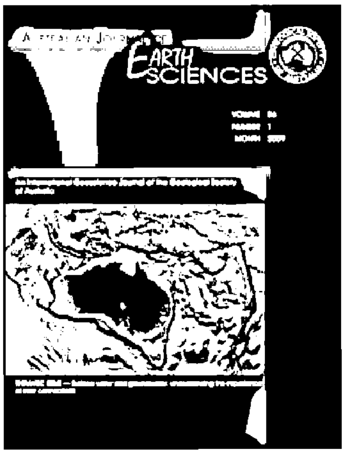

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Topographic data reveal a buried fluvial landscape in the Simpson Desert, Australia

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Buried river channels and valleys have proven to be valuable economic and agricultural resources. Often they are ecologically important refugia and in some instances, such as in the Sahara Desert, serve as dramatic reminders of the climatic changes that have taken place. Here we report the determination of a fluvial landscape that is substantially buried under the Simpson Desert using a digital elevation model (DEM) specifically derived for this purpose. The DEM is a grid of ground-level elevation points with a spacing of 9 s in longitude and latitude (~250 m). It was calculated by applying the ANUDEM gridding algorithm to national spot height elevation data taken from 1:100 000 scale topographic maps. The ANUDEM algorithm includes a drainage enforcement algorithm that has been found to reliably discern drainage structure from minimally sampled point elevation data in central Queensland and broad-scale paleodrainage structure in Western Australia. To avoid erroneously high-elevation information, source elevation data were only selected from between dunes in the Simpson Desert region, providing a more accurate basis for determination of the general surface topography and its underlying paleodrainage structure that existed prior to the development of the dunefields. The DEM reveals the broader, low-frequency topography in the Simpson Desert, reflecting the landscape buried up to 35 m below the sand surface. The paleodrainage analysis is in good agreement with data from the Shuttle Radar Topographic Mission (SRTM). It is now possible to trace a network of topographic lows that are likely to represent paleochannels through the driest desert in Australia and plot the former courses of the world's oldest rivers prior to their burial.

KEY WORDS: floodouts, groundwater flow, linear dunes, paleodrainage, paleovalleys, playas, Simpson Desert.

INTRODUCTION

Paleodrainage networks have proven to be valuable economic and agricultural resources. In Canada, for example, gold-bearing placer deposits were found in a former bedrock channel that was buried when ice damming occurred downstream from glaciation during the Tertiary to Early Pleistocene (Levson & Giles 1993; Levson & Blyth 2001). In Australia where climate changes during the Cenozoic have filled many paleovalleys with sediment, these features represent important aquifers as well as pathways for groundwater flow (Magee 2009). Because Australian paleovalleys have the ability to retain moisture and often interact with playas and pans on the surface (Beard 1973) they also represent ecologically important refugia (Morton *et al.* 1995). In some instances buried paleodrainage, such as those found in the Sahara, are also dramatic reminders of climatic changes that have taken place (McCauley *et al.* 1982).

Because of the subdued tectonics, limited Quaternary glaciation and long history of subaerial exposure, paleodrainage networks are fairly common features in Australia (Magee 2009). Early explorers recognised the linear relationship of many salt lakes and playas in Western Australia that seemed to indicate the courses of former rivers (Carnegie 1898, Gibson 1909). Subsequently Beard (1973) demonstrated that paleodrainage in Western Australia can be often delineated by the occurrence of vegetation such as trees, which live off the limited water collected in the persistent lows created by the former rivers. With the advent of elevation data released by the Bureau of Mineral Resources in the 1970s the ability to recognise and map paleodrainage networks improved substantially (van de Graaff *et al.* 1977). Modern remote sensing techniques, such as infrared and thermal data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), have also been used to map subtle variations in the surface soil mineralogy and local geology that are useful for delineating paleodrainage (Hou 2004; Hou & Mauger 2005). Additionally, geophysical techniques, such as electromagnetic (EM) or gravity surveys, can provide insight into the subsurface geology and identify

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sediments that have infilled paleovalleys or the groundwater that flows through these features (Hou *et al.* 2000; Hou 2004).

Using such a variety of techniques paleodrainage has been mapped draining from all of the cratonic blocks and Precambrian uplands in arid regions of Australia. Nevertheless, there are notable exceptions where the dunefields appear to be too thick to make identification of the underlying paleodrainage possible, including the Great Sandy Desert, the Great Victoria Desert and the Simpson Desert (Magee 2009). Yet the stratigraphy, surrounding geology, and presence of some paleovalleys near Lake Eyre suggest that paleovalleys should extend under the Simpson Desert (Magee 2009). Here we describe a technique that makes it possible to delineate this paleodrainage using topographic data. As part of the effort to create a national digital elevation model (DEM) for Australia, we derived a grid of ground-level elevation points with a spacing of 9 s in longitude and latitude ($\sim$250 m) calculated by applying the ANUDEM gridding algorithm (Hutchinson 2006). The ANUDEM algorithm includes a drainage-enforcement algorithm that has been found to reliably discern drainage structure from minimally sampled point elevation data in central Queensland, as well as the broad-scale paleodrainage structure previously identified in Western Australia (Beard 1973; van de Graaff *et al.* 1977). The resulting DEM shows the former courses of the world's oldest rivers prior to their burial by the Simpson sandsheet sometime during the Cenozoic. The results from our study will potentially influence conservation efforts in the national parks located in this region, mineral exploration and land-use practices. It is also possible that our technique can be applied to understanding the geological history of other deserts, particularly the Great Sandy and Great Victoria Deserts in Australia, and in other deserts of the world as well.

GEOLOGIC SETTING

The Simpson Desert is a $\sim$170 000 km^2 dunal desert that lies in the southeastern corner of the Northern Territory and extends east into Queensland and south into South Australia (Figure 1). It is dominated by northwest-oriented parallel linear dunes that are between 10 and 40 m in height and from one to several hundred kilometres in length. Interdune spacing is typically between 100 m and 1.5 km and varies inversely as a function of dune height (Ambrose *et al.* 2002). Our understanding of the chronology regarding the emplacement of the sandsheet and the subsequent formation of the dunes is a process that is rapidly evolving. Thermoluminescence (TL) dating of sand grains from the core of dunes indicates that the dunes were emplaced as early as $\sim$100 ka (Nanson *et al.* 1992). However, more recent cosmogenic isotope dating shows that the Simpson dunefield formed in the Early Pleistocene ($\sim$1 Ma) (Fujioka *et al.* 2009). The differences reflect the limitations of TL dating, which is affected by reworking of the sand primarily through biological processes (T. Fujioka & J. Chappell unpubl. data) that appears to be common particularly in the upper few metres of sediment (Bristow *et al.* 2007a). TL ages, therefore, represent dune-stabilisation ages rather than dune-formation ages (Hesse *et al.* 2004).

Another issue is the process responsible for the formation of the dunes themselves. Given the immense size of the Simpson Desert, the lack of primary sedimentary structures within the dunes due to biological disturbances and illuviation (Bristow *et al.* 2007a), and the complexity of age-dating described previously, at least three competing hypotheses have emerged. In the long-distance transport extension model proposed by Wopfner & Twidale (2001) sand was derived from a source upwind and transported over great distances as the sand accumulated in the lee of the dune's snout. In the wind-rift vertical accretion model (King 1960) sand was removed from the interdune corridors and deposited on top of the dune crests. Hollands *et al.* (2006) also described the wind-rift extension model where sand was derived from the interdune corridor, but accumulated primarily in the lee of the dune's snout. The consensus that is beginning to emerge is that linear dunes are composite features and that the relevant importance of all three formation mechanisms may change over time (Hollands *et al.* 2006; Bristow *et al.* 2007a, b).

Based on the physical and chemical characteristics of the sand (colour, grainsize, heavy minerals, quartz oxygen-isotope composition, zircon U–Pb ages), Pell *et al.* (2000) determined that the sandsheet in the Simpson Desert is composed of two principal sand deposits or groups that are restricted to particular regions. The sand group located in the southeastern Simpson Desert, which also includes the Tirari and Strzelecki Deserts, is characterised by its yellowish colour (hue 7.5–10 YR); is fine to medium grained ($Mz = 166 \pm 51\ \mu m$; contains abundant zircon, ilmenite and garnet with minor iron oxides; has grain surfaces characterised by Type II plate precipitation and polygonal cracking; and has high oxygen-isotope values ($\delta^{18}O = 10.8$–11.3‰). These characteristics suggests that this sand was derived from the deflation of floodplains of major rivers and salt lake systems. The sand group in the north and western region of the Simpson Desert is red in color (hue 2.5–5 YR); is medium grained ($Mz = 186\ \mu m$); contains abundant iron oxides and kaolinite; the grain surfaces are characterised by Type I plate precipitation and linear cracking; and has high oxygen-isotope values ($\delta^{18}O = 11.2$–11.7‰). Pell *et al.* (2000) suggested that this sand was derived from underlying sediments that had undergone significant weathering and erosion. Zircon ages indicate that the sand from both groups was derived from multiple protoliths that in many cases are located many hundreds of kilometres away suggesting that most of the sand was originally transported into the Simpson Desert region through fluvial processes.

The thickness of the sand cover in the Simpson Desert is often reported to be $\sim$1 m based on Wilson's (1973) work. However, this estimate was based on crude topographic measurements of dune heights and assumed that the dunes lie directly on the basement geology. Essentially, Wilson (1973) estimated the volume of sand contained in the linear dunes and determined the thickness of the cover by spreading this volume of

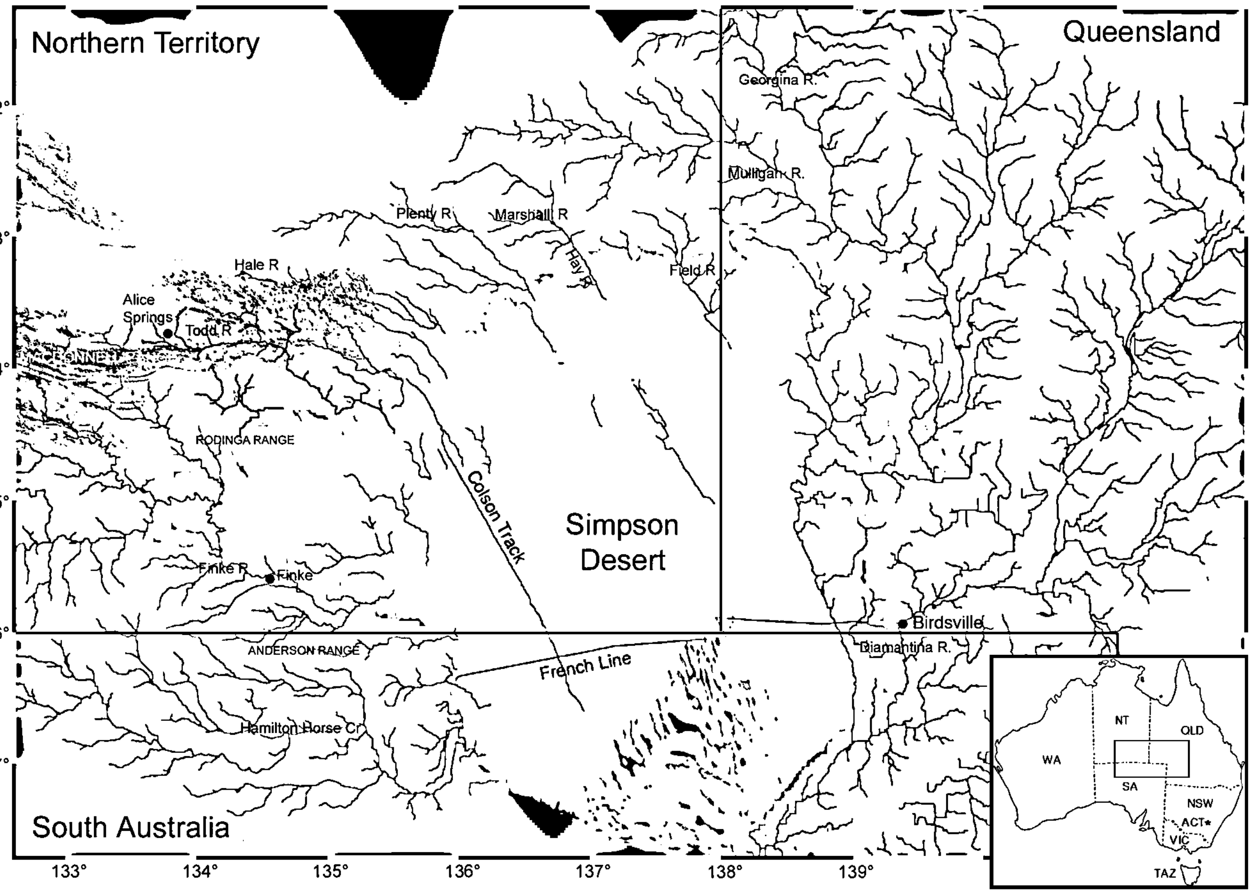

Figure 1 Simpson Desert and surrounding region, showing the locations of modern drainage systems and lakes in blue. Only drainage systems that debouch into the Simpson Desert are mapped. Major mountainous regions are show in grey. The locations of major 4WD tracks in the Simpson Desert are shown in red.

sand out evenly. Although a few dunes primarily located near the margin of the desert do lie on bedrock, a majority of the dunes are surrounded by sand that extends to considerable depths. Borehole data indicate that the sand cover is ~10–35 m thick (Wopfner & Twidale 1967). Although the cross-sectional geology varies across the desert and occasionally the sand blankets or is interbedded with Tertiary fluvial or lacustrine sediments, for the most part the sand cover sits unconformably on top of shale and siltstone of the Winton and Mackunda Formations that are Late Cretaceous (65 Ma) in age (Smith *et al.* 1963; Wopfner & Twidale 1967; Wells *et al.* 1968; Mond 1973; Joklik *et al.* 1985).

The Simpson Desert is part of a much larger desert complex that occupies most of the Great Artesian Basin, the lowest point of which is Lake Eyre. Lake Eyre is the focal point and terminus of the largest internal drainage system in the world, which includes major rivers such as the Finke, Todd, Hale, Georgina and Diamantina. The geological evidence suggests that many of these rivers are extremely old. The Finke River, for example, flows southward through the north–south structures that developed during the Alice Springs orogenic uplift that occurred during the Devonian–Carboniferous (~400–300 Ma) (Pickup *et al.* 1988; English 2002). Because these rivers pre-date the Simpson Desert by many millions of years, it seems likely that they once flowed continuously into Lake Eyre or a larger, ancestral predecessor represented by the Etadunna Formation, which is composed of limestone and dolomite that was deposited during a wetter climatic optimum during the Oligocene–Miocene (~35–12 ka) (Drexel & Preiss 1995; Magee 1997). Today the region around Lake Eyre typically receives only 120–180 mm of rainfall per year, making it the driest part of Australia, and many of the surrounding rivers only flow ephemerally. When intense seasonal monsoonal rains to the north cause these rivers to flood the waters typically become choked by sand in the Simpson Desert resulting in a series of floodout deposits that surround the region. The water then seeps into the sand and continues towards Lake Eyre as shallow groundwater flow. It is probable that the groundwater flow predominately follows the courses of the buried river channels, determining the location of major playas in the Simpson Desert and providing local sources of water for ecosystems in the region.

METHODOLOGY

Previously, Twidale & Wopfner (1990) analysed topographic data collected from helicopter gravity and seismic surveys and suggested that abandoned stream

5 channels from the Finke and Plenty Rivers are discernible in the morphology of the Simpson Desert (Figure 2). However, the resolution and coverage of these data were limited and are not amenable to advanced computer analyses. In the early 1990s, the Australian Surveying and Land Information Group (AUSLIG), the Australian Geological Survey Organisation (now Geoscience Australia), the Australian Heritage Commission, and the Centre for Resource and Environmental Studies (CRES) at the Australian National University agreed to undertake production of a national DEM of Australia with a spatial resolution of 9 s ($\sim$250 m). The original elevation data were captured from 1:100 000 scale topographic maps, and streamline data were captured from 1:250 000 scale topographic maps.

These data were gridded using the ANUDEM algorithm (version 4.4), which utilised a drainage-enforcement algorithm to significantly improve the shape and drainage structure of the elevation model. This algorithm systematically removes spurious sinks, from lowest to highest elevation, in such a way to build up a branching drainage structure that corresponds with the natural dendritic pattern commonly associated with fluvial landforming processes (Hutchinson 1989). Of significance for this study, the ANUDEM algorithm has been found to reliably discern drainage structure from minimally sampled point elevation data in central Queensland (Hutchinson 1989). It has also determined-broad scale drainage structure in Western Australia (Hutchinson & Dowling 1991) that is consistent with earlier analyses of relict Cenozoic drainage systems (van de Graaff *et al.* 1977).

The original release of the national DEM (Carroll & Morse 1996) contained a number of deficiencies related to the spatial density of streamline data and sporadic large errors in point elevation data (Kirby & Featherstone

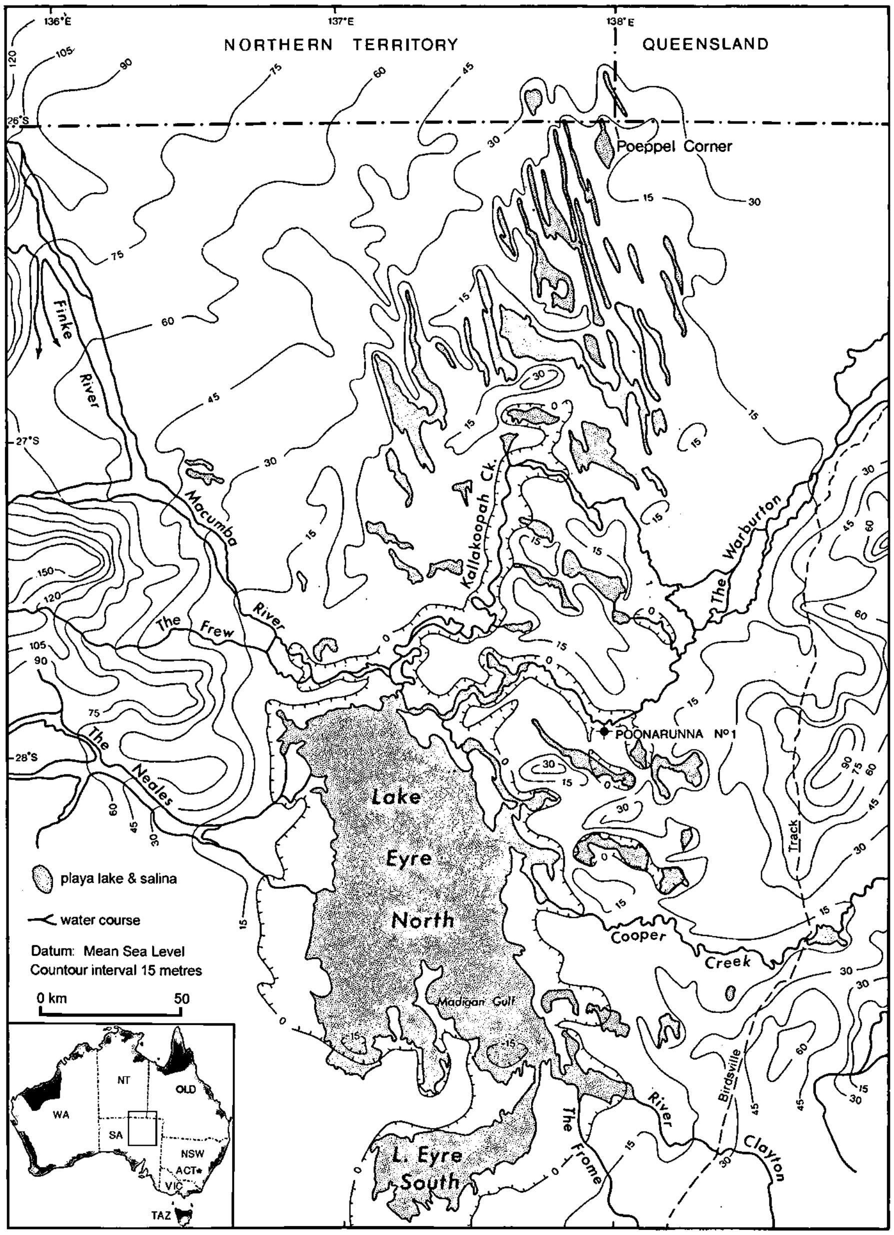

Figure 2 Topographic map of the Lake Eyre Basin generated from helicopter and gravity surveys that were collected in support of the construction of the French Line track (modified from Twidale & Wopfner 1990). Twidale & Wopfner (1990) originally interpreted V-shaped indentations in the contour lines to represented buried paleovalleys once associated with the Finke River. Our analyses indicate that this broad-scale topography represents buried paleovalleys that were once part of a larger Hale and Todd River drainage system.

1999). Dealing with the dune structure in desert regions provided additional challenges. In the Simpson Desert region data had been captured systematically from the tops of the dunes and the intervening swales. The resulting DEM had a corrugated appearance that did not accurately reflect the relief of the sand dunes or the basal topography, but rather was a poor combination of both (Figure 3). Because of the wide potential applicability of an accurate continental DEM, AUSLIG supported a proposal by CRES to carry out a comprehensive revision of all source data and to produce an upgrade of the DEM for general distribution. CRES carefully analysed sources of data errors in the original DEM, and corrected 5000 errors in point elevation data and

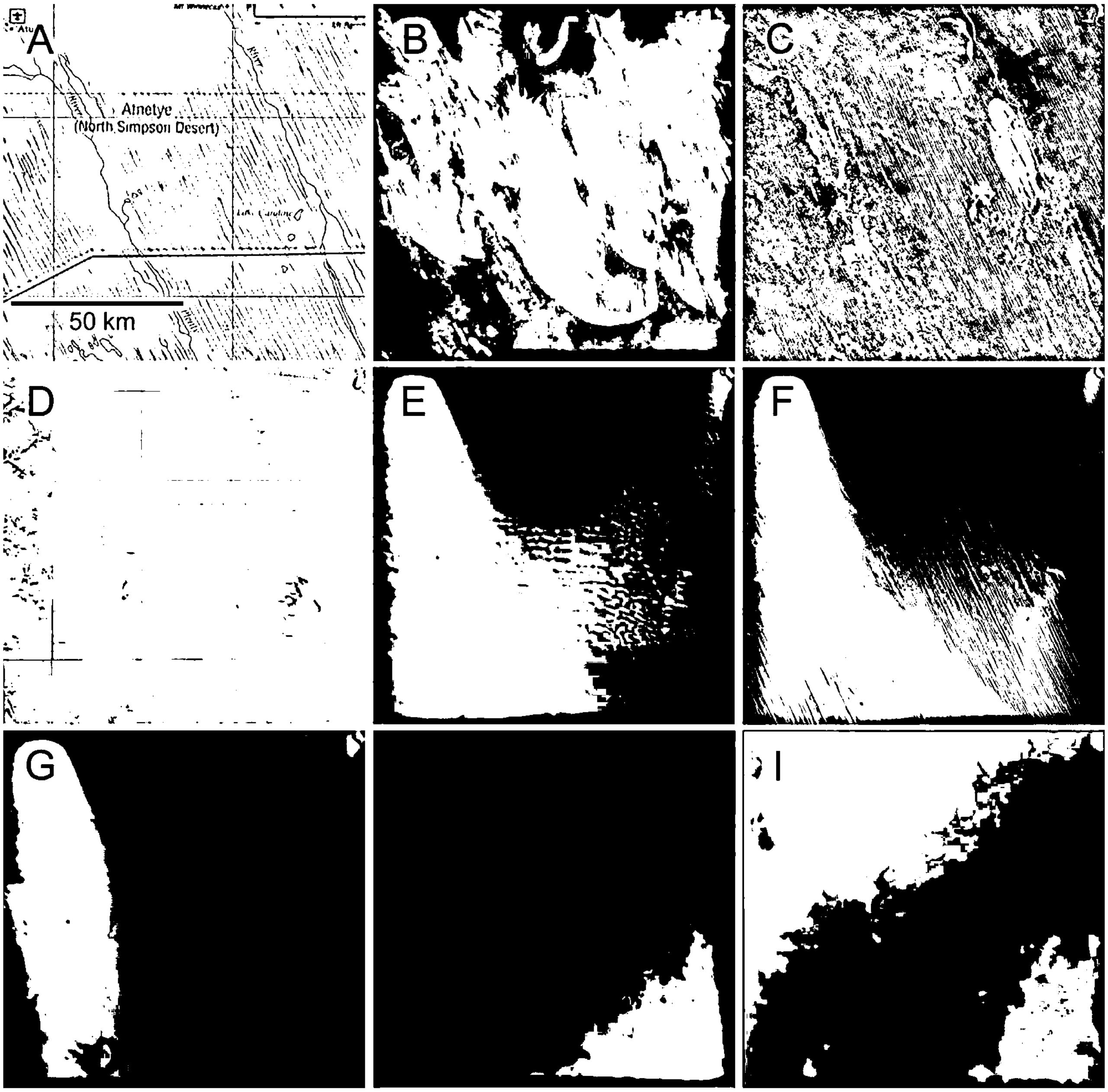

Figure 3 The same general area in the north Simpson Desert as depicted by a variety of data. (a) The area is centered at 23.7133°S, 136.8455°E in the Atnetye land trust between the Hay and Plenty Rivers. (b) Moderate Resolution Imaging Spectroradiometer (MODIS) image. The most dramatic differences in colour reflect the absence or presence of vegetation as a result of bush fires that occurred in June 2003. (c) Landsat Thematic Mapper (TM) image shows variation in vegetation cover, including fire scars from 2000. (d) Geological map of the area compiled from Smith *et al.* (1963), Wells *et al.* (1968), Mond (1973) and Joklik *et al.* (1985). (e) The original version of the 9 s national DEM of Australia was composed of spot-height data that included both topographic highs that occurred as on dune crests as well as topographic lows recorded in dune swales producing an unnatural corrugated topography in dunefields. (f) DEM composed of C-band SRTM at 90 m spacing. The linear dunes are obvious. (g–i) Close ups of the 9 s DEM that was generated in support of this study. The scenes depict different image stretches of the same DEM to accentuate the subtle variations in the low-frequency topography. The maximum relief in this DEM subsample is ~20 m.

9000 errors in streamline data. In the Simpson Desert region (20–28°S, 132–144°E) over 11 000 elevation points captured from the crests of sand dunes were also deleted. The revised source data contains 600 000 spot heights in the Simpson Desert region with a standard height accuracy of ~7.5 m.

The revised elevation data were gridded at a resolution of 9 s of longitude and latitude across the Simpson Desert using a revised version of the ANUDEM algorithm (version 5.2) (Hutchinson 2006). The revised algorithm significantly improved both the representation of surface drainage structure and the detection of errors in the source data. Because the locations of the modern streams in the Simpson Desert are strongly influenced by the orientation of the dunes, and our goal was to recover paleodrainage structure, modern streamline data were completely withheld from this analysis. The drainage-enforcement algorithm modifies the fitted DEM by removing spurious sinks. This is not applied universally but only where the modification is consistent with the values of the source elevation data, as gauged by a user-supplied elevation tolerance. The result is that remaining sinks are normally true depressions at the scale of the elevation model (Hutchinson 1989). An elevation tolerance of 20 m was applied to override the vagaries in the expression of the underlying drainage structure imposed by the sand surface. Because the 10
revised DEM depends only on natural surface points located between dunes, it depicts the broader-scale, low-frequency basal topography in the Simpson Desert and reveals an underlying landscape dissected by fluvial processes (Figure 3).

RESULTS AND DISCUSSION

The topographic expression of the buried river paleovalleys is subtle. Typically the relief of the valleys is only a few metres with a cross-sectional width of a few kilometres (Figure 3). It should be noted that the topography represented by the Simpson DEM is the surface expression of the underlying topography, not the underlying topography itself. Such slight variations in topography are not easily discernible on the ground even in ideal circumstances. Recognising valleys or channels is even more difficult in the presence of the sand dunes, which have a much higher frequency, a much greater surface relief and tend to obscure the regional perspective of the basal terrain. However, the branching nature of the paleovalleys appears to be well preserved at the broader scale represented by the Simpson DEM (Figure 4). Individual paleovalleys can

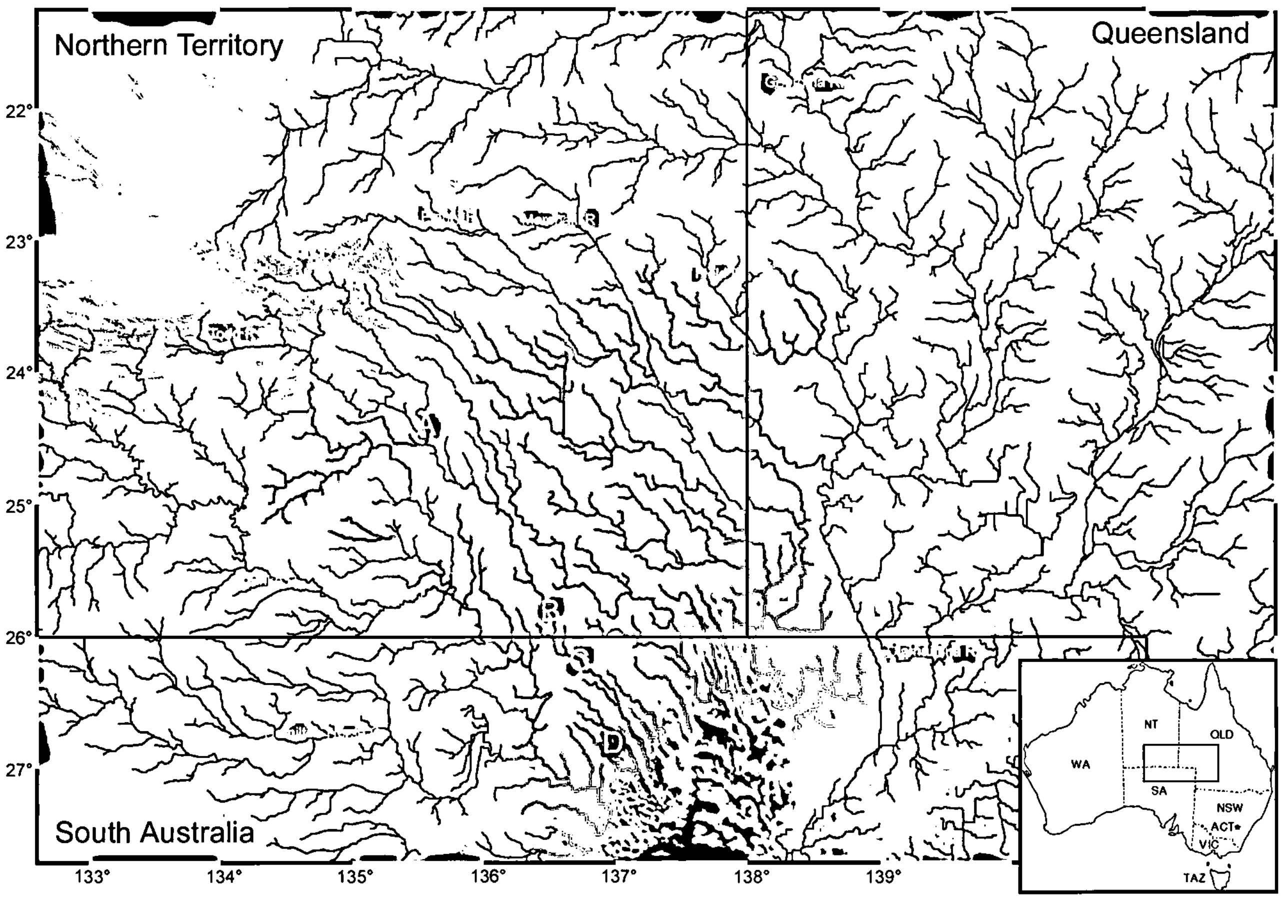

Figure 4 9 s DEM of the Simpson Desert and surrounding area; orange and yellow indicate higher elevations and the blues indicate lower elevations. The known locations of major rivers are marked in black and are labeled. The buried channels derived from the DEM are shown in red. The lower- and higher-order channels represent flow paths with respective contributing catchment areas of 2000 and 10 000 grid cells (~120 and 600 km^2). Letters indicate the location of profiles presented in Figure 5.

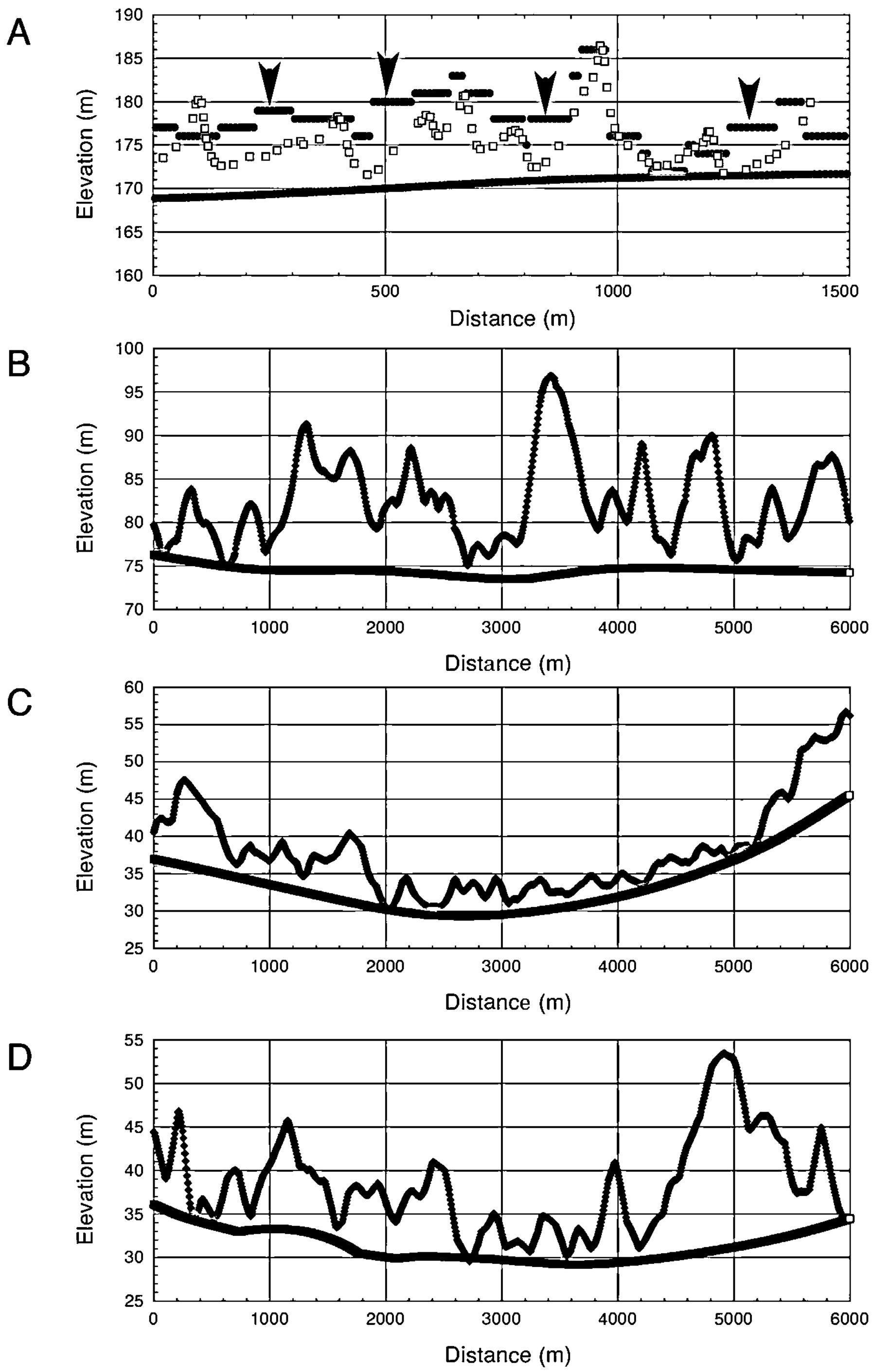

Figure 5 Comparison between the low-frequency topographic information derived by the 9 s DEM of Australia (red) and the higher-frequency topography derived from differential GPS surveys (black squares) and the SRTM (blue). (a) To test the accuracy of the SRTM data we conducted a ~1.5 km long differential GPS survey from ~25.0160°S, 136.1189°E to 25.0069°S, 136.1338°E. In general the SRTM data reflect the high-frequency topography of the dunes, but the elevation of any given point often has errors of 5–10 m, and many topographic depressions are missed (arrows). Thus the SRTM provide a poor proxy for the 9 s DEM in extracting the low-frequency topography of the paleodrainage. However, the overall shape of profiles extracted from the SRTM data often agrees with those derived from the 9 s DEM. (b) Segment of the Hale River from 25.8445°S, 136.5066°E to 25.8701°S, 136.5658°E. (c) Segment taken along the French Line leading to Birdsville and the intersection of the Colson Track from 26.1667°S, 136.6998°E to 26.1561°S, 136.7651°E. (d) Segment showing pronounced channel located north of Lake Eyre from 26.7654°S, 136.9237°E to 26.7385°S, 136.9647°E.

be traced up to an elevation of ~15–20 m near the border of Lake Eyre, which roughly coincides with the estimated extent of the putative Pleistocene Lake Dieri of Dulhunty (1983) or an expanded ancient paleolacustrine shoreline (Drexel & Preiss 1995; Magee 1997).

In an effort to trace the former channel pathways of the major rivers through the Simpson Desert, we subjected the DEM to several algorithms designed to extract watershed information from gridded elevation data (Palacios-Velez & Cuevas-Renaud 1986; Martz & Garbrecht 1992; Tarboton 1997). The basic algorithm is the D8 flow model, which determines flow direction in a DEM by calculating the steepest downhill slope from every grid cell to the eight surrounding grid cells. As the flow paths are traced from individual cells they encounter flow paths from adjacent cells. These flow paths combine to identify higher order streams and eventually define the entire drainage network as shown in Figure 4.

It is to be expected that these estimates of the paleodrainage structure will have a degree of imprecision, but the convergence in the networks is encouraging and appear to define the courses of the major trunk paleovalleys. Figure 4 indicates that most of the modern rivers that terminate in the Simpson Desert were actually tributaries of much larger drainage networks in the past. The Todd and Hale Rivers, for example, are part of a network that Twidale & Wopfner (1990) originally interpreted to be an abandoned channel of the Finke River. The Finke River network originally included many creeks that flow from the Rodinga and Anderson Ranges, most of which are now isolated. The Hay and Plenty Rivers are also found to be tributaries to a larger network as are the Field, Mulligan, and Georgina Rivers. Most of the pans and playas that occur in the Simpson Desert are situated along the paths of these larger occluded stream channels.

Other than the subtle, low-frequency topography derived in our DEM, there is no other geological expression of the buried paleovalleys that would lend verification through some other sensor, such as variation in vegetation visible in Landsat TM (Hou 2004; Hou & Mauger 2005) or secondary regolith features visible in ASTER data (Hou 2004). The Simpson Desert paleovalley are simply buried too deeply, so in order to further assess the placement of the abandoned river channels derived from the Simpson DEM, we compared the Simpson DEM with elevation data obtained from the Shuttle Radar Topographic Mission (SRTM) (Rabus *et al.* 2003). The interferometric synthetic aperture radar flown by this mission has been used to generate DEMs for public areas outside the United States with a resolution of 3 arc seconds ($\sim$90 m). The higher resolution of the SRTM products makes them well suited for conducting analyses of the dunes found in the Simpson Desert, but low-frequency topographic features, such as the buried channels, are not obvious. We conducted several 1–2 km-long differential GPS surveys near some of the putative paleochannels to assess the possibility of using the SRTM data for deriving an independent map of the paleodrainage system (Figure 5a). While the SRTM data are general reliable for identifying dune crests and swales, the elevations errors are often 3–5 m, and many low points within the swales are missed. Blumberg (2006) found that the SRTM X-band data products are more sensitive to the smaller scale undulations on the compound dunes than the C-band data. However, X-band data are only available for portions of the Simpson Desert, and the height accuracy of these data ($\sim$4 m) is still too large to be useful in delineating the buried paleovalleys. Basically, because the surface expression of the paleovalleys is only a few metres, we were unable to use the SRTM for reconstructing a reliable DEM consisting of topographic lows due to the problems with height accuracy. However, we used the STRM data to create dozens of profiles taken perpendicular across the derived locations of the buried channels. In most instances, the broad, low relief defining a buried channel obtained from the 9 s DEM compares well with the corresponding SRTM profiles (Figure 5b–d).

CONCLUSIONS

The revised 9 s Simpson DEM provides a detailed picture of the landscape buried beneath the Simpson Desert dunefields and records a wetter past climate and a fluvially dominated geomorphology regime that is virtually obscured in conventional visual or remote sensing data because of the pervasive cover of eolian sand deposits and fire scars. The results from this study, used in conjunction with geologic, geomorphic, and hydrological data will have practical applications for water-resource management, mineral exploration and land use in central Australia.

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