km downstream of the confluence of the streams is Little Moses Spring with its wetland at the base of a gentle slope but above the channels of the main stream (Figure 6).

Figure 6. Little Moses Spring with notable absence of scalded area

Heading downstream on the northern side of the Carmichael River and east of the Labona boundary fence is the large Yukunna Kumoo Spring, and then a cluster of small springs known as the Dusk Springs (Figure 7).

Figure 7. One of the Dusk Springs

Finally on the edge of Surprise Creek, which enters the Carmichael from the southwest, is Surprise Spring, which has formed a short gully from its ill-defined source in colluvial material (Figure 8).

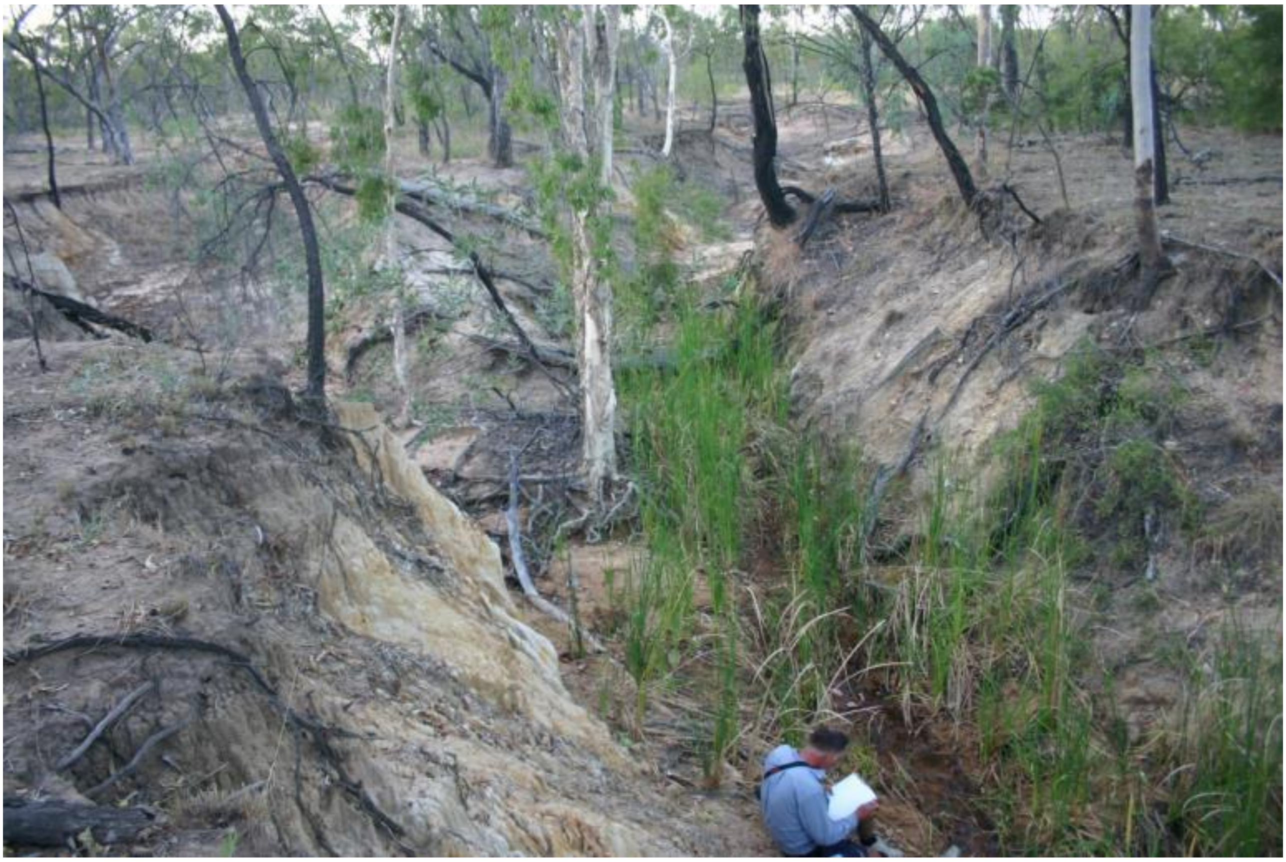

Figure 8. Head of Surprise Spring with discharge forming a channel in an incised gully within colluvial material.

The eastern springs, Little Moses, Yukunna Kumoo, Dusk and Surprise Spring have vents on the edge of wetlands at the base of gently sloping topography suggesting lateral discharge, a feature typical of outcrop springs.

The flat topography, mounded vents and absence of outcrop at the western springs (House, Mouldy Crumpet, Stepping Stone) is strongly suggestive of a vertical conduit through a confining bed typical of discharge springs. Whereas, the position of the vents of the eastern springs on sloping topography, and their association with outcropping sandstone, suggests a potentially horizontal discharge conduit through an unconfined aquifer typical of outcrop springs.

Hydrogeology

Geological setting

The geological sequence underlying this spring group includes the Rewan Formation, the Dunda Beds, the Clematis Sandstone and the Moolayember Formation (Figure 9). The existing geological mapping and available stratigraphic data indicates the Triassic Galilee Basin sediments dip to the west in the vicinity of the Doongmabulla Springs at less than 1° (Figure 9). Seismic data suggests that the dip near the base of the Triassic sequence is up to 5° in the east, but is almost flat lying 5km to the west (Velseis, 2012). The Rewan Formation forms the basal sedimentary unit and is overlain by the Dunda Beds, the Clematis Sandstone, and finally the Moolayember Formation. There are three bores in the vicinity of the springs which provide an understanding of the lithology of the underlying stratigraphy; C056C (GHD, 2013b, p. 99), C555 (QLD groundwater database) and Shoemaker 1 (ATP744P).

The Shoemaker bore suggests that the Rewan Formation is relatively fine-grained including 262m (94%) of fine grained siltstones and mudstones with two interbedded facies of sandstones. This is consistent with the available literature which suggests the Rewan Formation is dominated by fine-grained sediments which is generally characterised as an aquitard, separating the underlying Permian sediments (including the coal bearing Betts Creek Beds), and the overlying sandstones of the Dunda Beds and the Clematis Sandstone. A further stratigraphic bore C555P lies to east of Shoemaker 1. Here the Rewan has a thickness of 277m and comprises fine grain sediments similar to the Rewan Formation in Shoemaker 1.

The lithology recorded at C056C suggests that the Rewan Formation includes more sandstone than represented in the Shoemaker bore. It is represented as 89m (48%) of fine-grained sandstone, siltstones and mudstones, and the remaining 98m composed of sandstone in 11 interbedded facies.

The bores in the vicinity of the Doongmabulla Springs indicate that the Rewan Formation is between 187m and 280m thick (Table 2). The Rewan Formation is generally considered argillaceous (fine-grained) (Vine and Doutch, 1972), only rarely provides groundwater through pastoral bores (A. Bleakley pers. comm.), and is generally considered an aquitard.

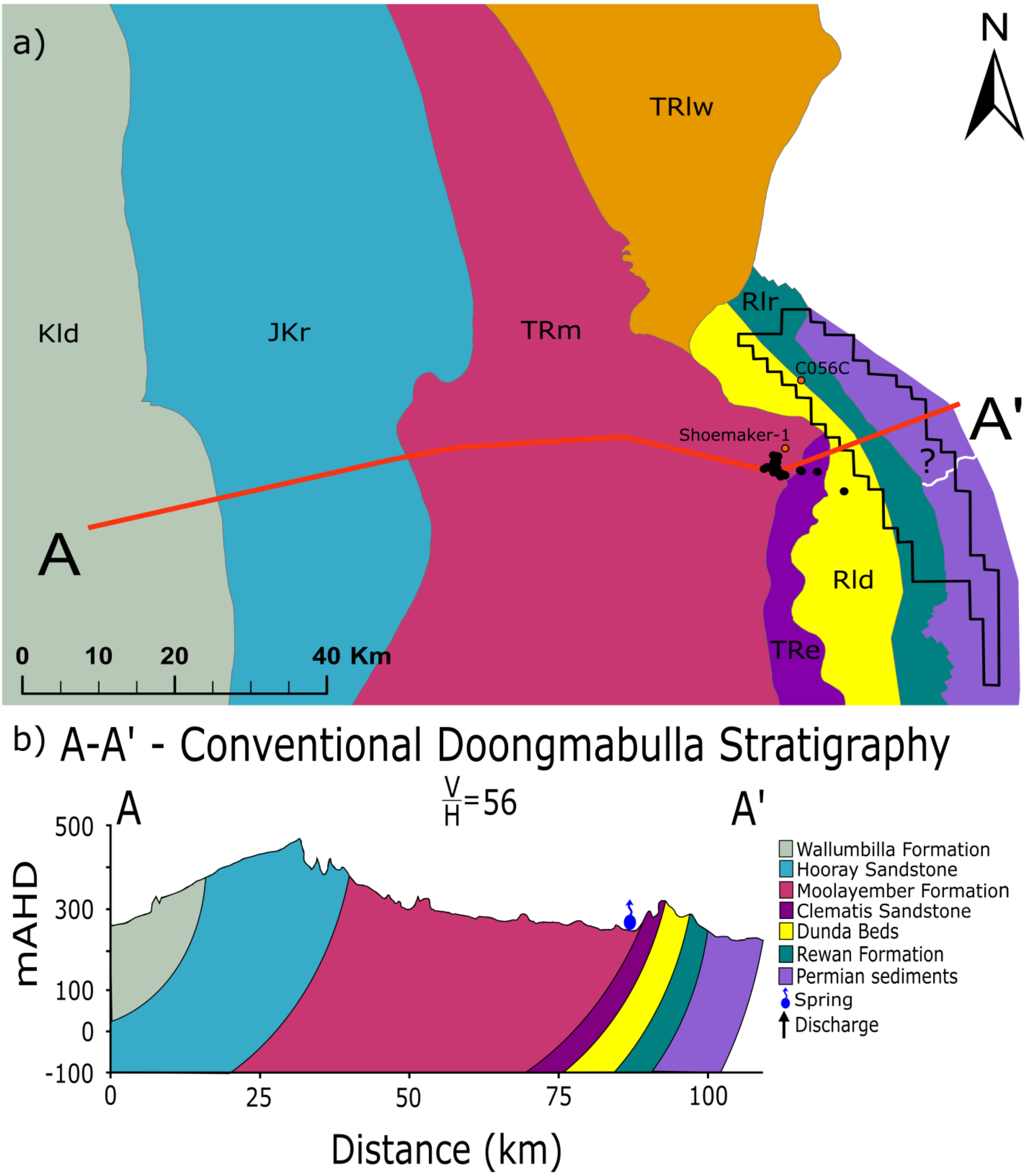

Figure 9. Representation of the regional geology (without Cainozoic) in the vicinity of the Doongmabulla Springs consistent with the existing geological mapping (Vine et al., 1972a). a) plan view with location of stratigraphy, the position of the Carmichael lease and the Doongmabulla Springs (black dots), and an area of uncertain geology north of the white line are also indicated. The location of two stratigraphic bores, Shoemaker and C056C, are indicated; b) Stratigraphic cross-section with discharge springs emanating under pressure through a thin layer of the Moolayember Formation; and outcrop springs in the Clematis Sandstone and Dunda Beds also indicated. The Permian sediments are buried beneath Cainozoic material and our interpretation here is consistent with mapped surface extent of Permian sediments.

Table 2. The lithology of the Rewan Formation as described in two bore logs near the Doongmabulla Springs: Shoemaker 1 (-22.066°S, 146.241°E) and C056C (-22.976°S, 146.278°E); all measurements are in metres (see Figure 9).

(Shoemaker 1)				C056C			
Lithology	**Top**	**Bottom**	**Thickness**	**Lithology**	**Top**	**Bottom**	**Thickness**
Mudstone	250	260	10	Fine grain sandstone	90	95	5
Siltstone	260	288	28	Silt	95	99	4
Mudstone	288	296	8	Claystone	99	104	5
Siltstone	296	308	12	Sandstone	104	123	19
Mudstone	308	315	7	Claystone	123	126	3
Siltstone	315	383	68	Silt	126	127	1
Sandstone	383	392	9	Very fine grain sandstone	127	128	1
Siltstone	392	440	48	Fine grain sandstone	128	135	7
Siltstone	440	490	50	Siltstone	135	136	1
Sandstone	490	499	9	Claystone	136	139	3
Siltstone	499	518	19	Fine to medium grain sandstone	139	146	7
Very fine sandstone	518	530	12	Silt	146	149	3
Total	*250*	*530*	*280*	Sandstone	149	157	8
				Silt	157	158	1
				Sandstone	158	159	1
				Silt	159	161	2
				Sandstone	161	170	9
				Silt	170	172	2
				Sandstone	172	174	2
				Fine grain sandstone	174	176	2
				Fine to medium grain sandstone	176	177	1
				Siltstone	177	186	9
				Fine grain sandstone	186	187	1
				Siltstone	187	189	2
				Silt	189	192	3
				Fine grain sandstone	192	193	1
				Siltstone	193	200	7
				Fine grain sandstone	200	202	2
				Siltstone	202	203	1
				Very fine grain sandstone	203	204	1

(Shoemaker 1)				C056C			
Lithology	Top	Bottom	Thickness	Lithology	Top	Bottom	Thickness
				Siltstone	204	207	3
				Fine grain sandstone	207	209	2
				Sandstone	209	212	3
				Siltstone	212	213	1
				Sandstone	213	258	45
				Very fine grain sandstone	258	259	1
				Siltstone	259	265	6
				Fine grain sandstone	265	267	2
				Siltstone	267	268	1
				Fine to medium grain sandstone	268	270	2
				Fine grain sandstone	270	272	2
				Siltstone	272	274	2
				Fine grain sandstone	274	275	1
				Siltstone	275	276	1
				Sandstone	276	277	1
				Total	*90*	*277*	*187*

The Rewan Formation is overlain by the Dunda Beds and Clematis Sandstone (Figure 10). The Dunda Beds are ‘quartzose to lithic, commonly contain a kaolinitic matrix, and are generally fine-grained. Argillaceous interbeds are more common in the Dunda Beds than in the Clematis Sandstone’ (Vine and Doutch, 1972). The Clematis Sandstone is described as ‘quartzose, commonly porous and medium to very coarse-grained’. The Clematis Sandstone ‘forms bluffs and cliffs’, while the Dunda Beds form ‘rounded foothills’ (Vine and Doutch, 1972). There are pastoral bores providing groundwater from the Dunda Beds, although supplies are not as substantial and reliable as those from the Clematis Sandstone (A. Bleakley pers. comm.). Both units are generally considered as relatively sandy units compared to the Rewan Formation.

While there is some groundwater in the overlying Moolayember Formation, it is generally considered as an aquitard separating the Triassic sediments of the Galilee Basin from the Jurassic sediments of the Eromanga Basin (Habermehl and Lau, 1997). The only bore describing the full Triassic stratigraphic sequence is the Shoemaker 1 bore. At this location (Figure 112a) the Moolayember Formation occurs from 4 to 82 m depth and the Clematis Sandstone from 82 to 200 m depth. The depth of the Dunda Beds is unclear from the available information and is interpreted in combination with the Rewan Formation, and is expected to occur from 200-250 m depth. The Rewan Formation is interpreted to occur from 250 m depth (Table 2).

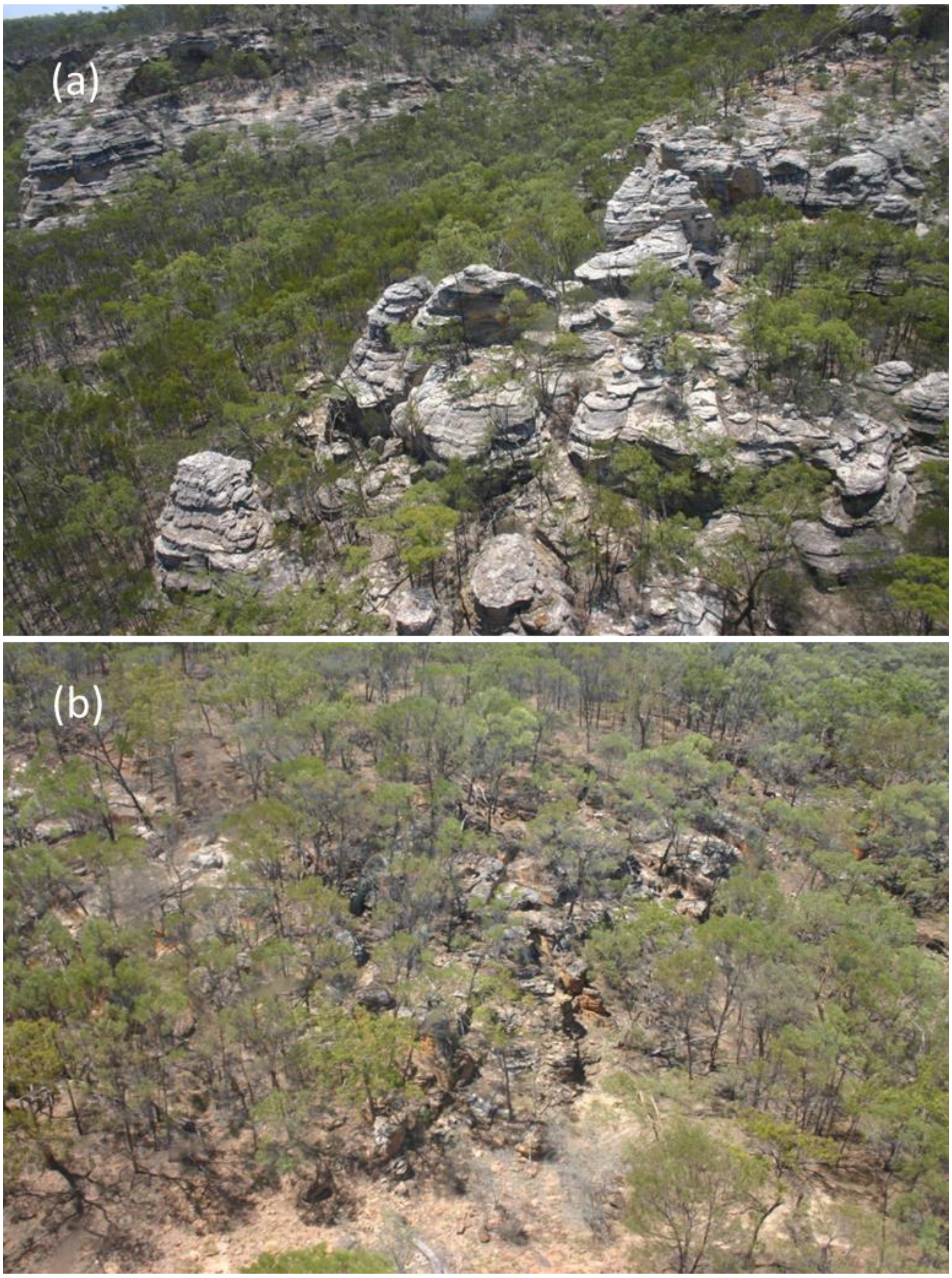

Figure 10. a) Outcrop of presumed Clematis Sandstone forming 'bluffs and cliffs' of pale quartz rich sandstone compared to b) presumed outcrop of Dunda Beds forming 'rounded foothills' of brownish sandstone (Source: Webb, 2015)

The variable thickness of the Rewan Formation interpreted from the Shoemaker 1, C056C, and C555P bores (279 m, 187 m and 277 m respectively) may be due to difficulty distinguishing between the Dunda Beds and the Rewan Formation. An alternative to the existing geological mapping of Triassic sediments around Doongmabulla was proposed by Dr John Webb (Webb, 2015) in evidence presented to the Queensland Land Court (Proceedings no. MRA428-14, EPA429-14, MRA430-14, EPA431-14, MRA432-14, EPA433-14). The Webb interpretation is based on aerial reconnaissance of the outcropping sediments (Figure 10), radiometric and seismic data. Generally, Webb suggested the dominant consolidated unit throughout the area of the Doongmabulla Springs is Dunda Beds. The divergent interpretations of the Triassic sedimentary sequence in the vicinity of the Dongmabulla Springs highlights that these units can be difficult to distinguish.

Hydrology of the springs

Two substantially different interpretations of the hydrology of the Doongmabulla Springs are presented in this section (Figure 9; Figure 11); the Triassic Scenario and the Permian Scenario. Both interpretations are consistent with the existing geological mapping in the area of Doongmabulla Springs (Vine and Doutch, 1972)(Figure 11a).

On the existing geological mapping the Surprise Spring is positioned within Dunda Beds. Little Moses, Yukunna Kumoo and Dusk Springs occur within Clematis Sandstone. The other springs to the west are located where there is a thin layer (<50 m) of Moolayember Formation overlying the Clematis Sandstone.

Under the ‘Triassic scenario’, the source aquifer for the springs is the Clematis sandstone. The springs within the outcropping sandstones (Little Moses, Yukunna Kumoo, Dusk, and Surprise) are interpreted as gravity-fed outcrop springs (Figure 11a). The Joshua, House, Bonanza, Moses, Stepping Stone and Mouldy Crumpet Springs are interpreted as discharge springs. Under this scenario sufficient artesian head in the Clematis Sandstone is required to provide discharge to the surface through a thin layer of the Moolayember Formation and/or surface alluvium thinned by erosion around the confluence of Carmichael Creek and Bimbah Creek (Figure 11a).

An alternative scenario, the Permian Scenario was suggested by Dr John Webb during the land court proceedings (Webb, 2015) (Figure 11b). Under this scenario, the source aquifer of the springs is the Permian sediments beneath the Rewan Formation and a fracture or fault and substantial potentiometric head is required to allow groundwater to discharge through the Rewan Formation and Dunda Beds to the springs at the surface (Figure 11b). This would require a conduit greater than 500m in length, and more importantly, it would also require a potentiometric surface in the Colinlea sandstone aquifer significantly above the natural surface of the springs, to overcome the potential headloss.

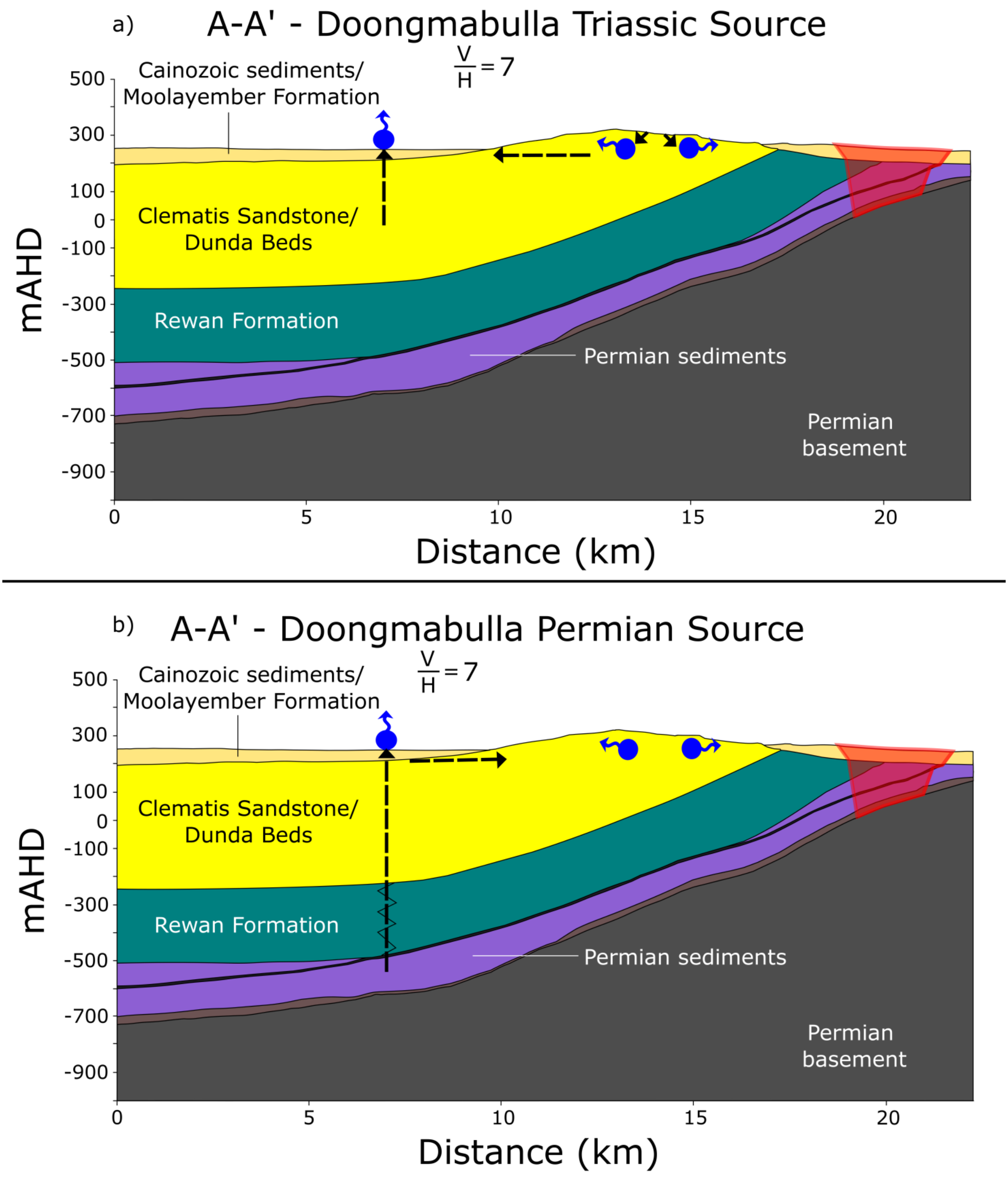

Figure 11. a) Hydrogeological conceptualisation of the springs at Doongmabulla (from the west-east) representing the Triassic Scenario with outcrop springs fed by gravity in the east and feeding an aquifer with sufficient head to supply artesian pressure to discharge springs in the west (Figure 9); b) Hydrogeological conceptualisation of the springs (from the west-east) representing the Permian Scenario whereby the source aquifer is in the Permian sediments emanating from a fracture through the aquitard (Rewan Formation) and some groundwater penetrating vertically to supply the mounded artesian springs and dispersing laterally to supplement an aquifer in the Triassic sediments that provides the source for outcrop springs to the east.

A key line of evidence to test these scenarios is the hydraulic head for the alternative source aquifers. Is there sufficient potentiometric head in the Triassic aquifer to supply water to the springs, or at least those western springs (House, Mouldy Crumpet, Stepping Stone and Moses; Figure 1) that are interpreted as discharge springs based on their morphology?

Data from relevant bores with reliable measurements of standing water level or pressure measurements were compiled to assess the potentiometric surface in a north-south direction in the vicinity of the springs (Figure 12). There is limited data available for interpretation. Data was sourced from the Queensland Groundwater Database and the position and data from those bores was also verified directly in the field and from landholders where possible. Unless otherwise stated, only those bores with adequate construction information and reliable water level measurements were included in the assessment.

The available data indicates a potential for horizontal flow in the Clematis Sandstone (Triassic Scenario) from both the north, west and south converging on the Carmichael River in the vicinity of the springs. This indicates that this area is a zone of groundwater discharge. It also suggests that there may be a marginal head at Surprise and Yukunna Kumoo springs within the Clematis Sandstone (Figure 13). With the caveat of considerable uncertainty, the north-south profile suggests marginal to insufficient head in the Clematis Sandstone to provide artesian flow to the springs in the western area, including House, Joshua, Mouldy Crumpet, Stepping Stone, Moses, Geschlichen, Keelback and Camp Springs (Figure 13).

The bore HD02 (RN158092) is 32 m deep (Clematis Sandstone) and HD03 (RN158036) is 37m deep (Dunda Beds) (GHD, 2013a) and represent Triassic aquifers above the Rewan Formation. These bores are located adjacent to Dyllingo Creek-Carmichael River and do not penetrate the full thickness of the formations and only tap the upper most aquifer. Furthermore since there is vertical flow of groundwater towards the spring vents and to the Carmichael River, it is feasible that the potentiometric head for the basal aquifer in the Clematis Sandstone and for the Dunda Beds would be higher than the potentiometric head observed in the bores (in the vicinity of the springs) shown on Figure 13F. This would place the potentiometric pressure (head) above the natural surface of the springs.

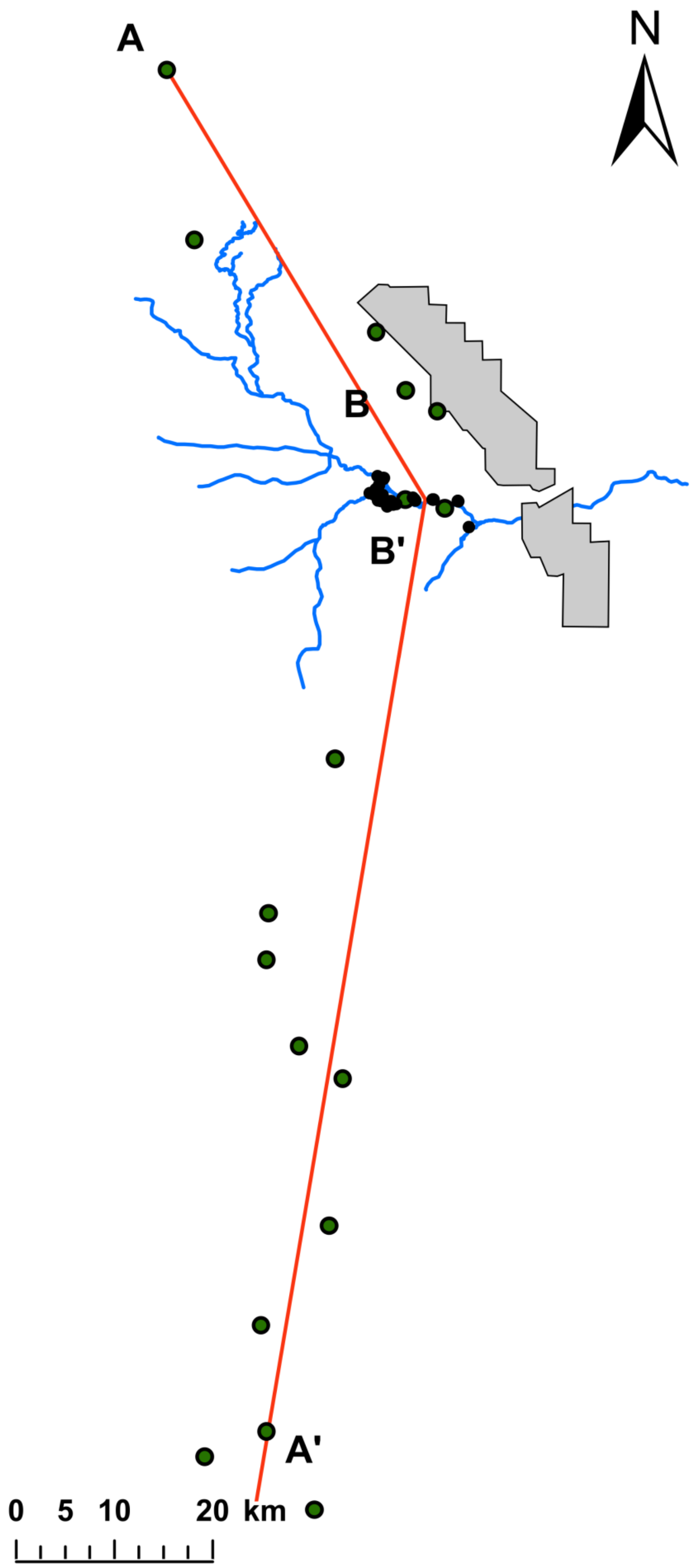

Figure 12: Location of the bores used to create the north-south stratigraphy (A-A') represented in Figure 13a and the fine-scale stratigraphy (B-B') represented in Figure 13b. Data was compiled by Ashley Bleakley (Department of Natural Resources and Mines) and where multiple water level records were available in some bores, an average water level was used. The black dots identify the location of the Doongmabulla Springs and the blue-line identifies the Carmichael River. The grey area identifies the location of the Carmichael Mine.

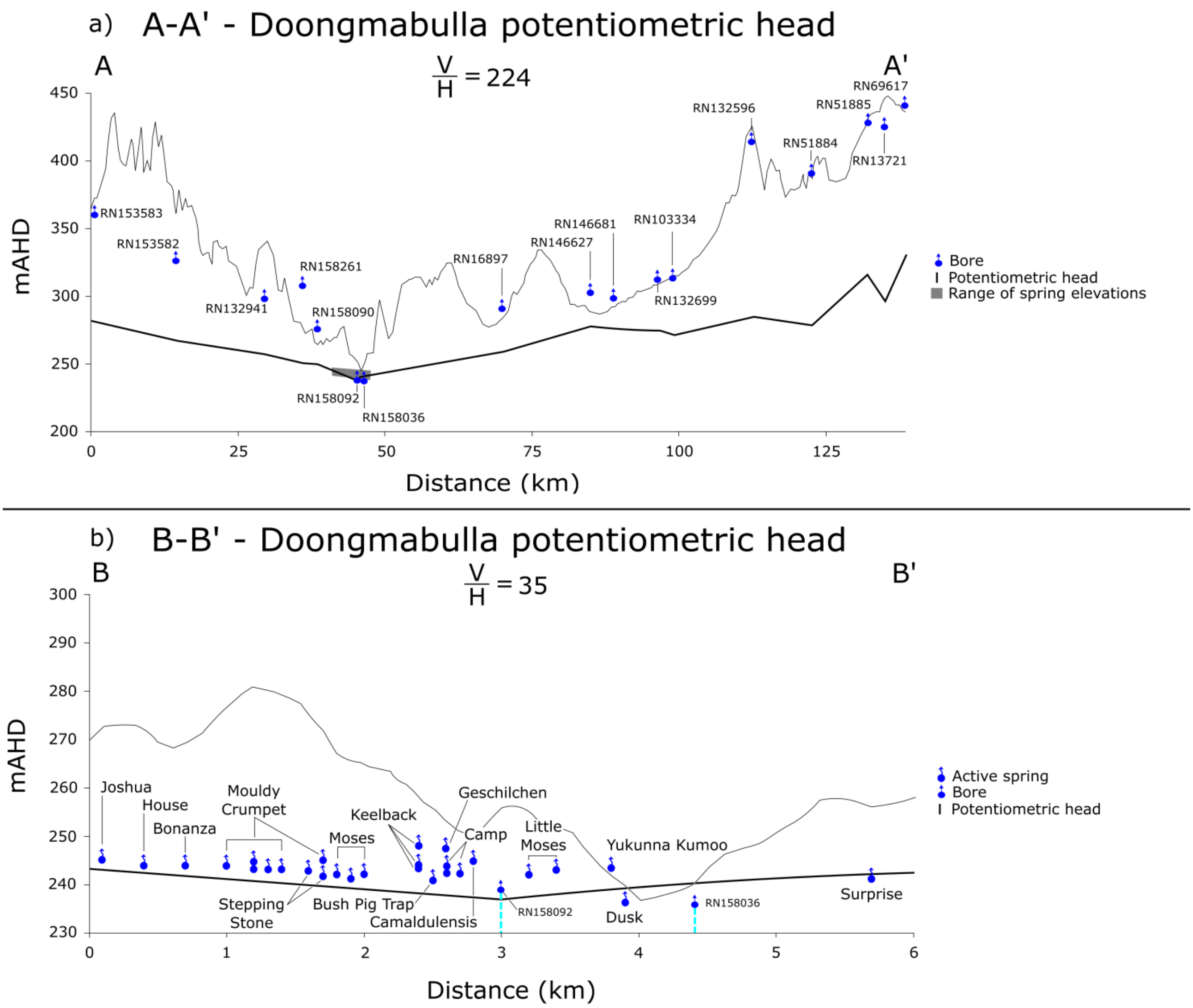

Figure 13. a) Ground surface (fine line) and potentiometric surface (coarse line) of the upper Triassic aquifer relative to the elevation of the springs at Doongmabulla. The position and elevation of the springs is identified by the grey box b) Fine-scale view of potentiometric surface in the vicinity of the springs. Elevations and standing water levels have been incorporated, so that the upper potentiometric head is represented relative to Digital Elevation Model employed here. Note the potentiometric head for the base of the Triassic aquifer may be several metres higher than the observed potentiometric surface of the upper aquifers.

Data from relevant bores (Figure 14a) were also compiled to assess the potentiometric groundwater surface in the Triassic sediments in the vicinity of the springs (Figure 14b) and to the north-west (Figure 14c), and south-west (Figure 14d) of the springs. Similar to the north to south sections, the data suggests the horizontal groundwater flow direction in the Clematis Sandstone is converging on the springs from the west, as well as the north and south. However, there are significant distances between the available data points. The potentiometric surface (Figure 14) suggests marginal to insufficient head to provide an artesian groundwater source to the springs from the Clematis Sandstone, but there is considerable uncertainty. As discussed above due to the shallow depth of HD02 and the potential for lowering of head in the vicinity of the springs, the potentiometric head for the base of the Triassic aquifer may be several metres higher than the observed potentiometric surface of the upper aquifers.

Additional local monitoring bores to the west, south or north of the springs would improve our understanding of the available pressure in the vicinity of these springs. A nest of deep bores to the base of each formation to the west of the springs would be a priority and the vicinity of -22.065, 146.218 is suggested.

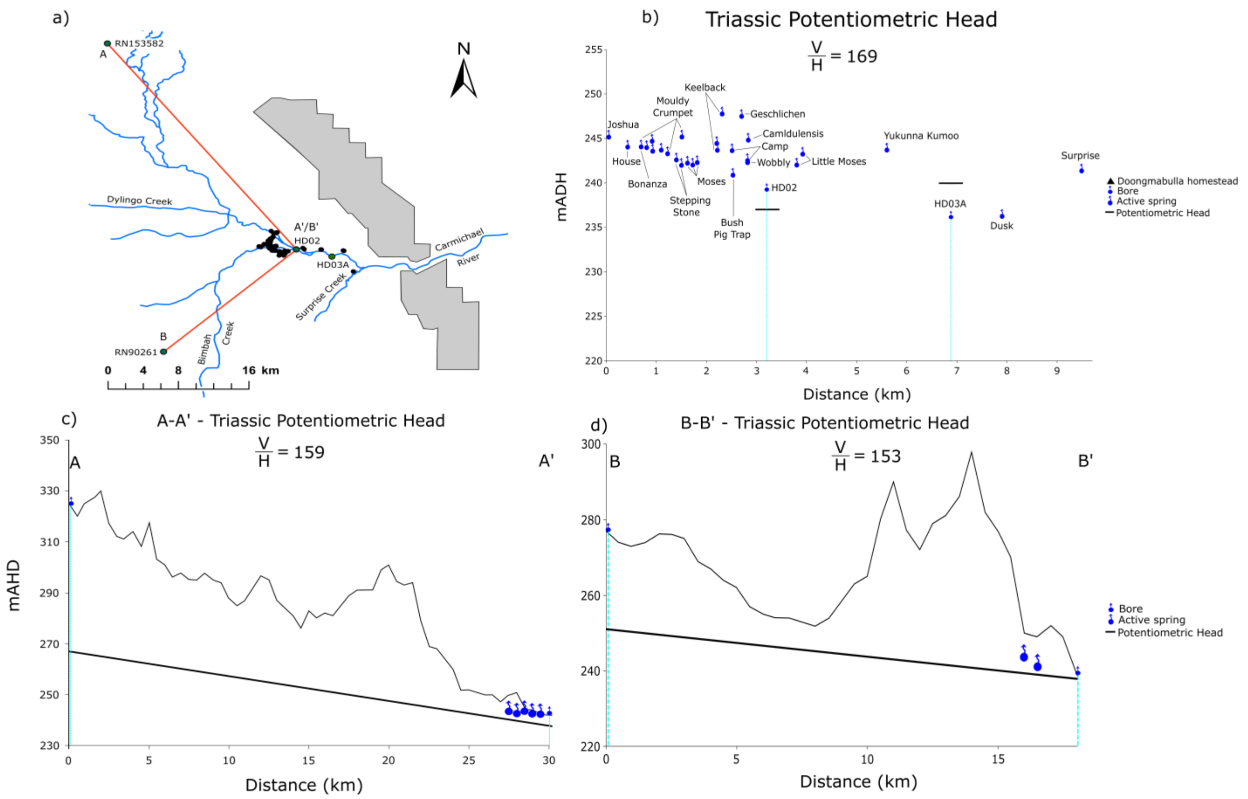

Figure 14. a) Location of the bores used to create the head profiles represented in b), c), and d); b) Potentiometric surface at HD02 (RN158092) and HD03 (RN158036) relative to the elevation of the springs at Doongmabulla; c) A-A' cross section of the inferred potentiometric surface in the Triassic Sandstone (attributed as Clematis Sandstone) and the elevation range of the springs along this cross-section; d) B-B' cross section of the inferred potentiometric surface in the Triassic Sandstone (attributed as Clematis Sandstone) and the elevation range of the springs along this cross-section. Elevations and standing water levels have been incorporated, so that the potentiometric head is represented relative to Digital Elevation Model employed here. Note the potentiometric head for the base of the Triassic aquifer may be higher than the potentiometric surface of the upper aquifers.

The potentiometric surface in the Permian Colinlea sandstone aquifer was compiled from the small number of available bores to provide an indication of the available pressure in the deeper sediments at this location. The interpretation suggests a horizontal flow direction in the Permian sequence from the west to east (Figure 15b) in addition to the main gradient with a south-north direction. A fine-scale view of this inferred surface (Figure 15c) suggests that the potentiometric surface in the Permian aquifer is slightly above the surface level of most of the Doongmabulla Springs except the Geschlichen, Camaldulensis, Yukunna Kumoo and Surprise Springs which have elevations above the inferred potentiometric surface. The band of potential head in the Permian aquifer at the left-hand side of Figure 15c results from two separate measures of head in the Shoemaker Bore with the uppermost measurement (590m depth) representing the higher measurement of head. The band of head at the right-hand side of Figure 15c results from differences in potentiometric head between bores. However, the inferred head in the Permian aquifer is marginal to insufficient. For the groundwater in this aquifer to rise through the aquitard of the Rewan Formation there would have to be exceptionally low resistance within the hypothetical fault/fracture.

A major source of imprecision is that the head in the Shoemaker Bore (Figure 15a) is inferred from two drill stem tests, an indirect measure of hydraulic head. There are also imprecision associated with determining hydraulic head at the site of the springs from the location of the bores informing the potentiometric surface (Figure 12; Figure 14, Figure 15a), and with the digital elevation model. The result is that all the inferred heads in both the Triassic and Permian aquifers can only be tentative. The possibility of reopening the Shoemaker bore to more accurately define the potentiometric surface in the Permian aquifer could be investigated.

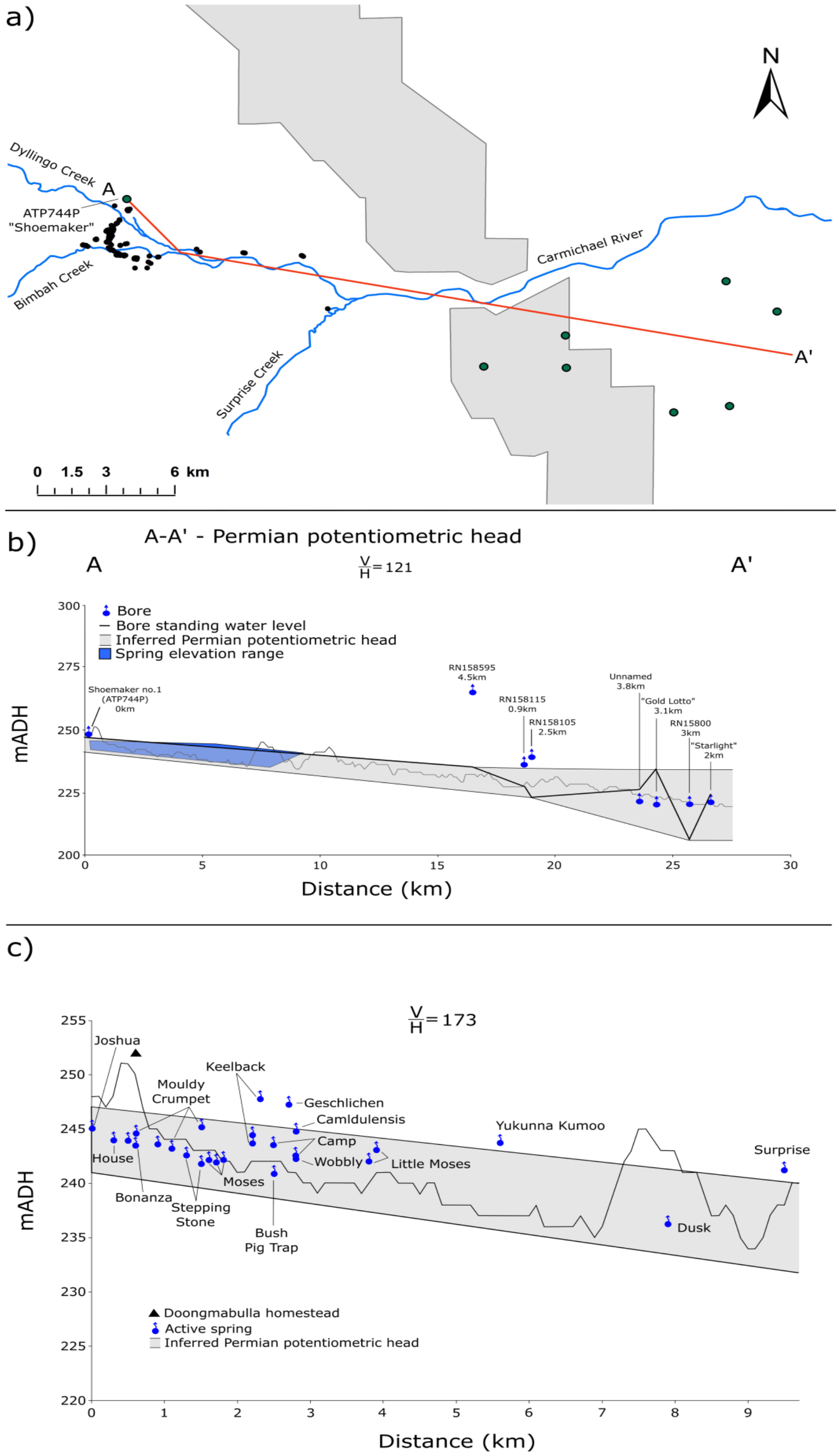

Figure 15. a) Location of springs (black dots) and the bores (green dots) used to create the potentiometric surface represented in b) and c); b) Inferred potentiometric surface (thick line) and topography (thin line) in an west-east cross section (A-A') of the Permian aquifer with bores identified (and the distance of their lateral displacement from the projection and the general position and elevation range of the springs (shaded blue); c) Close-up of the potentiometric head and the elevation of individual springs. The left hand end of the envelope of potentiometric head in the Permian aquifer on Figure 15c is a result of two pressure tests from the Shoemaker Bore with the uppermost head represented by a test from 590m and the lower from a test from 624 m deep.

While there is substantial uncertainty relating to the pressure surfaces in the Triassic and Permian aquifers, for the latter to provide a potential source for the springs, it is necessary to establish evidence of an open fracture or fault structure providing a conduit through the Rewan Formation. There has been some recent seismic survey in the vicinity of the Carmichael Mine 9km from the springs (Velseis, 2012) but there is no seismic data available in the vicinity of the springs. Thus no direct evidence of a fault structure in this location exists. Even if a fault should exist, the inferred head in the Permian aquifer may not be substantial enough to overcome the potential head loss.

The alignment of the western springs from Moses Spring in the south, arcing north through Stepping Stone and Mouldy Crumpet Springs, and then through Bonanza and House Springs (Figure 1) may be indicative of a structure potentially providing a conduit for vertical discharge. This would be consistent with the discharge character of these springs, including vertical conduits feeding discrete mounded vents (Figure 1; Figure 3). Fracturing in the vicinity of the Doongmabulla Springs could be the result of uplift to the west of the springs, and such a process has been invoked to explain the marked headward erosion of Dyllingo Creek (Figure 15) (Vine and Doutch, 1972).

A closed fault with displacement up to 100 m at the centre was recently identified from stratigraphic monitoring bores described in the Environmental Impact Assessment of the proposed China Stone coal mine (AGE, 2015) to the north of the Doongmabulla Springs (Figure 16). The fault is 30km from the Doongmabulla Springs, aligns with them, but its closure in the south is well-informed by stratigraphic information. It is possible that the geological forces creating the fault at China Stone had impacts elsewhere.

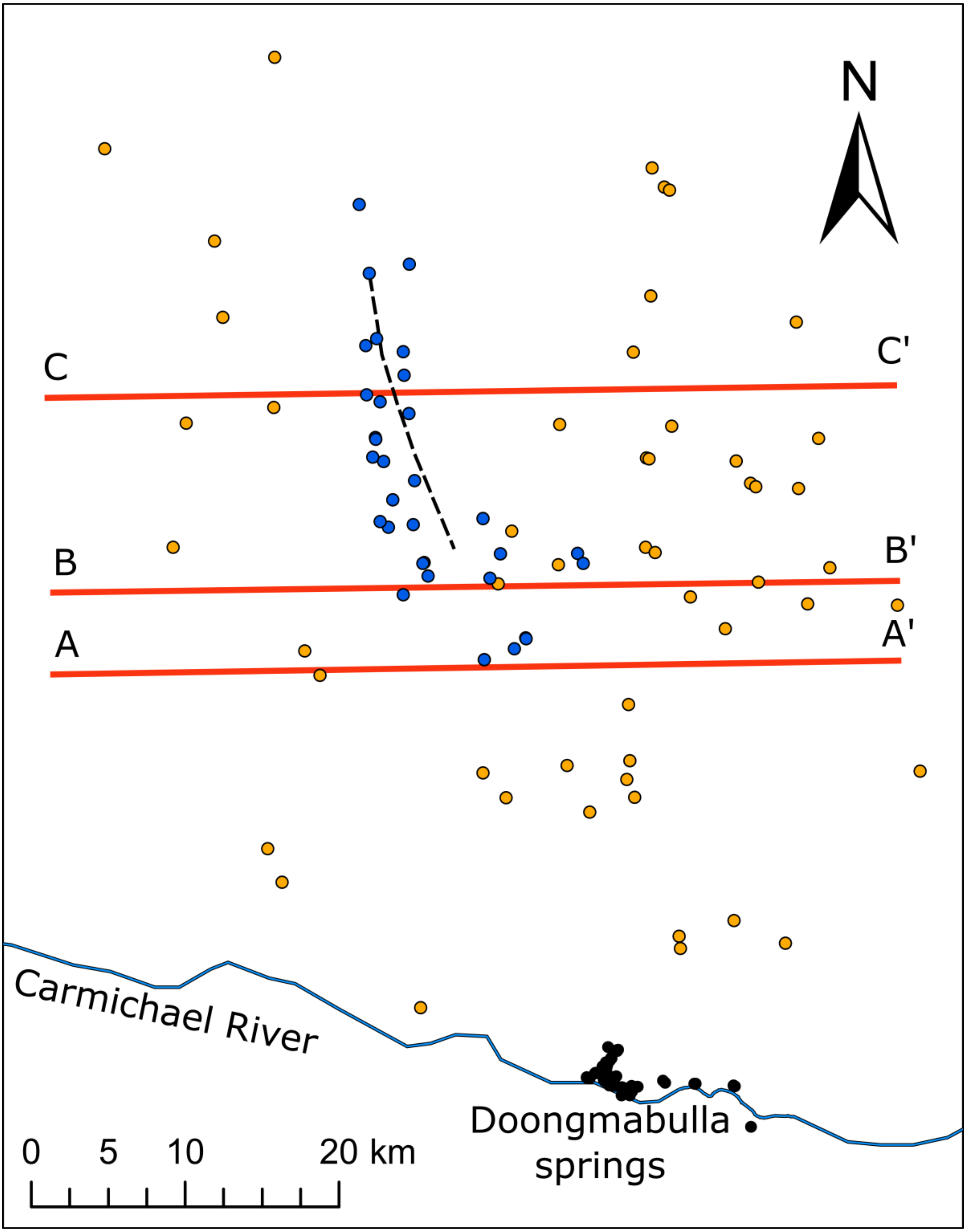

Figure 16. Fault structure at site of proposed China Stone mine (dashed line) with Doongmabulla Springs to the south. Stratigraphies informed by monitoring bores (blue dots) are also identified. While the information is not provided some pastoral bores (orange dots) may also have been included in the interpretation.

A local survey using high-resolution seismic reflection is an appropriate technique to reveal structural weakness within the Rewan Formation down to depths of about 500m (Steve Hearn pers. comm.). Such a survey should be conducted in the vicinity of the Mouldy Crumpet Springs where the location of the vents is suggestive of linear alignments (Figure 1) and there is excellent access for seismic equipment.

Analysis of isotopic signatures can be useful for determining source origins of aquifers. One of the tracers commonly applied is the $^{87}Sr/^{86}Sr$ ratios. Strontium ^{87}Sr is radiogenic; it is produced by decay from the radioactive alkali metal ^{87}Rb, which has a half-life of 4.88×10^{10} years. Thus, there are two sources of ^{87}Sr in any material: primordial that formed during nucleosynthesis along with other Sr isotopes, as well as that formed by radioactive decay of ^{87}Rb. The ratio $^{87}Sr/^{86}Sr$ is the parameter typically reported in geologic investigations and is partly controlled by water-rock interactions. Preliminary results of strontium signatures from bores and springs in the vicinity of the Doongmabulla and Mellaluka Springs are not conclusive. There is considerable overlap in the radiogenic signatures from confirmed Permian and Triassic sources making it difficult to attribute the springs at Doongmabulla to aquifers of either origin.

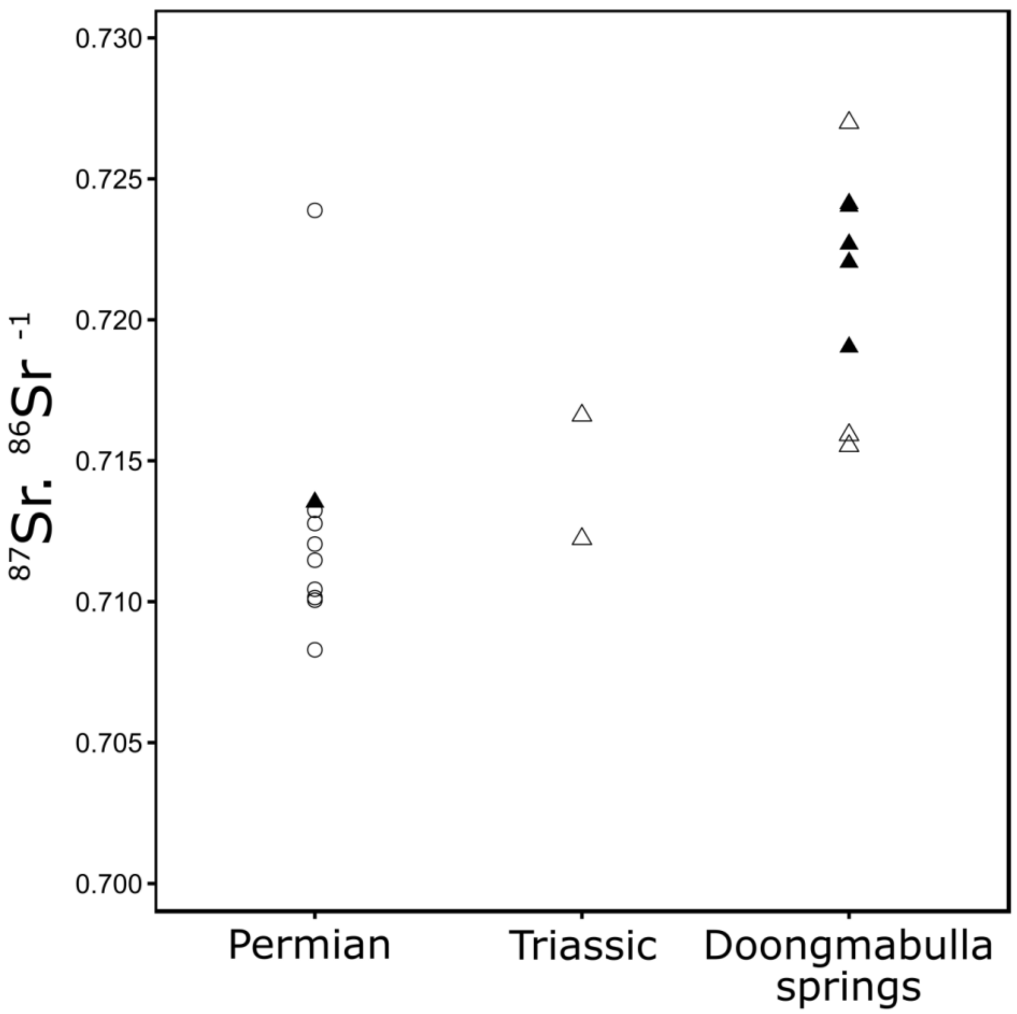

Figure 17. Strontium isotope signatures from bores and springs in the vicinity of Mellaluka and Doongmabulla. Circles are bores, triangles are springs with filled symbols representing springs with a discharge character; and open symbols represent springs with a recharge character.

Biological values

Doongmabulla Springs are a large spring group providing habitat for many endemic species and great diversity of wetland vegetation types. They occur in a sub-humid environment (mean annual rainfall is about 516 mm) and are situated adjacent to the Carmichael River which flows into the Belyando River which then joins the Burdekin River that flows to the east coast near Ayr. The environmental setting contrasts with most of the other springs in the Great Artesian Basin which occur in the internal drainage of the Lake Eyre Basin in more arid environments. They represent a large complex of wetlands with many individual vents feeding about 160 wetlands varying in size from small clumps of wetland vegetation fed by miniscule discharge to a spring wetland of about 8.7 ha in size. A unique feature of the Doongmabulla Springs is the diversity of forms and vegetation types, with various levels of endemism.

The wetlands at Moses, Keelback, Geshlichen, Camp, Stepping Stone and Mouldy Crumpet Springs provide habitat for many spring wetland endemics and the sedge that characterises discharge springs elsewhere *Cyperus laevigatus*. Spring endemics include *Eriocaulon carsonii, Chloris* sp. (Edgbaston RJ Fensham 5694), *Eriocaulon carsonii*, *Eryngium fontanum*, *Hydrocotyle dipleura*, *Myriophyllum artesium*, *Panicum* sp. (Doongmabulla RJ Fensham 6555), *Sporobolus pamelae* and *Utricularia fenshamii. Panicum* sp. (Doongmabulla RJ Fensham 6555) is only known from one spring in the Mouldy Crumpet spring group, but was chewed down by cattle when it was recently discovered and may be more widespread. The macro-algae *Nitella tumida* occurs in the wetland of Moses Spring, and is previously only known from the type specimen collected by A.T. Vogan in 1889 from the Mulligan River where it was probably associated with the permanent springs in this vicinity. Non-endemics also occur in the spring wetlands with high concentrations of endemics including *Baumea rubiginosa, Eleocharis equisetina, Ischaemum australe, Leersia hexandra* and *Phragmites australis* which can be dominant in local areas. *Melaleuca leucadendra* forms dense forest thicket around the head of the main vents feeding Keelback Springs (Figure 18). *Myriophyllum artesium* occurs in the wetlands fed by the outflow pipe of Joshua Springs. *Fimbristylis blakei* is a spring wetland endemic typically found on outcrop springs in northern areas and also occurs at Joshua Springs. There are populations of the introduced ponded pasture grasses *Hymenachne amplexicaule* and *Echinochloa polystachyus* that has established on the outflow channel of Joshua Spring.

Figure 18. Keelback Spring with a dense thicket of *Melaleuca leucadendra* around the vent, Small vents in the foreground are rich in endemic species.

In the scalded areas around the Moses and Mouldy Crumpet Springs are other 'scald endemics' including *Trianthema* sp. (Coorabulka R.W. Purdie 1404), *Sporobolus partimpatens, Sclerolaena "dioceia"* and *Dissocarpus* sp. (Doongmabulla E.J. Thompson+GAL21). *Dactyloctenium buchananensis* and *Sphaeromorphaea major* are also very restricted species that occur in these scalded areas. There are some scalded areas around the House Springs and Camp Springs but *Trianthema* sp. (Coorabulka R.W. Purdie 1404) is the only scald endemic occurring in these areas.

Little Moses spring has a diverse assemblage of wetland species but none of the endemic species known from the Moses and Mouldy Crumpet spring groups. *Baumea rubiginosa, Eleocharis equisetina* and *Fimbristylis blakei* are typical dominants. The populations of this species at Doongmabulla are outlying southern populations. The spring wetlands of the Dusk, Yukunna Kumoo, and Surprise springs do not have any endemic species. The wetland of Yukunna Kumoo Spring is shaded under a canopy of *Eucalyptus camaldulensis and Melaleuca fluviatilis* with scattered individuals of the palm *Livistona lanuginosa* (listed as Vulnerable under the Nature Conservation Act 1992) (Figure 19).

Figure 19. Yukunna Kumoo spring wetland.

There are no confirmed spring endemics amongst the invertebrate community at Doongmabulla, although the taxonomic status of the fauna assemblage is incomplete. The molluscs, particularly those in the family Hydrobiidae, are often represented by endemic species in spring wetlands. At Doongmabulla there are no Hydrobiidae, although other families, Bythiniidae (*Gabbia fontana*) and Planorbidae (*Glyptophysa* sp. and *Gyraulus* sp.) are represented. A species of aquatic mite (*Mamersella* sp. AMS KS85341) is of unknown endemic status.

Because of the diversity of wetland vegetation, the Doongmabulla Springs is an ideal location to examine spring processes and chemistry as determinants of the biological community and the habitat conditions required for spring endemics.

An ordination of the wetland species was conducted using individual wetlands as the sampling unit to assess variations in the composition of the flora with water pH and conductivity (at the vent). The NMDS ordination separates sites in two-dimensional space such that the distance between sites best approximates their floristic similarity. Site pairs with very similar species composition will be represented near each other in the ordination space and sites with few species in common will be distant. The first axis of the ordination seems to be related to floristic diversity with diverse but non-endemic assemblages at one end and small springs with low species richness at the other (Figure 20). The second axis of the ordination is related to the proportion of species always associated with discharge springs (*Chloris* sp. (Edgbaston R.J.Fensham 5694), *Cyperus laevigatus, Eriocaulon carsonii, Eryngium fontanum*, *Fimbristylis ferruginea*, *Hydrocotyle dipleura*, *Myriophyllum artesium*, *Sporobolus pamelae, Utricularia fenshamii*). The vectors for water pH and conductivity at the discharge vent are non-significant through the ordination space, which suggests that these are not important determinants of the plant species composition over the wetland as a whole.

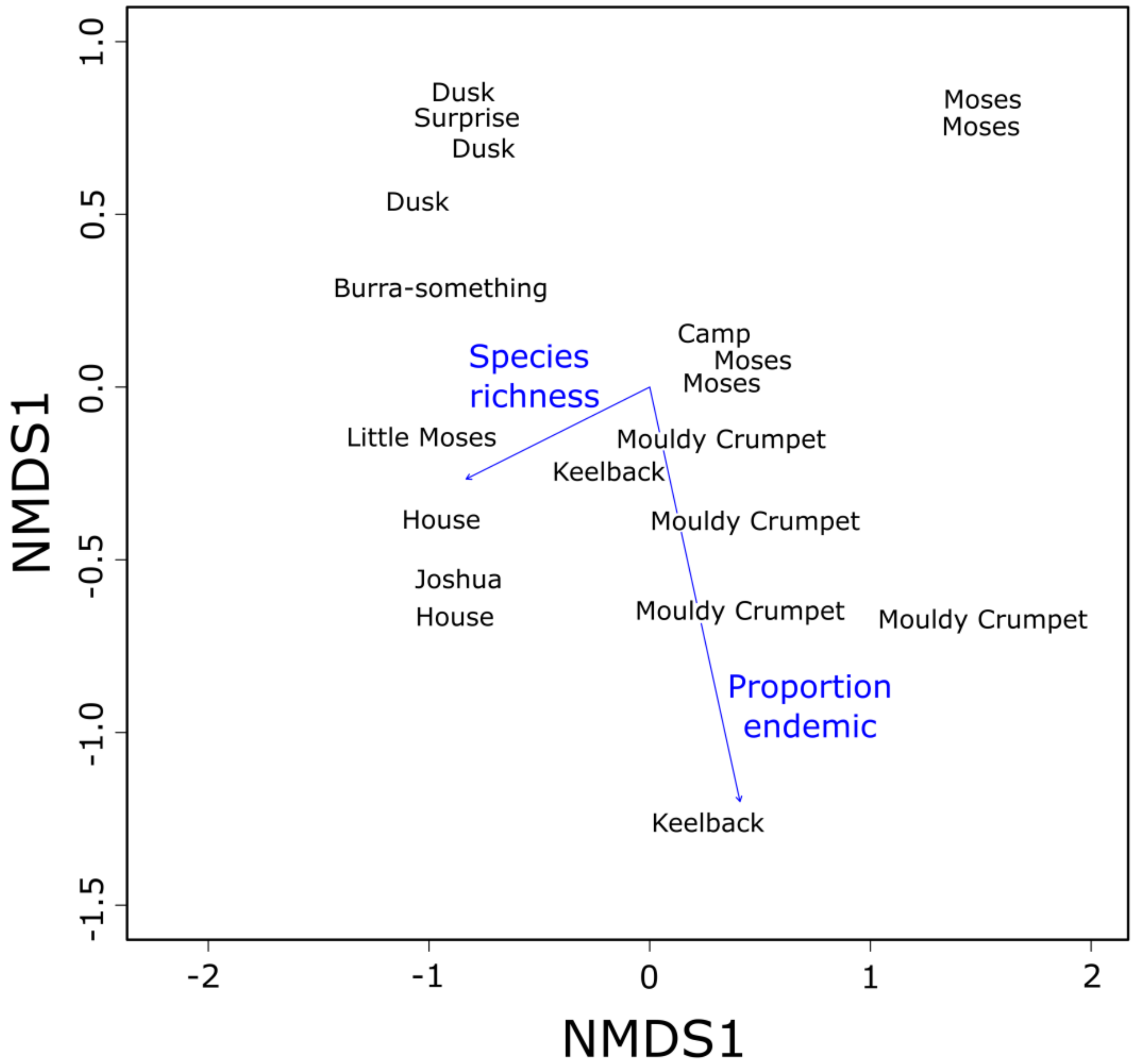

Figure 20. Non-metric multidimensional scaling ordination of wetlands of Doongmabulla Springs. Vectors providing the optimal direction of species richness and the proportion of endemics are also presented and labelled in blue.

Another preliminary analysis was conducted to examine these relationships at a finer scale. One m^2 quadrats were laid down throughout the wetlands of Camp, Geschlichen, Keelback and Moses Spring and all species were recorded. The water pH and conductivity was determined from the centre of these plots. An endemicity index was calculated based on the number of the 'discharge endemics' divided by the total number of species in the quadrat. There was no relationship between this endemism score and conductivity, but there was a weak relationship between endemism and alkalinity (Figure 21). This result suggests that the habitat conditions that suit the endemic species are partly a result of chemical changes that occur to spring water after leaving the vent. Alkalinity generally increases in the tails of springs with the degassing of carbonic acid, held in solution in groundwater, which converts to carbon dioxide under atmospheric conditions (Keppel et al., 2011). More work is required to understand the nature of chemical patterns in the spring environment and the habitat characteristics that favour the species endemic to discharge spring wetlands.

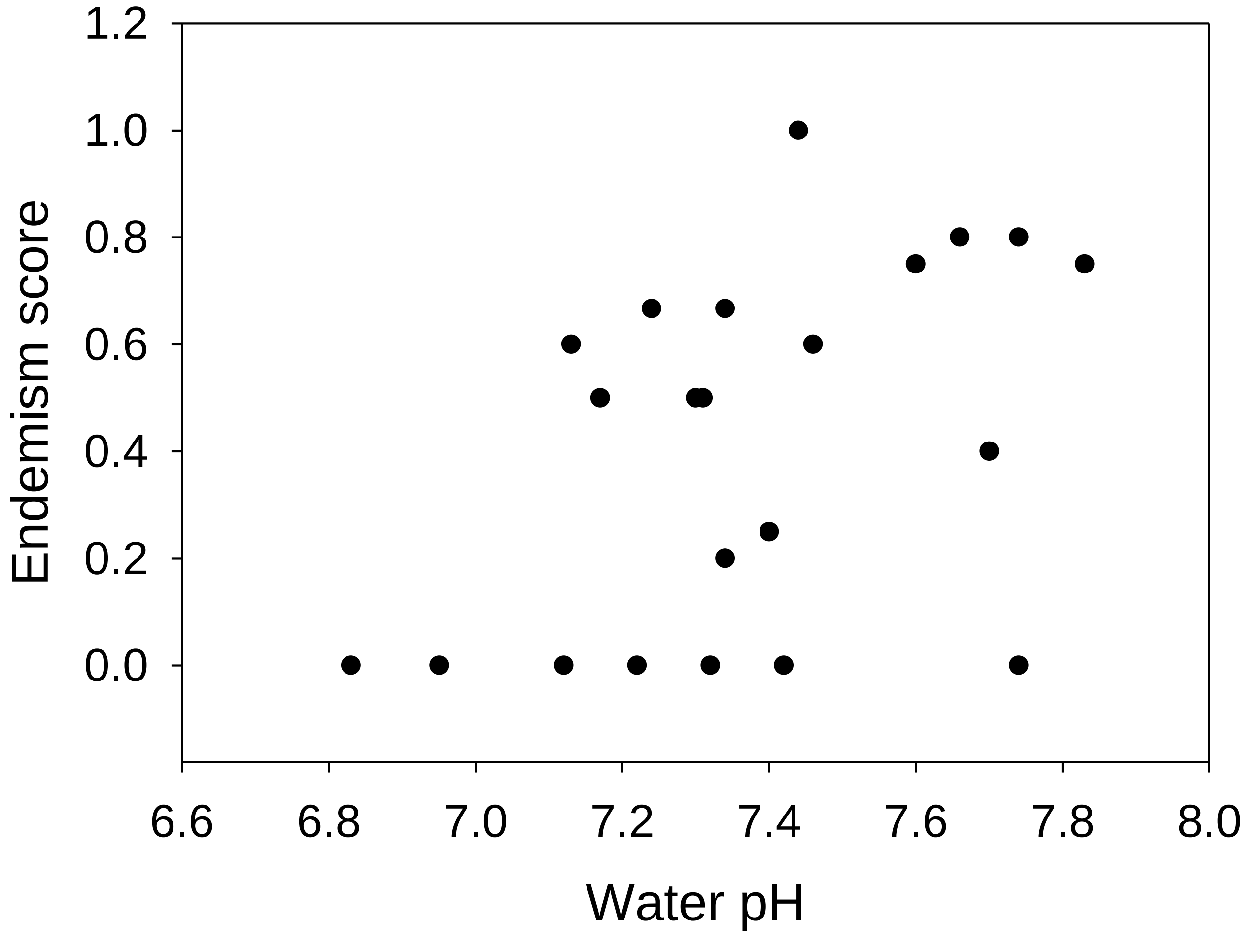

Figure 21. Preliminary results suggesting a positive relationship between water pH and endemicity in Camp, Moses and Keelback Springs (Spearman's Rank Correlation rho = 0.48, *P* = 0.024).

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