Prospectivity of the Camel Flat Syncline region with emphasis on the Chandler Formation

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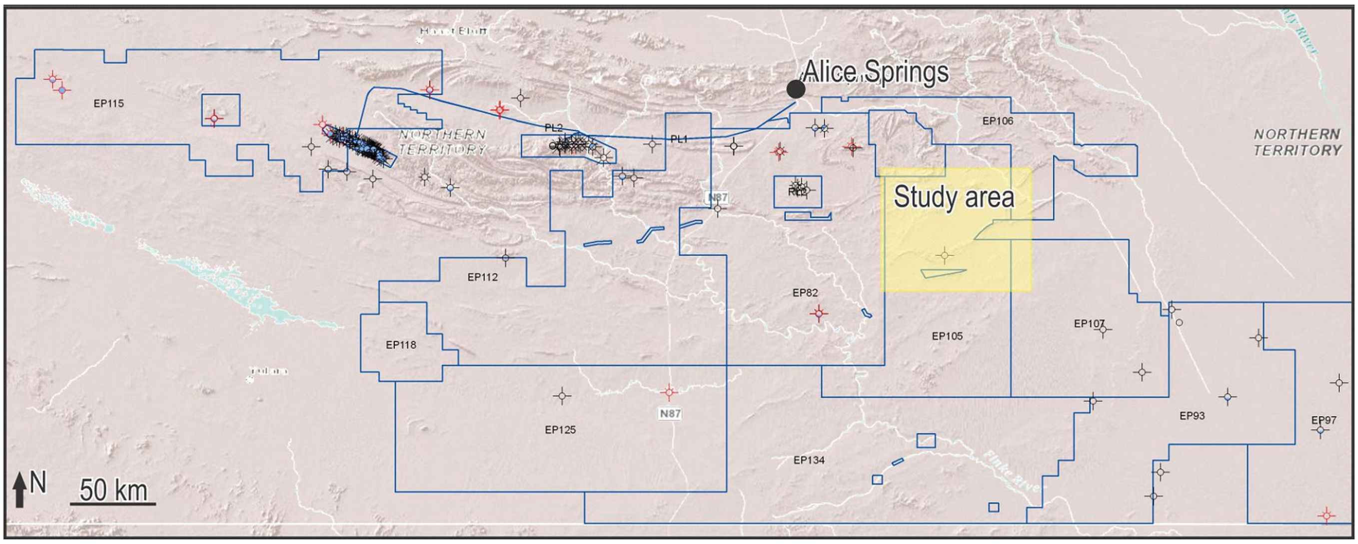

Figure 1. Location map of central Australia – permits, wells and the Camel Flat Syncline region (study area).

Introduction

The Chandler Formation of the Amadeus Basin is a thick early Cambrian sequence that contains evaporites (halite), carbonate, shale and minor sandstone/siltstone. The formation is widespread with a range of facies types occurring across the central and eastern parts of the basin. Where halite occurs it is an excellent seal, whereas foetid organic-rich carbonate and shale which are occasionally present have the potential to act as a hydrocarbon source for conventional oil and gas plays (Bradshaw, 1987). The evaporite unit is up to 1000m thick and, where present, the Chandler Formation facies are structurally deformed as a result of salt mobilization. Often the carbonate facies is fractured and associated with thrust faulting, raising the real opportunity for consideration of it also acting as a non-conventional shale/carbonate gas play; especially, where the organic rich intervals are interbedded with the salt (determined from outcrop and cores, Bradshaw, 1987).

The focus of this paper is on the prospectivity of the Chandler Formation and underlying units in the south-eastern part of the Amadeus Basin; specifically, the Camel Flat Syncline region (Figure 1).

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Overview of Chandler Formation Distribution

The Chandler Formation consists of two main lithofacies; namely, the Chandler salt and Chandler carbonate (determined from outcrop, core and seismic data; Figure 2). The Chandler carbonate occurs in the central-west part of the basin in the absence of the Chandler salt (Figure 3a). In contrast, it is interbedded between two thick Chandler salt layers in the central-east and the western end of the eastern part of the basin (Figures 3a, 3b). The Chandler salt lithofacies is widespread and extends across nearly all of the eastern and two thirds of the central parts of the basin (Figures 3a, 3b). The salt does not crop out but its distribution is defined by well and seismic data, and is inferred from the structural deformation of underlying units, which do crop out (Figure 3c). However, the salt's distribution is modified by subsurface leaching and withdrawal from basinal areas. The isopach map of the Chandler Formation shows thickness variations from ~ 1000m in the southeast to 30m in the west (Bradshaw, 1987). The salt's thickness in the salt provinces is modified by flowage into salt walls and anticlinal highs. When this structural thickening is removed, the Chandler Formation averages 450m in the Camel Flat Syncline (southeast) and 225m in the Orange Creek Syncline (north). The very thick sequences defined by seismic data, adjacent to very thin sections in wells (e.g. compare Finke-1, James Range-"A"1 and Highway-1 with seismic derived contours to the north) is due to dissolution of the salt in the breached anticlines (Bradshaw, 1987). All outcrops containing evaporites at depth are too structurally deformed to measure thicknesses and,

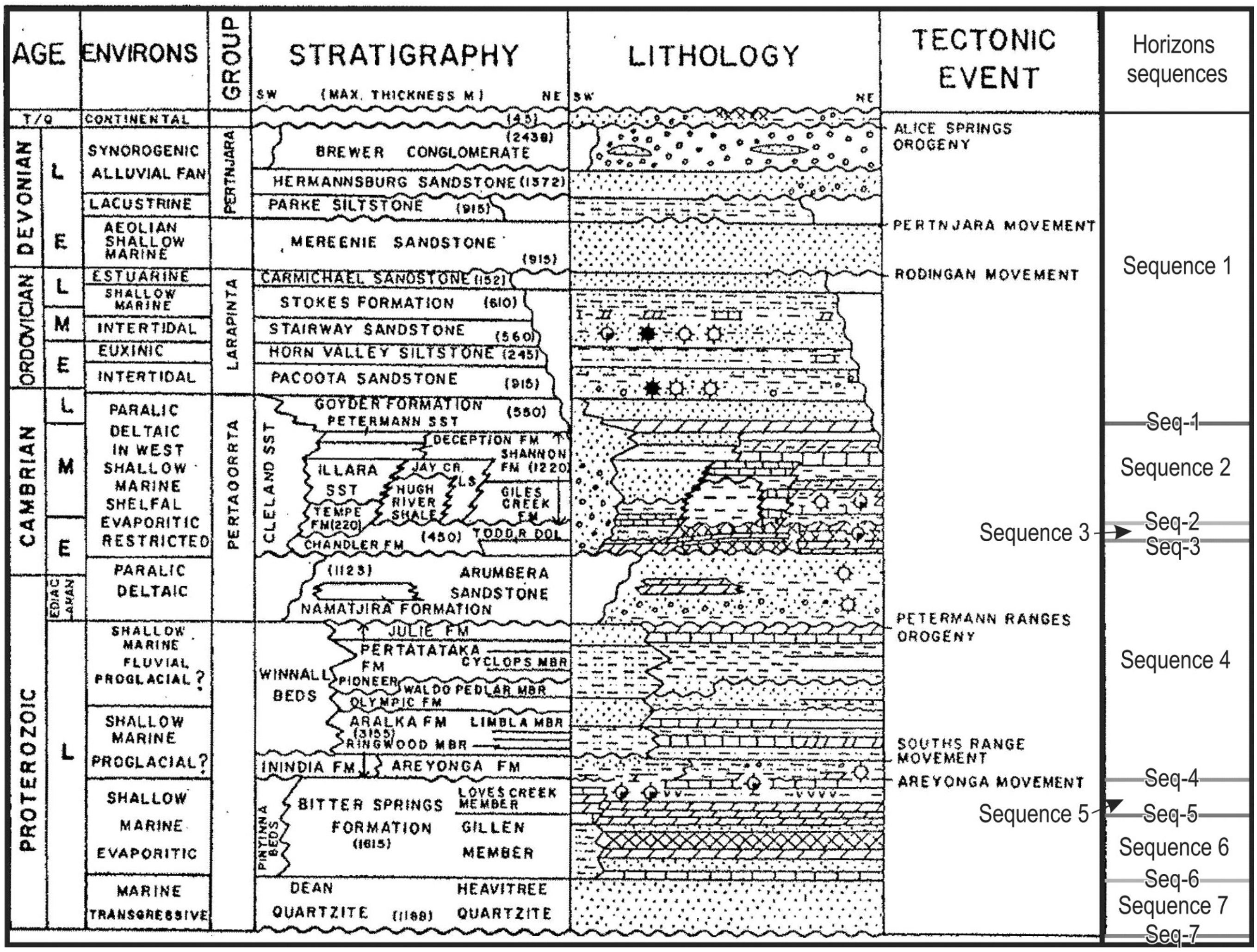


Figure 2. Tectonostratigraphic chart – Amadeus Basin. Altered after Bradshaw (1987).

thus, only where the Chandler Formation outcrops in the west, which does not contain evaporites, can reliable measurements of thickness be derived.

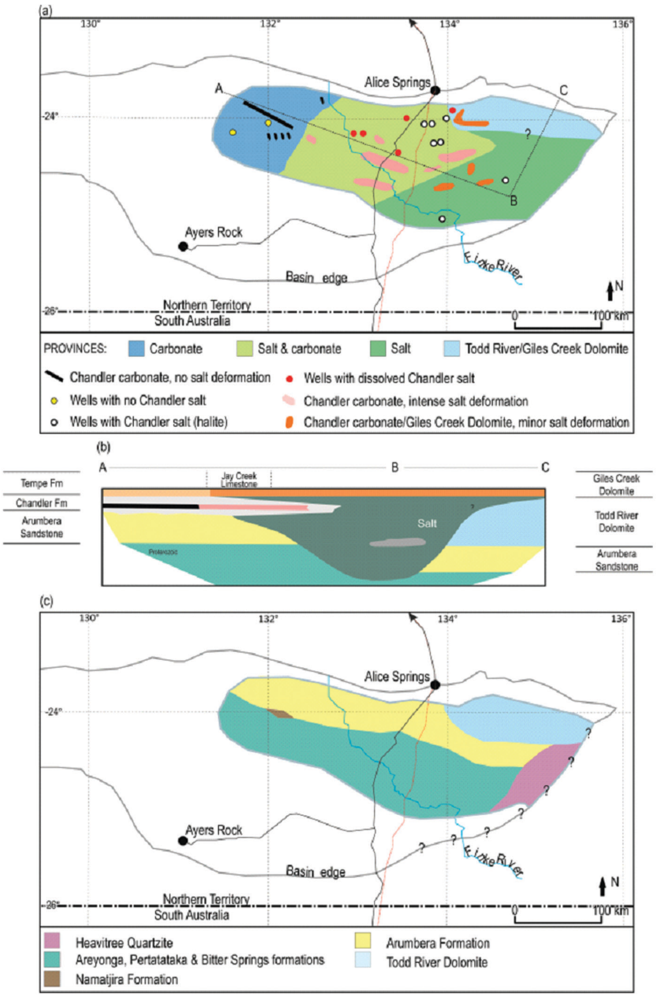
Environments of Deposition

The Chandler Formation records the transition from hypersaline evaporite conditions to a restricted carbonate regime. The environment then reverts back to an evaporite phase of deposition. Some of the main implications from the interpretation of the Chandler Formation as a marine evaporite sequence concern the mechanisms and setting in which it formed, as well as its petroleum potential in regards to reservoir, source and seal development.

Figure 3: Distribution of stratigraphic units (a) Plan view and, (b) diagrammatic cross-section of the mineralogical zonation of the Chandler Formation showing the three provinces of i) Chandler carbonate, ii) Chandler carbonate and salt, and iii) Chandler salt. (c) Subcrop map of the Chandler Formation. (Bradshaw, 1987).

Specifically as regards this paper, the northeast region is more likely than anywhere else in the basin to have been open, or at least, peripheral to a Cambrian ocean at the time of the deposition of the Chandler salt. In this region, mound features are present within the Todd River Dolomite (Bradshaw, 1987). To the southeast of the Amadeus Basin a petroleum well, McDills-1 (Amerada, 1965), intersected an Eromanga Basin sequence overlying red sandstones (Mereenie Sandstone (?)) in addition to a thick carbonate unit with a Todd River Dolomite fauna. There may have been quite an extensive carbonate sheet of Todd River Dolomite that rapidly thinned away both to the north and south from the northeast part of the Amadeus Basin (Laurie and Shergold, 1985). Thus, there may have been a broad north-south aligned front, or coastal strip, in the eastern most sector of the Amadeus Basin that could have acted as a barrier to deposition of the Chandler salt. In the Eastern Gardiner Range, there is not believed to be a temporal relationship of the Chandler Formation (evaporite or carbonate) with the mixed carbonate and clastic sequences of the Namatjira Formation (Bradshaw, 1988), but the possibility cannot be completely dismissed that the Namatjira Formation facies could exist at depth in other parts of the basin, or on other flanks of the basin. If so, it may represent an exploration target.

Of interest in the Camel Flat Syncline, is the potential stratigraphic relationship within the Todd River Dolomite, a potential reservoir facies. As shown in Figure 3c, facies underlying the Chandler Formation comprise Early Cambrian to Proterozoic sequences (Todd River Dolomite to Heavitree Quartzite, Figure 2). Evidence from the Camel Flat Syncline seismic and



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McDills-1, may indicate that there are stratigraphic relationships within the Todd River Dolomite where mound features (present in the southeast part of the basin) may represent potential petroleum exploration targets (discussed later).

Camel Flat Syncline

The Camel Flat Syncline is located in the south-eastern corner of the basin, flanking the Simpson Desert, and is in the salt wall province (see Figure 3a). One petroleum well has been drilled in the area, Bluebush-1, which encountered nearly 700m of Chandler salt. The only seismic survey over this region (Camel Flat 1981) was acquired prior to the drilling of this well.

The outcrop pattern adjacent to the Camel Flat Syncline is directly related to the structural modification of the stratigraphic section by salt withdrawal from the Syncline into steep salt walls. Also, Proterozoic salt (i.e. Gillen Salt Member – see Figure 2) is present but plays a minor role in the structural modification of the stratigraphic section. The Proterozoic salt does however influence the distribution of the overlying Aralka and Pertatataka formations, Arumbera Sandstone and Chandler Formation (discussed below).

Heavitree Quartzite, Bitter Springs Formation (Gillen Member, Loves Creek Member) – Proterozoic

Bluebush-1 intersected formations down to the Gillen Member; however, the seismic character is transparent at the well location so that ties can be considered jump-ties. It follows that the Heavitree Quartzite and Bitter Springs Formation members cannot be interpreted conclusively in the study area. Three seismic sequences and four seismic horizons have been interpreted (Sequences-7 to -5, Seq-7 to Seq-4, Figure 2); the horizons tie to top basement, near-top Heavitree Quartzite, near-top Gillen Member and near-top Bitter Springs, respectively (Figure 5).

The maps 'top basement', near-top Heavitree Quartzite and near top Gillen Member' mirror each other showing localised highs at and adjacent to Bluebush-1, with a sub-regional high area located in the eastern part of the study area (Figure 4a). The above three horizons merge in the eastern part of the study area as depicted by the onlap edge (Figure 6a). Substantiating any onlapping of the Heavitree Quartzite as is interpreted to the south at Mt Kitty (Palmer, Heugh et al., 2012) is difficult. The sub-regional low of the Camel Flat Syncline fringes the northern edge of the interpreted area. In contrast to the above, the map 'Near-top Bitter Springs Formation' shows several localised highs in the central west area of the Camel Flat Syncline (i.e. mounds A, B, C, Figure 4b). The localised highs are interpreted as shale–carbonate buildups resulting from salt mobilization and the underlying low-relief salt pillows that belong to the Gillen Member – an isopach best portrays the pillows (Figure 6a, also described below).

Julie, Pertatataka Formations (Proterozoic); Arumbera Sandstone, Todd River Dolomite (Early Cambrian)

Similar comments to the above apply here with regards to the well-tieing of the Julie and Pertatataka Formations, both intersected in Bluebush-1 (Bell, 1983). Individual formations have not been differentiated in this study due to the absence of obvious sequence boundaries in addition to direct well-ties. One seismic sequence and horizon are interpreted (Sequence-4, Seq-3, Figure 2). Sequence-4 is seismically distinct from the overlying sequence having mostly a high reflectivity, probably as a result of intercalating marine shales and carbonates present as opposed to the overlying dominantly salt-bearing section.

A number of mound features are present in seismic sequences 5 and 4 (Figures 4b, 4c, 6b); an onlapping relationship is observed in both sequences with truncational erosion of the upper section (Figure 5). A velocity pull-up exists underneath the mounds, as may be expected with a carbonate buildup; hence, the mound near the base of the Chandler Formation is interpreted as an archaeocyathid mound, as occurs in the Todd River Dolomite to the north of the Camel Flat area (Bradshaw, 1987). The mound is in the order of 3000m wide and up to 150m thick, and is of significance in that its presence indicates that deposition may have been synchronous with the basal Chandler salt deposition. This is important to the notion that in the northeast part of the basin where the Todd River Dolomite is well developed (see Figure 3c); carbonate buildups may have acted as a barrier behind which the Chandler salt deposition accumulated. An alternative interpretation is that the mound feature consists of

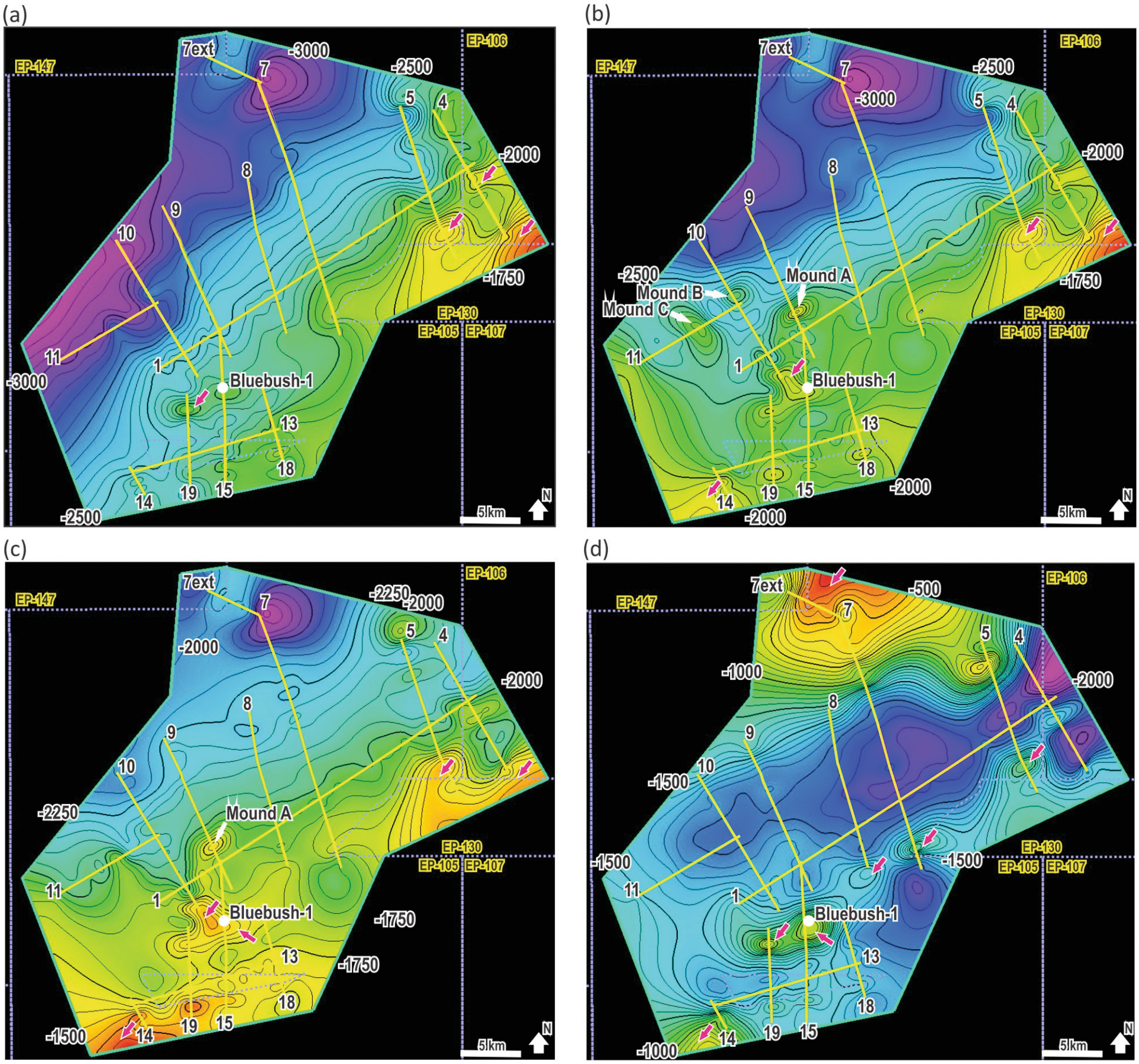

Figure 4. Depth structure maps (mKB, CI = 50m) of: (a) Seq-5 (top Gillen Mbr), (b) Seq-4 (top Bitter Springs Fm), (c) Seq-3 (base Chandler salt), and (d) Seq-2 (top Chandler salt). Pink arrows depict structural highs resulting partly from both Proterozoic salt although mostly from the mobilization of the Chandler salt.

debris left behind from salt mobilization with intercalated shale and siltstone also recorded from cuttings at Bluebush-1 (Bell, 1983). The direction(s) of salt flow are indicated by the rapid thickening of the salt (Figure 6c) as well as from sequences downlapping on the base-of-salt reflector (described below).

The Arumbera Sandstone was not intersected in Bluebush-1, although considered a drilling objective (Bell, 1983). However, the mapping here suggests that it may be present in the western part of the Camel Flat Syncline region; it is interpreted as onlapping the mound features (Figure 5, 6b). The surface of 'base Chandler salt' (Seq-3) deepens to the north while the 'top Chandler Formation' surface shallows (compare Figures 4c and 4d), the difference reflecting the presence of massive salt thickness in the form of salt walls on the northern edge of the Camel Flat Syncline. In comparison, the salt thickness is less marked on the southern edge of the Camel Flat Syncline.

Chandler Formation (salt and carbonates) – Early Cambrian

Similar comments to the above apply to the Chandler Formation with regards to well-tieing; the Chandler Formation is intersected in Bluebush-1 (Bell, 1983). One sequence and horizon is interpreted (i.e. Sequence-3 and Seq-2, Figure 2). Seismic downlap is observed on lines extending from the syncline towards the salt walls (Bradshaw, 1987). The basal downlap surface can be interpreted as a thrust ramp developed within the complex of mobilized salt, similar to that exposed at Three Mile Waterhole on the Finke River (Bradshaw, 1987).

In the eastern third of the Camel Flat area, the Chandler-Formation reflectors overlie steeply dipping reflectors that may coincide with metamorphic and/or igneous basement (eastern end of lines 1 and 4, Figure 4). The steeply dipping reflectors have

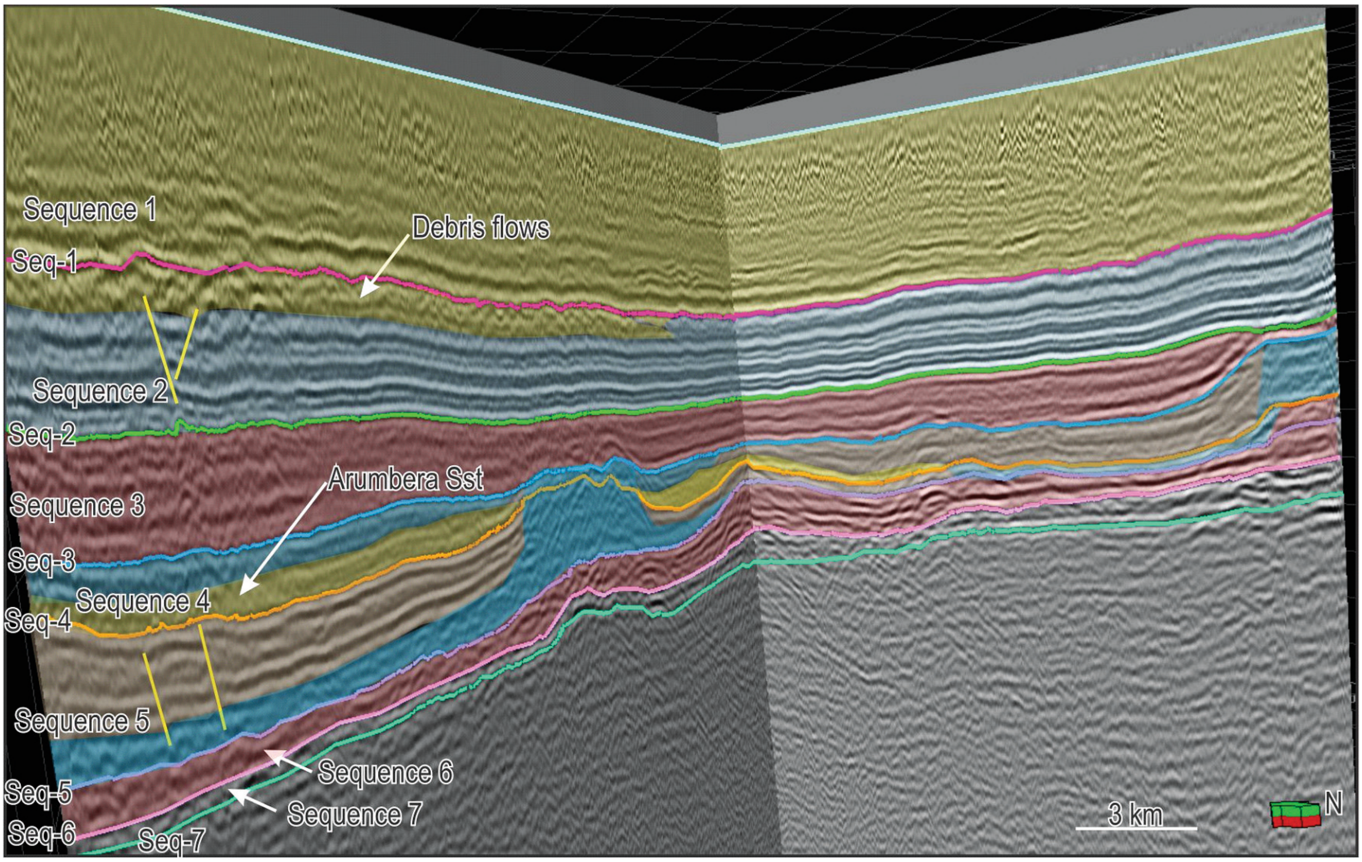

Figure 5. Seismic facies – Camel Flat Syncline (lines 10 and 11, see Figure 4 for location; refer to Figure 2 for stratigraphic nomenclature). Anticipated, dominant lithology is represented by colour shading and partly based from lithology intersected at Bluebush-1: salt (red), shale (brown), sand (?, yellow), carbonate (blue).

poor seismic reflectivity and diffractions are present; however, sequences 7 to 5 pinch out east of line 7. Depth-to-magnetic basement puts the basement at ~ 1700 mKB (Wells, Forman et al. 1970); thereby, compatible to that interpreted here on seismic data (-1700 to -1600 mKB, Figure 4a). The prognosed depth-to-magnetic basement is deemed shallow in comparison to the rest of the Amadeus Basin where basement depths are observed in excess of -9,000 mKB.

The isopach map of the Chandler Formation (Figure 6c) closely resembles the form of the depth structure map of the top Chandler Formation (Figure 4d) as the Chandler salt has flowed, and where it has formed steep salt walls, it is subsequently also very thick. The axis of the syncline coincides with the zone of maximum salt withdrawal, and is thus a structural low and an isopach thin: note that the Chandler Formation is interpreted as absent in the eastern part of the Camel Flat Syncline (Figure 6c). This trend is modified slightly where the Chandler Formation thins over the Proterozoic salt highs, the latter present along the synclinal axis.

Post-Chandler formations – Ordovician to Devonian

Similar comments to the above apply to post-Chandler formations with regards to well-tieing; the Giles Creek, Shannon and Goyder Formations may have been intersected while the Mereenie Sandstone was intersected in Bluebush-1 (Bell, 1983). Two sequences and one horizon are interpreted (i.e. Sequence-2 and -1, Seq-1, Figure 2). The seismic character across seq-1 changes from highly reflective to semi-reflective– transparent (Figure 5), interpreted as reflecting a change from shallow marine carbonates and shales to a dominantly fluvial clastic section. In addition, debris flows are interpreted on several lines (Figure 5), probably reflecting instability-of-slope conditions at the time of the Alice Springs Orogeny. Sequence-2 and -1 together reflect post-Alice Springs Orogeny deposition, with in excess of 2km of sediment shown to be present along the axis of the Camel Flat Syncline (Figure 6d). Ordovician formations were not intersected at Bluebush-1; thereby, a significant hiatus exists. The Mereenie Sandstone is tentatively interpreted; however, its presence does not add significantly to the geohistory of the Camel Flat Syncline region.

Structural considerations

A number of structural features in the Camel Flat area are described below.

- Proterozoic highs are present at the neck of the elongated basin shape of the Camel Flat syncline region; these may have controlled, in part, depositional patterns. The highs may have acted, in part, as barriers to Chandler salt deposition where a thinner salt layer would resist salt mobilizing into the salt walls known to be present on the southern and northern edges of the Camel flat Syncline. If the salt supply was exhausted or diverted from an even and continued flow, the development of salt walls could have been arrested. In this way, the Proterozoic highs may have constricted the extent of the salt withdrawal and influenced the shape and nature of the structural deformation.

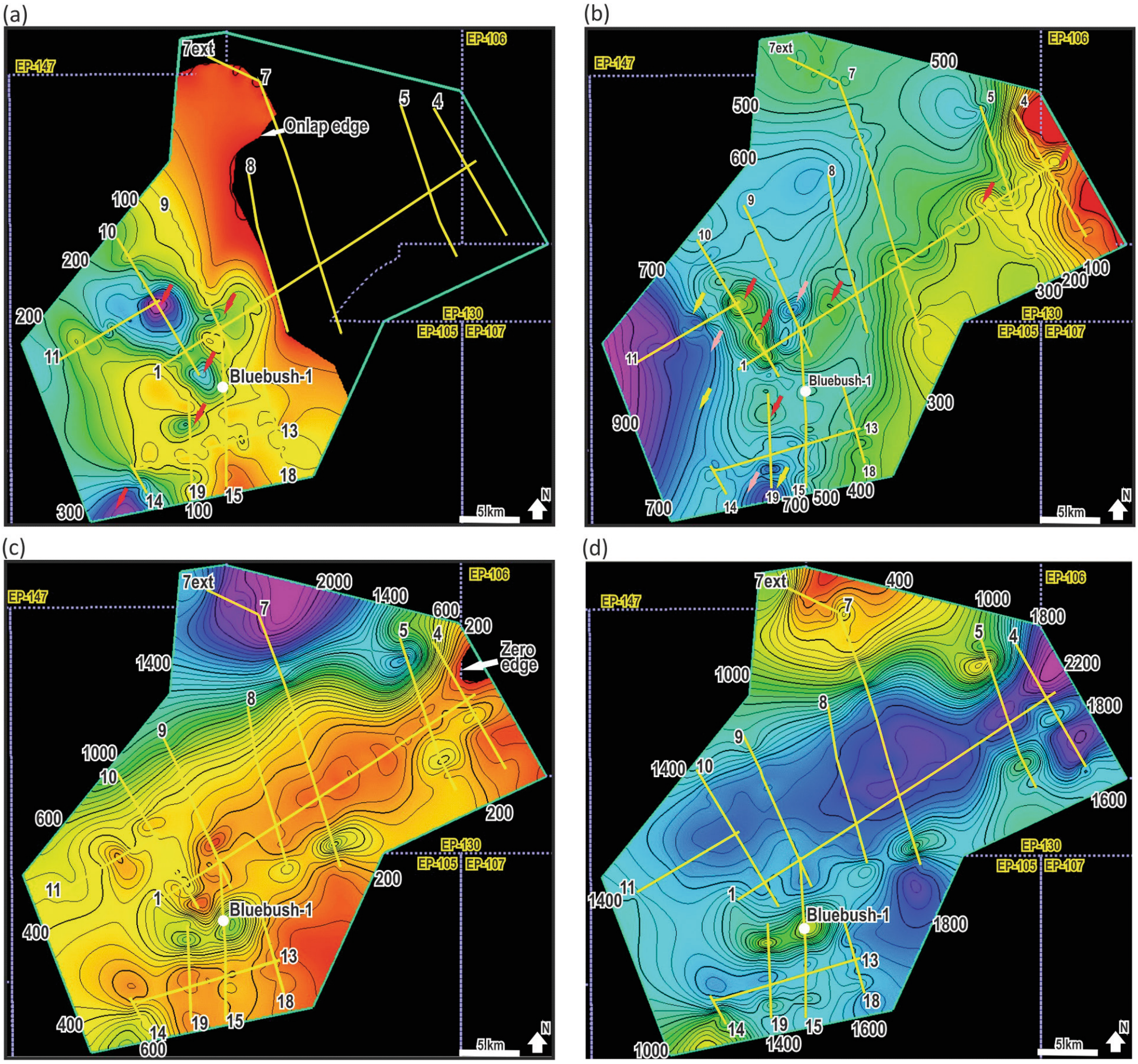

Figure 6. Isopach maps (m, CI = 25 & 50m) of (a) Sequence-6 (Gillen salt), (b) Sequences -5 and -4 (Loves Creek Mbr, Pertatataka Fm, Arumbera Sst, Todd River Dolomite), (c) Sequence-3 (Chandler Fm), and (d) Sequences -2 and -1 (post-Chandler formations). Red arrows show the location of Proterozoic salt (Sequence-6) pillows (in part a) with thinning of overlying sequences (in part b). Pink arrows show areas of back-reef (?) thicks (in part b; also see Figure 5). Yellow arrows show the area where the Arumbera Sandstone is interpreted to thin, also representing an onlap/pinchout play (in part b, also see Figure 5).

- Large-scale faults are absent in the Camel Flat Syncline region (Figure 4); in contrast, localised intra-sequence-2 faults are present above the Chandler salt (Figure 5). The vertical offset of the minor faults is less than one seismic cycle; the mode is normal with the exception of one fault that is reverse. These faults are interpreted as being caused by instability-of-slope and/or mobilization of the underlying salt; these do not cross/transect significant stratigraphic section and, thus, are unlikely to act as trap-breach conduits.

- Zones of seismic transparency exist, particularly prevalent at Bluebush-1; here, salt walls are interpreted from outcrop – the well is of little use in correlation. The seismic line on which Bluebush-1 was drilled (line 15) transects the Rodinga Ranges. The outcrop mapping produced by Oaks and others for Magellan Petroleum (1980s) interprets an elongated fault along the length of the ranges (Bradshaw, 1987). On the seismic records, there is no vertical displacement of the basal Chandler Formation horizon across the salt walls, and the salt body appears symmetrical. In both the Rodinga Ranges and the Train Hills, the Chandler Formation has been mapped as being thrust up against the Mereenie Sandstone (Bradshaw, 1987). The thrust faulting only displaces units above the Chandler salt; this observation is consistent with sequences downlapping on an interpreted thrust ramp.

- Timing of the compressional regime associated with the Alice Springs Orogeny is, in part, indicated by the absence of the Ordovician section at Bluebush-1, but also, by debris flows consistently interpreted from chaotic seismic facies (Figure 5). These facies are interpreted on the northern edge of the Camel Flat Syncline on lines 8 to 11 – they are possibly late Ordovician in age.

Exploration Opportunities

The stratigraphic interval of interest that is considered prospective includes the Arumbera Sandstone, Todd River Dolomite, Chandler Formation and potentially the Julie/Pertatataka Formation. The Chandler Formation incorporates the Chandler salt, with the interval thickening in excess of 1000m where salt walls are present (Figure 6c). Bluebush-1 drilled a salt wall on the southern edge of the Camel Flat Syncline. The well did not intersect hydrocarbons in the Chandler Formation and Todd River Dolomite; however, total organic content analyses in black shales present in the Gillen Member are ~ 1%, vitrinite reflectance analyses are 0.56% and 0.69%, hydrogen index estimates are ~ 200 – the above all-together indicative of a type III kerogen (Bell, 1983).

The primary play types in the Camel Flat Syncline are described below.

- The Arumbera Sandstone was not intersected in Bluebush-1 even though it was considered the primary exploration objective, being a petroleum-bearing reservoir further to the northwest (Bradshaw, 1987). However, the interpretation here suggests that it may be present in the western part of the Camel Flat Syncline where it onlaps mound features on its southwestern fringe. A pinchout play may be viable and be sourced from black shales of the underlying Gillen Member , the latter described in Bell (1983).

- Mound features are present below the base of the Chandler salt and within the sequence encompassing the Todd River Dolomite, basal Chandler (?), Arumbera Sandstone (?) and Loves Creek Member (?). The mounds form localised highs with a closure height of ~ 150–100 m (Figures 4b, 4c) – depths range from 2450–2100 m. Possible interpretations of the mound features include: (1) minor salt pillows linked to the salt wall underlying and adjacent to Bluebush-1, (2) debris accumulations resulting from withdrawal of the Gillen Member and/or Chandler salt from the syncline area; and (3) a carbonate buildup in the form of a bioherm such as an archaeocyathid mound (Todd River Dolomite) or buildups of stromatolite domes (Loves Creek Member). The biohermal interpretation is favoured for a number of reasons. The gradient of the depositional slope is anticipated to be shallow so that debris accumulations are less likely in terms of mound style shape; although large thicknesses of stacked thrust ramps of Chandler carbonate do occur in outcrop in the Chandler Ranges. The mound features are observed as being distinct seismic facies from the surrounding facies in contrast to being a merged salt body originating from below. The question remaining is whether these bioherm features represent a viable exploration target. Ultimately, fractured and/ or vuggy carbonate would be required for a reservoir to be established, or early hydrocarbon emplacement prior to or synchronous with diagenesis. Given that this is the pinchout edge of the basin, there is a possibility of less burial and diagenetic processes, compared with reservoir facies in the stratigraphically thicker parts of the basin.

- Intra-Chandler Formation stratigraphic traps may be present where sands may be interbedded with salt, shale and carbonate beds; this could potentially even include Namatjira Formation style facies. No seismic-based evidence of channelling has been observed within the Chandler Formation so that any viable petroleum play would encompass tight gas production from shale–carbonate facies.

- A combined pinchout edge for pre-Chandler salt units is interpreted in the northeast part of the Camel Flat Syncline area; thus, pinchout traps could exist. However, the viability or reservoir that lacks a vuggy and/or fractured matrix is deemed low. Fracturing may be a distinct possibility with the salt mobilisation that has occurred due to the two evaporite sequences present. The timing of generation of such fracture systems with hydrocarbon emplacement would be a future aspect requiring consideration.

- The Chandler evaporite and carbonate environments and depositional model (not discussed here in any detail) includes periods of evaporation to dryness in parts of the basin and flooding of the entire basin (marine evaporite), which from a petroleum system viewpoint has lead to formation of;

    - Karst surfaces in exposed limestone sequences, including the Chandler carbonate, Todd River Dolomite, and Loves Creek Member; thus potential reservoir facies, and

    - Formation of alternating anoxic and hypersaline conditions; thus, both forming and preserving source rock intervals, and

    - Mapping these source and reservoir relationships and considering where they may be juxtaposed could provide new insights for petroleum prospectivity both for conventional and non-conventional plays associated with the Chandler Formation, either on the flanks of the basin or in the more central regions.

Conclusions

Five play types have been differentiated in this study. Future work in this area would include opportunities to look in more detail at the depositional systems within the Todd River Dolomite and Chandler Formation, both in the Camel Flat Syncline region and at the regional level. Exploration opportunities could exist throughout the Chandler Formation if invoking a non-conventional shale/carbonate gas play, particularly in the central parts of the basin where the organic rich intervals of the Chandler carbonate are enveloped within the thick halite units, but also in the development of karstic surfaces for reservoirs.

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