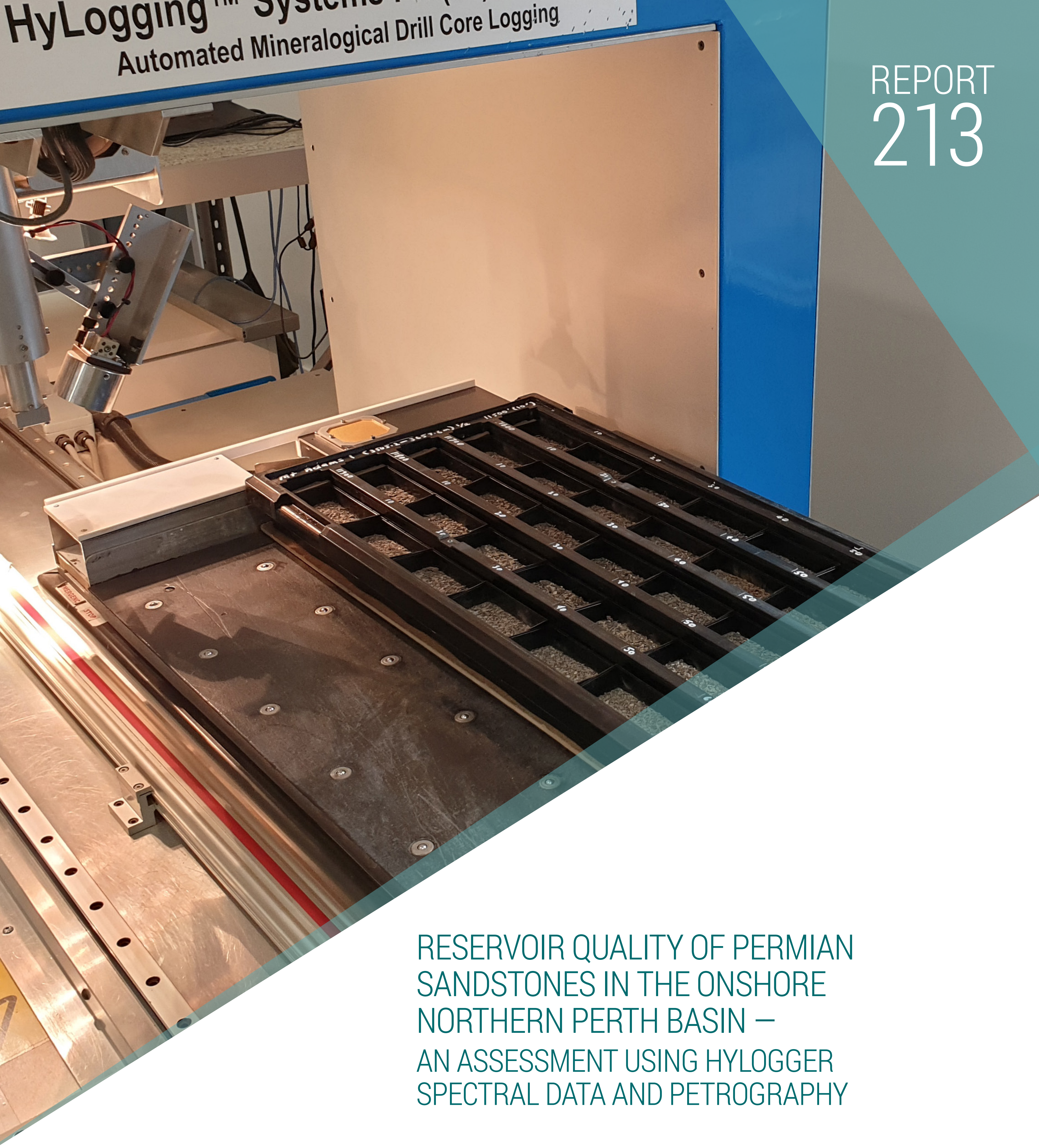

REPORT
213

RESERVOIR QUALITY OF PERMIAN SANDSTONES IN THE ONSHORE NORTHERN PERTH BASIN — AN ASSESSMENT USING HYLOGGER SPECTRAL DATA AND PETROGRAPHY

by

IA Copp, MJ Wawryk and EA Hancock

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Geological Survey of Western Australia

MINISTER FOR MINES AND PETROLEUM
Hon Bill Johnston MLA

DIRECTOR GENERAL, DEPARTMENT OF MINES, INDUSTRY REGULATION AND SAFETY
Richard Sellers

EXECUTIVE DIRECTOR, GEOLOGICAL SURVEY AND RESOURCE STRATEGY
Jeff Haworth

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Cover image: Hyperspectral scanning of cuttings from the Dongara–Wagina reservoir in Mt Adams 1

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Reservoir quality of Permian sandstones in the onshore northern Perth Basin — an assessment using HyLogger spectral data and petrography

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Abstract

The onshore northern Perth Basin is a prolific hydrocarbon province, with 21 commercial hydrocarbon fields discovered since the early 1960s, including the 2014 discovery of the large Waitsia gasfield. The primary reservoirs within the basin are shoreface to shallow-marine siliciclastic facies within the Lower Permian 'Kingia sandstone' and High Cliff Sandstone, and the Upper Permian Dongara and Wagina Sandstones. Diagenetic alteration and burial compaction, which strongly influence the amount and types of porosity development, have been interpreted using newly acquired HyLogger spectral data from 75 wells and historical petrographic data from the northern Perth Basin. The regional diagenetic progression of authigenic replacement by illite is characterized by zones of kaolinite, then kaolinite–illite and then illite with increasing burial and temperature (>80 °C). A likely byproduct of this process is an increase in quartz overgrowths, which is a primary control on porosity reduction. Regionally, the reservoirs transgress all diagenetic zones and show predictable differences in the relative abundance of kaolinite and illite with depth. These differences are largely controlled by burial temperature, with provenance, facies and salinity gradients likely acting as secondary influences. For individual wells, marked vertical changes in the relative abundance of kaolinite vs illite within the kaolinite–illite zone probably reflect a combination of controls, including differences in permeability, grain mineralogy and hydrocarbon- vs water-bearing zones. Grain-rimming chlorite has significantly preserved porosity from quartz overgrowths in the 'Kingia' – High Cliff reservoir and to a lesser extent within the Dongara–Wagina reservoir. For these reservoirs, average porosity is greater than 16% in the kaolinite zone, 9–16% in the kaolinite–illite zone and less than 9% in the illite zone. Along with porosity loss due to burial compaction, this steady decrease in porosity is also consistent with a model of progressive illitization and quartz overgrowths with increasing burial temperature. Illitic clays appear to have minimal effect on porosity development, but have a stronger influence on permeability.

KEYWORDS: diagenesis, Dongara Sandstone, High Cliff Sandstone, 'Kingia sandstone', sedimentary geology, Permian, Perth Basin, petrology, petroleum, Wagina Sandstone

Introduction

Understanding the distribution and styles of porosity within reservoirs, and predicting where they are best developed, is fundamental to petroleum systems analysis, carbon sequestration and geothermal exploration. Porosity development is primarily controlled by the extent and style of diagenesis during burial and heating, which forms clays such as kaolinite, illite (white micas) and chlorite, and carbonate and SiO_2 (quartz overgrowth) cements. Whereas some of these minerals help preserve primary porosity (e.g. chlorite), others significantly reduce porosity (e.g. quartz overgrowths).

The types, distribution and abundances of authigenic minerals are influenced by many variables during a basin's history, including:

- facies and provenance — these influence the contribution of clay-forming minerals such as feldspars, micas and lithoclasts (labile grains)
- burial (heating) history — this influences the depths at which mineral transformations such as illitization take place
- formation water chemistry — this includes salinity and pH controls that help drive mineral transformations like kaolinization and illitization
- structural compartmentalization — this helps drive localized fluid flow like hydrothermal fluids and hydrocarbon migration.

Quantitative assessment of each variable is required to determine their relative importance in driving diagenetic processes and hence their significance in controlling porosity development. Underpinning robust assessments of these variables is the need for a stratigraphically comprehensive, basinwide authigenic mineral dataset. Historically, such datasets were derived from petrographic and X-ray diffraction (XRD) analyses; however, the advent of HyLogger spectral data now allows novel and rapid regional assessments of clay and cement development in reservoirs, which can be verified with petrographic and XRD data.

HyLogger applications for reservoir analysis

The recent use of HyLogger data to assess diagenetic development in reservoirs is such that there are few publications that document this approach. In particular, its use of cuttings samples can significantly aid regional and stratigraphic assessment of diagenetic alteration that is otherwise not possible using core alone, which generally provides incomplete stratigraphic coverage. Whereas well completion reports mostly contain lithological descriptions of cuttings, albeit simplified or coded, relatively few intervals are used to make thin sections or for analyses (e.g. geochemistry and palynology) — the majority of these samples remain unanalysed long after being collected. Scanned cuttings, however, can provide high-resolution mineralogical and compositional data, as well as digital images that can be used to help plan future sampling programs.

HyLogger data for individual wells also provide diagenetic profiles across reservoirs that can be incorporated with facies and petrophysical analyses. This data also can help identify or confirm significant sequence stratigraphic surfaces from indicative authigenic mineral assemblages (Morad et al., 2013).

Acquiring HyLogger data from onshore northern Perth Basin wells provides a regionally and stratigraphically extensive approach to document the diagenesis of its proven Permian reservoirs. Integrating this data with existing petrography and testing it against contemporary diagenetic models will help develop regional predictive diagenetic-porosity models.

Geological setting

The northern Perth Basin is part of the southerly trending, elongate rift along the west coast of Australia containing mostly Lower Permian to Lower Cretaceous continental clastic facies. The northern onshore part of the basin is dominated by the Dandaragan Trough, which is flanked by structurally defined terraces and shelves. The trough formed a major depocentre containing up to 12 km of sedimentary rocks in which subsidence was largely controlled by the Darling and Urella Faults (Fig. 1). Sediments were deposited in a rift system that culminated with the breakup of Gondwana in the Early Cretaceous. Two major tectonic phases are recognized: Permian southwest–northeast extension, and Early Cretaceous northwest–southeast transtension during breakup. Sinistral and dextral movements are inferred along major north-striking faults during these phases, particularly during breakup when wrench-induced anticlines formed and further faulting took place. Two major regional episodes of heating and cooling (burial and erosion) are evident — the first mostly during the Cretaceous (135–65 Ma), and the second spanning the Oligocene to Quaternary (30–0 Ma). The most recent discussions of the basin's tectonic framework and burial history are by Thomas (2014) and Ghori (2018), respectively.

The Phanerozoic onshore northern Perth Basin is a mature exploration terrane with 21 commercial hydrocarbon fields discovered since the early 1960s. The recent large gas discoveries in deeply buried Lower and Upper Permian siliciclastic reservoirs (Waitsia, Beharra Springs Deep 1 and West Erregulla 2; Fig. 1) demonstrated that understanding diagenetic changes at depth is critical in predicting reservoir quality. Several works have assessed the relationships between diagenesis and porosity in these reservoirs (Rasmussen, 1992; Tupper et al., 1994, 2016; Rasmussen and Glover 1996; Laker, 2000; Ferdinando et al., 2007); however, there is no regional synthesis integrating all available petrographic data. Additionally, since the late 1990s there has been substantial research published on the diagenesis of siliciclastic systems that can now be applied to this dataset (e.g. Morad et al., 2000; Worden and Morad, 2002; Ziegler, 2006; Taylor et al., 2010; Beaufort et al., 2015).

Petroleum geology

Oil and gas has been produced from 21 fields in the onshore northern Perth Basin of which the largest is the Waitsia gasfield discovered in 2014. Many of these fields are now either depleted (e.g. Mondarra, Mount Horner, North Yardanogo and Yardarino), shut in (e.g. Apium, Corybas, Dongara, Eremia, Hovea, Red Gully, Xyris and Xyris South) or not yet developed (e.g. gas in Beharra Springs Deep, Senecio and West Erregulla; Fig. 2). In 2019–20, gas and condensate was being produced from Beharra Springs, Redback and Waitsia, and oil from Jingemia. Productive reservoirs lie within the Upper Permian Wagina and Dongara Sandstones in Beharra Springs, Dongara, Hovea and Redback, the Lower Permian 'Kingia sandstone'* and High Cliff Sandstone in Waitsia, tight sandstone within the Lower Permian Irwin River Coal Measures in Corybas, and the Jurassic Cattamarra Coal Measures in Red Gully. Source rocks with predominantly gas–condensate generating potential have been identified within Permian, Triassic and Jurassic intervals (Thomas, 1979; Thomas and Barber, 2004).

The majority of oil and gas–condensate that has been produced is correlated with source rocks within the Lower Triassic Hovea Member of the basal Kockatea Shale in the Dandaragan Trough. The source of the gas in the Waitsia field is thought to be the Irwin River Coal Measures and the Carynginia Formation (Tupper et al., 2016). Peak hydrocarbon charge and expulsion took place between the Late Jurassic and mid-Cretaceous during a major period of burial within the Dandaragan Trough (Crostella, 1995; Thomas and Barber, 2004; Tupper et al., 2016). The organic geochemistry and petroleum systems modelling of the Perth Basin are discussed by Ghori (2018). A list of all petroleum wells mentioned in this Report is included in Appendix 1, and formation tops of selected wells are listed in Appendix 2.

Permian reservoir stratigraphy

The primary reservoirs in the onshore northern Perth Basin are the Lower Permian 'Kingia sandstone' and High Cliff Sandstone ('Kingia' – High Cliff reservoir), and the Upper Permian Dongara and Wagina Sandstones (Dongara–Wagina reservoir, Fig. 2). Informal subdivisions of the Lower Permian reservoir interval as used by petroleum exploration companies and referred to in publications (e.g. Tupper et al., 2016) are used within this Report.

* Informal stratigraphic name

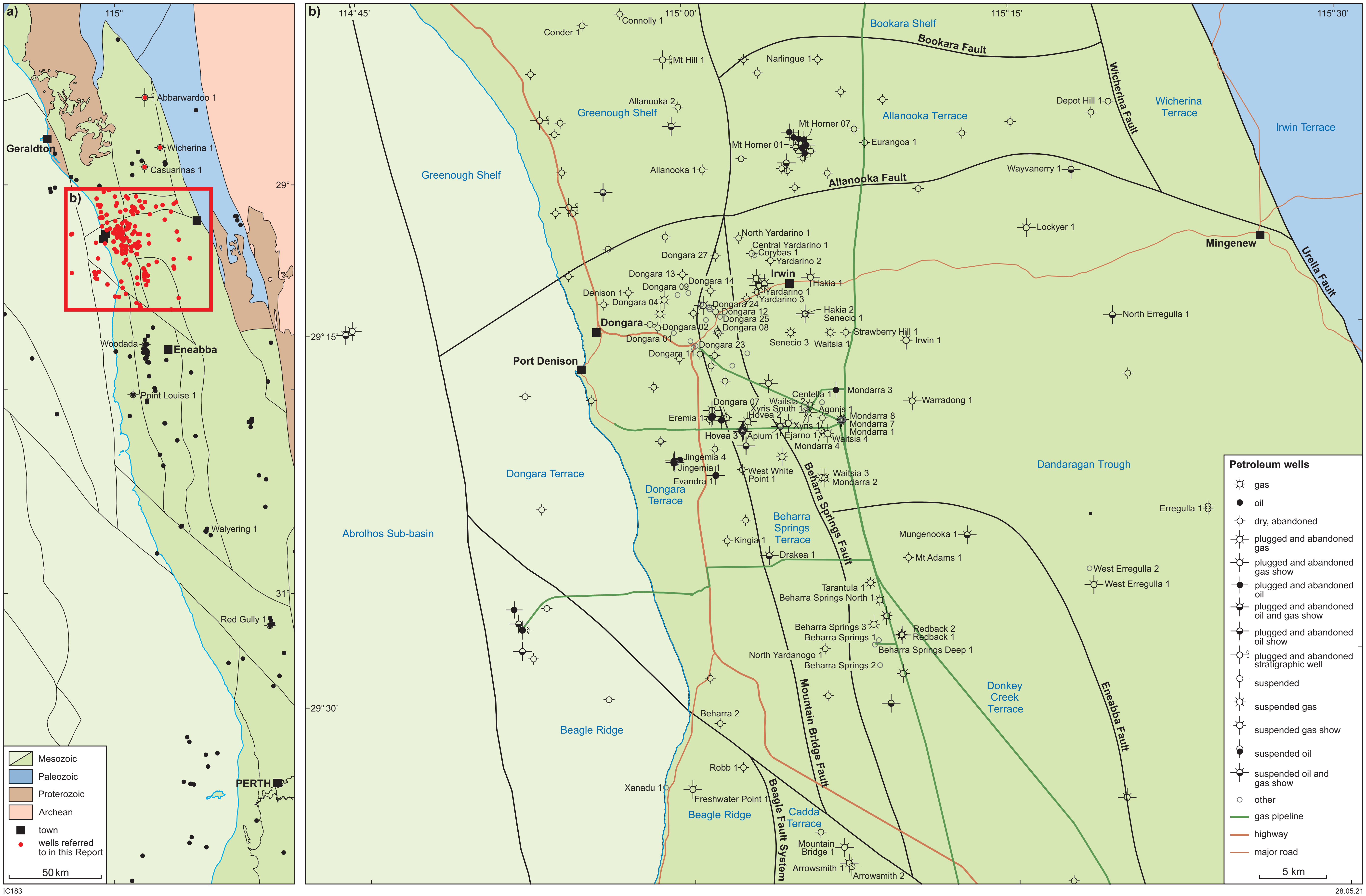


Figure 1. Map of the northern Perth Basin study area: a) location and regional tectonic setting of the study area (region bounded by the red box) with selected petroleum wells; b) tectonic units, exploration wells and petroleum discoveries within the study area

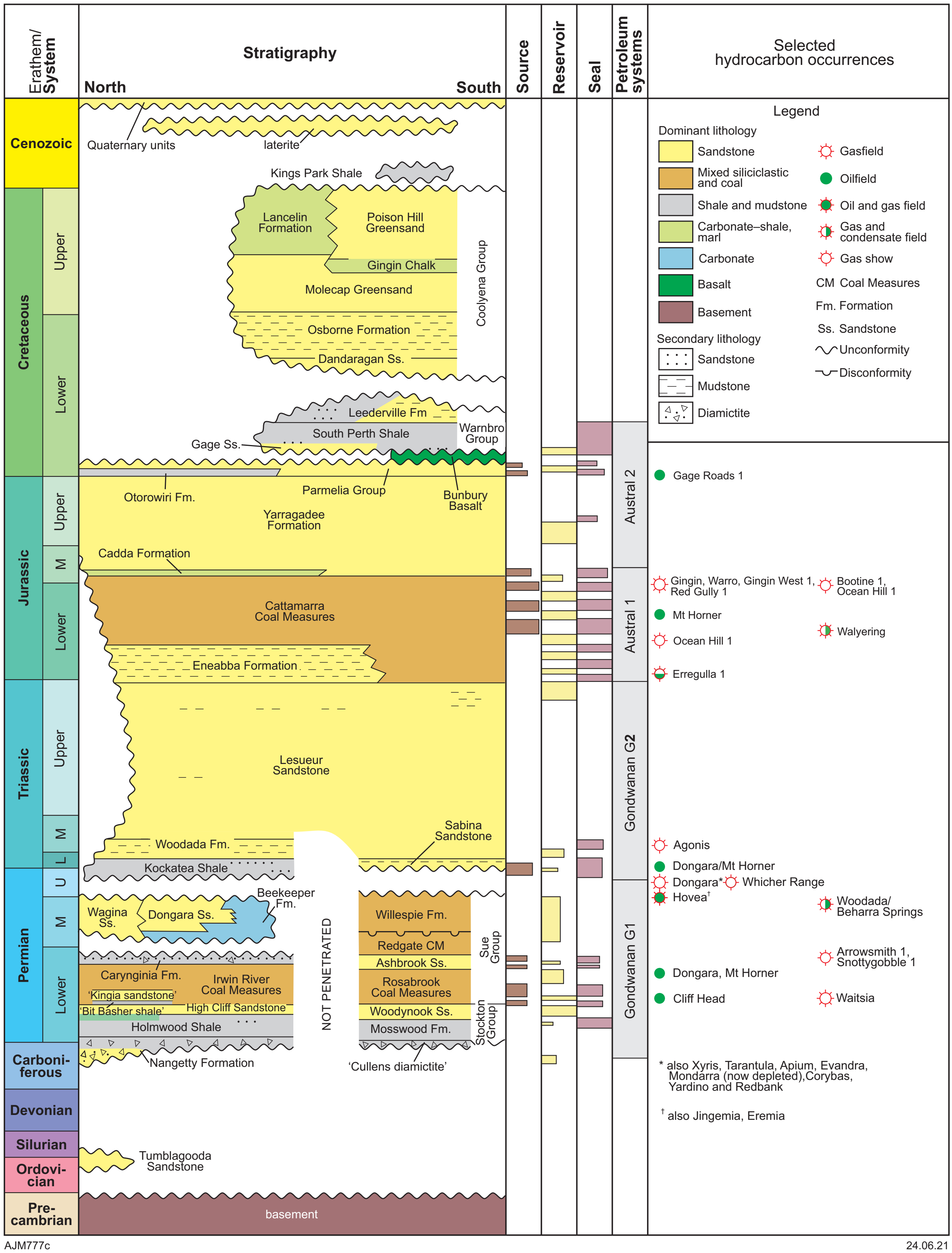


Figure 2. Stratigraphy and petroleum sources, reservoirs, systems and discoveries in the Perth Basin

Assessing these units and formalizing the nomenclature was beyond the scope of this study. For convenience, Permian reservoir names are abbreviated from their stratigraphic antecedents such that the formal qualifier is replaced with the informal term 'reservoir'.

The Dongara–Wagina and 'Kingia' – High Cliff reservoirs, although predominantly quartz rich, also contain lithoclasts, mica and feldspar derived from Archean and Proterozoic terranes. The grains have been variably diagenetically altered to kaolinite and illite clays, and less commonly to chlorite and carbonate. Authigenic grain-rimming chlorite (after an Fe-rich clay precursor) in the 'Kingia sandstone' and less commonly within the High Cliff Sandstone and Dongara–Wagina reservoir, has helped preserve primary porosity by inhibiting porosity-occluding quartz overgrowths (Tupper et al., 2016). Consequently, excellent reservoir quality is present at great depths in the Dandaragan Trough (e.g. at 4800 m in West Erregulla 2; Strike Energy Ltd, 2019).

There is significant variation in the proportion of labile grains between wells and reservoirs as measured during petrography, which probably reflects a combination of provenance and facies controls, modified by diagenetically controlled alteration and dissolution.

'Kingia' – High Cliff reservoir

The High Cliff Sandstone outcrops along the Irwin Terrace where it consists of sandstone and conglomerate deposited in shallow-marine, beach-ridge and lower-deltaic environments (Mory and Iasky, 1996). In the subsurface, it is up to 150 m thick (in Mt Horner 1) and comprises thickly bedded quartzose sandstone and minor siltstone deposited in a shoreface setting. The High Cliff Sandstone conformably overlies the Holmwood Shale. It is conformably overlain by the 'Bit Basher shale'*, which is only recognized in the subsurface where it is between 5 and 50 m thick, comprising silty sandstone and siltstone deposited in a lower-shoreface to inner-shelf environment (Tupper et al., 2016).

The informal Lower Permian 'Kingia sandstone' is currently recognized only in the subsurface. It overlies the 'Bit Basher shale' and is conformably overlain by the Irwin River Coal Measures. It is up to 50 m thick and consists of thickly bedded quartzose sandstone deposited in an upper-shoreface to fluvial environment (Ferdinando et al., 2007; Tupper et al., 2016).

Poor biostratigraphic control throughout the Lower Permian and the similarity of facies within the High Cliff Sandstone and Irwin River Coal Measures makes correlation of the 'Kingia sandstone' uncertain. Tupper et al. (2016) assigned the 'Kingia sandstone' and the 'Bit Basher shale' to the upper High Cliff Sandstone. Alternatively, it may be a sandier shoreface facies of the lowermost fluvio-deltaic Irwin River Coal Measures. Most intersections of the 'Kingia sandstone' are within the Dandaragan Trough in the Waitsia field (Waitsia 1–4, Senecio 3), but it has also been drilled on the adjoining terraces and shelves, for example, Hovea 2 and Mt Horner 1. In wells such as Abbarwardoo 1, Wicherina 1 and Depot Hill 1, the High Cliff Sandstone and uppermost Holmwood Shale (with interbedded sandstone) could be equivalent to the 'Kingia sandstone', 'Bit Basher shale' and High Cliff Sandstone succession; however, better biostratigraphic control is required to assess this correlation.

* Informal stratigraphic name

Dongara–Wagina reservoir

The Upper Permian Wagina Sandstone outcrops along the Irwin Terrace and has been widely intersected in wells across the northern Perth Basin. In outcrop, the Wagina Sandstone consists of clayey sandstone and pebbly sandstone with minor conglomerate, siltstone and coal deposited in a proximal-fan to deltaic environment next to the Darling Fault. It is up to 336 m thick in Depot Hill 1 adjacent to the Urella Fault. The Wagina Sandstone is unconformable on the Carynginia Formation and in the subsurface is overlain by the Dongara Sandstone.

The Dongara Sandstone is a quartzose sandstone with minor conglomerate and siltstone, and was deposited in proximal-fan, deltaic and shoreface to shallow-marine environments (Mory and Iasky, 1996). It overlies the Wagina Sandstone, and the Carynginia Formation on the Dongara Terrace and Allanooka Terrace. It is conformably overlain by the Kockatea Shale and could be coeval with the Beekeeper Formation to the south (Mory and Iasky, 1996).

The Beekeeper Formation, although not part of the Dongara–Wagina reservoir, is restricted to the subsurface predominantly on the Beharra Springs Terrace and in the northern Dandaragan Trough (e.g. Warradong 1). It is the reservoir for the Woodada gasfield in the central Perth Basin (Mory and Iasky, 1996), consists of sandstone, limestone and shale deposited in an inner-shelf environment and is up to 134 m thick (in Point Louise 1). The Beekeeper Formation unconformably overlies the Carynginia Formation and is either coeval with (Mory and Iasky, 1996), or older (Jorgensen et al., 2011), than the Dongara Sandstone.

Aims and methodology

The primary aim of the project is to provide a summary of the regional diagenesis and reservoir quality of the Dongara–Wagina and 'Kingia' – High Cliff reservoirs in the onshore northern Perth Basin, based on HyLogger and petrographic data. This Report also provides datasets and initial interpretations as a basis for future research and exploration work. The secondary aims are to:

- document the vertical distribution of authigenic minerals in reservoir intersections
- assess the relative accuracy of authigenic minerals identified from HyLogger vs petrographic data
- document regional relationships between authigenic minerals and core porosities and permeabilities
- identify depth–temperature changes in the proportions and types of authigenic clays and cements
- identify chlorite (a potentially porosity-preserving clay) using HyLogger data for wells with minimal or no petrographic data
- compare regional diagenetic trends against established

diagenetic models of global siliciclastic systems.

Seventy-five wells, including those with existing open-file petrographic data (Table 1, Appendix 3), were chosen across the northern Perth Basin to document the diagenesis of the Dongara–Wagina and 'Kingia' – High Cliff reservoirs. Petrography is mostly from conventional cores and less commonly side-wall cores (SWC) and cuttings.

Some of these aims were carried out in an earlier stage of the project that investigated the Dongara–Wagina reservoir in Senecio 3 and the 'Kingia' – High Cliff reservoir in Waitsia 1 (Copp and Hancock, 2018). Work included core logging, ichnology, HyLogger analysis of core and cuttings, and integration of existing petrography. A composite core log for each reservoir is included in Appendix 4. Initial results showed that using the HyLogger to scan cuttings was an effective and rapid technique for diagenetically profiling formations, and so this method was extended to several other wells to further test this hypothesis (Copp and Hancock, 2018). Diagenetic clays identified from both scanned core and petrography compared well against HyLogger data from cuttings, validating the methodology. Additionally, a trend with increasing depth from dominantly kaolinite to illite was identified, which was hypothesized as being controlled by burial temperature. The current stage of the project further examines these diagenetic trends in a basinwide and systematic approach, and their relationship with burial temperature and reservoir quality (core porosity and permeability).

HyLogger

HyLogger data (core and cuttings) from 75 wells were primarily collected over reservoir intervals and adjoining parts of overlying and underlying formations, including the Kockatea Shale, Carynginia Formation, Irwin River Coal Measures and Holmwood Shale. In addition, Jurassic and Triassic formations (Yarragadee Formation, Cadda Formation, Cattamarra Coal Measures, Eneabba Formation, Lesueur Sandstone, Woodada Formation) from Mondarra 1, North Erregulla 1, Wicherina 1 and Yardarino 1 were scanned and included in the dataset. In total, 930 m of core and 20 240 m of cuttings were scanned. Summary plots of all scanned intervals, including 69 intersections of the Dongara–Wagina reservoir and 28 intersections of the 'Kingia' – High Cliff reservoir are included in Appendix 5.

Analysing cuttings using the HyLogger is a new application of this system, developed by the Geological Survey of Western Australia for basin analysis. The concept of using cuttings to assess the diagenesis of northern Perth Basin reservoirs was first presented by Copp and Hancock (2018), who found a good correlation between scanned data from cuttings and core over the same interval. Despite the composite nature of cuttings and the small sample size, the data consistently exhibited similar authigenic mineral assemblages and compositional changes — few issues with downhole contamination were noted. Mineralogical changes at formation contacts are common and correlate with gamma-ray log breaks for most wells.

Table 1. Number of wells scanned

	Dongara–Wagina reservoir	'Kingia' – High Cliff reservoir
Total wells scanned	67	29
Wells with scanned core	37	5
Wells with scanned cuttings	58	25

Cuttings from wells over the reservoirs comprise mostly 5 m and less commonly 10 m composites, whereas more recent wells have 2 or 3 m composites. A representative sample of dry, washed cuttings was placed in black plastic boxes to minimize reflectance from box walls. Up to 50 boxes (spanning 250–500 m) were placed in black plastic HQ core trays and then scanned. Each sample typically provides 8–10 data points using an instantaneous-field-of-view diameter of 10 mm. Each box was then washed and dried before being reused.

Processing and interpretation of HyLogger data were carried out using The Spectral Geologist (TSG) software, and available petrographic data were used in places to help interpret problematic spectra and compare interpreted mineralogy. Summary mineral plots of thermal infrared (TIR) and short-wave infrared (SWIR) mineralogy were created for each well, showing the relative abundance of minerals with a standard 5% cutoff (Appendix 5). Bin sizes for cuttings are mostly the same as for the composite interval. Authigenic minerals such as kaolinite, illite and chlorite are mainly identified by SWIR, whereas TIR typically highlights framework (silicate) grain composition, which is dominated by quartz (sandstone).

'Illite' clay as used in this study is a general term for white mica minerals of similar composition identified using HyLogger data, including muscovitic, illitic and phengitic varieties. Illite, which is a dioctahedral phyllosilicate and structurally similar to muscovite but with a K^+ deficit (Doublier et al., 2010) and higher water content (for non-end member compositions), commonly forms a multi-layered structure resembling an illite–montmorillonite assemblage. Due to this complexity, illite is not present in the TSG mineral spectral library and therefore its automated interpretation is referred to as either illitic white mica or Al-rich smectite. Volume scattering leads to SWIR aspectral data being common for dark-coloured, low spectral-reflectance lithologies such as mudstone and shale. Consequently, illite–smectite clays that would be expected in such lithologies are missing in the SWIR spectral response. In contrast, TIR radiation produces reflectance spectra from the surface of the analysed material without penetration. TIR spectra are therefore not sensitive to dark lithologies, but do show reduced spectral contrast for cuttings, porous core and loose, fine-grained particles (Hancock et al., 2013). Thermal infrared results are less reliable for identifying clay minerals and are set up to automatically copy available SWIR data. Nevertheless, although there is some complexity in the identification of clay mineral types using HyLogger data, it accurately identifies stratigraphic trends and helps place formation and facies contacts.

The summary plots provide a proxy diagenetic profile through the scanned intervals. The relative-abundance data are not directly comparable to petrographic mineral percentages, which require normalizing before comparison.

HyLogger acquisition issues

The potential for cuttings being contaminated by caving from higher levels needs to be considered when interpreting HyLogger data. However, at the scale of interpretation and from results to date, such contamination adds very little uncertainty to a diagenetic profile (typically 50–100 m thick). From previous work and as part of the current project, the main uncertainties in assessing cuttings with the HyLogger are:

- washed cuttings have probably been stripped of much authigenic clay, and some clays might be more susceptible to this process. Some samples comprise loose sand grains, where most of the clay fraction (detrital and authigenic) has likely been lost
- remnant drilling mud can add significantly to the diagenetic signature (e.g. Mondarra 8 cuttings are contaminated by carbonate drilling mud)
- large composites (e.g. 10 m) can dilute the response of minor and rare minerals such as chlorite
- argillaceous components within sandstone samples, either in situ or due to caving from overlying shaley formations (especially the Kockatea Shale and Irwin River Coal Measures), possibly contributes to the interpreted digenetic clay signature of the reservoirs.

Some uncertainties can be minimized by comparing the data from the cuttings with equivalent scanned core intervals in the same wells where available; however, further work is required to determine the extent to which they may bias the diagenetic interpretation. Acquiring routine petrographic and XRD data over selected intervals of cuttings will help towards resolving these issues.

Petrography

Selected petrographic data were compiled from unpublished open-file reports from 1968 to 2018 (well completion reports and multi-well studies, e.g. Laker, 2000) and from several PhD studies (Appendix 6). For the Dongara–Wagina reservoir, there are 397 samples from 49 wells, and for the 'Kingia' – High Cliff reservoir there are 120 samples from 11 wells. Covariance analysis (where r is the correlation coefficient) was carried out to determine the strength of relationships between authigenic minerals and depth; between authigenic minerals; and between authigenic minerals and core porosity and permeability.

Most samples are quartz arenites containing very little (less than 3%) depositional matrix, and consequently clay percentages primarily reflect authigenic minerals (up to 20%). Where clay or cement percentage is recorded as 'trace' in reports, it is arbitrarily assigned here as 0.05% for statistical analyses. The main authigenic minerals are kaolinite, illite, chlorite, SiO_2 (quartz overgrowths), carbonate (calcite, dolomite, siderite and ankerite), and rare pyrite and baryte. Extracted petrographic data includes the percentages of framework grains (quartz, feldspars, micas, lithoclasts), authigenic clays (kaolinite, illite, chlorite) and cements (quartz overgrowths, carbonate). Modal analyses (point counting) from core provides the most reliable dataset for statistical analyses. More recent wells also have XRD data and scanning electron microscope (SEM) images.

There are several biases inherent in the datasets that should be considered when interpreting the data, namely:

- the number of samples per reservoir intersection ranges from one (Conder 1) to 32 (Mondarra 1)
- the stratigraphic position and thickness of cored intervals are extremely variable, and consequently petrographic analysis is not representative of the entire formation
- the vertical distribution of samples varies greatly between wells, with sampling typically biased towards porous zones
- petrographic data include modal (50%) and visual (50%) estimates
- the form of authigenic clay (i.e. grain rimming, pore lining, pore filling or grain replacement), is rarely quantified in older reports
- little to no petrography is available for wells with no shows. Prior to discoveries in the deep 'Kingia' – High Cliff reservoir, very few petrographic analyses were carried out on these units and the data, particularly for shallower intersections, is therefore minimal.

Comparison of HyLogger and petrographic data

HyLogger summaries were visually compared with petrographic data in each well, and the types of clay and cement were found to be broadly consistent. However, absolute proportions of clays cannot be compared as the HyLogger only records relative abundances. In addition, most wells do not have an extensive set of petrographic samples at regularly spaced intervals, so for much of the reservoir interval, the only clay determinations are from HyLogger data.

Relative proportions of clays (kaolinite vs illite) for individual petrographic samples are not consistently comparable with HyLogger data, but the correlation is much more reliable where an entire sampled interval (typically over tens of metres) is compared. Several conclusions can be made about HyLogger vs petrographic data:

- Core yields more consistent results than cuttings and is typically similar to clay mineralogy and proportions identified by petrography.
- Chlorite is consistently identified in scanned cuttings and cored intervals where it is greater than 2–3% of the total composition (based on associated petrographic data).
- Smectite is commonly identified in scanned argillaceous intervals of cuttings, but not consistently identified from equivalent cored intervals. Smectites are not identified in petrography, but are mostly evident as mixed-layer smectite–illite, illite–smectite and chlorite–smectite clays in XRD analyses.
- Dickite is identified in scanned cores, less commonly in cuttings and rarely by petrography.
- Carbonate identified by petrography is consistently identified in equivalent intervals of scanned cores and cuttings.

Porosity and permeability

Porosity and permeability analyses from core plugs and SWC were compiled from open-file data. In addition, probe permeability core measurements are available for more recent wells. For the current study, porosity and permeability data at ambient pressures were used, or where that was not provided, the lowest overburden pressure was used (predominantly more recent wells). Not all core samples used for porosity and permeability measurements have associated petrographic data, so correlating between these variables is not possible in all wells. Therefore, average core porosity, permeability, clay and cement percentages were calculated independently for each well, and then these values were used to aid correlations between wells.

Burial-history modelling

The burial-history models of Ghori (2018) were used to determine the thermal history of scanned intervals from petroleum wells. Paleotemperatures were reconstructed by adjusting thermal conductivities and heat flow to constrain his maturity models against measured corrected bottom hole temperatures, vitrinite reflectance (%R_O), temperature at maximum hydrocarbon generation (T_{max}) and apatite fission track analysis data.

Regional diagenesis

A regional diagenetic model of a basin requires significant petrographic data throughout the entire stratigraphy, and consequently is rarely achievable. More commonly, diagenetic studies focus on single intervals, such as the Dongara–Wagina reservoir. A drawback of this approach is that the dataset is not easily interpreted within a broader diagenetic framework for the basin, so the role of regional diagenetic controls on clay and cement formation can be difficult to resolve.

HyLogger data

Most of the HyLogger data for the northern Perth Basin was acquired over the Dongara–Wagina and 'Kingia' – High Cliff reservoirs; however, a substantial number of diagenetic profiles were also collected through parts of other formations (Lower Permian to Jurassic). This stratigraphically and spatially extensive dataset therefore provides a regional diagenetic profile of the basin within which the diagenesis of its Permian reservoirs can be interpreted.

Kaolinite and illite are the dominant authigenic clays identified using the HyLogger and by petrography. To assess how these clays vary within, and between, formations and their relationship with depth, each scanned interval was assigned a diagenetic subzone based on the proportion of illite relative to kaolinite:

- subzone 1 — very low illite
- subzone 2 — low illite
- subzone 3 — moderate illite
- subzone 4 — high illite
- subzone 5 — very high illite.

Scanned formations were then assigned a present-day temperature based on available burial-history models or from a nearby well with similar formation depths. Assigned subzones were then plotted against depth and temperature (Figs 3–5). Using this methodology, three regionally extensive diagenetic zones are interpreted for the northern Perth Basin:

- kaolinite zone (subzone 1; <80 °C)
- kaolinite–illite zone (subzones 2–4; 80–120 °C)
- illite zone (subzone 5; >130 °C).

The data show that with increasing depth there is a progressive increase in the relative proportion of illite relative to kaolinite (r = 0.72; Fig. 3), coincident with an increase in temperature. This is best illustrated in samples from Depot Hill 1, for which the entire section was scanned. In this well, SWIR can be used to identify authigenic clays (kaolinite, illite, chlorite, carbonate) as well as aspectral phases. Thermal infrared can be used to identify framework silicate grains (quartz and feldspar) and smectite clays. The kaolinite–illite zone lies within the upper Holmwood Shale; however, the base of the zone is uncertain. It is placed where illite becomes dominant and smectite is markedly reduced, which likely reflects a change in mixed-layer clays from smectite–illite to illite–smectite (Fig. 6). Using a least-squares fit for both the clay and temperature data to best approximate the relationship regionally, illite commences (subzone 2) at around 1900 m (80 °C) and becomes dominant (subzone 4) at about 3200 m (130 °C). Although only parts of non-reservoir formations were scanned (except in Depot Hill 1), the intervals are sufficiently thick and stratigraphically and geographically widespread to identify a regional diagenetic zonation within the basin stratigraphy (Fig. 7). The relative abundance of illite vs kaolinite across all formations shows a moderate to very strong positive correlation with depth (r = 0.63 – 0.89). Note that many wells have both scanned cores and cuttings over the same interval (mostly for the Dongara–Wagina and 'Kingia' – High Cliff reservoirs), and therefore these wells appear more than once on cross-plots.

The mixed kaolinite–illite zone (subzones 2–4; approximately 80–130 °C) is interpreted as the illitization window where, with increasing temperature (and depth), smectite clays, kaolinite and labile grains are progressively transformed into illitic clays. This is comparable with illitization temperatures interpreted in other basins (70–90 °C), with smectite illitization beginning around 70 °C and feldspar illitization around 90 °C, and pervasive illite development above about 130 °C (Worden and Morad, 2002). The kaolinite–illite zone also lies mostly within the oil window (60–120 °C).

Within each diagenetic subzone, however, there is a significant range of depths and associated formation temperatures, as well as an overlap between subzones. The spread of data points is interpreted as primarily reflecting different temperature gradients across the basin due to differences in lithology and compaction, and thus thermal conductivities (Ghori, 2018). It probably also reflects an irregular and gradational transition from kaolinite- to illite-dominated diagenesis (i.e. illitization), perhaps operating over depth intervals, salinity levels and within a temperature range that are not entirely consistent across the basin.

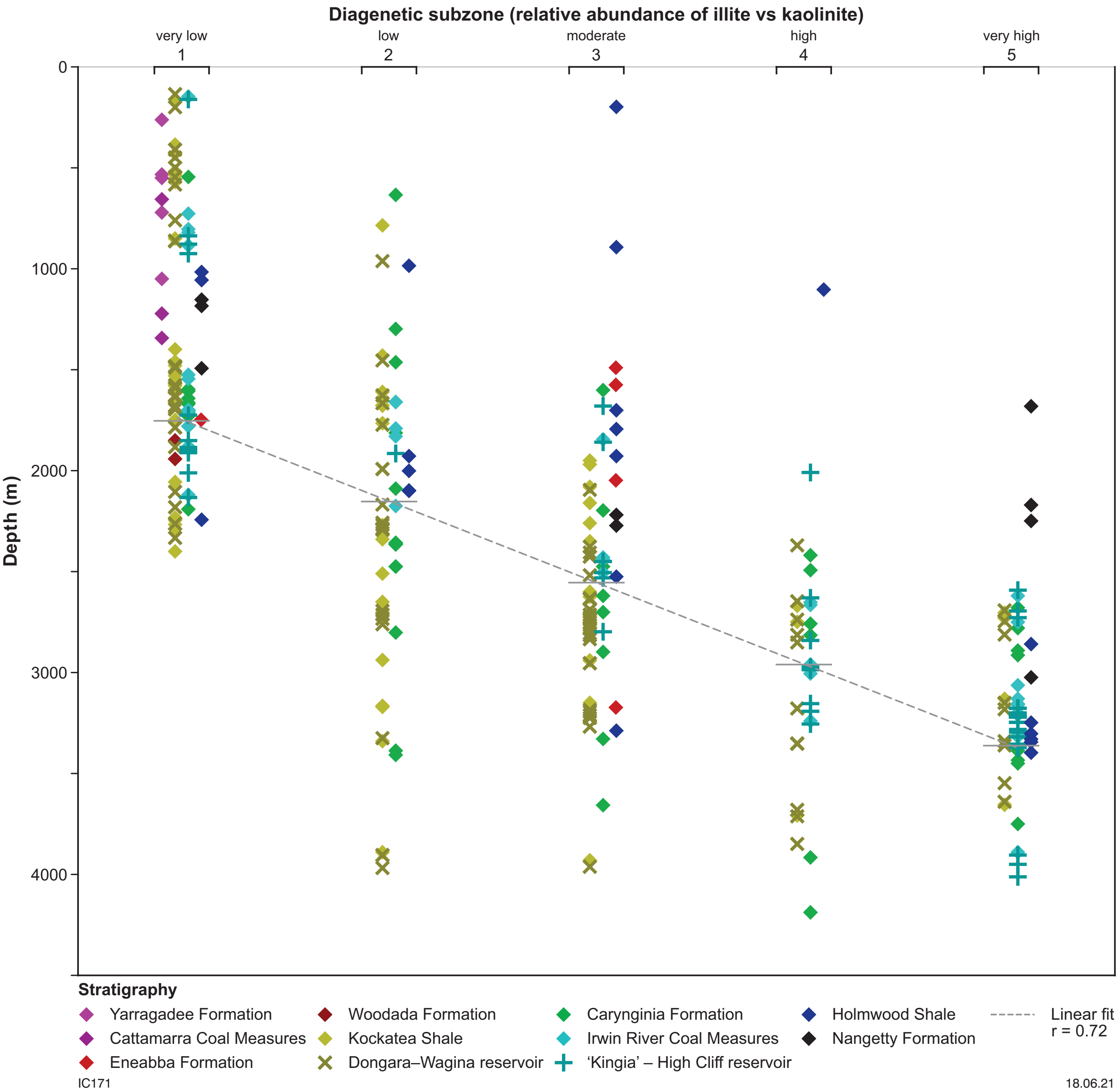


Figure 3. Depth distribution of diagenetic subzones based on scanned cores and cuttings from 75 wells. Sample points include the Upper Jurassic to Lower Triassic in Depot Hill 1, Mondarra 1, North Erregulla 1, Wicherina 1 and Yardarino 1

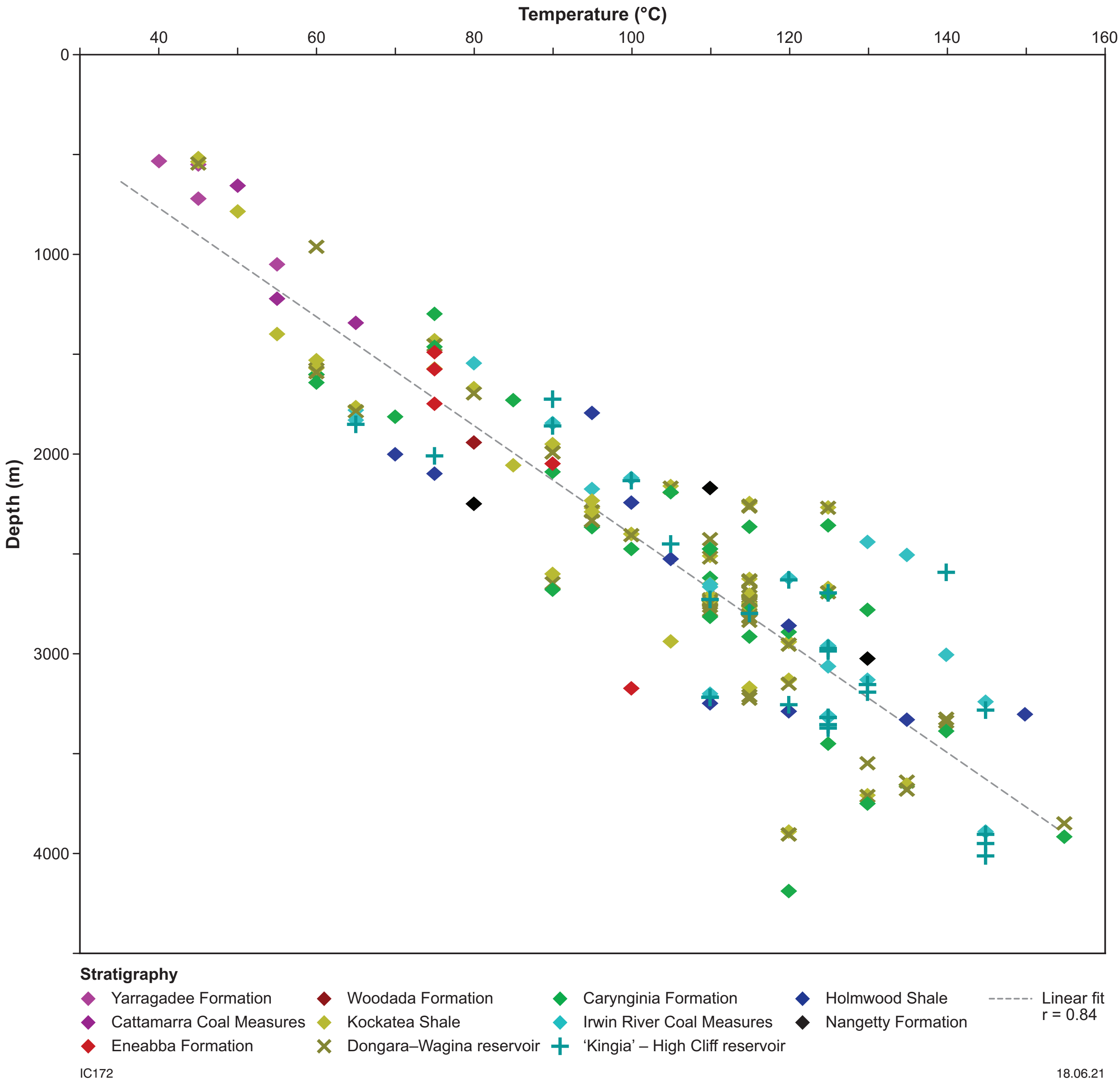


Figure 4. Relationship between current temperature (40 intervals scanned using the HyLogger with temperature data) and depth

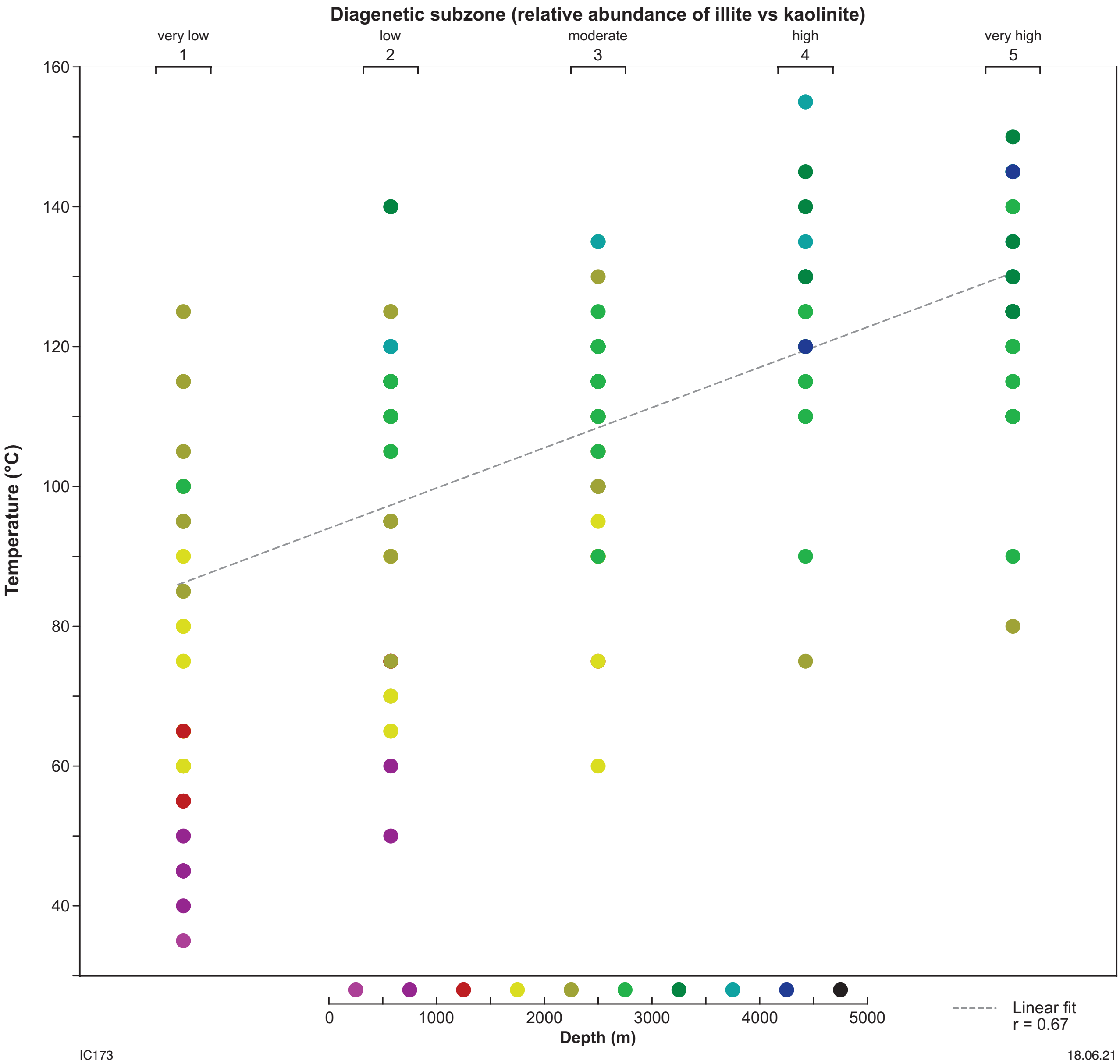


Figure 5. Relationship between diagenetic subzone and present-day temperature from the same scanned cores and cuttings in Figure 4. With increasing temperature (and depth) there is an increase in illite relative to kaolinite (r = 0.67)

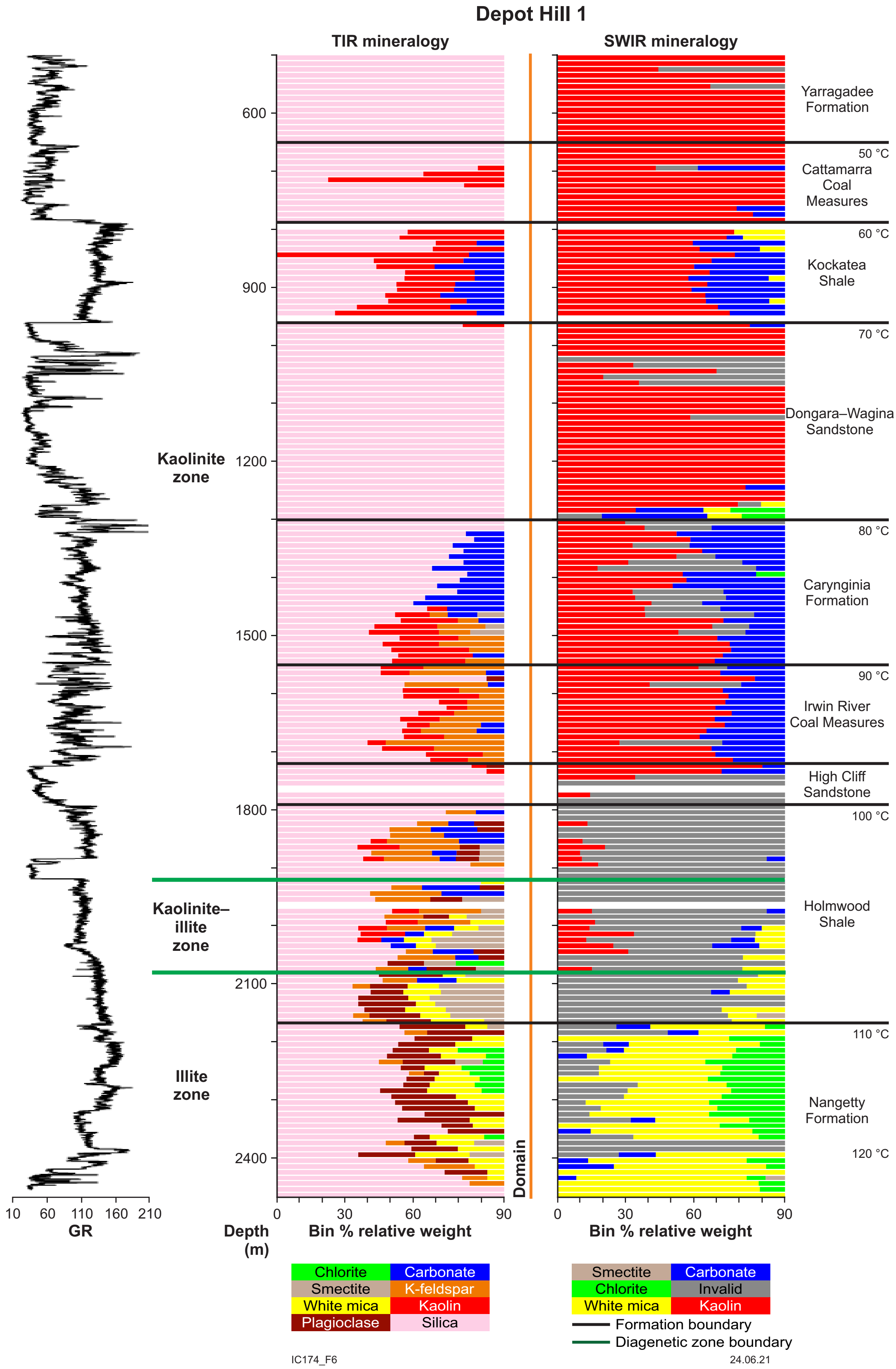


Figure 6. Scanned profile of Depot Hill 1 from cuttings (5 and 10 m composites) showing present-day temperatures from burial-history modelling

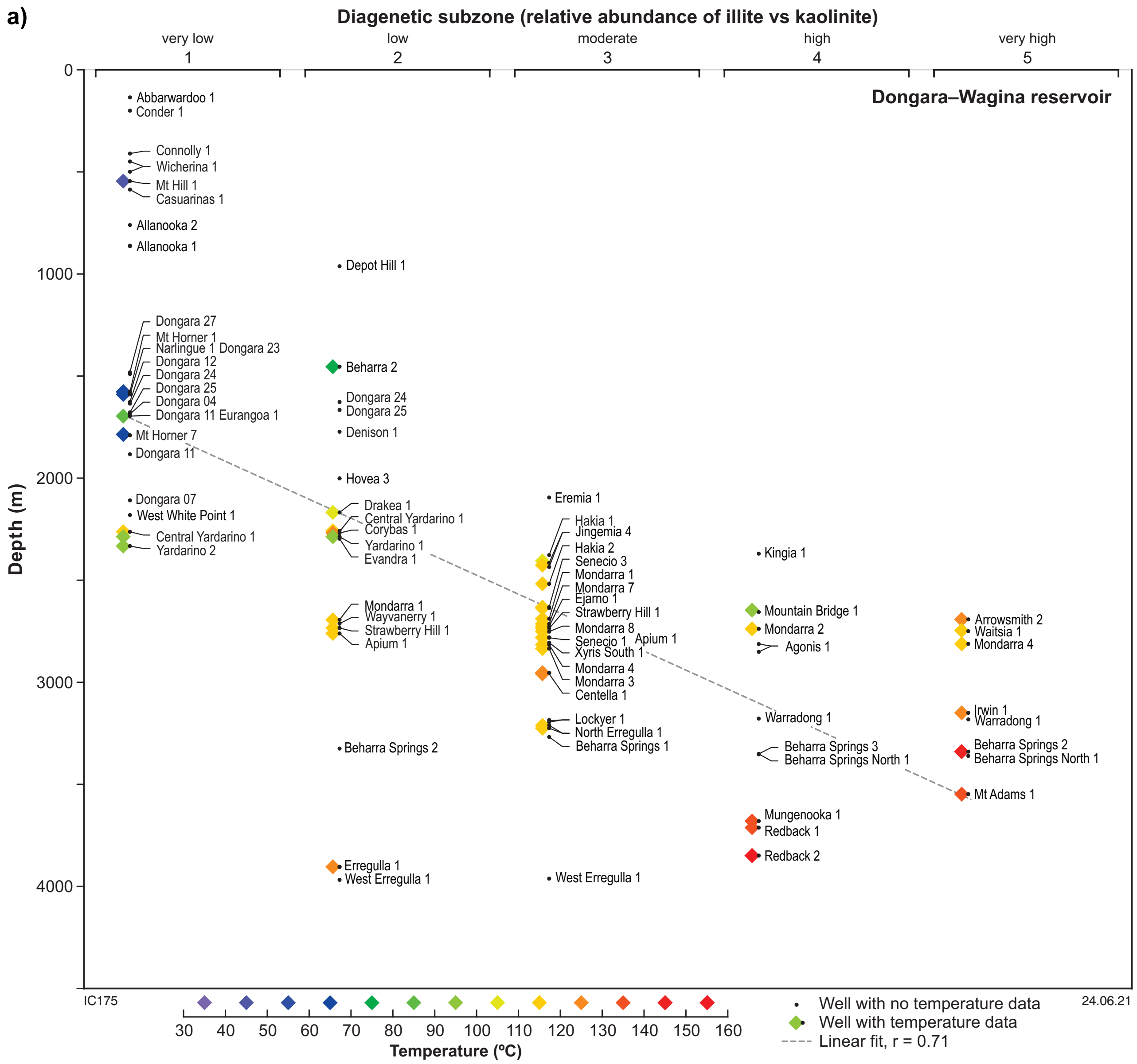
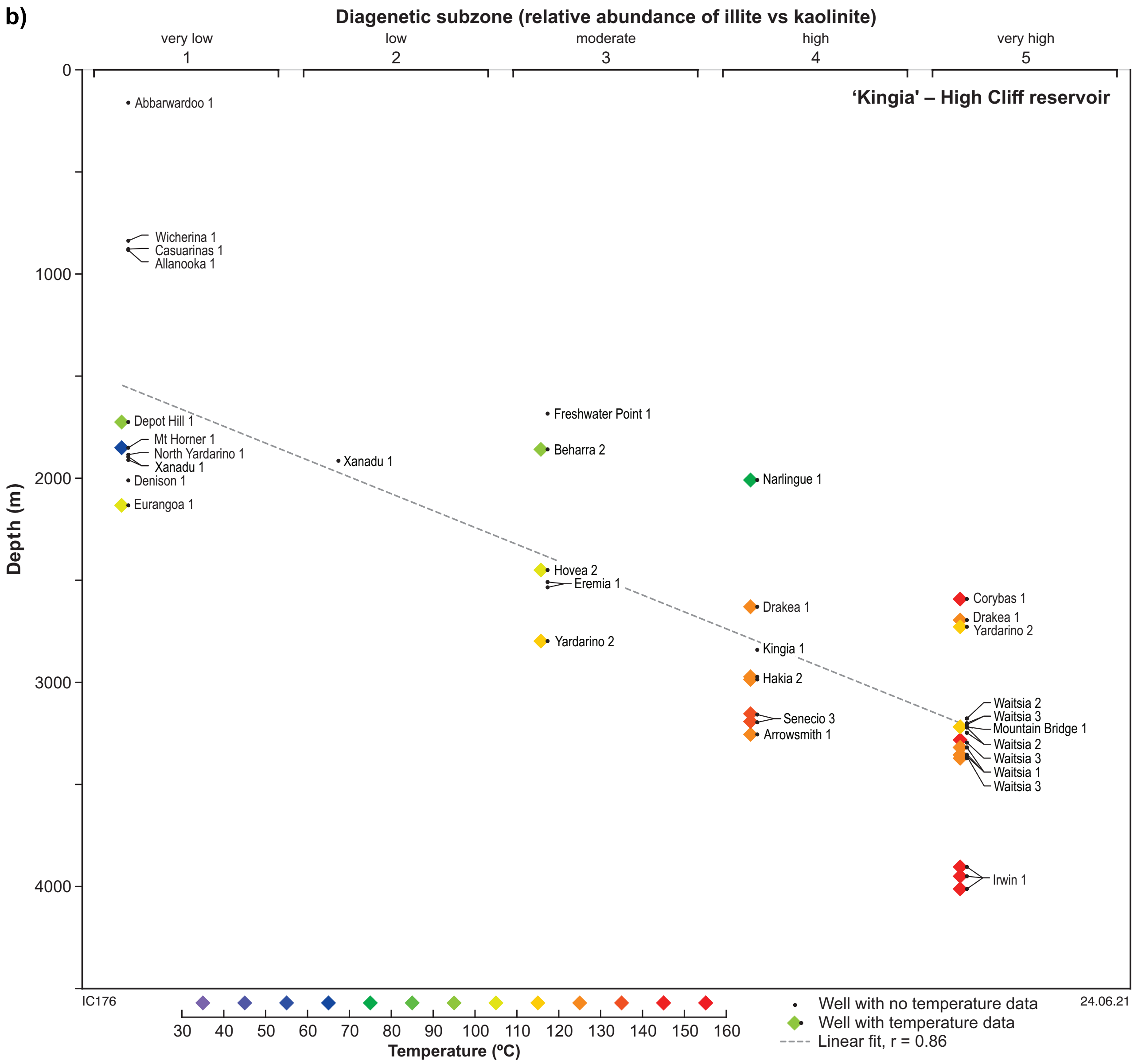


Figure 7. Scanned cores and cuttings from Lower and Upper Permian formations showing diagenetic subzones and current temperatures where available (Appendix 6): a) Dongara–Wagina reservoir; b) 'Kingia' – High Cliff reservoir; c) Kockatea Shale; d) Carynginia Formation; e) Irwin River Coal Measures; f) Holmwood Shale; g) Nangetty Formation



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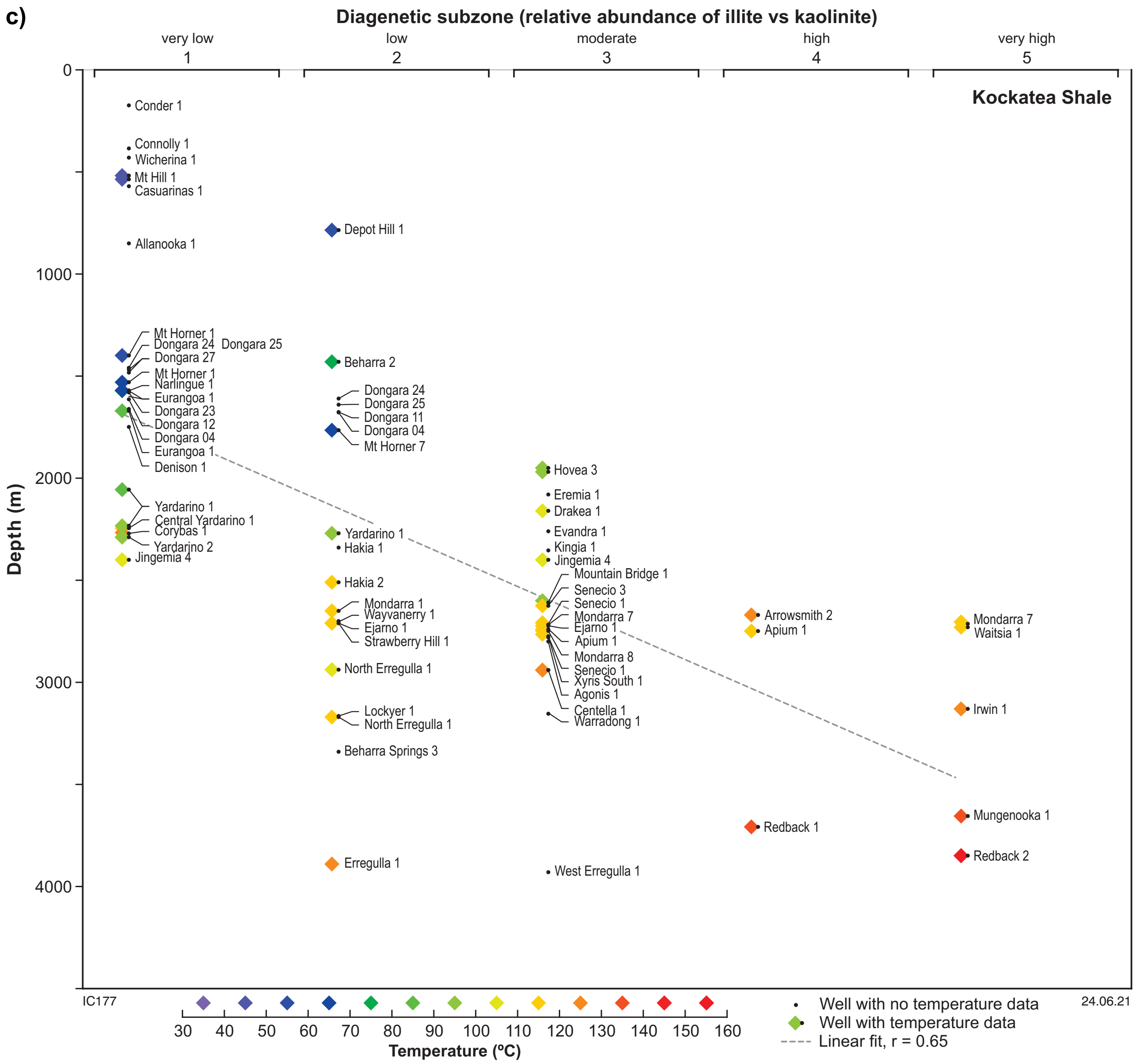

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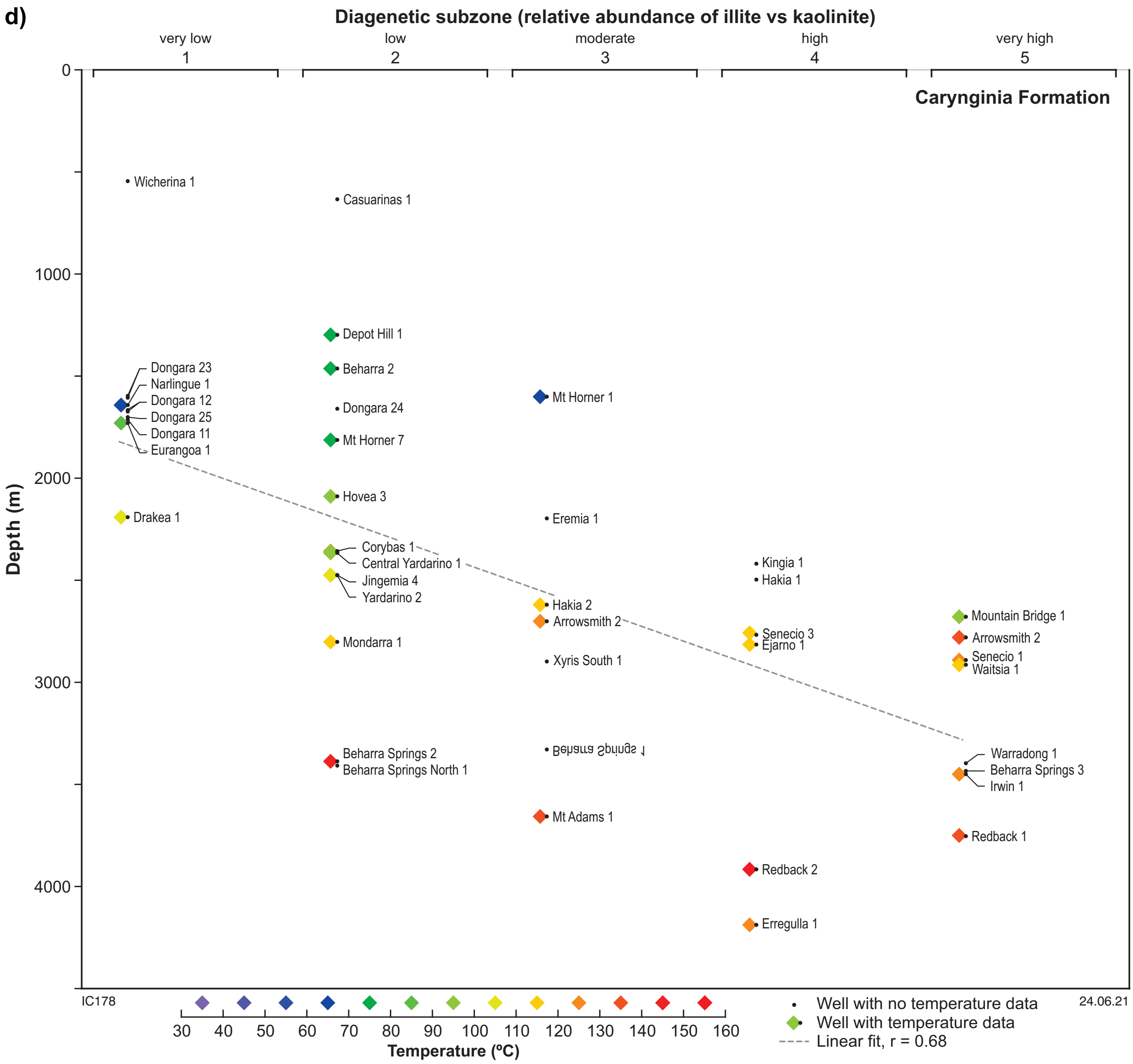

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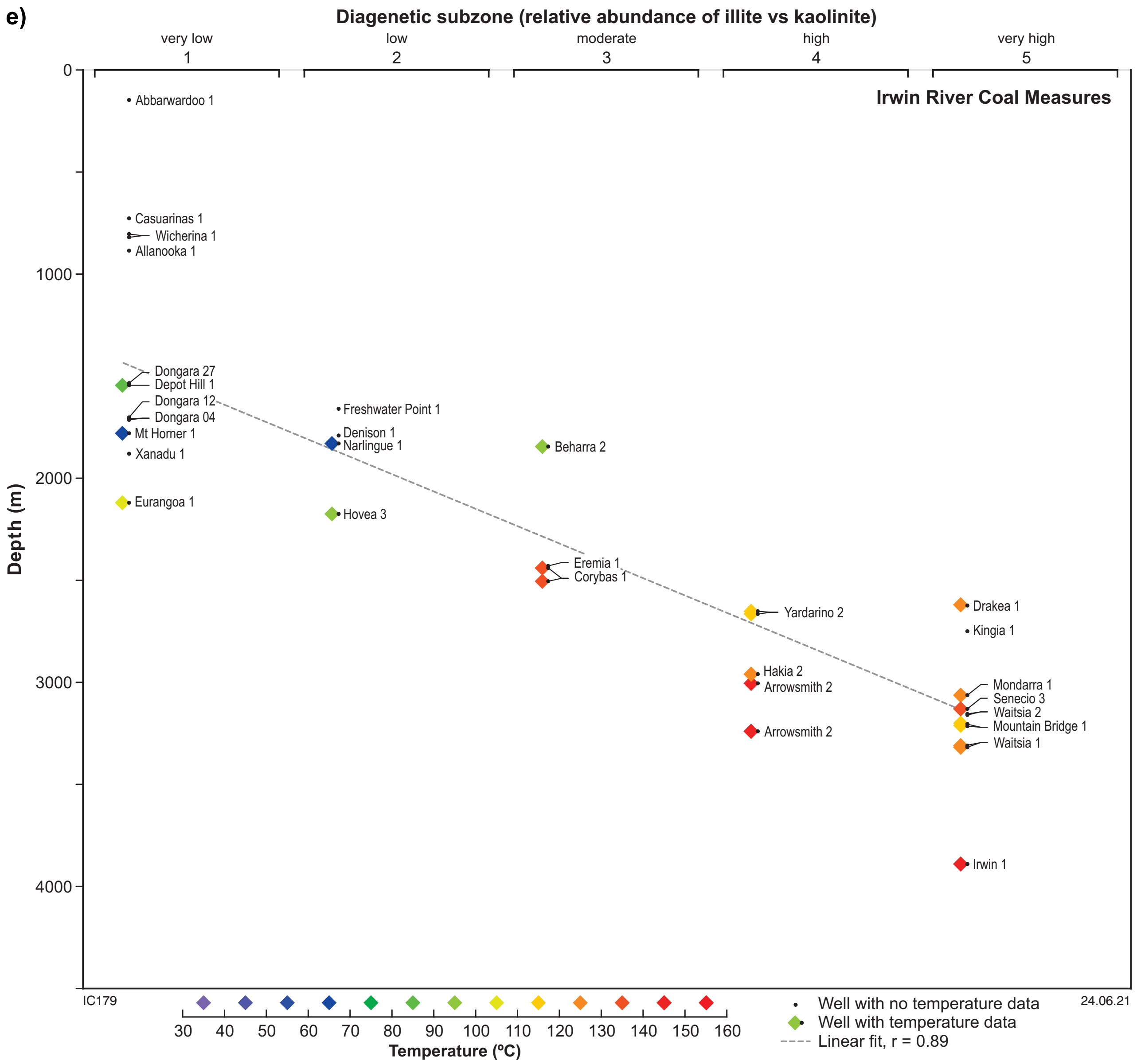

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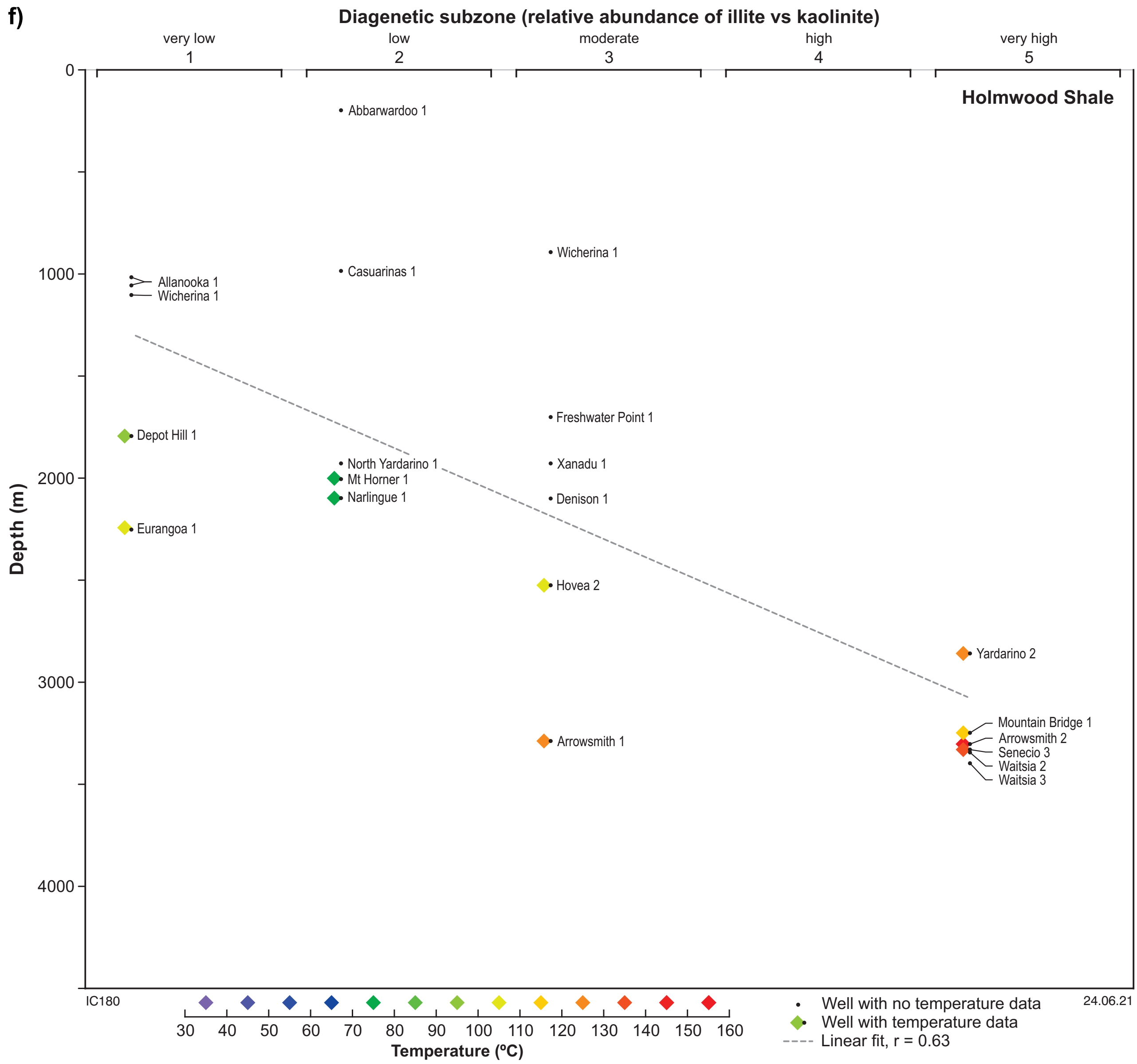

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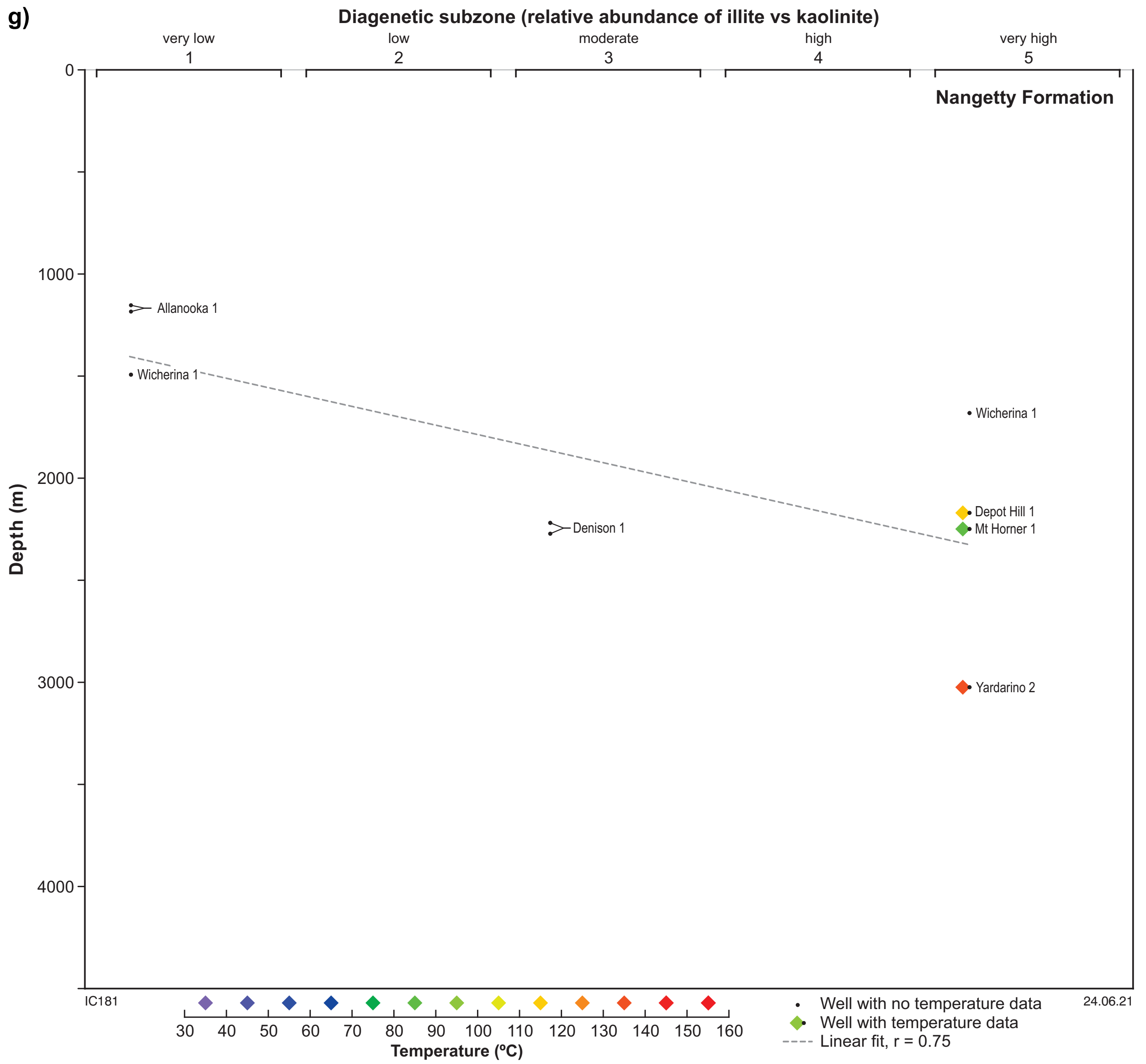

Figure 7. continued

This is difficult to quantify with the current dataset of single, thin scanned intervals, as the true thickness, temperature range and variability of the kaolinite–illite zone within each well remains uncertain.

Distinct shifts in kaolinite–illite ratios within the kaolinite–illite zone, particularly at formation changes, suggests that lithological and petrophysical differences (e.g. grain size, argillaceous content, permeability) also contribute to variability within this zone. As a consequence, subdividing such scanned intervals into several subzones also inherently contributes to the overlapping depth–temperature data points present in Figures 3–5.

As illitization is primarily controlled by burial temperature, there are no defining depths for the top of the kaolinite–illite or illite zones due to the variable temperature gradients in the basin. The most accurate zone depths are only measurable from thick scanned sections such as for Depot Hill 1, and less accurately determined in wells for which only isolated cores are available to be scanned, such as Yardarino 1. For all other wells where one or two Permian intervals have been scanned, only an estimated maximum depth to the zone-top can be determined.

Apart from differences in temperature gradients, several other variables probably also operate concurrently in controlling zone depths and thicknesses:

- insufficient feldspar or kaolinite to allow complete conversion to illite
- fault compartmentalization, which might provide localized sources of illitizing (potassium-rich) fluids and which may affect fluid-flow dynamics
- hydrothermal fluid flow along fault systems, resulting in localized temperature increases
- high proportions of argillaceous lithologies (lower permeabilities), resulting in reduced K^+ fluid flux for illitization compared with high-permeability sandstone beds.

The result of variable zone depths is that the top of the illitization window transgresses formation boundaries so that the Dongara–Wagina and 'Kingia' – High Cliff reservoirs span all three zones depending on their depths across the basin (Fig. 7). For the Dongara–Wagina reservoir, some wells and fields lie within the kaolinite zone (e.g. Dongara field), the kaolinite–illite zone (Senecio 3) or the illite zone (Irwin 1). The 'Kingia' – High Cliff reservoir similarly transgress diagenetic zones, that is, kaolinite zone (Allanooka 1), kaolinite–illite zone (Yardarino 2) and illite zone (Corybas 1 and Waitsia field). The transgression of diagenetic zones through each reservoir rather than facies changes, is considered the controlling factor in explaining clay differences between wells.

Regional clay differences in the Dongara–Wagina reservoir have previously been explained primarily by facies or provenance controls (Tupper et al., 1994; Laker, 2000) and the salinity of formation water (Rasmussen and Glover, 1996; Laker, 2000). In the absence of a comprehensive well-based facies analysis across the basin for comparison, a regional diagenetic zone model dependent on burial temperatures as proposed here, is interpreted as a fundamental control on clay distribution. This model is also supported by similar changes in other formations, from dominantly kaolinite to illite with increasing burial temperatures (Fig. 7). The relationship between regional salinity gradients as presented by Laker (2000) and illitization trends shown here for the Dongara–Wagina reservoir remain unclear, and further work is required to reconcile these datasets.

It is possible that the illitization process itself, which releases Mg^+, Fe^{2+}, Na^+ and Ca^+ ions through illitization of smectite (Morad et al., 2000) is responsible for the regional salinity differences rather than solely meteoric water flushing and preservation of meteoric water lenses as proposed by Laker (2000). However, it is likely that such hydrological processes operated across the basin alongside temperature-dependent mineral transformations in both open and closed diagenetic systems, influencing water chemistries within compartmentalized fault blocks.

Petrographic data

The illitization process identified from HyLogger data is also supported by petrographic data for the Dongara–Wagina and 'Kingia' – High Cliff reservoirs. Normalized percentages of kaolinite vs illite plotted against depth show a progressive increase in illite relative to kaolinite (r = 0.66), with a broad interval between about 2400 and 3300 m where these clays are in similar proportions (Fig. 8a). This interval is interpreted as lying within the broader kaolinite–illite zone as defined by HyLogger data. Overall, the HyLogger dataset is superior to the current petrographic dataset in that it better constrains the approximate depth of this zone, as it includes kaolinite and illite data from many wells across a greater depth range.

Petrographic data show that illite has a weak positive correlation (r = 0.13; Fig. 8b) with increasing depth, and kaolinite a moderately strong negative correlation (r = –0.60; Fig. 8c), as does feldspar (r = –0.46; Fig. 8d). Although several wells have relatively higher percentages of illite (e.g. Mountain Bridge 1, Senecio 3 and Corybas 1), the average illite content for most wells is less than 5%. The lack of an abrupt increase in illite and concomitant decreases in kaolinite and feldspar (K source for illitization) supports a model of progressive illitization with increasing temperature (depth). This is also supported by a steady increase in quartz overgrowths (r = 0.18), which are byproducts of the illitization process (Fig. 8e; Worden and Morad, 2002).

Timing of illitization

From burial-history modelling, most scanned reservoir intersections entered the illitization temperature window, even though the data spread reflects different temperature gradients across the study area (80–130 °C; Fig. 4) during rapid burial in the Middle to Late Jurassic, with the deeper 'Kingia' – High Cliff reservoir in some wells probably entering it in the Early Jurassic (e.g. Jingemia 1, Senecio 3, Robb 1, Beharra 2, Eurangoa 1). Most wells currently within the kaolinite–illite zone had remained within the illitization window since the Jurassic, but with slight cooling by up to 20 °C during uplift in the Cenozoic. Some wells, however, cooled substantially by up to 40 °C during uplift, such as Yardarino 1, Arrowsmith 1 and Eurangoa 1. In Yardarino 1 and Eurangoa 1, scanned Permian–Jurassic formations currently in the kaolinite zone reached temperatures of up to 135 °C (illite zone), and formations currently within the kaolinite–illite zone in Arrowsmith 1 reached temperatures of up to 150 °C (illite zone). It is uncertain why these formations were not pervasively illitized, but it could be due to the rapid rates of burial (heating) and subsequent uplift (cooling) that both areas underwent during the late Mesozoic and Cenozoic.

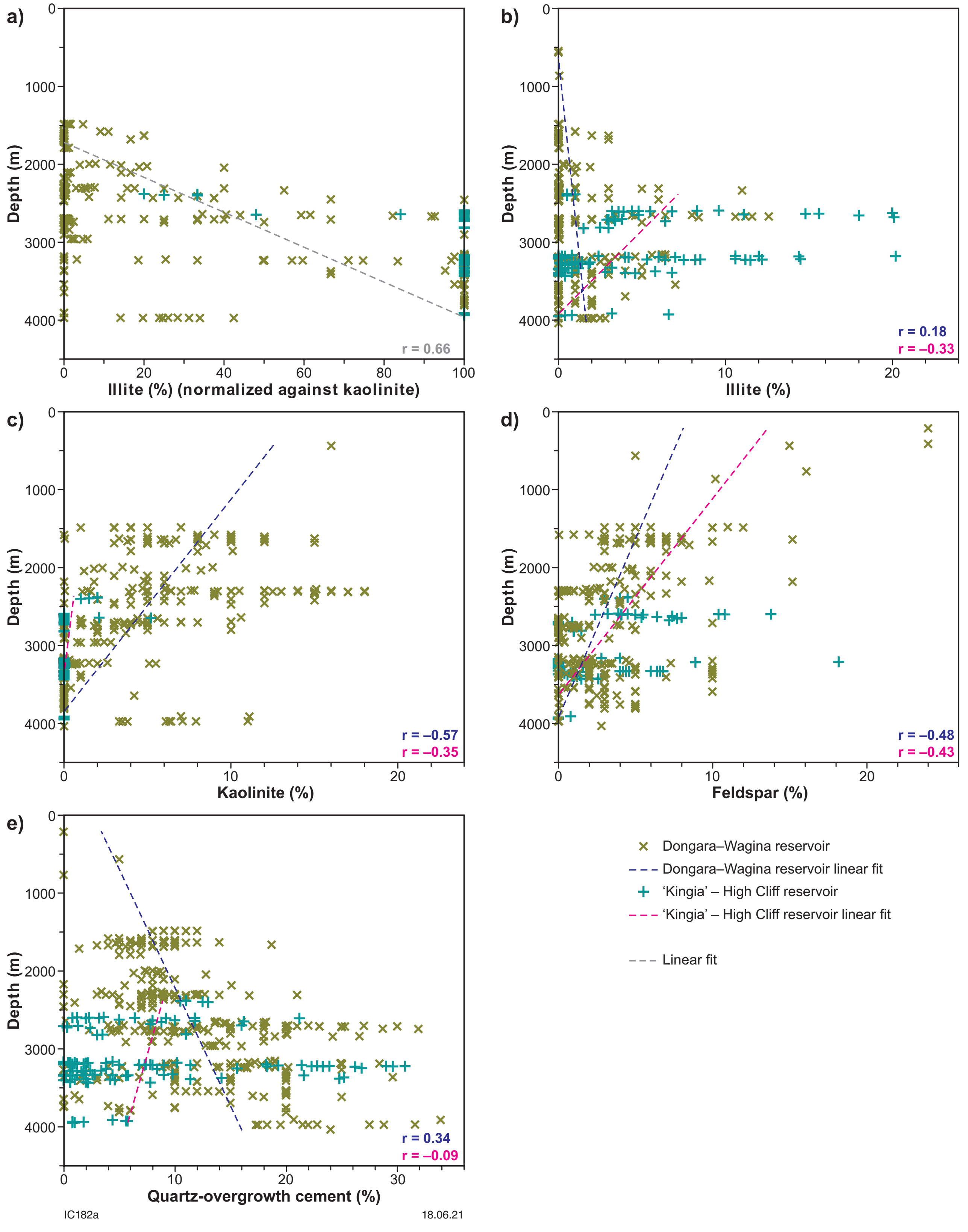

Figure 8. Relationships between authigenic minerals and increasing depth: a) illite (normalized against kaolinite; r = 0.66); b) change in the percentage of illite (r = 0.13); c) change in the percentage of kaolinite (r = −0.60), showing extremely low proportions at depths greater than 3300 m (except for West Erregulla 1); d) change in the percentage of feldspar (r = −0.46); e) change in the percentage of quartz overgrowths (r = 0.18), strongly influenced by low percentages in the 'Kingia' – High Cliff reservoir between about 3200 and 3500 m

Perhaps prolonged and more regular heating was required for pervasive illitization in the northern Perth Basin.

Alternatively, late-stage kaolinite formation (possibly after illite) due to an influx of acidic meteoric water during uplift in the Cenozoic might explain a kaolinite–illite assemblage for shallower formations, but petrographic evidence is equivocal. In Yardarino 1, this process would require pervasive kaolinization of the Dongara–Wagina reservoir and overlying Kockatea Shale and Woodada and Eneabba Formations. In the absence of meteoric waters, modification of pore waters by acidic burial fluids would be required, which may have taken place in Senecio 3 where kaolinite is interpreted as having replaced illite (Weatherford Laboratories, 2015).

Regional diagenetic trends

Trends between authigenic minerals and depth were measured using petrographic data (Appendix 6, Table 2) and are discussed in detail below. Data are available from the Dongara–Wagina reservoir to a depth of 3974 m (49 wells), whereas analyses for the 'Kingia' – High Cliff reservoir are only available from 2380–3947 m (11 wells). Although there are several significant differences between these reservoirs (i.e. illite, chlorite and quartz overgrowths), their datasets (number of samples and wells) are not entirely comparable. Over similar depths, however, r values (positive or negative) are relatively more consistent (Table 3). HyLogger data over similar depths for the 'Kingia' – High Cliff reservoir reveal relatively more illite than for the Dongara–Wagina reservoir; however, there is a strong bias in the number of data points from each (33 vs 12 wells, respectively) as well as in their geographical spread. The present-day temperature trend through this depth interval indicates no anomalous heating that might also explain differences in the extent of illitization, nor any substantial heating episode based on burial-history models where available. Differences between petrographic and HyLogger data for reservoirs at depths greater than around 2400 m in the current dataset most likely reflect sampling bias; however, facies differences between reservoirs and local diagenetic effects (see below) could also be influencing illite proportions.

Kaolinite

Kaolinite is the most common authigenic clay recorded by petrography and is commonly present as pore-filling and grain-replacement types and as zones of patchy pseudomatrix after alteration and dispersion of mica and feldspar grains. It has a moderately strong negative

Table 2. Statistical relationships between authigenic minerals and depth in the Dongara–Wagina and 'Kingia' – High Cliff reservoirs. Abbreviation: r, correlation coefficient

	Dongara–Wagina reservoir (49 wells; 397 samples; 214–3974 m)			'Kingia' – High Cliff reservoir (11 wells; 120 samples; 2380–3947 m)			Dongara–Wagina and 'Kingia' – High Cliff reservoirs (60 wells; 517 samples)	
Authigenic mineral	Maximum (%)	Average (%)	r	Maximum (%)	Average (%)	r	Average (%)	r
Kaolinite	18.00	4.21	−0.57	5.20	0.12	−0.35	3.23	−0.60
Illite	12.60	1.00	0.18	20.20	3.64	−0.33	1.65	0.13
Chlorite	22.50	0.67	0.24	14.40	2.56	0.46	1.13	0.33
Quartz overgrowths	33.90	11.57	0.34	30.70	7.40	−0.09	10.61	0.18
Carbonate	52.05	2.20	0.23	39.40	4.09	0.22	2.64	0.24
All authigenic clays and cements	52.15	20.3	0.25	55.10	18.8	0.07	19.96	0.17

Table 3. Statistical relationships between authigenic minerals and depths greater than 2380 m in the Dongara–Wagina and 'Kingia' – High Cliff reservoirs

	Dongara–Wagina reservoir (21 wells; 254 samples; 2405–3974 m)			'Kingia' – High-Cliff reservoir (11 wells; 120 samples; 2380–3947 m)		
Authigenic mineral	Maximum (%)	Average (%)	r	Maximum (%)	Average (%)	r
Kaolinite	15.00	1.95	−0.34	5.20	0.12	−0.35
Illite	12.60	1.38	−0.11	20.20	3.64	−0.33
Chlorite	22.50	1.04	0.13	14.40	2.56	0.46
Quartz overgrowths	33.90	13.25	0.10	30.70	7.40	−0.09
Carbonate	52.05	2.66	0.28	39.40	4.09	0.22
All authigenic clays and cements	52.15	20.99	0.20	55.10	18.8	0.07

correlation with depth (r = –0.60, Fig. 8c). This trend is similar to that in the Dongara–Wagina reservoir (r = –0.57) but weaker than in the 'Kingia' – High Cliff reservoir (r = –0.35). The highest percentages are recorded in the shallower Dongara–Wagina reservoir within the kaolinite zone. Below about 3300 m within the illite zone, kaolinite is mostly less than 1%, except in West Erregulla 1 where illitization may have been retarded (see next paragraph). For the 'Kingia' – High Cliff reservoir, kaolinite is absent in deeper intersections that lie within the illite zone, such as at the Waitsia field, but is present at shallower depths in Hovea 2 (2380 m) and Drakea 1 (2623 m) within the kaolinite–illite zone.

The kaolin polytype, dickite, is common in many scanned reservoir intervals. It is rarely identified by petrography, but is more obvious in SEM images, suggesting that it is probably much more common than revealed by historical petrography. Dickitization of kaolinite is a dissolution–precipitation process that progressively replaces thin, vermicular and booklet-like kaolinite crystals by thick, well-developed euhedral crystals of dickite (Worden and Morad, 2002). Dickite has a wider stability field than kaolinite and therefore extensive dickitization during diagenesis enhances preservation of reservoir quality by retarding illite formation (Morad et al., 2000). The transformation is also typically more pervasive in higher permeability sandstones. Consequently, sandstone with good reservoir quality might be expected to have extensive dickite; this is strongly supported by HyLogger data for the Dongara–Wagina reservoir in the kaolinite zone (e.g. Yardarino 2, and Dongara 7, 11 and 12). Dickite is also present in the kaolinite zone of Depot Hill 1 in sandstone intervals of the Cattamarra Coal Measures, Dongara–Wagina reservoir and Carynginia Formation, suggesting that these zones possibly have greater permeability. There are probably additional zones, but detection of dickite in cuttings by the HyLogger is imprecise. In Hovea 3, there is a marked change from dickite to kaolinite within the Dongara–Wagina reservoir coincident with a decrease in grain size and permeability — reflecting a change from shoreface–foreshore to distal tidal-channel facies (Fig. 9; Origin Energy Ltd, 2002).

Dickite is also identified using the HyLogger in the kaolinite–illite zone within both the Dongara–Wagina reservoir (e.g. Jingemia 4, Mondarra 8, Senecio 1, 3 and Apium 1) and 'Kingia' – High Cliff reservoirs (e.g. Yardarino 2, Hovea 2). Dickite distribution is mostly irregular in 'Kingia' – High Cliff reservoir intersections (e.g. Yardarino 2, Abbarwardoo 1, Eurangoa 1), which could reflect heterogeneous permeability throughout the reservoir. This contrasts with the mostly thicker dickite zones in the Dongara–Wagina reservoir that reflect vertically more continuous permeable zones. This is well illustrated in Dongara 12, which contains intervals of dickite with higher permeabilities than within kaolinite zones (Fig. 10).

Illite

Illitic clays are present in both Dongara–Wagina and 'Kingia' – High Cliff reservoirs as grain-rimming, pore-lining, pore-filling and grain-replacement forms. It is also developed as zones of patchy pseudomatrix after alteration and dispersion of labile grains, particularly mica. Illite abundance shows a weak positive correlation with depth (r = 0.13; Fig. 8b; Dongara–Wagina reservoir: r = 0.18), and this trend is also

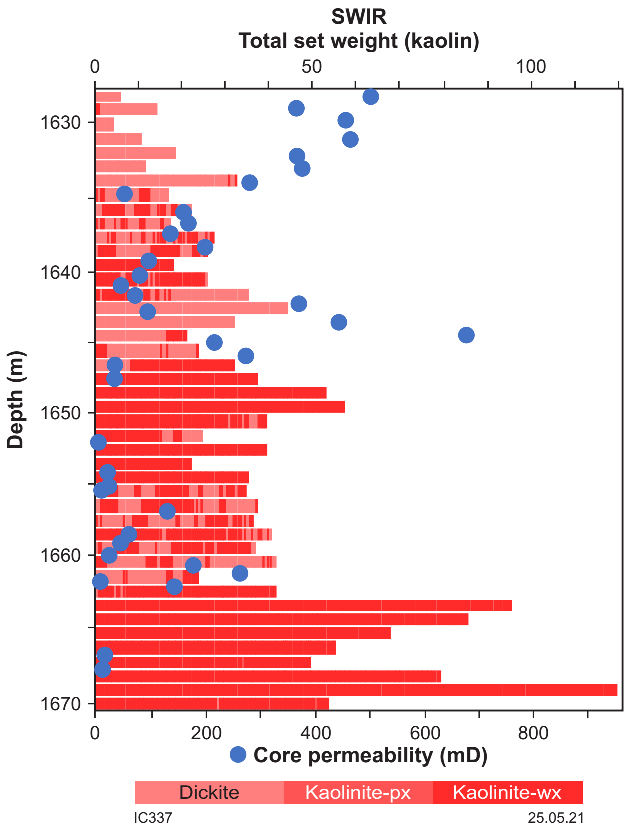

Figure 9. Relationship between kaolinite–dickite, grain size and core permeability in the Dongara–Wagina reservoir in Hovea 3. Dickite is developed in the coarser, more permeable sandstones

reflected by a marked relative increase in illite vs kaolinite (Fig. 8a; r = –0.21). The 'Kingia' – High Cliff reservoir has a moderately weak negative correlation of illite abundance with depth (r = –0.33), as does the Dongara–Wagina reservoir for the same depth interval (r = –0.11).

A major driver for illitization is the reaction between K-feldspar and kaolinite, which are inherently unstable together and form illite, quartz and water (Worden and Morad, 2002). This relationship is apparent in Depot Hill 1, which has a broad relative decrease in K-feldspar and kaolinite with a corresponding increase in illite from the base of the kaolinite zone through to the illite zone. Regionally (with the exception of West Erregulla 1), this relationship is also seen in petrographic data, which shows with increasing depth a decrease in kaolinite (r = –0.60) and feldspar (r = –0.46), and an associated increase in illite (r = 0.13) and quartz overgrowths (r = 0.18). However, below about 3200 m the percentage of kaolinite sharply declines to mostly less than 1% (average 0.62%; Fig. 8c), but feldspar remains up to around 4% (average 2.1%; Fig. 8d). Below about 3500 m, illite similarly decreases to less than 2% (average 1%). The paucity of illite at depth within the illitization window could indicate that at a regional scale, although feldspar is available as a source of K^+ ions for continued illitization, there may be insufficient kaolinite to drive the reaction to completion, regardless of appropriate temperatures. Similarly, insufficient feldspar may also limit the extent of illitization in West Erregulla 1. Here, the Dongara–Wagina reservoir lies within the kaolinite–illite zone and contains significant kaolinite (up to 11% at 3960 m), despite being at around 120 °C (based on burial-history modelling of the Erregulla wells in Ghori (2018, figs 39, 40) at which illitization

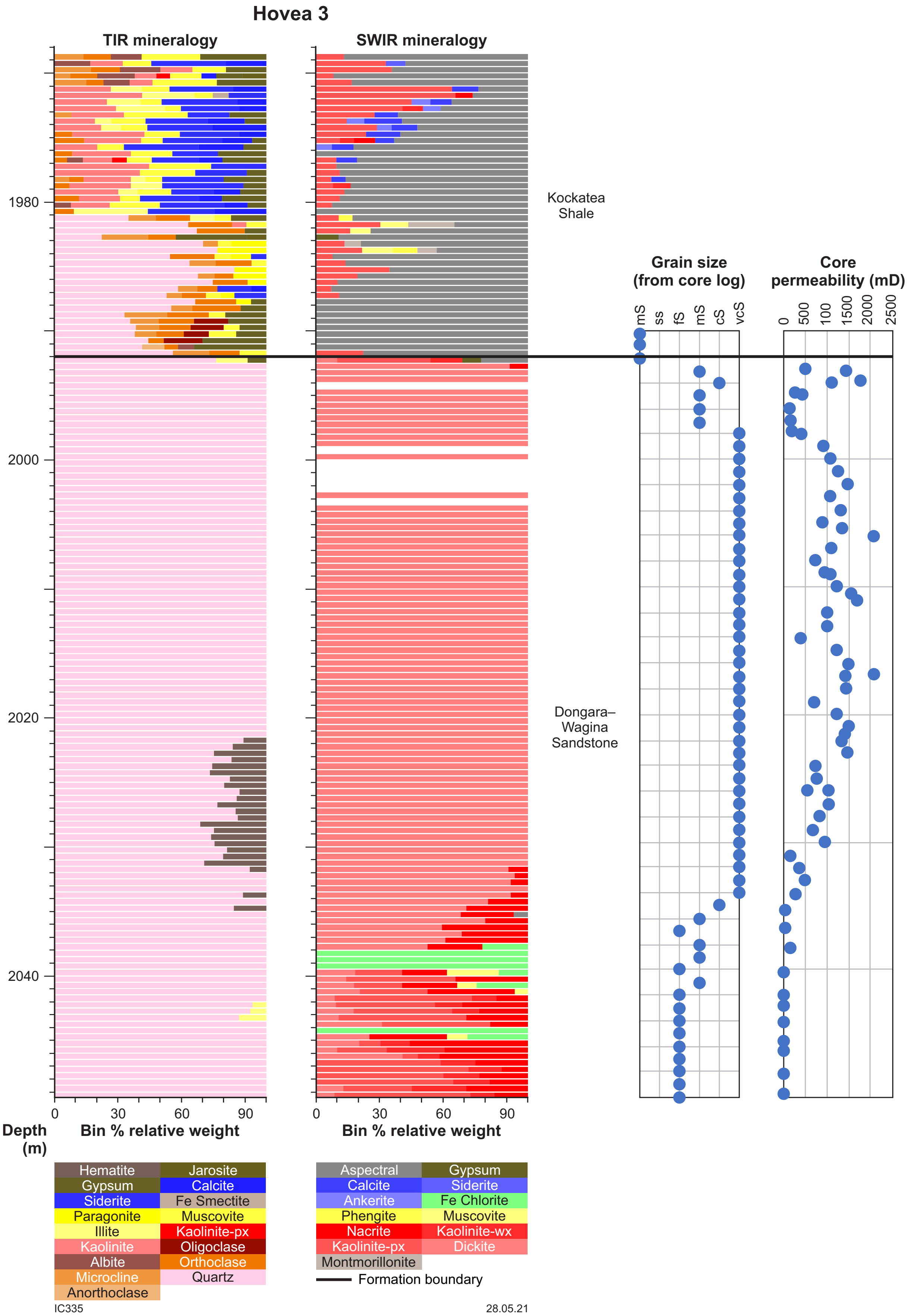

Figure 10. Core permeability and relative abundance of kaolinite and dickite determined using SWIR within the Dongara–Wagina reservoir in Dongara 12. Significantly higher permeabilities are associated with dickite zones

of kaolinite is typically almost complete. However, the reservoir is almost devoid of feldspar (both in petrographic and HyLogger data), again suggesting that the illitization process may have been compromised. The reduced feldspar content could be due to a combination of both provenance factors and early diagenetic processes (i.e. meteoric leaching); whereas insignificant kaolinite is likely due to its prior conversion to illite. An additional control on reduced illite formation could also come from dickite, which is less susceptible to illitization (Morad et al., 2013).

The limitation of feldspar or kaolinite in driving the illitization process in the northern Perth Basin might be significant in controlling the thickness of the kaolinite–illite zone (and depths to the top of the illite window), rather than temperature alone. Where these minerals are not exhausted, however, illitization is likely to be more complete and yielded a greater proportion of illite with increasing burial temperatures. In addition to a possible mineralogical control on illitization, the uppermost Dongara Sandstone in West Erregulla 1 is also gas saturated, which may have helped retard the illitization process by limiting the availability of K^+ ions and SiO_2.

An additional source of K^+ needed for illitization of kaolinite is through the associated albitization of K-feldspar, which in the process also releases SiO_2 available for quartz overgrowths (Worden and Morad, 2002). Based on HyLogger data, albitization appears to have taken place in Depot Hill 1 from about 1300 to 2500 m (total well depth). In Depot Hill 1, K-feldspar in the kaolinite zone has been increasingly replaced by albite with depth, until albite becomes the dominant feldspar in the illite zone. This relationship is more difficult to identify elsewhere in the basin due to the lack of stratigraphically continuous HyLogger profiles. Consequently, there are probably several factors working in combination that limit the illitization process, but their relative influence will differ between well locations.

Several factors operating together could be contributing to the weak illite vs depth relationship (r = 0.13) operating within the basin's depth (temperature)-controlled illitization process. Firstly, at shallower depths (<2000 m), the proportion of illite from petrography may have been over estimated by the inclusion of smectite, which is difficult to differentiate from illite except by XRD and SEM analyses. Secondly, at deeper depths (>3500 m) the proportion of illite decreases rapidly, possibly due to a lack of available kaolinite in some wells for the illitization process. In addition, the proportion of illite at moderate depths (2500–3500 m) is extremely variable (also seen in HyLogger data), and is possibly due to a combination of variable thermal gradients and diagenetic processes (see below).

Chlorite

Grain-rimming chlorite is known to help preserve primary porosity by inhibiting porosity-occluding quartz overgrowths in the 'Kingia' – High Cliff reservoir (Tupper et al., 2016), and to a lesser extent in the Dongara–Wagina reservoir (Beharra Springs Terrace; Tupper et al., 1994; Laker, 2000). However, only about 60% of the petrographic data differentiates between the forms of chlorite clays (i.e. grain rimming, pore filling, pore lining or grain replacement), so chlorite grain rims may be more widely developed than reported.

Plotting total-chlorite percentages (i.e. all forms of chlorite) against depth shows a weak to moderate positive correlation (r = 0.33; Fig. 11a; Dongara–Wagina reservoir: r = 0.24, 'Kingia' – High Cliff reservoir: r = 0.46). Higher well averages between 2700 and 3500 m are associated with grain-rimming chlorite in the 'Kingia' – High Cliff reservoir in the Waitsia field, and in the Dongara–Wagina reservoir on the Beharra Springs Terrace and in the Mondarra field. The correlation is weaker (r = 0.13) for the Dongara–Wagina reservoir at the same depth interval as the 'Kingia' – High Cliff reservoir.

Chlorite increases regionally below about 1650 m, which may reflect a burial-temperature control that is estimated to begin at a minimum of about 40 °C (Beaufort et al., 2015). Grain-rimming chlorite recorded at depths greater than 2700 m (Mondarra, Beharra Springs, Waitsia) is interpreted as being controlled by depositional environment (Tupper et al., 1994, 2016; Laker, 2000), probably after a diagenetically altered Fe-rich precursor clay such as berthierine (Beaufort et al., 2015). Its rarity at shallower depths is most likely due to unsuitable paleogeographic settings rather than inadequate temperatures (which are well within the chloritization window, i.e. above about 40 °C). In addition, chlorite is scarce in shallower 'Kingia' – High Cliff reservoir intersections which may reflect the lack of petrography for meaningful comparison. Grain-rimming chlorite could therefore be present at shallower depths in the northern Perth Basin, but in better paleogeographic locations than currently drilled. In those depositional settings where Fe-rich clay rims are not predicted, however, grain-rimming illite–smectite could be developed instead. This diagenetic form also has significant reservoir potential for preserving primary porosity, for example, the fluvial facies of the 'Kingia' – High Cliff reservoir in Corybas 1 (Ferdinando et al., 2007) — grain-rimming chlorite is developed in equivalent shoreface facies in the Waitsia field.

HyLogger identification

The HyLogger has been successful in identifying chlorite zones in both core and cuttings in reservoirs with known chlorite from petrography (Appendix 7); however, it is not currently able to differentiate between grain-rimming, pore-filling or grain-replacement forms. In HyLogger profiles, chlorite is typically in rare, thin, discrete zones within a background of illite or kaolinite clays.

Where chlorite abundance is less than about 2–3% (from associated petrography), it can rarely be identified from HyLogger data. Chlorite has been identified in cuttings where there is no recorded chlorite on petrographic data, such as Hakia 1, 2 and Kingia 1 in the Dongara–Wagina reservoir; and Beharra 2, Depot Hill 1 and Eremia 1 in the 'Kingia' – High Cliff reservoir. Chlorite has also been detected in wells with no petrography or over unsampled intervals within reservoirs, such as Agonis 1, Depot Hill 1 and Eremia 1 in the Dongara–Wagina reservoir; and Beharra 2, Denison 1, Eremia 1 and Hakia 2 in the 'Kingia' – High Cliff reservoir. Although additional petrography is required to confirm the presence and form of chlorite, its detection using the HyLogger, particularly in cuttings, demonstrates an important application in helping map the regional stratigraphic and spatial distribution of chlorite, and its porosity-preserving potential.

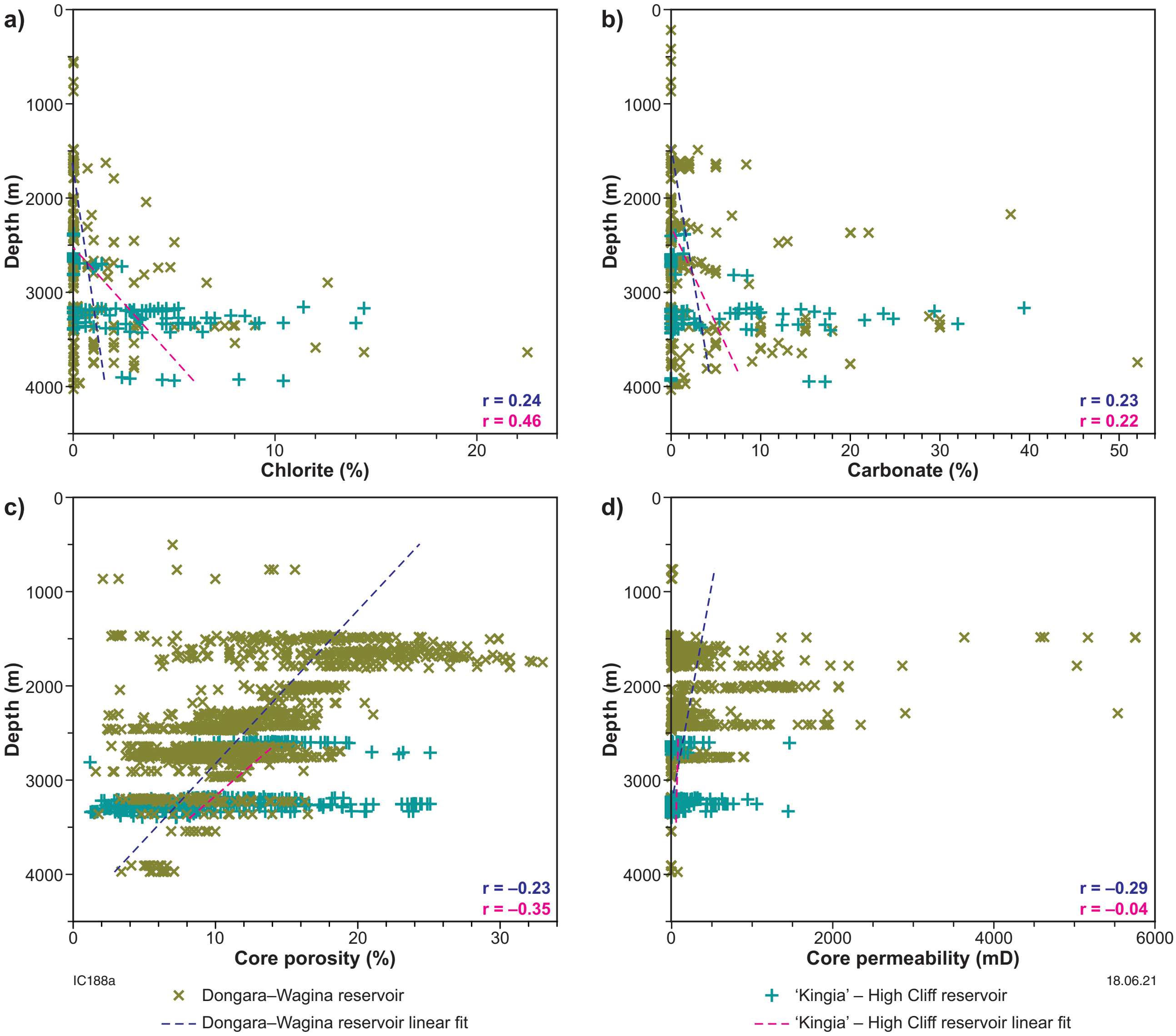

Figure 11. Relationships between authigenic minerals, cement, porosity and permeability with increasing depth: a) change in the percentage of chlorite (r = 0.33); b) change in the percentage of carbonate cement (r = 0.24); c) change in core porosity; d) change in core permeability

Grain-rimming illite is closely associated with grain-rimming chlorite in the Waitsia field (Baker, 2016, 2017a,b), but it is also not currently possible to differentiate it from other forms of illite using the HyLogger (e.g. the porosity-preserving grain rims in Corybas 1; Ferdinando et al., 2007). In addition, the common presence of illite throughout reservoir intervals in both the kaolinite–illite and illite zones also makes current HyLogger data less useful for identifying discrete zones of porosity-preserving, grain-rimming illite.

Quartz overgrowths

Quartz overgrowths are ubiquitous throughout both the Dongara–Wagina and 'Kingia' – High Cliff reservoirs and are the primary cause of porosity occlusion with increasing depth. Quartz cements are formed through a combination of chemical compaction, the illitization of kaolinite and smectite, and through the dissolution of detrital feldspars (Morad et al., 2000). Laker (2000) recognizes at least three generations of quartz cements that have occluded porosity in the Dongara–Wagina reservoir. The last two phases (Q1 and Q2) were probably produced during illitization and were responsible for the most extensive porosity reduction.

Regionally, quartz overgrowths are weakly positively correlated with depth (r = 0.18; Fig. 8e). However, the strength of this correlation is significantly diminished by inclusion of deep (greater than 2400 m) 'Kingia' – High Cliff reservoir samples, which contain minimal quartz overgrowths due to grain-rimming chlorite. A stronger correlation is returned when only Dongara–Wagina reservoir samples are used (r = 0.34). In this reservoir the proportion of cement increases steadily to a well average of about 15% at 4000 m, with a spike to about 17% at 2700 m associated with the Mondarra field. Here, quartz overgrowths have formed in the water leg of the reservoir, with retarded diagenesis and reduced cementation (and increased porosity) in the overlying hydrocarbon column (e.g. Mondarra 1; Rasmussen, 1992; Laker 2000). Quartz overgrowths are on average up to 7% within the kaolinite zone, between 7% and 14% in the kaolinite–illite zone, and greater than 14% in the illite zone.

For the 'Kingia' – High Cliff reservoir, quartz overgrowths decrease from a well average of around 10% at 2400 m to about 5% at 3900 m as a consequence of grain-rimming chlorite that limits cement growth (Tupper et al., 2016). For the Dongara–Wagina reservoir, quartz overgrowths increase from around 12% to 14%; however, there are local decreases on the Beharra Springs Terrace due to chlorite development.

Currently, the proportion of quartz overgrowths cannot be discriminated by HyLogger data as the measured quartz spectra provides a composite signature of framework quartz grains and quartz cements. However, recent work shows it can potentially identify zones in cores that are relatively more cemented by SiO_2 (Copp and Hancock, 2018).

Carbonate

Carbonate cements are widespread throughout both the Dongara–Wagina and 'Kingia' – High Cliff reservoirs, where they formed during early through to late diagenesis. Carbonate cements have a weak positive correlation with depth (r = 0.24; Fig. 11b) although this is biased by the higher carbonate percentages in the Beharra Springs area. Higher well averages between 3000 and 3500 m are mostly on the Beharra Springs Terrace where the calcareous Beekeeper Formation is well developed. However, HyLogger data do not easily differentiate carbonate cement from primary carbonate.

Early carbonate cements are predominantly siderite, with later-formed calcite and ankerite developed by replacement of grains and detrital-clay matrix, which commonly occludes secondary porosity. HyLogger data record carbonate throughout the basin in both the Dongara–Wagina reservoir (e.g. Beharra Springs 3, Beharra Springs North 1, Irwin 1, Redback 1, 2) and the 'Kingia' – High Cliff reservoir (e.g. Waitsia 2, Eurangoa 1, Mountain Bridge 1, Senecio 3).

Carbonate dissolution during burial of the underlying calcareous Beekeeper Formation may, in part, be the source of the carbonate cements in the Dongara–Wagina reservoir. The formation is thickest and best developed in the southern Beharra Spring Terrace where the highest proportions of carbonate cement in sandstones of this reservoir are recorded (up to 52% in Redback 1). It becomes thinner in the basal part of the Dongara–Wagina reservoir in the Dandaragan Trough (Warradong 1, Irwin 1), but carbonate cement remains substantial (i.e. 30% in Warradong 1). Other sources of carbonate may have been derived through illitization of smectite, which releases Mg^{+}, Fe^{2+} and Ca^{+} ions, particularly from adjoining mudrock units during smectite alteration (Morad et al., 2000).

Well-scale diagenetic trends

At a well scale, the HyLogger also allows identification of distinct vertical changes in the relative abundances of clays within the kaolinite–illite zone (e.g. Senecio 3 and Centella 1 in the Dongara–Wagina reservoir). These trends are mostly unclear from petrographic data due to low sample density, making the HyLogger extremely useful for profiling diagenetic changes at the reservoir scale. Such datasets are potentially useful for comparing against, and as an input for, automated petrophysical mineral interpretations.

Strong vertical changes in clays, mainly in the kaolinite–illite zone probably reflect both depositional and diagenetic processes, operating separately or in combination, including:

- facies and provenance differences reflecting availability of labile grains such as feldspars, lithoclasts and mica for later kaolinization and illitization
- shallow diagenetic processes caused by meteoric leaching and kaolinite formation
- permeability differences causing greater illitization and dickite formation in higher permeability zones
- formation water chemistries, causing modified salinities and pH during burial
- hydrocarbon- vs water-bearing zones, causing retardation of illitization in the hydrocarbon leg of reservoirs.

The vertical distribution of clays might therefore reflect: primary mineralogy (facies) overprinted by zones of localized fluid flux in higher permeability intervals (kaolinite to dickite transformation, K-rich fluids for illitization); zones where illitization may have been retarded due to lack of kaolinite or feldspar, or by hydrocarbons. For example, a vertical pattern of decreasing kaolinite and increasing illite is commonly developed in the Dongara–Wagina reservoir in the Dandaragan Trough (e.g. Senecio 3, Mondarra 8, Hakia 2, Centella 1, Erregulla 1). Although this might reflect a primary facies control, with an upper kaolinite zone developed from early meteoric leaching these wells also have hydrocarbon columns that could be controlling the vertical distribution of clays. In Mondarra 1, there is significantly more quartz overgrowths in the lower (water leg) part of the reservoir (Rasmussen, 1992; Laker, 2000) supporting a model, at least for this field, of fluid stratification as a control for authigenic clay patterns. In the illite zone, kaolinite is rare and so similar vertical changes are less apparent in HyLogger data, as they also are for the kaolinite zone, which lacks significant illite.

With increasing depth through the kaolinite–illite zone, both regionally and at a well scale, kaolinite abundance is overall reduced relative to illite (Fig. 8a). Although a simplified illitization model of kaolinite to illite transformation might explain this change, petrographic data indicate a much more complex and variable process. Illite commonly replaces labile grains (feldspar, lithoclasts and mica), is an alteration product of smectite clays (mixed-layer smectite–illite from XRD analyses), is pore lining and pore filling, and post-dates or is synchronous with kaolinite formation (Rasmussen, 1992; Laker, 2000). In addition, illite is replaced by kaolinite (dickite) in the Dongara–Wagina reservoir of Senecio 3 as the final product of micaceous grain alteration (Weatherford Laboratories, 2015), suggesting that pore fluids became increasingly acidic. This is also evident in the Irwin Coal Measures of Corybas 1 (Baker, 2006). Consequently, the kaolinite–illite zone is not simply due to temperature-dependent alteration of kaolinite to illite, but a complex interplay of sedimentary and fluid chemistry variables acting together within a window of increasing temperature, coincident with source-rock maturation and hydrocarbon generation.

Porosity diagenetic relationships

Regionally, with increasing depth, core porosity decreases from an average of about 16% at 1500 m to about 6% at 4000 m (r = –0.58; Fig. 11c), with elevated porosities at depth in the 'Kingia' – High Cliff reservoir in the Waitsia field. Core porosity (r = –0.58) is strongly negatively correlated with increasing quartz overgrowths and carbonate cements. Higher porosities from about 3200–3400 m are associated with grain-rimming chlorite and reduced quartz overgrowths within the 'Kingia' – High Cliff reservoir in the Waitsia field. Core permeability decreases from an average of around 400 millidarcies (mD) at 1500 m to less than 1 mD at 4000 m (r = –0.24; Fig. 11d), with average permeability remaining constant at around 200 mD. For the Dongara–Wagina reservoir, average core porosity is moderately negatively correlated with depth (r = –0.52) and average permeability is weakly correlated with depth (r = –0.29). For the 'Kingia' – High Cliff reservoir, both average porosity (r = –0.23) and permeability (r = –0.20) are weakly negatively correlated with depth.

Clay and cement percentages were compared with porosity and permeability data to determine the strength of their relationships (Figs 12, 13; Table 4). Not all core samples have associated petrographic data, and therefore average core porosity and permeability, clay and cement percentages were calculated independently within each well, and then these values were used to measure correlations between wells. There are 37 wells for the Dongara–Wagina reservoir and six wells for the 'Kingia' – High Cliff reservoir that have average core porosity, permeability, clay and cement percentages data for comparison. For the 'Kingia' – High Cliff reservoir, data are only available between 2591 and 3397 m. Correlation coefficients for the 'Kingia' – High Cliff reservoir are consequently less robust than for the Dongara–Wagina reservoir due to the small number of wells and narrow depth range. Future work using petrophysics-generated porosity compared to HyLogger data would significantly add to a better understanding of porosity vs clay relationships and reduce uncertainty caused by small petrographic datasets based on core samples.

Significant trends for the Dongara–Wagina reservoir include:

- a strong correlation between decreasing core porosity and increasing quartz overgrowths (r = –0.82; Fig. 12d)
- a weak correlation between decreasing core porosity and increasing carbonate cement (r = –0.26; Fig. 12e), which is well developed on the Beharra Springs Terrace
- a weak correlation between core permeability and increasing total authigenic clays and cements (r = –0.29), suggesting that grain size or sorting, or both (i.e. facies control) are also likely significant regional controls
- average core porosity is greater than 16% within the kaolinite zone, 9–16% for the kaolinite–illite zone, and less than 9% for the illite zone (Fig. 11c). This steady reduction reflects the associated increase in quartz overgrowths with increasing depth.

For the 'Kingia' – High Cliff reservoir, although data for only six wells are available for comparison, several trends are apparent:

- decreasing core porosity is strongly correlated with increasing carbonate cement (r = –0.75; Fig. 12e)
- decreasing core porosity is moderately correlated with increasing quartz overgrowths (r = –0.64; Fig. 12d)
- decreasing core permeability is moderately correlated with increasing quartz overgrowths (r = –0.65; Fig. 13d), illite (r = –0.62; Fig. 13b) and total clay and cement (r = –0.59; Fig. 13f).

Although kaolinite is known to significantly clog pores throughout the Dongara–Wagina reservoir, it has a weak positive correlation with porosity (r = 0.27; Fig. 12a). This positive relationship might reflect a combination of microporosity in kaolinite (e.g. Dongara and Yardarino wells; Tupper et al., 1994) and the association of kaolinite with secondary porosity developed from grain dissolution. It is unclear from petrographic data if these processes are equally developed throughout the depth range of the reservoir. In the 'Kingia' – High Cliff reservoir, the absence of kaolinite (except Drakea 1, average 0.56%) is moderately positively correlated with porosity (Fig. 12a).

The regional relationship between porosity and chlorite is not as clear as for other diagenetic clays and cements. For the 'Kingia' – High Cliff reservoir in the Waitsia field, using average total-chlorite and average core porosities for each well (Waitsia 1–3) returns a negative correlation (r = –0.52), which suggests that porosity increases moderately with decreasing chlorite, counter to petrographic observations. A moderately strong positive correlation (r = 0.47), however, is returned when all core porosities and their associated total-chlorite percentages are plotted, and this is stronger again if only grain-rimming chlorite is used (r = 0.53). Plotting the same chlorite data against visual porosities from petrography, however, returns a weak positive correlation (r = 0.22), whereas using grain-rimming chlorite shows a stronger positive correlation (r = 0.39). Alternatively, measuring the percentage that each grain surface is covered by clay rims (both chlorite and illite) against visual porosity returns a very strong correlation (r = 0.81; Waitsia 3; Baker, 2017b).

Overall, these comparisons indicate that measuring chlorite-related porosity is sensitive to the scale and type of data collected, with grain-rimming measurements and associated visual porosities providing the best quantitative estimation. Measuring the effects of grain-rimming illite on porosity preservation (e.g. in Corybas 1) is also likely to be similarly sensitive. Unfortunately, only a few wells have sufficiently detailed petrographic datasets to measure the influence of grain-rimming clays on porosity (mostly recent Waitsia wells). For the Dongara–Wagina reservoir, average total-chlorite vs average core porosities similarly shows a moderately negative correlation with depth (r = –0.42; Fig. 12c), which probably also does not truly reflect its effect on porosity. Current petrographic data, however, is very limited for the purpose of further assessment.

Diagenetic zonation and porosity development

Although a regional synthesis of porosity styles, and clay and cement diagenesis was not carried out as part of the current study, the summary of porosity styles within each diagenetic zone (Table 5) is based on an initial review of open-file petrographic reports and work by Rasmussen (1992), Tupper et al. (1994) and Laker (2000). Currently, only the 'Kingia' – High Cliff reservoirs are known to

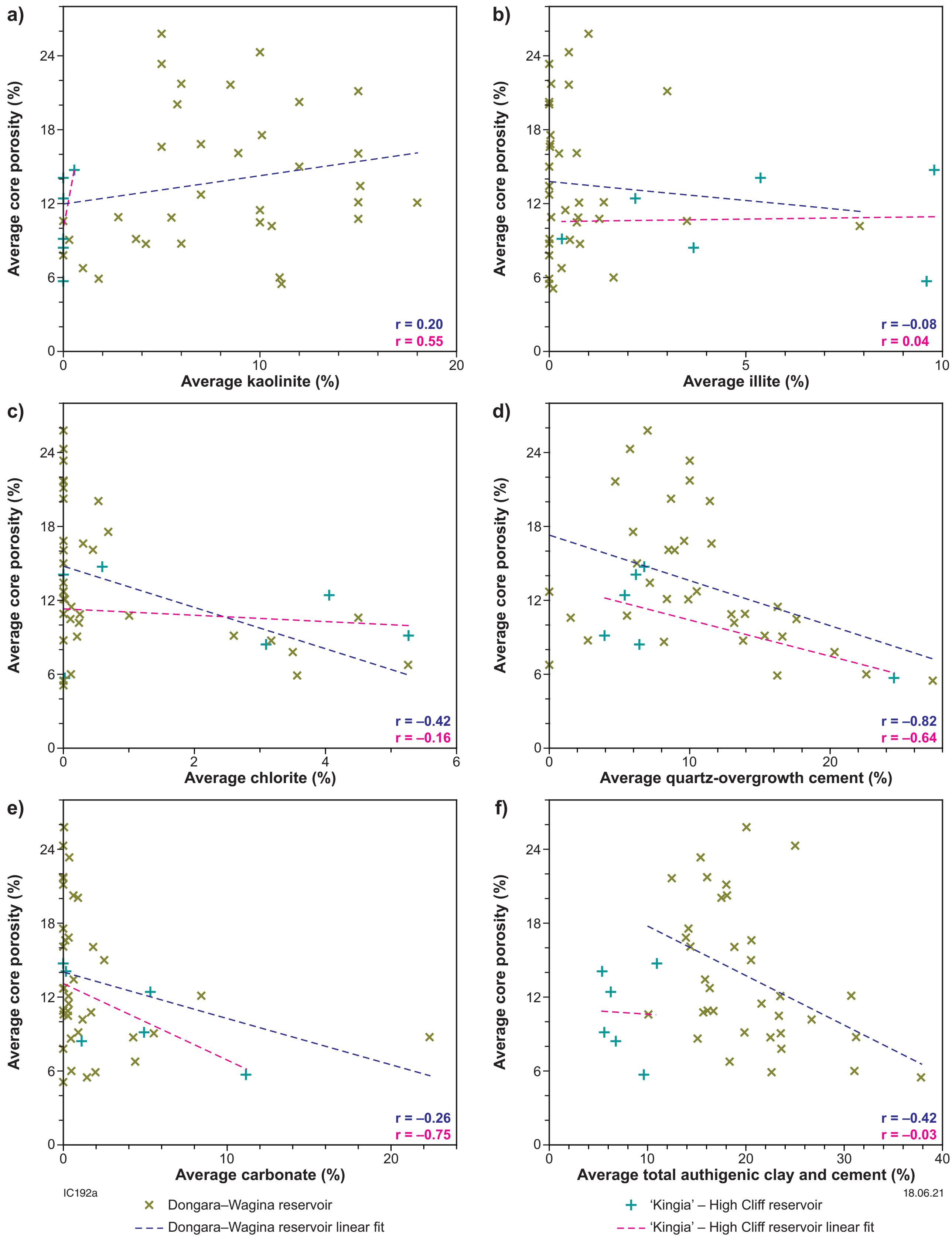

Figure 12. Relationships between average core porosity and authigenic minerals: a) kaolinite; b) illite; c) chlorite; d) quartz overgrowths; e) carbonate; f) total authigenic clays and cements

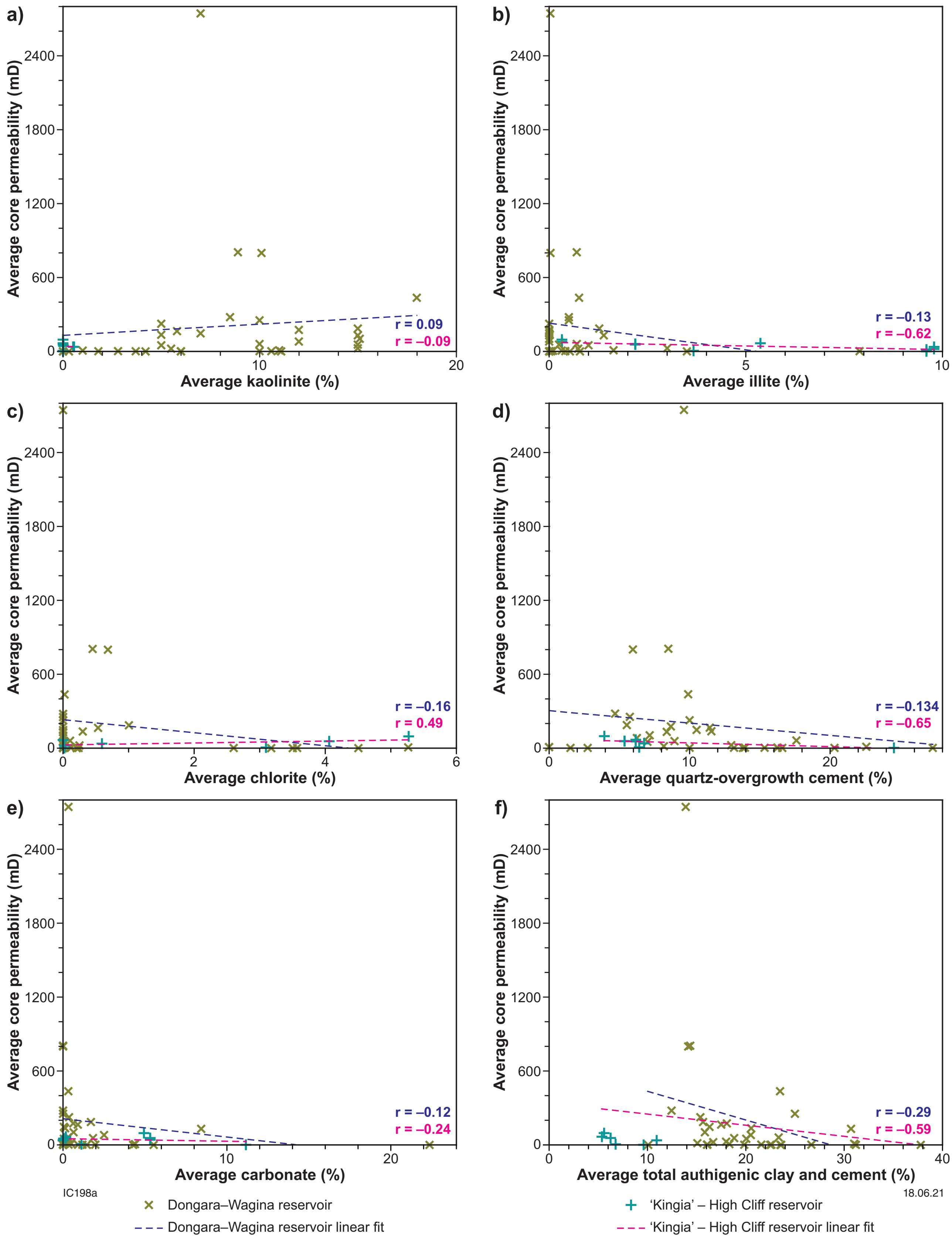

Figure 13. Relationship between average core permeability and authigenic minerals: a) kaolinite; b) illite; c) chlorite; d) quartz overgrowths; e) carbonate; f) total authigenic clays and cements

Table 4. Correlation coefficients for the relationships between authigenic mineral abundance and average core porosity and permeability

	Dongara–Wagina reservoir (37 wells)		'Kingia' – High Cliff reservoir (6 wells)		Dongara–Wagina and 'Kingia' – High Cliff reservoir (43 wells)	
	Well average porosity	Well average permeability	Well average porosity	Well average permeability	Well average porosity	Well average permeability
Kaolinite	0.20	0.09	0.55	−0.09	0.27	−0.14
Illite	−0.08	−0.13	0.04	−0.62	−0.15	−0.16
Chlorite	−0.42	−0.16	−0.16	0.49	−0.4	−0.16
Quartz overgrowths	−0.82	−0.13	−0.64	−0.65	−0.39	−0.11
Carbonate	−0.26	−0.12	−0.75	−0.24	−0.32	−0.14
All authigenic clays and cements	−0.42	−0.29	−0.03	−0.59	−0.19	−0.14

Table 5. Diagenetic zones and porosity styles for the northern Perth Basin

Diagenetic zone	Reservoir	Field	Porosity style
Kaolinite	Dongara–Wagina	Dongara, Mt Horner, Hovea, Yardarino	Primary intergranular and early secondary dissolution pores; kaolinite microporosity
Kaolinite–illite	Dongara–Wagina	Waitsia (e.g. Senecio 3), Mondarra, Apium, Jingemia, West Erregulla, Eremia, Evandra	Secondary dissolution pores; minor clay microporosity; minor primary porosity (coarser grain size)
	Dongara–Wagina/Beekeeper	Beharra Springs, Redback, Xyris	Primary intergranular pores preserved by pore-lining chlorite–illite; minor secondary dissolution pores; minor clay microporosity
Illite	Dongara–Wagina	Waitsia (e.g. Irwin 1)	Secondary dissolution pores; minor clay microporosity; very minor primary porosity (coarser grain size)
	'Kingia' – High Cliff	Waitsia, West Erregulla	Primary intergranular pores preserved by grain-rimming chlorite–illite; minor secondary dissolution pores

contain significant hydrocarbons in the deep illite zone (West Erregulla, Waitsia, Beharra Springs Deep). In these fields, grain-rimming chlorite and illite have helped preserve primary porosity from occlusion by quartz overgrowths. However, there is potential porosity development at shallower depths within the kaolinite–illite zone, where secondary dissolution porosity could be present, similar to the porosity style in the Dongara–Wagina reservoir of Senecio 3 and Irwin 1. This secondary porosity style is largely absent at greater depths due to occlusion by quartz overgrowths and clays. If chlorite is also present in the kaolinite–illite zone, then porosity development may be similar to the Dongara–Wagina reservoir at Beharra Springs, that is, grain-rimming chlorite and illite and secondary dissolution.

Porosity evolution in the Dongara–Wagina reservoir is primarily caused by compaction, cementation and dissolution events during burial diagenesis. These processes operated concurrently during burial and heating, alongside progressive illitization that created secondary porosity through grain dissolution, and with associated porosity occlusion by quartz overgrowths and carbonate cements. Consequently, at the time of hydrocarbon charge (Late Jurassic to mid-Cretaceous) reservoir position relative to the illitization window is expected to strongly influence the extent and style of porosity development and the authigenic mineral assemblage. For example, dependent on the burial history of an area during charge, a reservoir may have been either within the kaolinite zone, the kaolinite–illite zone or the illite zone. Also, during this time in the same area, the shallower Dongara–Wagina reservoir and the deeper 'Kingia' – High Cliff may have been in different diagenetic zones.

In those areas where reservoirs continued to be buried and heated (e.g. Dandaragan Trough), further illitization would have progressively modified porosity styles and clay and cement petrogenesis (e.g. illite zone in Irwin 1). Such changes, however, might not be recorded in shallower, cooler diagenetic zones where illitization had not commenced or was at an early stage (e.g. kaolinite zone in the Dongara field). Consequently, diagenetic sequences interpreted for wells will not be entirely comparable across the basin — some phases of grain-dissolution secondary porosity or porosity-occluding quartz overgrowths, for example, might not have an equivalent everywhere in the basin. As reservoirs transgressed the illitization window at different times during burial, the relative timing of available secondary porosity and hydrocarbon charge also could vary within the Dandaragan Trough. Further work is required to test these hypotheses, integrating all available diagenetic sequences against burial-history models from across the basin.

An illitization model for the northern Perth Basin therefore provides a framework to help interpret the diagenesis and porosity development of the of the Dongara–Wagina and 'Kingia' – High Cliff reservoirs. Although the formation of illite appears to have had minimal direct effect on influencing porosity (r = –0.08 and 0.04, respectively; Table 3), it helped reduce permeability (r = –0.13 and –0.62, respectively; Table 3) by clogging pore throats. Illitization created secondary porosity through grain dissolution, but this was progressively occluded by quartz overgrowths as a byproduct of the same process, alongside compaction-driven porosity loss. To date, only grain-rimming chlorite and hydrocarbon charge is known to have significantly helped preserve porosity during illitization.

Conclusions

Developing a regional diagenetic model is fundamental to basin analysis and for helping understand and predict porosity development. It is critical for designing robust fluid-flow models for petroleum and geothermal exploration and for carbon sequestration. HyLogger spectral data provide diagenetic profiles through basin stratigraphy and, in combination with petrographic data, can be used to create regional diagenetic models that help inform basinwide fluid-flow models.

In the onshore northern Perth Basin, authigenic clay formation is primarily controlled by burial temperature, resulting in a change from a shallower (<80 °C) kaolinite zone, through a mixed kaolinite–illite zone, to a deeper (>130 °C) illite zone. This model is supported by both HyLogger and petrographic data. This clay transformation is a product of regional illitization with increasing temperature during burial, with the illitization window lying approximately between 80 °C and 130 °C. The top of this zone is temperature dependent and so it transgresses both depth and stratigraphy, resulting in the Dongara–Wagina and 'Kingia' – High Cliff reservoirs transgressing all diagenetic zones.

Facies, provenance and formation water chemistry have previously been invoked as primary controls of authigenic clay distribution in the northern Perth Basin; however, the current study interprets temperature-related illitization as the fundamental regional control. The kaolinite–illite zone is extremely variable in the relative proportions of kaolinite vs illite and is thought to be influenced by local variables such as temperature gradients, hydrocarbons, salinity gradients, insufficient minerals for complete illitization and thermal anomalies.

Porosity reduction by authigenic mineral growth in reservoirs across the basin is primarily due to quartz overgrowths. Average core porosity within the kaolinite zone is greater than 16%, for the kaolinite–illite zone is between 9 and 16%, and is less than 9% for the illite zone. Along with porosity loss due to burial compaction, this steady decrease in porosity with depth is also consistent with a model of progressive illitization where the release of SiO_2 for quartz overgrowths progressively occludes porosity with increasing burial temperature and depth. Illitic clays appear to have minimal direct effects on porosity development, but have a stronger influence on permeability through clogging pore throats.

Anomalously high porosities at great depths in the 'Kingia' – High Cliff reservoir are due to diagenetically formed chlorite clay rims (after a Fe-rich clay precursor) around framework grains that have helped preserve primary porosity and significantly reduce later quartz overgrowths. Similar rims are also developed in places within the Dongara–Wagina reservoir, particularly on the Beharra Springs Terrace.

The diagenetic zone model therefore provides a regional framework for predicting authigenic clay composition and complements the current petrographic dataset that helps estimate the amount of quartz overgrowths and resultant porosity of prospective areas. Although HyLogger analysis does not replace petrography, it adds significantly and rapidly to the understanding and prediction of diagenetic processes within a basin.

HyLogger data for the onshore northern Perth Basin have important applications for ongoing diagenetic research and provide a fundamental baseline dataset for basin analysis. In particular, acquiring HyLogger datasets for entire wells using cuttings (e.g. Depot Hill 1) provides a novel technique for testing hypotheses about basin-scale diagenetic processes, such as open- vs closed-system diagenesis and thermal effects that drive localized kaolinization, illitization and carbonate cementation processes. Further petrographic analyses, and integration of clay and cement diagenesis, are required to develop porosity models for different diagenetic zones during hydrocarbon charge.

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RESERVOIR QUALITY OF PERMIAN SANDSTONES IN THE ONSHORE NORTHERN PERTH BASIN – AN ASSESSMENT USING HYLOGGER SPECTRAL DATA AND PETROGRAPHY

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Recent large gas discoveries in the northern Perth Basin within deeply buried Lower and Upper Permian siliciclastic reservoirs (Waitsia, Beharra Springs and West Erregulla) demonstrate that understanding diagenetic changes at depth is critical in predicting reservoir quality. HyLogger hyperspectral data from the Lower Permian 'Kingia' – High Cliff reservoir and the Dongara–Wagina reservoir enable a regionally and stratigraphically extensive approach to the diagenesis of proven Permian reservoirs. Integrating this data with existing petrography and testing it against contemporary diagenetic models has helped develop a regional predictive diagenetic-porosity model for the basin. These datasets indicate that authigenic clay is primarily controlled by burial temperature, from a shallower kaolinite zone through a mixed kaolinite–illite zone to a deeper illite zone, consistent with regional illitization during burial. Porosity reduction by authigenic mineral growth is mainly due to quartz-overgrowth cements, with illitic clay having minimal effect on porosity development but a stronger influence on reducing permeability. Chlorite clay rims at deeper depths have helped preserve primary porosity.

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