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PAPER

Hydrogeological implications of active tectonics in the Great Artesian Basin, Australia

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Abstract
Derangement of surface drainage systems across central and eastern Australia testify to subtle tectonic modification of the landscape on the million-year timescale that is relevant to groundwater residence in the Great Artesian Basin (GAB). In the central part of the overlying Lake Eyre Basin, spatial variations in drainage channel form, and lateral offsets in drainage channels, reflect an active north to northwest-trending fault system that correlates with a distinct potentiometric anomaly in the deeper GAB aquifers. There are correlations in both the distribution of seismic activity and drainage form with changes in lithospheric thickness. This suggests that active faulting reflects, in part, stress sourced from sublithospheric mantle flow beneath the GAB. These observations have implications for hydrogeological interpretations and the understanding of groundwater processes, while also providing constraints on water balance studies and studies on the distribution of pressure within GAB aquifers.

Keywords Tectonics · Australia · Earthquake · Groundwater flow

Introduction

With an aerial extent that covers some 22% of the Australian continent (~1.7 million km^2), and a characteristic groundwater residence time in the order of 10^6 years (Habermehl 1980, 2019; Mahara et al. 2009), the Great Artesian Basin (GAB) in central east Australia forms one of the world's iconic groundwater systems. Its origins are intimately tied to tectonic processes that formed the Eromanga Basin in the hinterland of the convergent proto-Pacific margin of the Gondwanan supercontinent in the Mesozoic (Ransley et al. 2012a).

Since cessation of proto-Pacific subduction along the east Gondwana margin, and the associated rifting of Australia from Antarctica in the Late Cretaceous, the Australian continent has experienced relatively low levels of tectonic activity (Sandiford 2003). However, there is growing appreciation of the dynamic nature of the Australian plate (Sandiford 2003, 2007; Braun et al. 2009; Quigley et al. 2010) and the widespread distribution of neotectonic features that can be related to evolving plate margin activity as well as interactions with the sublithospheric mantle (Sandiford and Quigley 2009). There is an emerging recognition that even the relatively mild tectonism experienced in the Neogene through to the present day can have important implications for the evolution of surface drainage and groundwater systems (Radke et al. 2000; Kernich et al. 2009; Smerdon et al. 2012; Lawrie et al. 2012; Smerdon and Turnadge 2015).

Several previous studies have noted that intraplate tectonism has impacted on GAB hydrogeology (e.g., Radke et al. 2000; Smerdon et al. 2012; Kellett et al. 2012; Turnadge et al. 2014; Smerdon and Turnadge 2015). Harrington (2014, p. 189) noted "Anomalous decreases in potentiometric pressure that are coincident with major faults have been observed in the northeast of the Eromanga Basin" and "significant tectonic disruption of the Eromanga Basin has compromised the sealing capacity of what were traditionally viewed as confining beds in many parts of the Basin". Kellett et al. (2012) demonstrated material impact of active faulting between Innamincka (27°45′ S, 140°44′ E) and Tibooburra (29°26′ S, 142°00′ E) on shallow subartesian aquifers, and speculated that the faulting may have facilitated hydraulic connectivity between deeper artesian and

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shallower subartesian aquifers beneath the Innamincka Dome. Smerdon and Turnadge (2015) argued that fault-related compartmentalisation is critical to understanding the distribution of recorded changes in artesian aquifer pressure, evidenced by historical borehole records. Smerdon et al. (2012) provide several additional specific examples, whereas Love et al. (2013) succinctly captured the critical importance of this knowledge gap in opening their final recommendations (p. 207): “Future research should concentrate on studying all groundwater that can make a contribution to the GAB, including the important role of vertical connection via faults”. However, detail on how ongoing tectonic activity impacts large-scale hydrogeology of the GAB remains scant.

This paper explores a specific example where tectonic landforms associated with faulting correlate spatially with changes in the inferred pattern of groundwater flow in key GAB aquifers in ways that provide strong prima facie evidence for a causal connection. The paper summarises key data sources that inform this study and provides some further context for this research. There are descriptions of the key attributes of the groundwater systems associated with the Cadna-owie and Hooray formations, which together comprise one of the primary GAB aquifers (Habermehl 1980, 2019), and it includes a summary of the groundwater flow pattern inferred from the distribution of potentiometric head and artesian pressure. Later sections of the paper outline attributes of the surface landscape in the corresponding part of the Lake Eyre Basin (e.g. Callen et al. 1995) that testify to ongoing drainage derangement associated with localised tectonic doming, from which a deeper, active fault system can be inferred. This extends the observations of Kellett et al. (2012) and Jansen et al. (2013) showing that the spatial form of channel derangement indicates an active fault system with displacement in the order of 100 m, likely accrued over a period of order 1 million years, extending north-northwest from Innamincka towards Birdsville (25°54′ S, 139°21′ E). In the ‘Discussion’ section, a conceptual model is developed in which fault-related occlusion in the deep artesian aquifers impacts the pressure field. Finally, the paper alludes to the complex interplay of tectonic processes expressed in the landscape and provides some speculative comments as to how they may have contributed to the modern form and temporal variability in the GAB aquifer systems. The motivation of this study is to help bridge the knowledge gap identified by Love et al. (2013) and, in so doing, strengthen the case established by Kellett et al. (2012), Smerdon et al. (2012) and Smerdon and Turnadge (2015), that understanding the link between deformation, surface landscapes and hydrology and basin hydrogeology is critical to understanding the detailed hydrodynamics and therefore aid management of the GAB.

Data sources

A number of open source datasets were used to develop the arguments presented here. Surface drainage catchments and channel networks are derived from the Geofabric Version 2 products (Bureau of Meteorology 2017), while aquifer, groundwater and potentiometric data are derived from the GAB Atlas digital datasets (Ransley et al. 2015; Geoscience Australia 2015) and wurface elevation data are from the Geoscience Australia’s (2009) Australian Bathymetry and Topography Grid and the SRTM shuttle radar mission’s 3-arcsecond grids. Lithospheric thickness data were provided by Nick Rawlinson (University of Cambridge, personal communication, 2017; see Rawlinson et al. 2017 for methods), whereas earthquake data were provided by Gary Gibson (University of Melbourne, personal communication, 2019; see Attanayake et al. 2019 for details). The GAB spring location data were provided by Mark Keppel (Department for Environment and Water, South Australian Government, personal communication, 2019) derived in part from Habermehl (1982).

A caveat applies to the gridded potentiometric datasets derived from borehole observations that are unevenly distributed across the GAB. Such gridding inevitably results in some smoothing with consequent loss of fine detail at local scales, especially in areas of steep gradients and sparse primary borehole data—see Ransley et al. (2015) and Geoscience Australia (2015) for the methods and uncertainties associated with their gridding interpolations. As such, subtle details of local fault-related compartmentalisation—as revealed, for example, by Smerdon and Turnadge (2015)—are excluded in this study which instead focuses on the hydrogeological impacts of active tectonics at the regional scale. Figure 1 illustrates the location of the GAB and the Lake Eyre Basin (LEB), in the broader Australian context., whereas Figs. 2, 3 and 4 detail relevant geophysical features as well as key geographic localities. All figures have been processed using the primary data sources in ‘R’ (R Core Team 2019). Scripts and summary data are available on request.

Background

Ongoing tectonic influences on the Australian Plate occur at a range of scales (Sandiford 2007; Quigley et al. 2010; Lawrie et al. 2012). At long wavelengths (>10^3 km), dynamic topographic effects induced by the northward motion of the Indo-Australian plate have contributed to tilting of the continent (Sandiford 2007) and regional landscape warping (Celerier et al. 2005; Czarnota et al. 2013) that has produced a relatively small topographic range and low hydraulic gradients. This has resulted in slow-moving regional groundwater flow systems in sedimentary basins such as the GAB. At intermediate (10^2–

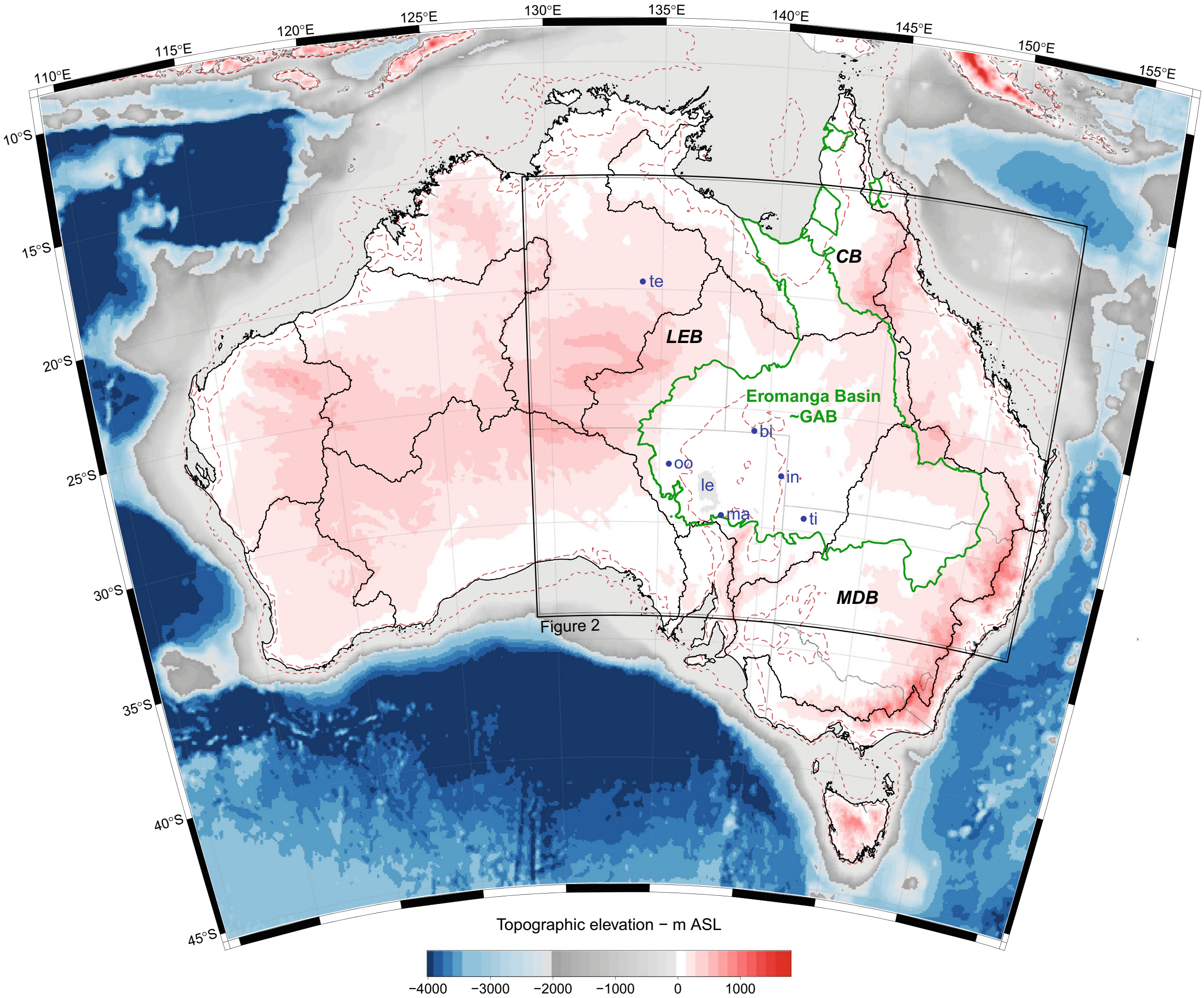

Fig. 1 Topographic elevation map of Australia, showing regional setting of the Great Artesian Basin. Key surface catchment systems in heavy black lines: LEB Lake Eyre Basin, MDB Murray Darling Basin, and CB Carpentaria Basin. GAB Great Artesian Basin. Towns: bi Birdsville, in Innamincka, ma Marree, oo Oodnadatta, te Tennant Creek, ti Tibooburra. Lakes: le Lake Eyre. The green line bounds the mapped distribution of the Cadna-owie Formation and equivalents within the Eromanga Basin, which forms one of the main aquifers in the GAB. Topographic elevation contours at ±50 m above sea level (ASL) are shown as dashed red lines

10^3 km) wavelengths, regional dynamic topography effects have played a significant role in the development of major drainage basins, valleys and river morphology. Regional tilting has important consequences for the development of regional- to intermediate-scale groundwater flow systems. At short wavelengths ($<10^2$ km), active deformation is manifested by the development of discrete intra-plate fault systems that modify local landscapes and often control and modify the surface drainage network, as represented by both modern and palaeo-river features (Sandiford 2003; Kernich et al. 2009; Hillis et al. 2008; Clark et al. 2008; Lawrie et al. 2012; Moya et al. 2014). This in turn can influence the configuration and evolution of fluvial depositional and erosional processes, and surface-water/groundwater interaction (Kernich et al. 2009; Lawrie et al. 2012). At basin to local scales, mapped fault systems and associated tectonic ridges are often localised by reactivation of crustal-scale faults and/or are localised at zones of crustal heterogeneity (Lawrie et al. 2012; Flottman et al. 2013).

When, why and how fault systems influence hydraulic connectivity is dependent on many factors, including their geometric relationship to the prevailing in-situ stress field. For example, spatial and temporal changes in stress regimes, either in magnitude or orientation, impact the sealing potential of faults. Because active fault systems are necessarily required to relate to the prevailing stress fields in specific ways, they provide unique opportunities to explore the diversity of fault-related groundwater

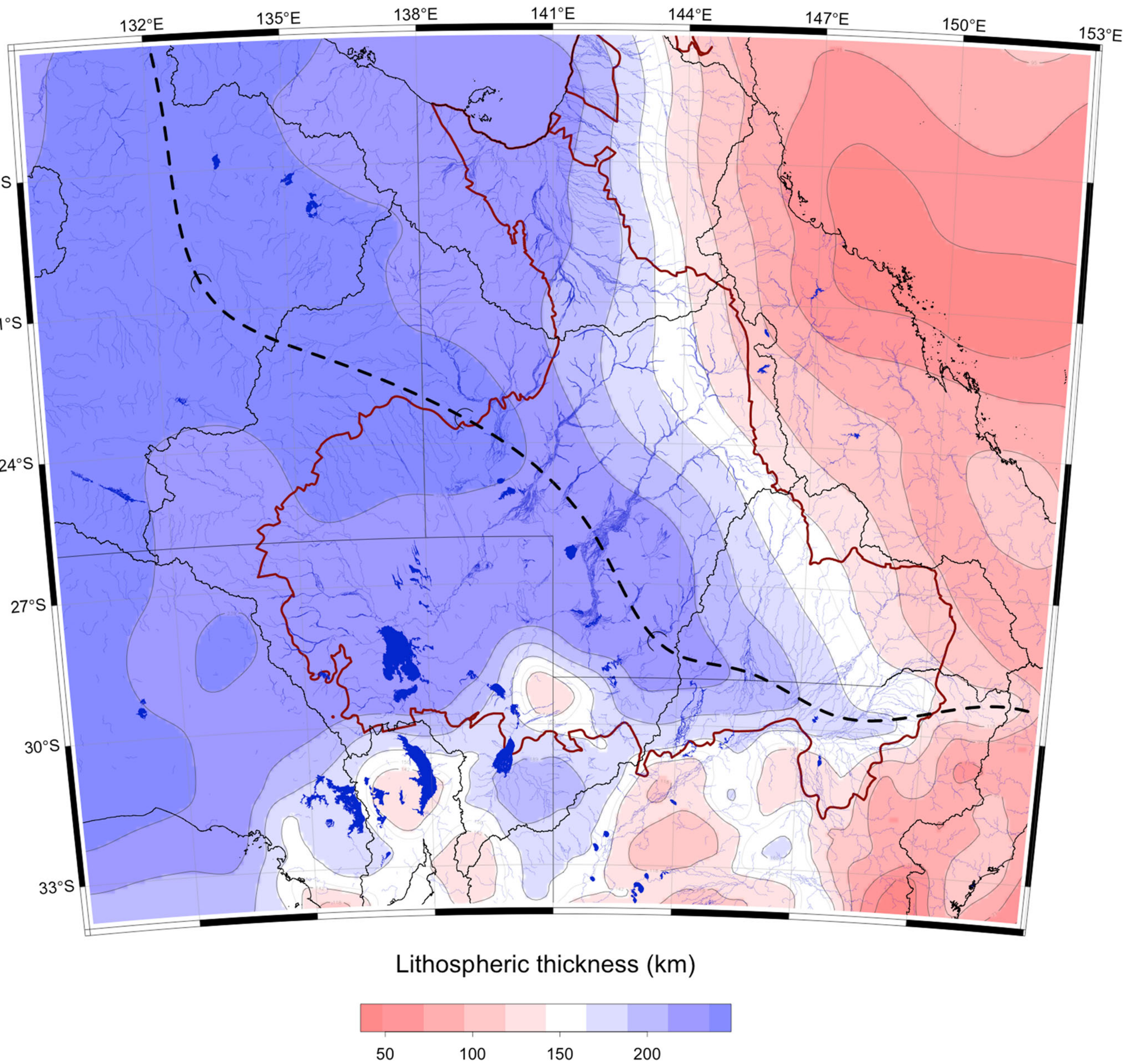

Fig. 2 Distribution of lithospheric thickness (Rawlinson et al. 2017); see Fig. 1 for location. Outlines of Eromanga Basin-GAB (red line), surface catchments (black line), drainages (blue line), and axis of lithospheric keel (dashed black line)

impacts. In eastern Australia, forces generated at plate boundaries remain the major control on the regional crustal stress patterns; however, local perturbations of the stress field commonly related to intra-plate fault systems cause substantial local-scale stress-field rotations and vertical interplay between geomechanical components which ultimately control hydraulic permeability distribution (Flottman et al. 2013; Brooke-Barnett et al. 2015; Rajabi et al. 2015).

Tectonics within the GAB includes both active and inactive systems (Radke et al. 2000; Smerdon et al. 2012; Love et al. 2012; Smerdon and Turnadge 2015), and has produced considerable stress and strain heterogeneity, in both space and time (Smerdon et al. 2012; Love et al. 2012; Flottman et al. 2013; Harrington et al. 2013; Brooke-Barnett et al. 2015). Deformation of the GAB is primarily manifested as intra-plate fault systems (fault and associated fracture networks and/or discrete fault structures) and/or by fault-related folds (buried features or surface topographic ridges and domes).

The mechanisms by which faults may impact GAB hydrogeological systems include: (1) enhanced exchange of water (and dual phase flow) between aquifers (Smerdon et al. 2012; Love et al. 2012), including increased inter-aquifer leakage through aquifer juxtaposition and potential discharge to the surface including baseflow and gas

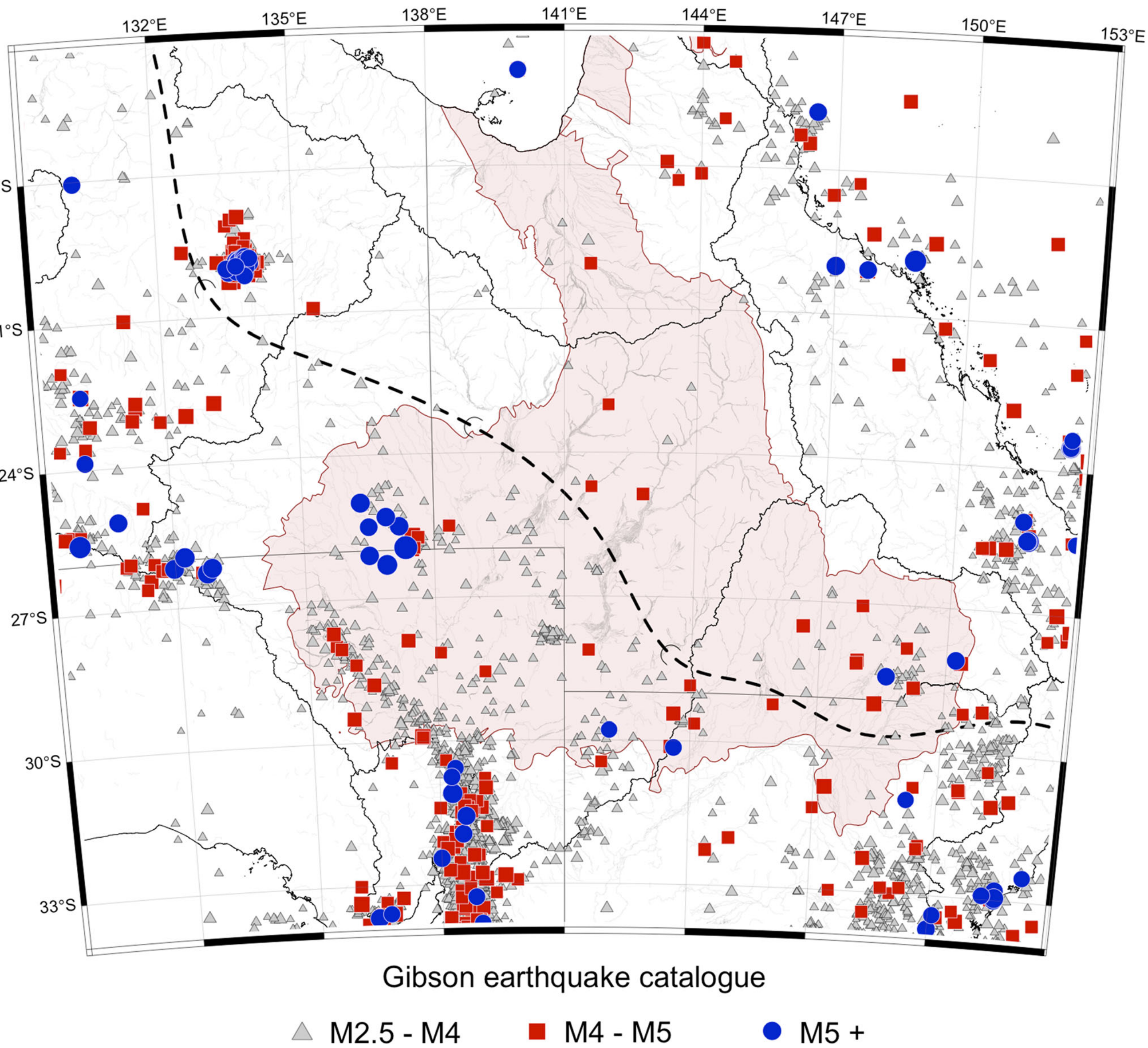

Fig. 3 Earthquakes epicentres (Gary Gibson Catalogue). Outlines of Eromanga Basin-GAB (red line and red shade), surface catchments (black line), drainages (grey line), and axis of lithospheric keel (dashed black line, see Fig. 2). M refers to the local magnitude scale. Events of M > 2.5 are depicted, with ornament shape, colour and size scaled for magnitude. Grey triangles: M2.5–M4, red squares: M4–M5, blue circles: M5 +

seepage into rivers (Smerdon et al. 2012; Moya et al. 2014); (2) ingress of fluid sourced from reservoirs much deeper in the crust and/or mantle (e.g. Torgersen et al. 1992; Love et al. 2012; Turnadge et al. 2014); and (3) impedance of lateral flow, resulting in aquifer and aquitard compartmentalisation and the creation of semi-isolated compartments where lateral groundwater flow may be diminished or absent (Radke et al. 2000; Smerdon et al. 2012; Smerdon and Turnage 2015). In addition, because intraplate tectonism has the potential to tilt the hydrostratigraphy at a range of scales (e.g. Sandiford and Quigley 2009), it may modify groundwater hydraulic gradients and groundwater flow paths through time.

Active faulting in the GAB is most clearly evident along the southwest margin, where enhanced seismicity is associated with the Norwest fault system that extends between Marree (29°39′ S, 138°04′ E) and Oodnadatta (27°33′ S, 135°27′ E, Fig. 1, Alley 1998). The Norwest fault is inferred to play an important role in localising discharge to the environmentally significant mound springs in one of the principal GAB discharge zones that borders Lake Eyre (Habermehl 1982; Costelloe et al. 2008; Crossey et al. 2012). While several significant historic earthquakes have been recorded elsewhere in the internal parts of the GAB (Fig. 3), most notably in the Simpson Desert to the west of Birdsville (25°54′ S, 139°21′ E, Fig. 3), the general level of recorded seismic

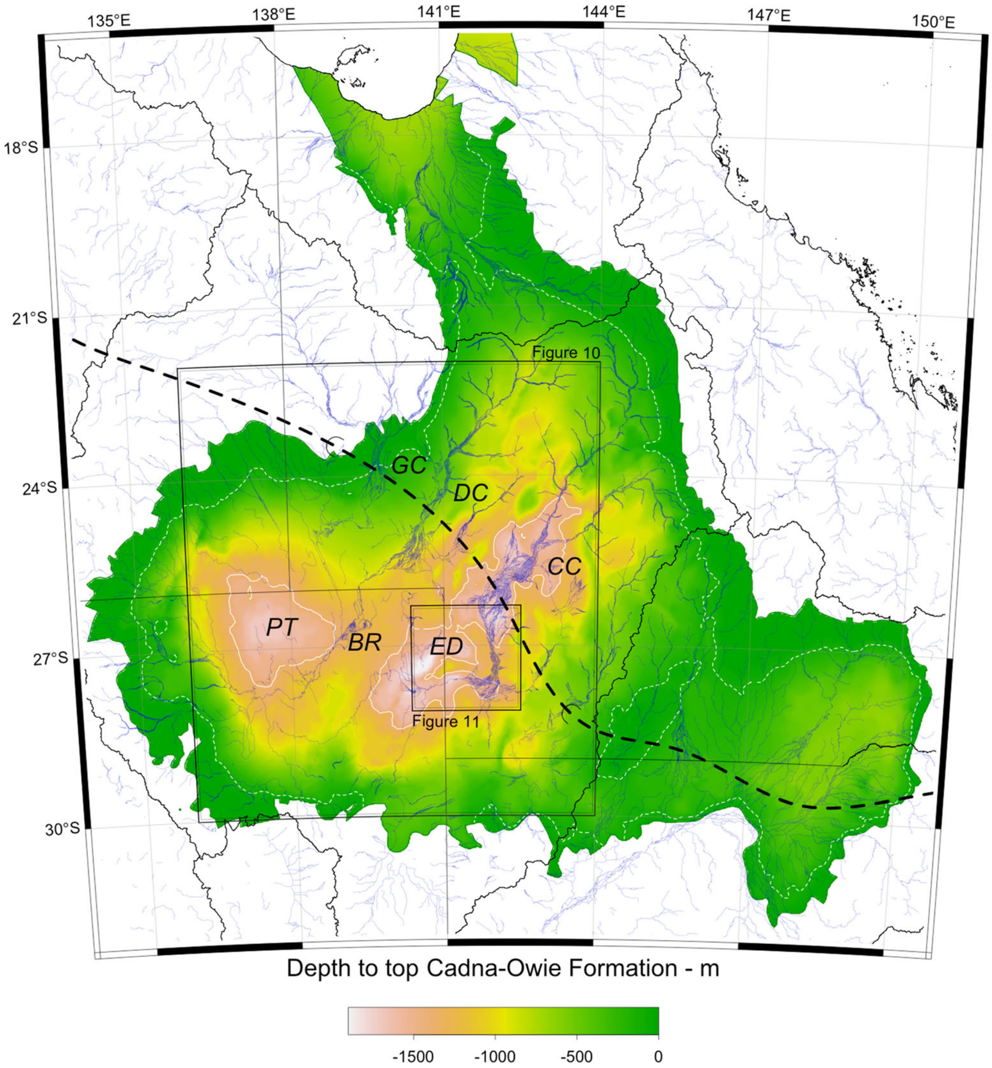

Fig. 4 Cadna-owie Formation top-surface depth (Geoscience Australia, 2015). Contour lines: dashed white = 100 m, solid white = 1,400 m. PT Poolawanna trough, ED Central Eromanga Depocentre, BR Birdsville Track Ridge (terminology Ransley et al. 2012b), GC Georgina River, DC Diamantina River, CC Cooper Creek. Outlines of surface catchments (black line), drainages (blue line), and axis of lithospheric keel (dashed black line, see Fig. 2)

activity across the GAB is low, even by Australian standards. As such, the role active faulting plays in the internal parts of the GAB remains unclear.

The objective for this contribution is to highlight observations that indicate the potentially important, albeit subtle, role that active faulting plays in the central part of the GAB, and to explore evidence that it impacts the configuration of the GAB artesian aquifer system. Because the level of seismic activity across the Australian continent is low (e.g. Braun et al. 2009), the duration of the earthquake catalogue is relatively short and the network coverage across the remote parts of the continent has (until recently) been poor, the record of historic seismic activity offers only a somewhat opaque guide to the distribution of active faulting. Further insight into the nature of fault-related deformation must be gleaned by landscape responses, using the techniques of tectonic geomorphology such as evident in anomalous drainage diversions and/or channel gradients (e.g. Holbrook and Schumm 1999; Burbank and Anderson 2001; Kernich et al. 2009; Lawrie et al. 2012).

Structure of the Candna-owie Formation and associated aquifers

The GAB comprises a complex compartmentalised groundwater system that extends from Lake Eyre in the southwest, to the Gulf of Carpentaria in the north, and the western flanks of the Great Dividing Range in the east (Radke et al. 2000; Smerdon et al. 2012; Ransley et al. 2015; Smerdon and Turnadge 2015). While the GAB substantially underlies the Lake Eyre Basin (LEB, Callen et al. 1995), it also extends beneath the northern part of the Murray-Darling Basin (MDB) and catchments that flow north into the Gulf of Carpentaria (Fig. 1). Importantly, the GAB overlies a complexly structured lithosphere as evidenced by significant variation in lithosphere thickness (Fig. 2), as well the older Cooper and Galilee basins with a complex history of faulting. Intriguingly, the eastern and southern boundaries of the GAB coincide approximately with the 150-km lithosphere thickness contour (Fig. 2), which may suggest the fundamental lithospheric structure established at the time of formation of the

GAB. Here the focus is on the central part of the GAB in the tri-border region between the states of South Australia, New South Wales and Queensland. This region forms part of the eastern subbasin of the GAB (Habermehl 1980) in which groundwater sourced along the western flanks of the Great Dividing Range flows both westwards and southwards across the basin to discharge zones along its southern margin.

The Cadna-owie and Hooray formations comprise mostly siltstones and arkosic sandstones up to several hundred metres thick and host one of the key GAB aquifer systems (Krieg et al. 1995). As part of the Eromanga Basin, the Cadna-owie and Hooray formations were deposited in marginal marine environments in a broad intracontinental depression in the hinterland of the convergent margin developed along the eastern Proto-Pacific margin of the Gondwana Supercontinent. The specific reasons for Eromanga subsidence remain debated, but include dynamic mantle processes associated with ongoing proto-Pacific subduction to the east (Gurnis et al. 1998; Waschbush et al. 2009; see also review of Ransley et al. 2012a). A key observation in regard to the dynamics of Eromanga Basin subsidence and its subsequent uplift relates to the timing of global sea level changes. Eromanga subsidence preceded the peak in the Late Cretaceous global sea level by several 10's of millions of years, with uplift already in effect while global sea stands continued to increase (Gallagher and Lambeck 1989). Differential uplift across the basin can be attributed to relaxation of the dynamic loads following cessation of proto-Pacific subduction, explaining in part the regional westerly slopes across the basin. The gradients were likely further amplified by later Cenozoic relief generation along the eastern highlands and by ongoing episodic subsidence in the Lake Eyre region (e.g. Sandiford and Quigley 2009). The resulting relief is expressed in the elevation of the peripheral exposures of the Cadna-owie-Hooray Aquifer around the GAB, which varies from ~600 m above sea level (ASL) along the northeast margin to around sea level in the southwest in the vicinity of Lake Eyre. This regional relief establishes the topographic head that organises the broad pattern of flow connecting the principal recharge in southeast Queensland, to the most distal discharge zones in South Australia, some 1,400 km away (Habermehl 1980), although more recent investigations suggest much greater segmentation and more complex groundwater flow paths (Radke et al. 2000; Smerdon et al. 2012; Smerdon and Turnadge 2015).

In detail, the structure of, and pressure within, the deeper GAB aquifers shows significant internal variation (Figs. 4, 5, 6, 7 and 8; Smerdon et al. 2012). The deepest GAB aquifer sequences occur in a set of subbasins along the central and western part of the Eromanga Basin, where the depth to the top of the Cadna-owie Formation reaches approximately 1,500 m. The thickest Eromanga succession occurs in the elongate northeast-trending Central Eromanga Depocentre that extends beneath Cooper Creek for approximately 500 km. The intimate alignment of surface drainage with this depocentre (e.g. Fig. 4) suggests an effective surface-drainage training either by ongoing compaction-related subsidence or by subtle fault-related activity. A noteworthy feature is a 180-km long southward diversion of Cooper Creek, coincident with small anomalies in the depth to the Cadna-owie Formation across the Central Eromanga Depocentre, evident in the structure of the red 1,400-m-depth contour line in Fig. 4.

The potentiometric head in the Cadna-owie-Hooray Aquifer (Fig. 5) generally decreases westwards across the basin, from the principal recharge zone in southeast Queensland. The gradient map of the potentiometric head (Fig. 6) illustrates steep head drops in the region where Cooper Creek diverts south, suggesting some compartmentalisation of the aquifer. In this context, it is noted that Smerdon and Turnadge's (2015) numerical modelling of potentiometric surfaces for the Cadna-owie–Hooray aquifers showed significant changes in potentiometric surfaces when faults were included. In their modelling, faults contribute to creation of semi-isolated groundwater compartments resulting in more complex regional groundwater flow paths (Smerdon and Turnadge 2015).

The regional structure of the Cadna-owie-Hooray aquifer system is revealed by taking the planform-curvature of the potentiometric head (Fig. 8). Positive planform curvature implies divergent groundwater flow around groundwater 'divides' as indicated in red in Fig. 8. Of note is the prominent east–west trending groundwater divide that connects the principal recharge zone in the eastern GAB with the central GAB at 27°S, terminating abruptly to the east of the diverted Cooper Creek section. The role of structuring beneath the Cooper Creek deflection is further emphasised by mapping the artesian component of the groundwater system, obtained by subtracting the smoothed topography (using a 1° median filter) from the potentiometric head (Fig. 7). The observation that the largest artesian anomalies (order 100 m) are co-located with the main Cooper Creek diversion, begs the question as to whether they manifest a common cause. To address this question, and other relevant issues, the following section explores the reasons for the diversion in Cooper Creek and other drainages in the central LEB.

Geomorphic signals of active tectonics in the Lake Eyre Basin

The Lake Eyre Basin (LEB) forms an internal drainage system that covers ~15% of the Australian continent (Harbeck-Fardy and Nanson 2014). The principal surface drainage systems are the Georgina, Diamantina and Cooper creeks (Figs. 1 and 9), that drain south across almost the full extent of the LEB eventually into Lake Eyre. These systems share several common features including significant anabranching (Nanson and

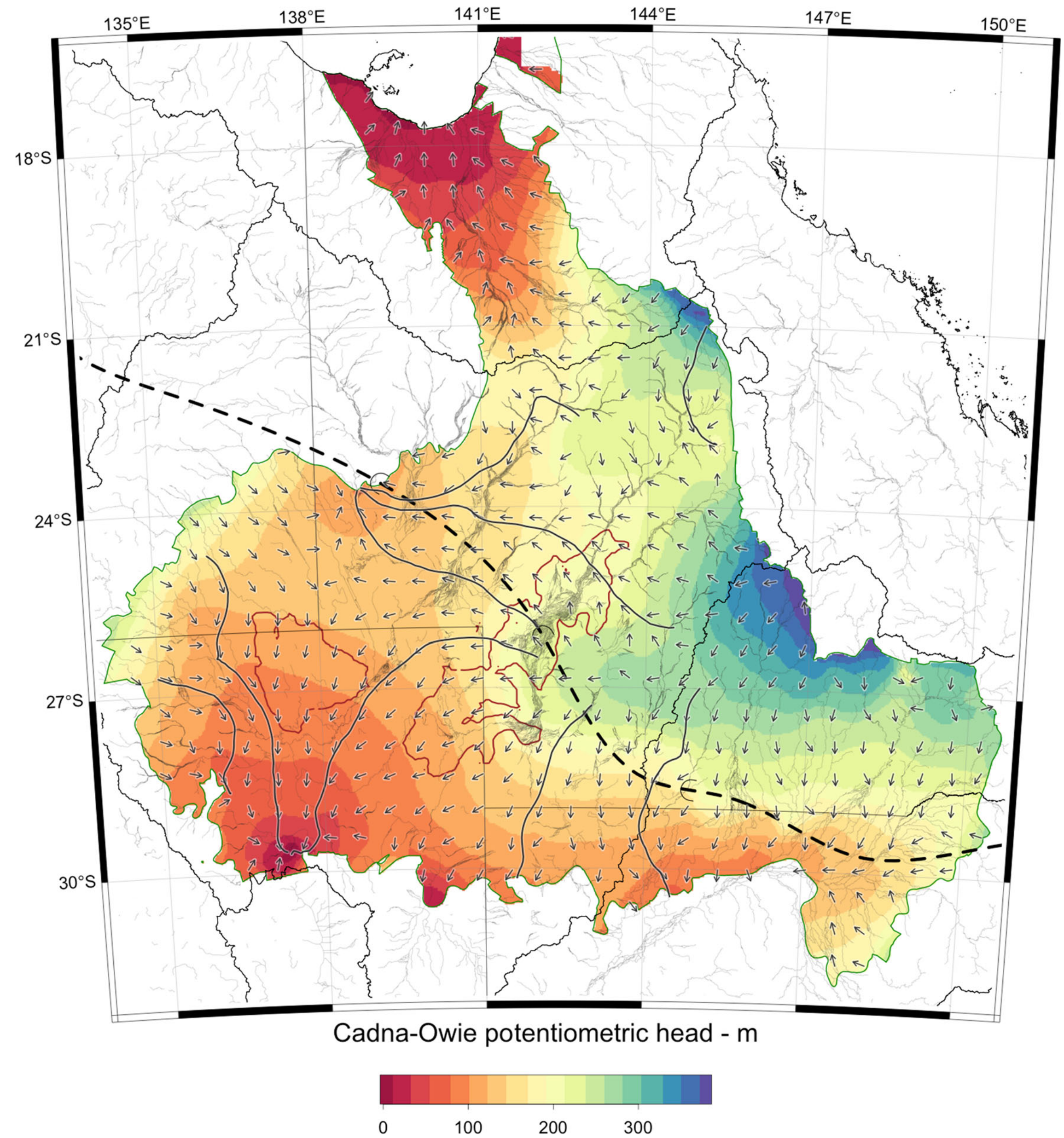

Fig. 5 Cadna-owie-Hooray Aquifer potentiometric head (m above sea level, Geoscience Australia 2015). Black arrows indicative flow vectors; solid black lines indicative flow paths. Outlines of surface catchments (black line), drainages (grey line), 1,400-m depth to Cadna-owie (red line) and axis of lithospheric keel (dashed black line, see Fig. 2)

Knighton 1996). In each case, the anabranching is most prominent in the mid-reach sections at 23–28°S (Figs. 9 and 10). The distribution of anabranch segments in each of these creek systems defines a distinctive northwest trending zone across southwest Queensland that terminates down-stream in zones where the channels are deflected significantly from the regional topographic gradient (Figs. 9 and 10). Intriguingly, the zone of anabranching overlies the keel in lithospheric thickness revealed by seismic tomographic imaging (Fig. 2). The discussion here focusses on the Cooper Creek diversion, where the offset with the regional slope is particularly strongly expressed. The discussion builds on insights from a recent detailed quantitative geomorphic study of this region (Jansen et al. 2013).

The Cooper Creek anabranch system near the South Australia–Queensland border to the northeast of Innamincka is illustrated in Figs. 10 and 11. The southward deflection of Cooper Creek at around 141°50′ E, 26°15′ S, follows a topographic low between elongated regions of elevated topography (order 100 m in relief) both to the west and to the east. In detail, the elongated domal structures that border the south flowing Cooper Creek segment are part of a larger set of domal structures that border the eastern edge of the Simpson Desert (Figs. 10 and 11). All involve warped duricrust

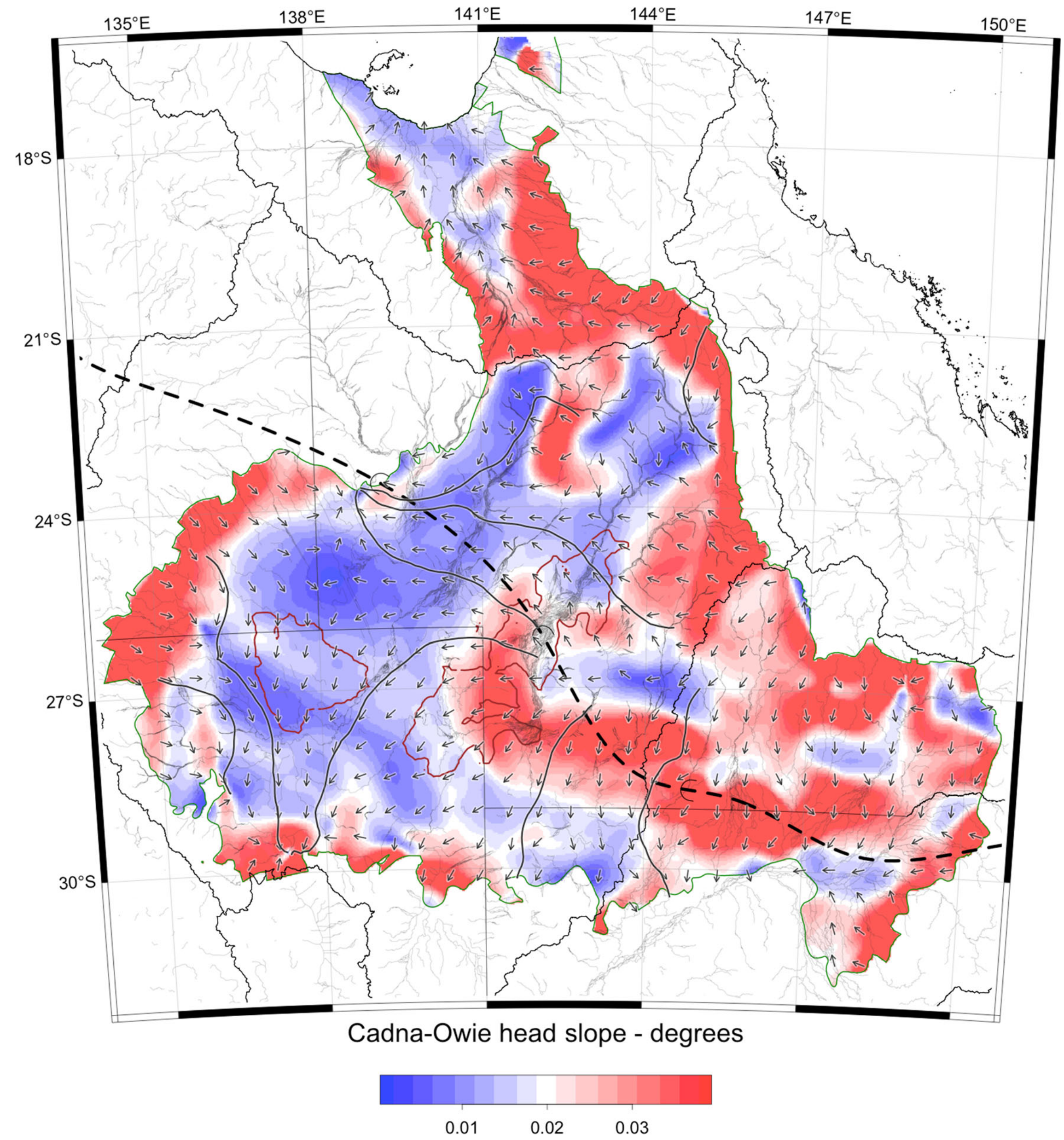

Fig. 6 Canda-owie-Hooray Aquifer gradient (degrees) in potentiometric head (Geoscience Australia 2015). Black arrows indicative flow vectors; solid black lines indicative flow paths. Outlines of surface catchments (black line), drainages (grey line), 1,400-m depth to Cadna-owie (red line) and axis of lithospheric keel (dashed black line, see Fig. 2). Colour scale truncated to range (0–0.04)

surfaces, with distinct anticlinal forms (Wopfner et al. 1974; Alley 1998). At the downstream end of the diverted segment, Cooper Creek turns abruptly westward and gathers into a much narrower channel incised between the Innamincka Dome to the north and another dome to the south before entering the Tirari Desert (Fig. 11). Jansen et al. (2013) documented abandoned strath surfaces in the most constricted part of the west-flowing reach immediately south of the Innamincka Dome that record the progressive growth of the domes. Jansen et al. (2013) obtained minimum uplift/incision rates of 1.1–2.4 cm/kyr, and noted the 'shift in river pattern was a product of base-level rise linked with the slowly deforming syncline–anticline structure, coupled with a climate-forced reduction in discharge' but did not speculate on the broader tectonic significance of the domes.

The Jansen et al. (2013) study highlights the active nature of the deformation, expressed across the central LEB as elongate domal uplifts with amplitude order 100 m; this shows how the deformation deflects the major drainage systems and localises aggradation expressed by the distinct zones of anabranching. Although the surface deformation required for such doming is small (around 10–20 m per million years), it has implications for subsurface structure. Continuity arguments require that the deformation expressed by the surface

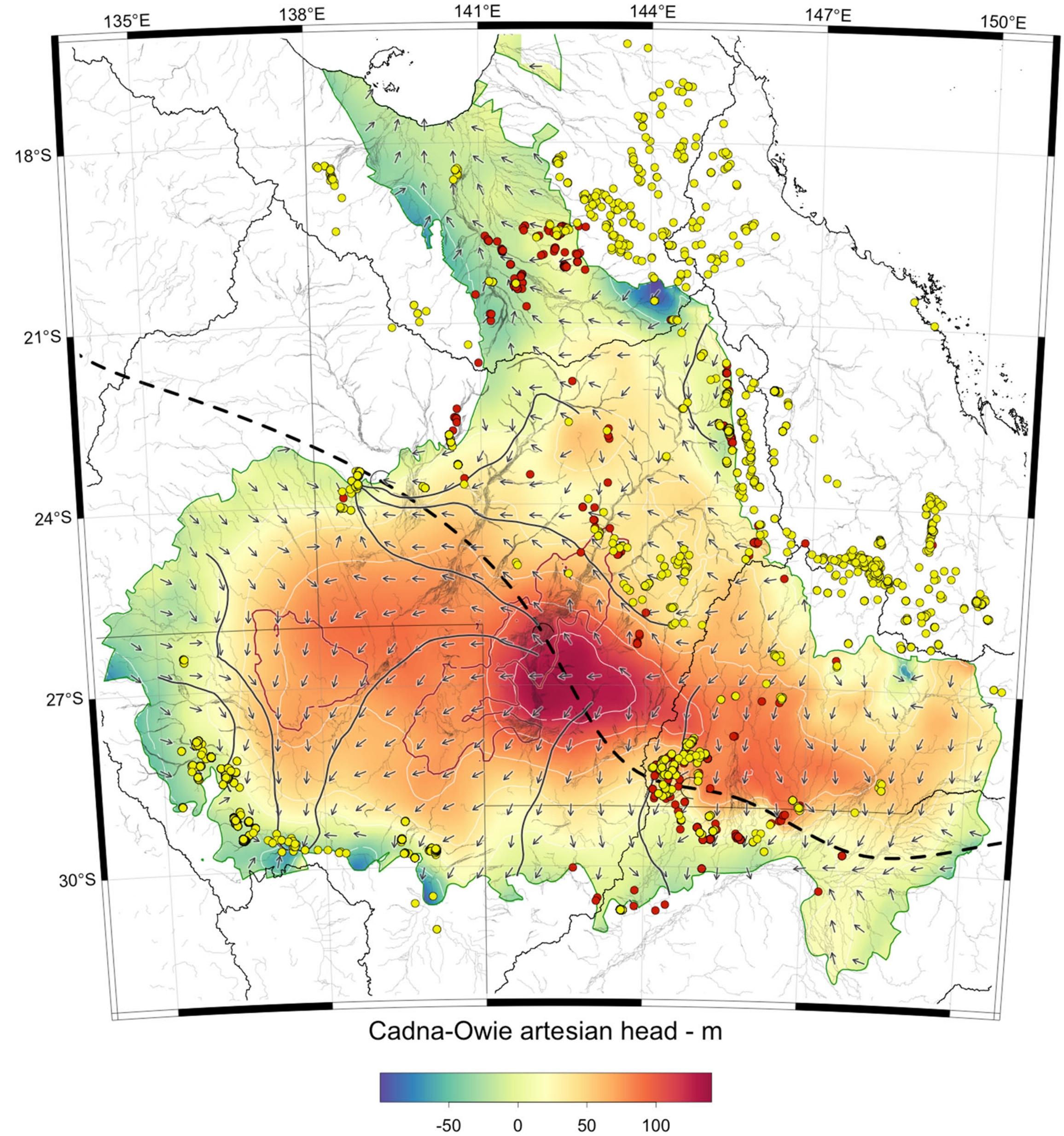

Fig. 7 Cadna-owie-Hooray Aquifer regionalised artesian head derived from the difference in potentiometric head (Geoscience Australia 2015) and smoothed topography (1° median filter, see Fig. 8). Yellow circles: active groundwater-fed springs; red circles: inactive springs (spring locations provided by Mark Keppel, South Australian Department of Environment and Water, personal communication, 2019), Black arrows indicative flow vectors; solid black lines indicative flow paths. Outlines of surface catchments (black line), drainages (grey line), 1,400-m depth to Cadna-owie (red line) and axis of lithospheric keel (dashed black line, see Fig. 2)

doming must connect to a crustal-scale strain field. The standard structural interpretation is that the domes are 'fault-tip propagation folds' formed above the tips of 'blind' faults that terminate at some shallow depth beneath the surface. Slip rates on the principal faults beneath fault-tip propagation folds are required to be of the same order as the fold amplification rates.

The existence of active faults is further supported by the results of a fluid injection/stimulation experiment at the deep (4 km) geothermal Habanero borehole near Innamincka designed to test injectivity (Baisch et al. 2006). The location of the induced microseismic cluster at the southern end of the Innamincka Dome is shown in the lower left of Fig. 11. These events are localised along a discrete fault at around 3 km depth, that slipped by about 1 cm during the injection, apparently impacting the borehole integrity (Doone Wyborn, Geodynamcis Pty Ltd., personal communication, 2008). Focal mechanisms of the larger induced seismic events (as shown by the focal mechanism 'beach balls' in Fig. 11) point to thrust-related slip on a south-east dipping structure that would likely project to the surface on the western side of the

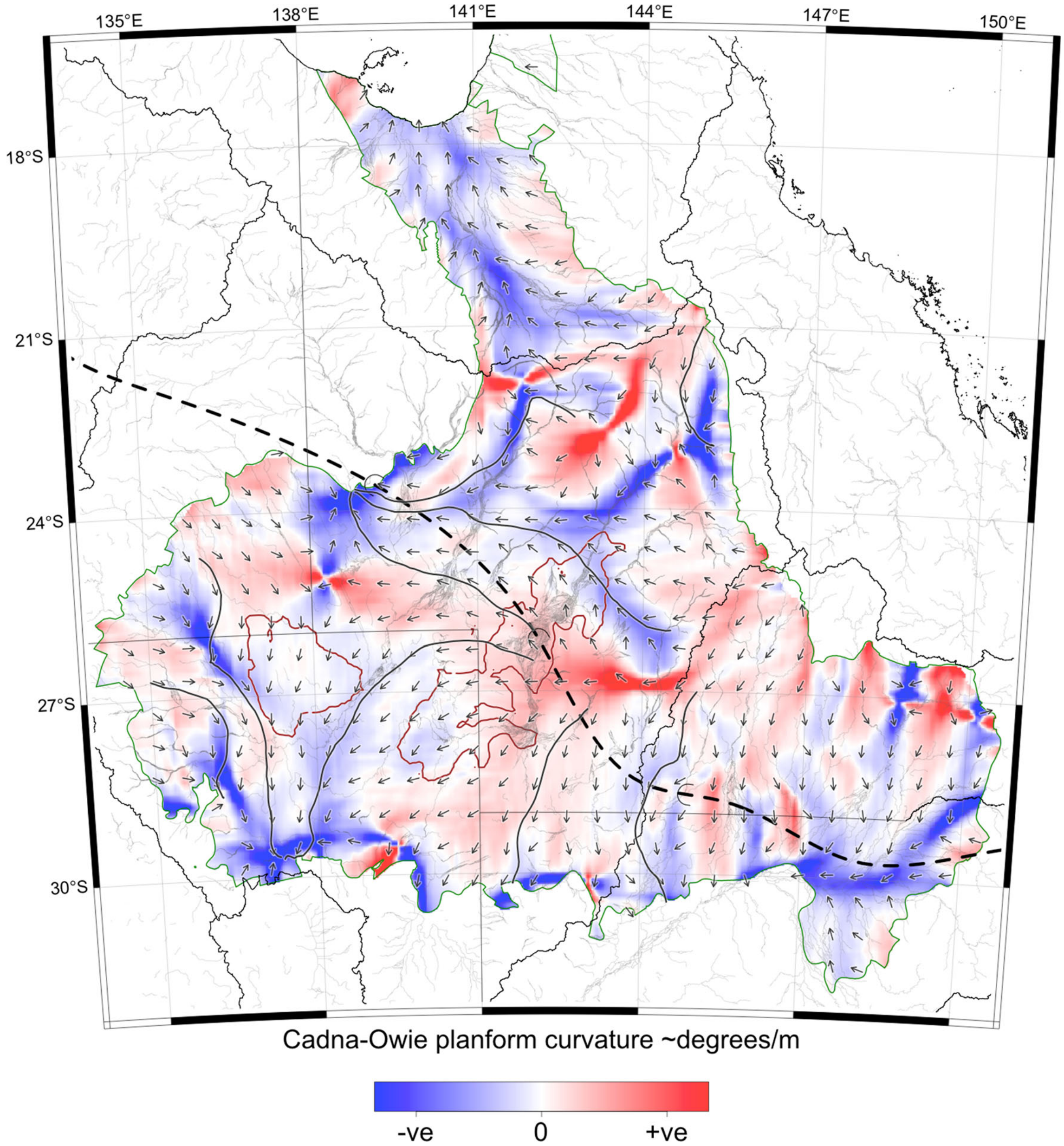

Fig. 8 Canda-owie-Hooray Aquifer planform curvature in potentiometric head (Geoscience Australia 2015). Red colours: divergent (positive planform curvature) flow 'divides'; blue colours: convergent (negative planform curvature) flow 'channels'; black arrows: indicative flow vectors; black solid lines indicative flow lines; solid black lines indicative flow paths. Outlines of surface catchments (black line), drainages (grey line), 1,400-m depth to Cadna-owie (red line) and axis of lithospheric keel (dashed black line, see Fig. 2)

Innamincka dome, as illustrated by the hypothetical fault trace (barbed grey line in Fig. 11).

While the faulting associated with doming is inferred to be blind, it is relevant that Kellett et al. (2012) have reported a surface lineament that extends south–southeast from near Innamincka towards Tibooburra. The surface drainage is clearly deflected along this lineament and shows local impoundments that resemble sag ponds that have been documented along surface rupturing faults elsewhere in Australia (e.g. Clark et al. 2011). Kellett et al. (2012) estimate a total displacement of ~20 m and briefly discussed its implications for shallower subartesian aquifers in the GAB. Similarly, the prominent linear nature of the north-west face of the Innamincka Dome (Fig. 11) resembles that of a fault scarp, the orientation of which is consistent with north to north-east trending nodal planes of the focal mechanisms reported by Baisch et al. (2006).

In summary, the observations cited here indicate that the active tectonic doming of the landscape in the central LEB clearly impacts the function of surface drainage. As part of an active crustal-scale strain field, the doming is inferred to be accommodated at depth as a complex network of blind thrust

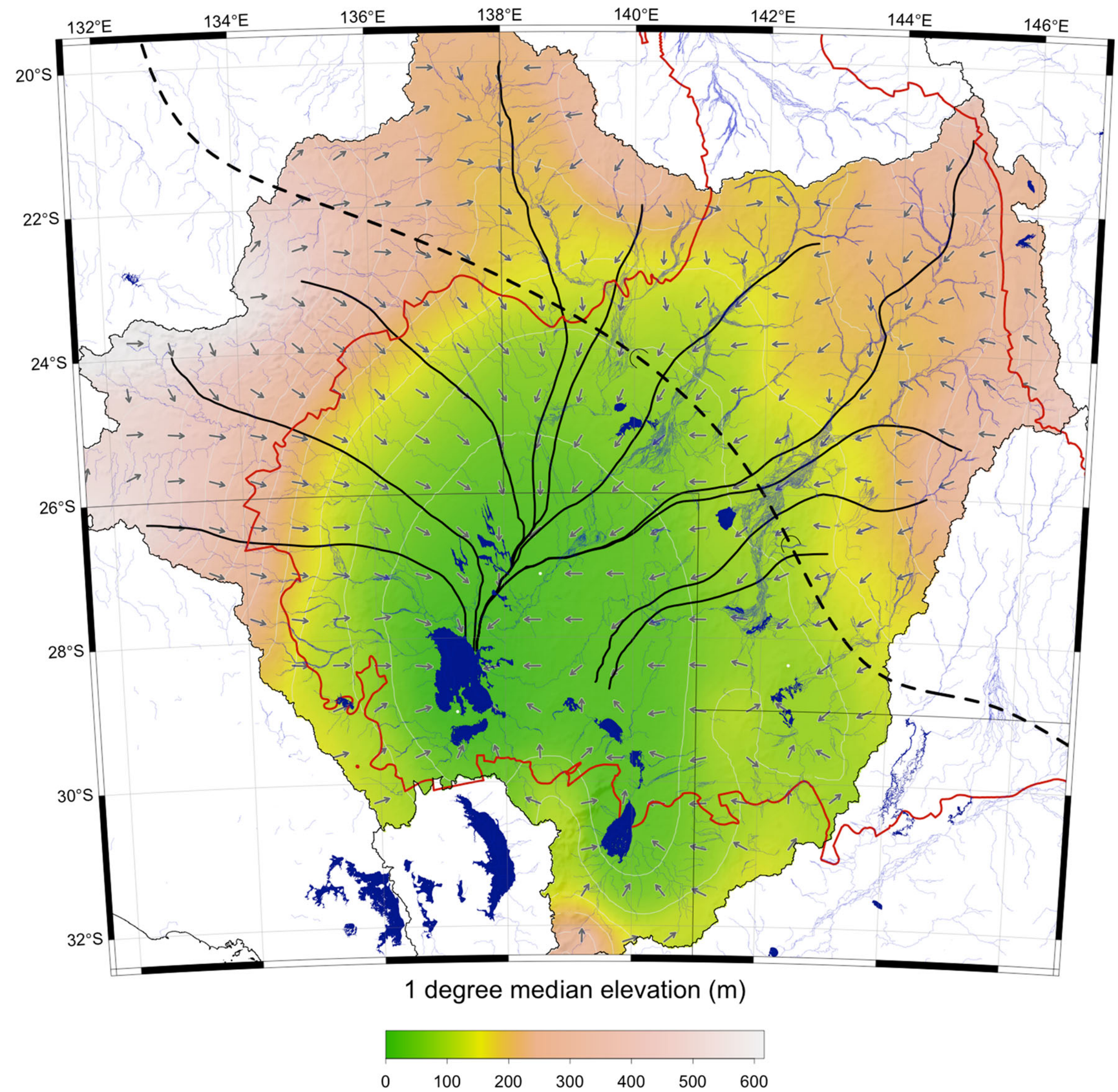

Fig. 9 Lake Eyre Basin smoothed surface topography (1° median filter). Grey arrows: regional (smoothed) topographic gradient; solid black lines: regional (smoothed topography) flow lines; outlines of Eromanga Basin: GAB (red line), drainages and ephemeral lakes (blue line) and axis of lithospheric keel (dashed black line, see Fig. 2)

faults forming part of a system termed here the Innamincka Fault System (IFS). While the extended geometry of this system remains unclear, the form of the domes that conspire to deflect Cooper Creek is suggestive of a linked set of fault strands of varied orientation, each with a length of a few 10's of km's, organised in a north- trending zone of length ~200 km. At the larger scale, similar deflections in the Diamantina and Georgina systems suggest the IFS comprises an en-echelon array of linked fault sets arranged in a curvilinear zone trending north from Innamincka then bending northwest into the Simpson Desert near Birdsville (Fig. 10). It is notable that the historic seismic catalogue includes several significant earthquakes within the Simpson Desert west of Birdsville (Fig. 3), as part of a diffuse seismic zone broadly coincident with the IFS.

While the overall trend of the IFS is broadly similar to the trend of the seismically active Norwest fault system along the southwest margin of the GAB (Fig. 3), it differs in that its component fault strands appear less connected than is the case for the latter, likely reflecting an earlier stage in development and/or lower bulk strains. The cumulative fault offset is required to be comparable to the 100 m amplitude of the associated domes. Assuming the amplification rates obtained by Jansen et al. (2013) are comparable to long-term averages, the IFS has likely been active since the late Miocene, consistent with inferences about the longevity of active fault systems across southern Australia, where numerous observations point to renewed activity commencing in the late Miocene (e.g. Sandiford 2003; Sandiford et al. 2004; Celerier et al. 2005). This has been attributed to progressive build-up of

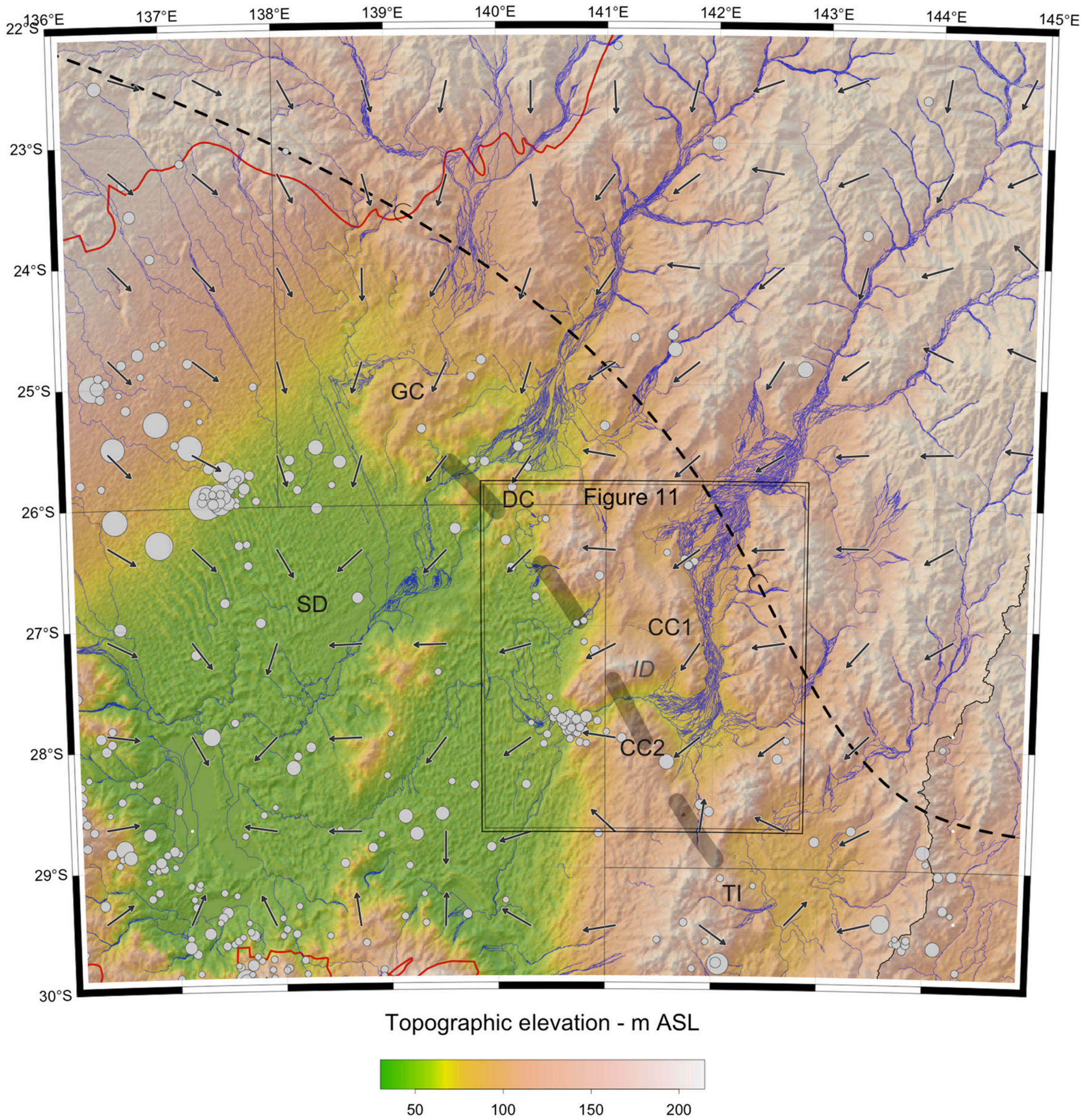

Fig. 10 Central Lake Eyre Basin showing zone of deformation (heavy dashed line) associated with diversions and changes in channel form in the Cooper (CC1 and CC2), Diamantina (DC), and Georgina (GC) drainage systems around domal anticlines within the Innamincka Fault System. See Fig. 11 for further detail. Locations: SD Simpson Desert, ID Innamincka Dome. Arrows and contours show regional slopes; the contours are derived from the 1° median filtered topography (Fig. 9). Grey circles: earthquake epicentres, scaled for magnitude (see Fig. 3). Outlines of Eromanga basin: GAB (red line), drainages (blue line), and axis of lithospheric keel (dashed black line, see Fig. 2). Colour scale truncated to elevation range 50–300 m

compressive stress in response to distant plate boundary forcing (e.g. Coblentz et al. 1995, 1998). As such, the IFS can be viewed as part of a broader pattern of distributed late Neogene intraplate deformation widely expressed across the Australian continent (e.g. Hillis et al. 2008).

Discussion

The spatial correlation between the ongoing fault-related deformation and the structure of the deeper GAB aquifers raises the question of causal connections as might apply if the IFS effected partial cut-out of the Cadna-owie-Hooray Aquifer. Strong prima facie evidence for this is provided by the observed gradient in potentiometric head across the IFS. The key observation is that the potentiometric anomaly that terminates the Cadna-owie-Hooray flow divide in the central GAB occurs directly beneath the deflected southern section of Cooper Creek. In contrast, the absence of evidence of potentiometric anomalies associated with the Central Eromanga Depocentre suggests any older northeast trending structures associated with Eromanga subsidence play a subordinate role in aquifer

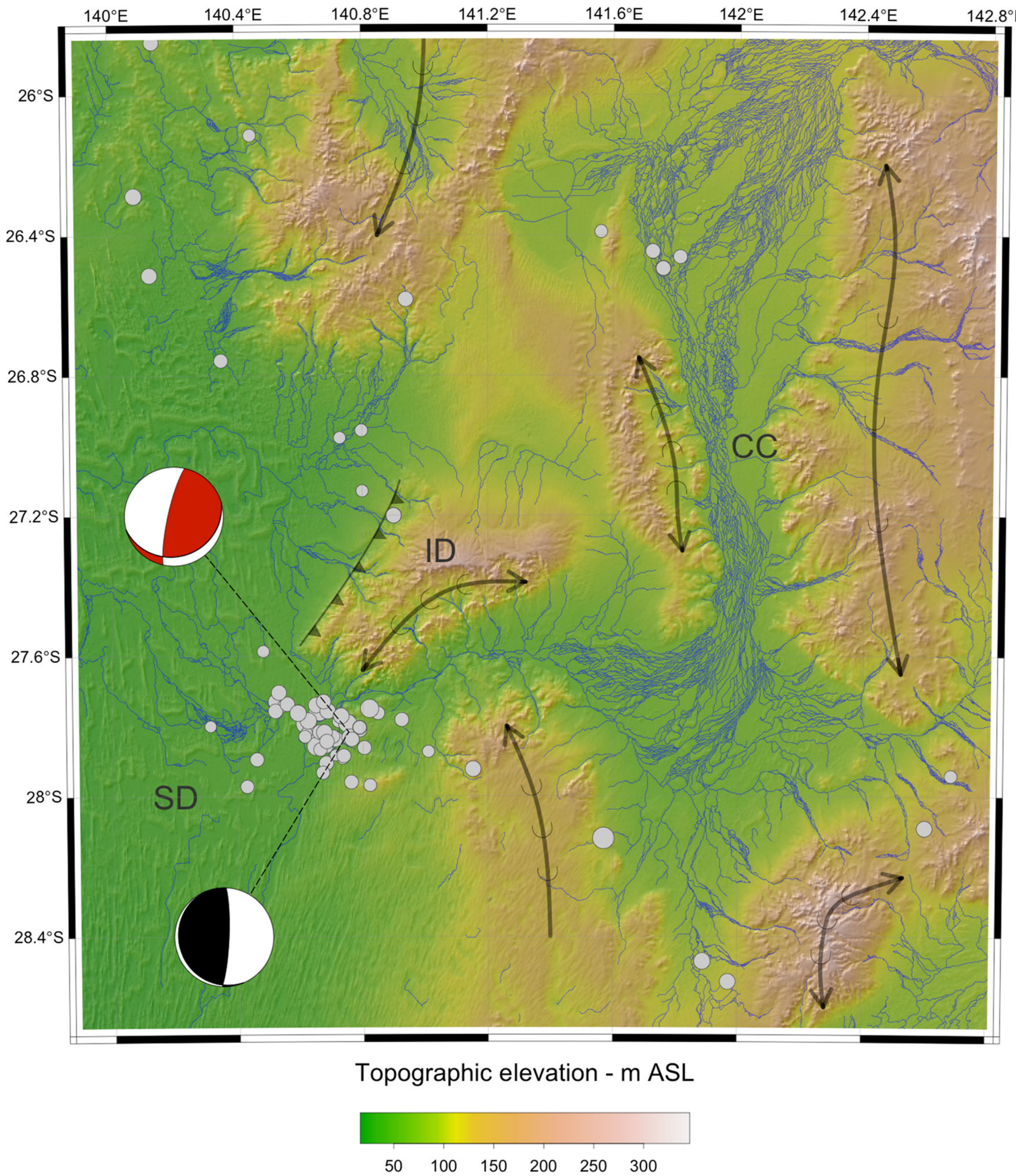

Fig. 11 Tectonic geomorphology of the southern Cooper Creek (CC) section along th eastern edge of the Simpson Desert (SD) near Innamincka (see Fig. 10 for map location). Arrowed black lines: axes of domal folds in early Tertiary silcrete surfaces (see Wopfner et al. 1974 and Jansen et al. 2013) that form a zone of distributed deformation above the largely blind Innamincka Thrust system. Barbed grey line: possible expression of surface rupturing, evident in the prominent linear topographic feature along the NW boundary of the ID (Innamincka Dome). Circles: earthquake epicentres, scaled for magnitude (see Fig. 3); 'beach balls': focal mechanism solutions (Baisch et al. 2006, see text for further discussion); blue lines: drainage channels

occlusion. In reality, as shown by Smerdon and Turnadge (2015), compartmentalisation of the Cadna-owie-Hooray aquifer is likely the integrated function of a complex history of fault systems that continues to this day.

The high artesian pressures beneath the south-flowing branch in Cooper Creek imply that (1) aquifer connectivity along the regional east–west flow path is partially occluded and (2) transmission to shallower aquifers and/or the surface is impeded. In this regard, it is notable that the IFS is a substantial blind fault system, with fault tips typically terminating beneath the more distributed zone of shallow deformation expressed by the doming. As previously noted, this style of deformation can be contrasted with the more organised, and arguably more mature, Norwest fault system that breaks through to the surface and which is characterised by significant surface discharge in mound springs (see Fig. 7). Intriguingly, Kellett et al. (2012) noted the significant groundwater mounding evident in the shallower subartesian aquifers in the core of the Innamincka Dome and commented that while the favoured interpretation is of a local recharge mound, "given the very low regional recharge rates, this groundwater mound may conversely be an expression of upward leakage from the underlying Cadna-owie–Hooray Aquifer." However, it is noted that the residual effects of paleo-recharge component cannot be discounted, as there were most likely much higher recharge rates earlier in the Holocene and Quaternary.

The source of stress that drives intraplate deformation in central Australia, is informed by the observation that the zone of anabranching in the central LEB drainages maps directly onto the axis of a prominent keel in the lithospheric thickness. Previous analysis of the origin of the tectonic stress in the Australian continent have appealed to distant plate boundary forces such as subduction beneath Indonesia, and continent-arc collision in Papua New Guinea (e.g. Coblentz et al. 1995, 1998). Importantly, these modelling studies provide a plausible explanation for the observed pattern of in-situ stress inferred from earthquakes, neotectonic structures and bore-hole break outs (e.g., Hillis et al. 2008) without the need for any significant tractions applied to the base of the plate. Several of the observations presented here suggest that such basal tractions might play a more significant role than previously recognised. An interesting feature of the seismic catalogue is the apparent difference in activity rates in the GAB across the lithospheric keel, with earthquakes much less frequent to the north especially in the central and western parts of the basin (Fig. 3). With the Australian plate drifting north-northeast at around 6 cm/year, the lithospheric keel presents a significant obstacle to sublithospheric flow. The general requirement for a system such as plate tectonics in which subduction drives large-scale mantle circulation is that the surface plates typically move faster than the sublithospheric mantle. In the case of Australia, its northerly motion will necessarily force sublithospheric mantle southwards, relative to the plate, and through the narrowing channel beneath the keel. The accelerations associated with such constricting flow require to be balanced by tractions at the base of the overriding plate inducing both by resistance, as expressed in the stress field (i.e. elastic strains), and surface deflections, as expressed in the gravity field (i.e. potential energy). It is suggested here that the asymmetry in GAB seismic-activity rates across the lithospheric keel reflects a southward increase in the magnitude of horizontal tectonic stress due to the accumulative impact of tractions associated with resistive flow imposed at the base of the lithosphere.

Several tectonic consequences follow this interpretation relevant to the long-term functioning of the GAB groundwater systems. Firstly, the degree of tectonic stressing, and the magnitude of tectonic response, will be expected to increase in direction counter to plate motion. For the GAB, this implies that any resultant tectonic activity will be expected to be best developed in the southern half of the basin, on the downstream side of the lithospheric keel. Secondly, spatial variations in bulk mechanical properties of the sublithospheric mantle, for example due to slight variations in mantle volatile content, will likely lead to temporal variations in the tractions transmitted to the plate as that mantle is traversed. The expression of this will be expected in both tectonic stress magnitudes, and subtle changes in surface topographic elevation and surface gradients. It is plausible that the anabranching sections of the LEB drainages reflect not only landscape response to IFS activity, as already discussed, but also subtle long-term landscape tilting. Further, any such variations in stress magnitudes may be propagated through deeper aquifers in terms of the pressure field, in ways that express in discharge zones. It is therefore interesting to conjecture whether such forcing is revealed in temporal variability in groundwater discharge as recorded for example by recent U-series dating studies (Priestley et al. 2018). Understanding whether this is the case or not will help better constrain temporal variability in aquifer stress regimes, which has implications for variations in hydraulic conductivity of fault systems on appropriate timescales. Finally, the inference that the IFS has materially impacted the artesian flow regimes implies a likely expression in the pattern of discharge. Constraints on the early chronology of discharge, especially along the southern boundary of the GAB (e.g. Fig. 7), would provide a critical test of these ideas.

The observations presented here are also likely to have implications for (1) understanding the geomechanics of the GAB more generally and differential stresses and the rotation of stress fields in three-dimensional (3-D) within subbasins, as observed in the Surat and other Eastern Australian basins (Flottman et al. 2013; Brooke-Barnett et al. 2015; Rajabi et al. 2015), and (2) GAB hydrogeological interpretations and groundwater process understanding. Understanding tectonic compartmentalisation and the timing of deformation place constraints on groundwater conceptual models, as well as numerical groundwater flow models and water balance studies. Recognition of tectonic control on pressures within key aquifers has groundwater management and monitoring implications, while the larger-scale approach has more general utility for developing a regional-scale conceptual understanding of stress heterogeneity.

Conclusions

Surface drainage systems across central and eastern Australia testify to ongoing mild tectonic processes that continue to modify the landscape in subtle ways on timescales on the order of 1 million years. Further, the distribution of channel forms and offsets in the drainage catchments in the Lake Eyre Basin provide evidence of an active fault system that correlates with compartmentalisation of deep aquifers in the central part of the GAB. Correlations in the distribution of seismic activity and drainage form with changes in lithospheric thickness suggests that stress sourced from sublithospheric mantle flow has played an influential role in shaping the GAB.

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