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1 **Controls on generation and accumulation of blended gases (CH₄/H₂/He) in the**
2 **Neoproterozoic Amadeus Basin, Australia.**

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8 **Abstract**

9 Various gases are generated in the subsurface, by diagenetic processes, fluid/rock
10 interactions, maturation of petroleum source rocks and microbial activity. Often these
11 gases just leak at the surface but sometimes they may accumulate in a subsurface trap.
12 The present study investigates the case of the southern part of the Amadeus Basin,
13 Australia, where exploration wells tested a blend of hydrocarbon (HC), helium (He) and
14 hydrogen (H₂). In Mt Kitty-1 well, He- and H₂-rich gases were reported (He ~9%, H₂
15 ~11.4%) with traces of HC, whereas C₁ and C₂₊ HC gases associated with He were
16 discovered in Magee-1 well. Seismic and well data elucidate accumulation of the gas
17 blend within a classical subsurface system with a structural trap, a permeable reservoir
18 and a thick salt layer as seal. This salt, the Proterozoic Upper Gillen, is overlying the
19 Heavitree sandstones and fractured basement reservoirs. The former is dominated by
20 intergranular porosity (~13%), whereas the latter is commonly associated with complex
21 patterns of fractures associated with deep-seated faults. The sources of blended gases
22 are different: thermal cracking of organic matter for hydrocarbons, radiolytic decay of
23 radioelements for helium. Radiolysis, and water reduction as well as oxidation of
24 hydrocarbons are open hypotheses for H₂ generation in the study region.
25 Neoproterozoic and Early Paleozoic tectonic episodes (e.g. Petermann; Alice Springs)
26 allowed the formation of various structural traps where the gas blend was accumulated.

27 The large quantity of He, light gas slowly generated by the crustal radioactivity
28 indicates that the seal is very efficient and that accumulations could have been in place
29 for millions of years very likely with an evolving CH₄/H₂/He ratios through time. The
30 presence of gas chimneys and surface depressions in the basin indicate that the
31 generation, and/or migration of the gases are still active. All the data are consistent with

32 a long-term accumulation of this gas blend, different from the short term H₂ retention in
33 the reservoir that was proposed in other contexts such as in Mali.

34 **Keywords:** Natural hydrogen; helium; hydrocarbon gases; Amadeus Basin; Australia.

35 **1. Introduction**

36 Generation of hydrocarbon and non-hydrocarbon gases is mostly dependent on the
37 complex interactions between three main genetic processes (biogenesis,
38 thermogenesis and abiogenesis) (Bernard, 1978; Schoell, 1983; Whiticar, 1999; Lin et
39 al., 2005; Vacquand et al., 2018 and references therein). Deciphering the origin of these
40 gases and various mechanisms of their generation is crucial for a proper exploitation of
41 the geo-resources. Hydrocarbons (HC) are often expelled from thermally-mature
42 organic-rich rocks after reaching the oil and gas window maturities, whereas biogenic
43 processes commonly generate dry HC by consuming the light liquid HC phases at low
44 temperature levels (Schoell, 1983; Peters and Casa, 1994; Whiticar, 1999; Leila and
45 Moscariello, 2017). Radiolysis also generates helium (He) and hydrogen (H₂) gases via
46 the radiolytic decay of radioelements coupled with a possible dissociation of water
47 (Ballentine et al., 1991; Warr et al., 2019, Klein et al., 2019 and references therein). The
48 abiogenic processes can produce light hydrocarbon (mainly C₁ and C₂₊) and non-
49 hydrocarbon (H₂, CO₂) gases at a wide range of temperatures in various geological
50 environments (Coveney et al., 1987; Holloway and O'Day, 2000; Taran et al., 2010;
51 Etiope, 2017; Prinzhofer et al., 2019; Moretti et al., 2021a, b; Leila et al., 2021; Radwan
52 et al., 2022). These processes include redox reactions between water and Fe⁺²-bearing
53 rocks (mafic, ultramafic rocks and ironstones) (Charlou et al., 2002; McCollom and
54 Bach, 2009; Vacquand et al., 2018), radiolytic dissociation of water by radioelements
55 (uranium, thorium) in crustal rocks (Lin et al., 2005; Sherwood Lollar et al., 2014),
56 volcanism and volcanic degassing (Stefánsson and Arnórsson, 2002) as well as thermal
57 metamorphism (Orlando et al., 2010).

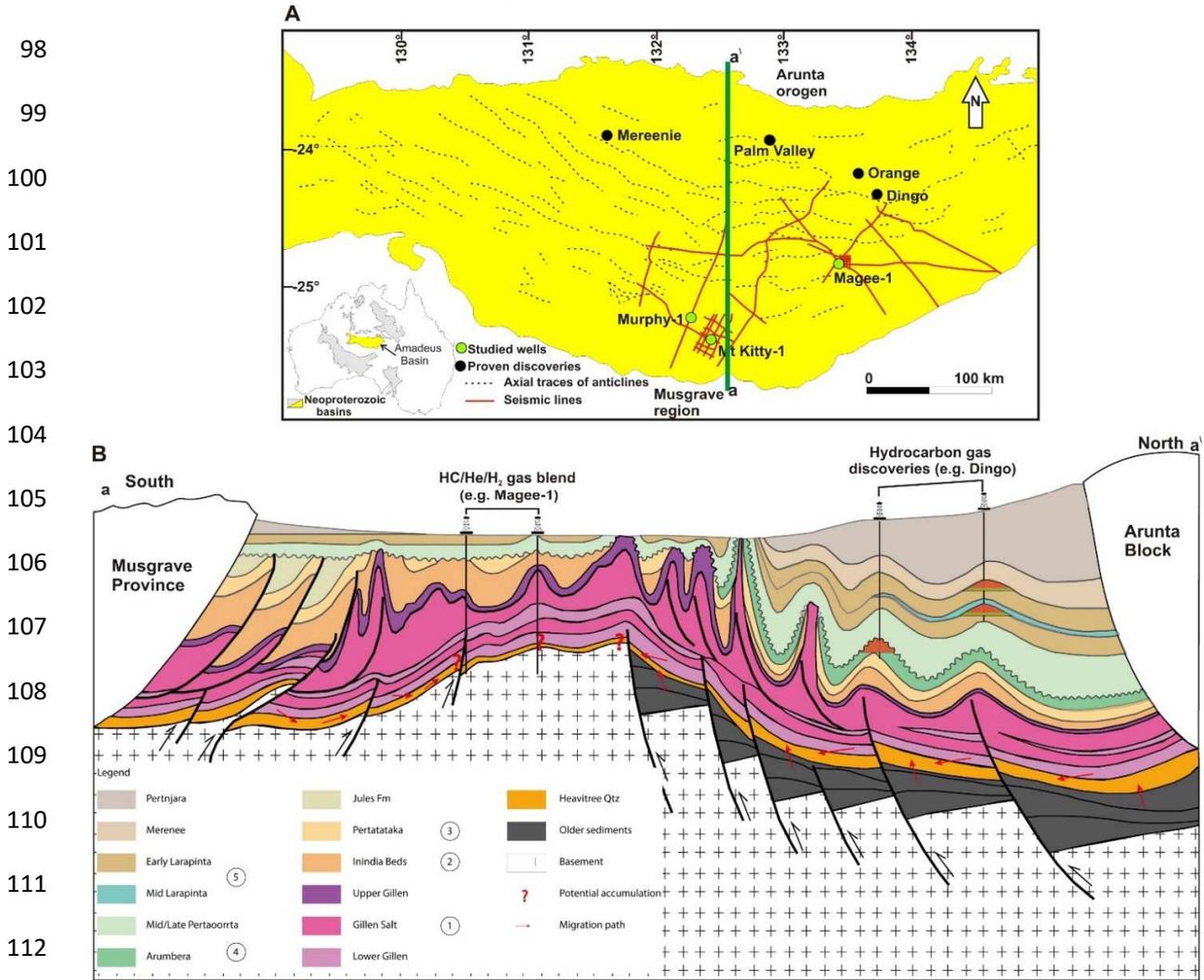
58 Natural H₂ generation via abiogenic processes was recently estimated at 2.8 M-
59 tonnes/year (Truche et al., 2020), nonetheless, this estimation could be much more
60 under-estimated (Zgonnik, 2020). Moreover, recent discovery of shallow H₂-rich (~98
61 mol%) gas in Bougou-1 well, Taoudeni Basin, in Mali (Prinzhofer et al., 2018), highlights
62 the potentiality of subsurface natural H₂ exploitation. Just a few years ago, it was

63 claimed that H₂ does not exist as a free gas in the Earth's crust and the fact that a
64 natural seal did not exist for such a low molecular weight gas was often affirmed and
65 published (e.g. [Zgonnik et al., 2015](#); [Moretti et al., 2021a, b](#)). The implications of the
66 subsurface H₂ storage and of the discovery in Mali was not really considered.
67 Additionally, some geoscientists believe that the subsurface H₂ will be mainly produced
68 within a dynamic system and a flow of H₂ may exist in a porous medium such as in
69 Mali ([Prinzhofer et al., 2018](#)) or within the steam of the geothermal plants ([Stefánsson
70 and Arnórsson, 2002](#); [Combaudon et al., 2022](#)). Hydrogen currently presents a zero
71 carbon alternative for the traditional fossil fuels and the advances in H₂ exploration and
72 production may aid in the decarbonization of the global energy supply (e.g. [Gielen et al.,
73 2019](#)). Similarly, other non-HC gases such as helium is widely used in high-tech
74 industries such as cryogenics, and the global demand for this important gas is currently
75 increasing ([Skirrow et al., 2013](#); [Waltenberg, 2015](#); [Haines and Allen, 2019](#)).

76 Blended hydrocarbon and non-hydrocarbon gases were reported from several
77 places in Australia such as the Cobar copper mine, New South Wales (~75% H₂ and ~
78 25% CH₄; [Stack and Rabone, 2018](#)), Yorke Peninsula and Kangaroo Island
79 ([Woolnough, 1934](#)) as well as in some exploration wells offshore Victoria (Golden
80 Beach-1 ~38 mol.% H₂) and in Amadeus Basin (Mt. Kitty-1 ~11 mol.% H₂) ([McInnes et
81 al., 2017](#)). In addition, surficial evidence for subsurface gas emanations is recognized
82 by sub-circular depressions (SCD) that have been reported from all over the globe
83 (Russia, USA, Brazil, and Ukraine) ([Larin et al., 2015](#); [Zgonnik et al., 2015](#), [Prinzhofer et
84 al., 2019](#); [Zgonnik, 2020](#); [Moretti et al., 2021a, b](#), [Geymond et al., 2022](#)). They are
85 visible on satellite images and have been observed in several places in Australia where
86 seeps of H₂-rich gases have been reported ([Moretti et al., 2021b](#), [Frery et al., 2021](#)).

87 The present study focuses on the HC and non-HC gas blend discovered in the
88 Amadeus Basin, central Australia ([Fig. 1](#)). The Amadeus Basin is an extensive
89 intracratonic structure covering an area of approximately 170,000 km². It is one of the
90 Australia's most petroliferous provinces with hydrocarbon exploration history that has
91 been started since the early 1960s ([Young and Ambrose, 2007](#)). The basin contains
92 proven HC reserves estimated at approximately 37 million barrels of oil and more than
93 400 BCF (billion cubic feet) of gases ([Jackson et al., 1984](#)). It constitutes a thick (~ 17

94 km) sedimentary cover of Proterozoic to late Devonian rocks (Fig. 2). Five distinct
 95 petroleum systems have been identified in the Amadeus Basin; the first four are mainly
 96 hosted in the Neoproterozoic rocks with sub-economic gas discoveries (e.g. Magee-1,
 97 Mereenie, Orange-1, -2 and Dingo-1 to -5).



113 **Fig. 1.** A) Location map illustrating the location of the studied wells and proven gas
 114 gas discoveries in Amadeus Basin, central Australia, B) Illustrative N-S cross-section (not to
 115 scale) in central Amadeus Basin showing the main structural elements, the distribution
 116 of different stratigraphic units (modified from Johns et al., 2017) and the kind of plays
 117 that have been targeted.

118 The youngest petroleum system comprises the Ordovician sandstones hosting the
 119 economic accumulations of large oil and gas such as the Mereenie and Palm Valley

120 fields (Fig. 1; Marshall, 2003). The source rock potential of the Neoproterozoic systems
121 was considered to be poor or rather negligible (Jackson et al., 1984; Summons and
122 Powell, 1991). However, the recent organic-geochemical and geologic data have
123 demonstrated several potential source rocks in the Neoproterozoic successions in some
124 parts of the basin (Marshall, 2003; 2004). Today, the non-hydrocarbon gas plays (H₂,
125 He) in the Neoproterozoic systems are actively explored (Hissey et al., 2016;
126 Scrimgeour, 2019; Haines and Allen, 2019). The case of HC/He/H₂ gas blend in the
127 Amadeus Basin is especially interesting since their kinetics are rather different and the
128 gases have variable residence times in the reservoir (Lin et al., 2005). The factors
129 controlling the generation, mixing and accumulation of this gas blend remain poorly
130 constrained but in Australia the subsurface data are publicly available and we took this
131 opportunity to investigate the surface and subsurface data, seismic and wells for
132 potential geo-energy exploration plans. Additionally, with proven resources of both HC
133 and non-HC gases, Amadeus Basin presents a natural laboratory where we can
134 examine the controls on generation and accumulation of various gas plays.

135 **2. Geologic setting**

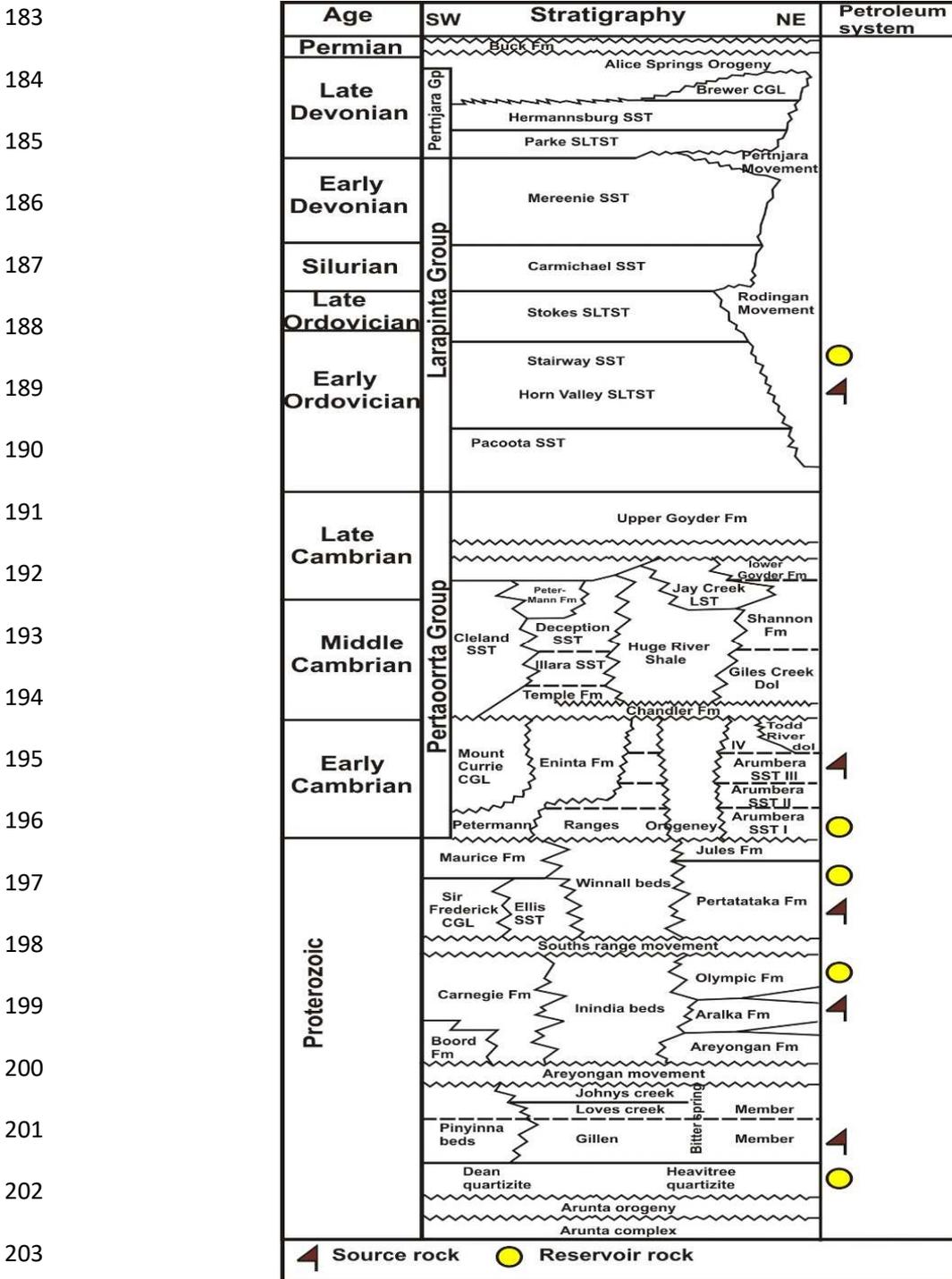
136 The Amadeus Basin presents an E-W trending belt of folded Neoproterozoic-Early
137 Paleozoic (Cambrian-Devonian) sedimentary successions in central Australia overlying
138 unconformably the Paleo- to Mesoproterozoic crystalline basement complex (Wells et
139 al., 1970; Jackson et al., 1984; Marshall et al., 2007; Edgoose, 2013; Carr et al., 2016).
140 The basement rocks are exposed in the northern (Arunta Orogen) and southern
141 (Musgrave Complex) parts of the basin due to their uplift during Petermann (Ediacaran-
142 Early Cambrian) and Alice Springs (Paleozoic) orogenies. Northward, the exposed
143 basement complex consists of deformed meta-sedimentary and meta-igneous felsic and
144 intermediate rocks, whereas the southern basement is constituted by high-grade
145 metamorphic feldspathic gneiss and intrusive igneous bodies (Jackson et al., 1984;
146 Marshall et al., 2007; Carr et al., 2016). The Amadeus Basin extended westwards
147 where an NNE-striking shallow ridge of crystalline basement was emplaced during the
148 Late Paleozoic orogeny. Prior to latest Paleozoic, sediment accumulation in Amadeus
149 Basin was linked to a continuous deposition southward (Powell et al., 1994). The
150 sedimentary basin-fill was initiated during the Early Neoproterozoic and the pre-salt

151 sediments comprise a quartzite-rich siliciclastic package of the Dean/Heavitree
152 Formation which is exposed along the northern margins of the basin (Fig.2; Walter et
153 al., 1995).

154 The Petermann and Alice Springs orogenies controlled sedimentation and
155 distribution of the basin-fill sedimentary successions in Amadeus Basin. During
156 Petermann Orogeny (~550-535 Ma), parts of the Amadeus Basin was either uplifted,
157 eroded or locally metamorphosed along the southern margin with synchronous
158 deposition of thick siliciclastic materials that were sourced from the uplifted parts (Bagas
159 et al., 1996; Haines et al., 2015). The Petermann uplift phase was likely accompanied
160 by salt movements; however, the irregular patterns of the folds reveal that the salt-
161 related structures were evolved as earlier growth features prior to their reactivation
162 during the orogenic uplift. Alice Springs orogeny (~400 Ma) largely affected the
163 northeastern part of the basin and was accompanied by a contemporaneous deposition
164 of synorogenic sedimentary facies that are preferentially localized in the northern and
165 northeastern parts of the basin.

166 The Heavitree Formation comprises quartz-rich sandstones overlying unconformably
167 the basement complex. The sandstones are intercalated with siltstones and
168 conglomerate, and are mostly of fluvial to shallow marine origin. The Heavitree
169 sandstones are followed by carbonates and fine-grained siliciclastic and evaporites of
170 Bitter Springs Group. The Heavitree-Bitter Springs contact is only conformable in the
171 eastern parts of the basin. In the northern parts, the Bitter Springs Group comprises,
172 from bottom to top, the Gillen, Loves Creek and Johnny Creek formations (Fig. 2). The
173 Gillen Formation consists of thick evaporite deposits (halite, gypsum) interbedded with
174 dolomite, shale and siltstone. The Loves Creek Formation is made of stromatolitic
175 dolomite facies unconformably overlying the Gillen facies and conformably followed by
176 the lacustrine red dolomitic and evaporitic mudstone of the Johnys Creek Formation.
177 The post-Bitter Springs stratigraphy comprises thick mixed carbonate and siliciclastic
178 sediments resting unconformably above the evaporitic mudstone and dolomite of the
179 Johnys Creek Formation. The Amadeus Basin contains thick, well-developed Paleozoic
180 sedimentary successions (mostly shales, siltstone and minor sand interbeds) except in

181 the western regions where the Paleozoic sediments are comparatively thinner
 182 (Marshall, 2003; Haines et al., 2010; Normington et al., 2015).



204 **Fig. 2.** Generalized composite stratigraphic column for the Amadeus Basin illustrating
205 the tectono-stratigraphic framework of the basin and the possible source rocks and
206 reservoir intervals (Marshall, 2004).

207 Hydrocarbon exploration to date in the Amadeus Basin focused on the Paleozoic
208 successions principally targeting the structural and combined structural-stratigraphic
209 plays in the shallow salt-related structures in the north. The discoveries so far are post-
210 salt and located in the northern part of the basin, however, the subsalt strata are
211 shallower southward and exploration has been started there since the last decade. For
212 the pre-salt petroleum systems, Heavitree Formation presents a potential reservoir that
213 could be sourced from the shale intervals in Bitter Springs Group (Marshall, 2003). The
214 evaporites of Gillen and Loves Creek Formations are likely to be effective cap rock for
215 the gases that may accumulate in Heavitree reservoir.

216 **3. Data and methods**

217 The Australian policy towards the dissemination and sharing of scientific advances
218 allows access to a lot of information directly on the government site of the Department
219 of Geosciences (<https://www.ga.gov.au/>). The available subsurface dataset utilized in
220 this study includes 2D seismic, wireline logs as well as analytical internal reports.

221 **3.1. Seismic dataset**

222 The subsurface seismic dataset constitutes regional post-stack 2D seismic grid
223 covering an area of approximately 30,000 km² in the eastern and central parts of the
224 Amadeus Basin. In addition, local 3D seismic blocks around the studied Magee-1 and
225 Mt Kitty-1 wells have also been utilized in this study (Fig. 1). The seismic data was
226 interpreted using Petrel Schlumberger 2017 software following the standard seismic
227 interpretation scheme of Herron (2011). The seismic data (time) was tied with well logs
228 (depth) using check shots that were available for all the studied wells.

229 **3.2. Wireline logging analysis**

230 A complete set of wireline logs for Magee-1, Mt Kitty-1, and Murphy-1 wells have
231 been interpreted using the Schlumberger Techlog 2017 software. The available well
232 logs include gamma ray (GR), bit size (BS), caliper (Cal), spontaneous potential (SP),
233 shallow and deep resistivity (LLS, LLD), photoelectric factor (PEF), neutron (NPHI) and

234 density (RHOB). The GR and NPHI logs were corrected for environmental effects such
235 as borehole size, mud weight and salinity. DST data from Magee-1 well was used to
236 drive R_w values which is approximately $0.04 \Omega m$ at $77^\circ C$. The cementation exponent
237 “m” was derived using the triple porosity model (Aguilera and Aguilera, 2004). The
238 wireline logging interpretation includes a qualitative and semi-quantitative estimation for
239 the different petrophysical (porosity Φ , permeability K , water saturation S_w) and
240 lithological parameters using the standard logging interpretation technique.

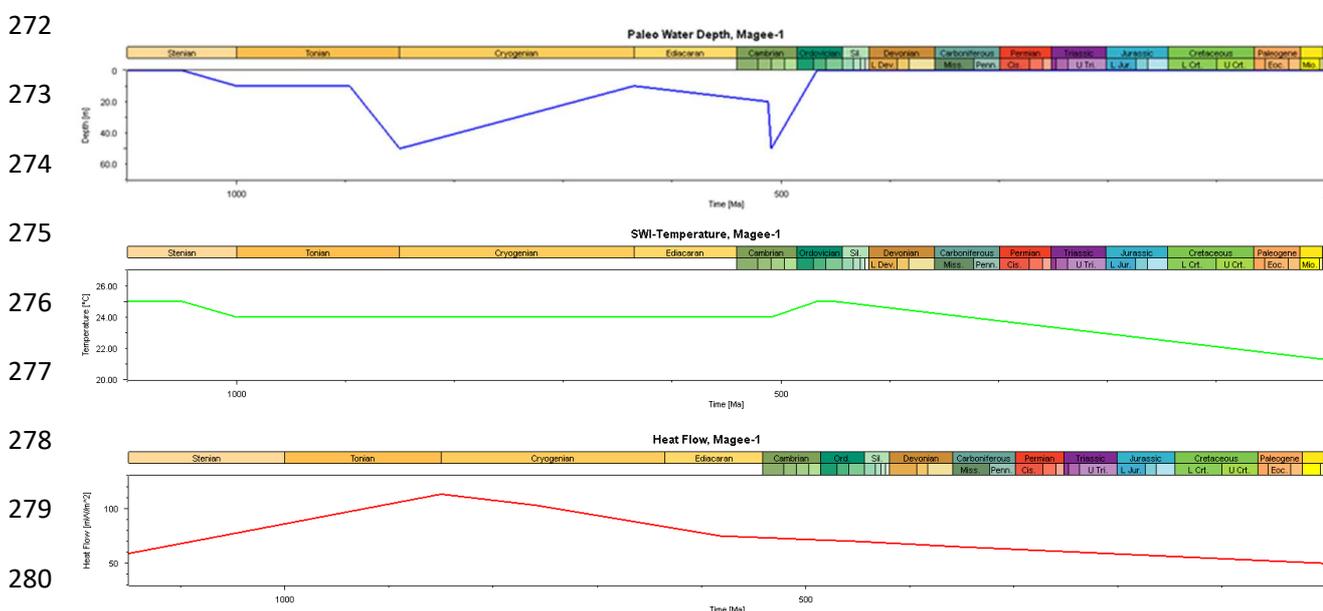
241 **3.3. Source rock evaluation and gas analysis**

242 Available analyses for Total Organic Carbon (TOC) and Rock-Eval pyrolysis carried
243 out by the operators on 12 cutting samples from Upper (2 samples) and Lower Gillen (8
244 samples) member as well as Inindia Beds (2 samples) in Magee-1 and Murphy-1 wells
245 were utilized in this study (Table 1, Geotech, 1992). At that time, the cuttings were
246 analyzed using Rock-Eval 2 apparatus following the procedure described by Espitalié et
247 al., (1986). The Rock-Eval pyrolysis peaks include S_1 , S_2 and S_3 values which
248 respectively reflect the amount of free, pyrolyzed and organically-bound CO_2
249 hydrocarbons. Additionally, the temperature at S_2 peak (T_{max}) reflects the source rock
250 maturity (Peters and Cassa, 1994). Geochemical gas analyses comprise the
251 measurement of the molecular gas composition and relative abundance of different
252 hydrocarbon and non-hydrocarbon gases using chromatographic separation. The
253 identified hydrocarbon gas phases comprise C_1 , C_{2+} components whereas the non-
254 hydrocarbon gases constitute N_2 , Ar, CO_2 , H_2 , and He (Table 2).

255 **3.4. Basin modelling procedure**

256 Burial and thermal history models were constructed for Magee-1 well using
257 Schlumberger PetroMod 1D software to simulate the conditions of hydrocarbon
258 generation and expulsion. The input data for the models comprises a detailed
259 stratigraphic information, thermal boundary conditions, as well as the present-day
260 thermal maturity values. The thermal boundary conditions include the sediment-water
261 interface temperature (SWIT) and the basal heat flow (HF). The paleowater depth
262 (PWD) was determined based on the depositional environment of the sediments. This is
263 an important parameter to define the thermal boundary condition (SWIT). The surface

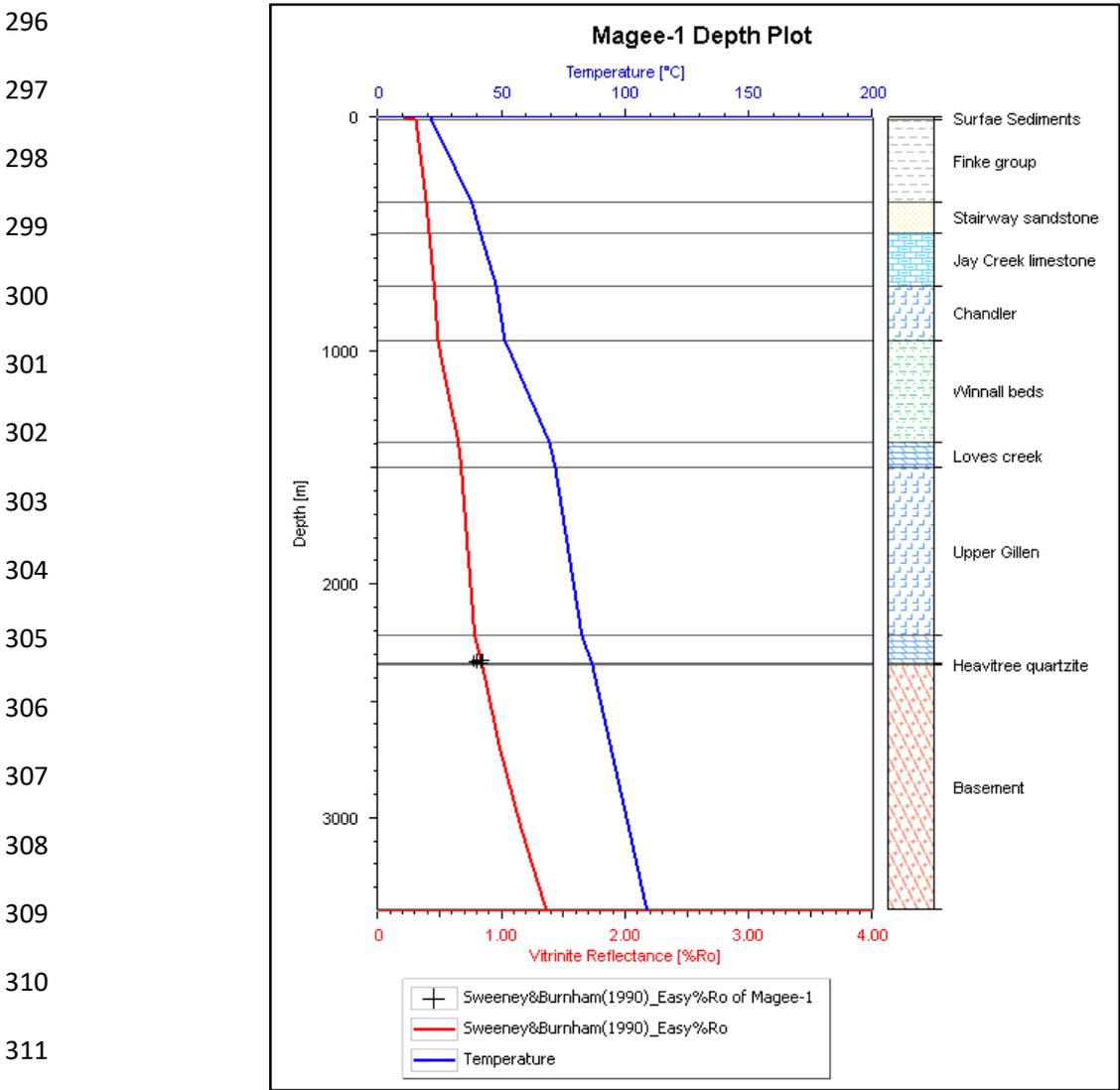
264 temperature trends have been synthesized for Magee-1 well in southern Australia
 265 (24°S) using the time-latitude diagrams (Wygrala, 1989). The lower thermal boundary
 266 condition, paleo heat flow (HF, values in mW/m²) values were calculated using the
 267 known plate tectonic framework and crustal evolution models (Fig. 3; Allen and Allen,
 268 1990). The basal heat flow values follow a general trend reporting a maximum value of
 269 113 mW/m² during the main rifting phase of Areyonga, reducing progressively during the
 270 compressional tectonic phases of Petemann, Bloodwood, and Rodingan movement and
 271 finally reached to 50 mW/m² in the present-day (Fig. 3).



281 **Fig. 3.** The thermal boundary condition assessment for Magee-1 well including: (top)
 282 the paleowater depth (PWD, in meter) and (middle) the sediment-water interface
 283 temperature (SWIT, in °C), and (bottom) the paleo-heat flow (HF, in mW/m²). The basal
 284 heat flow values were specified for each geologic event using the present-day analogs
 285 and extrapolated through time (Allen and Allen, 1990).

286 The simulation results were calibrated using equivalent vitrinite reflectance data
 287 (VRE) deduced from the measured Rock-Eval T_{max} values (Fig. 4). The calculated
 288 vitrinite reflectance from temperature histories was carried out using the EASY-%R_o
 289 algorithm of Sweeney and Burnham (1990). The predefined kinetic model_TII(B) of
 290 Pepper Corvi (1995) was designated based on the source rock type and depositional
 291 environment. The timing of hydrocarbon expulsion was deduced considering that 20%

292 of the porous volume of source rocks should be filled by hydrocarbons prior to the
 293 expulsion onset (Ungerer, 1990). The assigned initial TOC and HI (TOC_o , HI_o) were
 294 calculated from the measured TOC and HI following the procedure described by (Peters
 295 et al., 2005).



312 **Fig. 4.** The depth plot of the present-day thermal maturity of the Magee-1 well calibrated
 313 with the theoretically calculated equivalent vitrinite reflectance (VRE) values.

314 **3.5 Petrography**

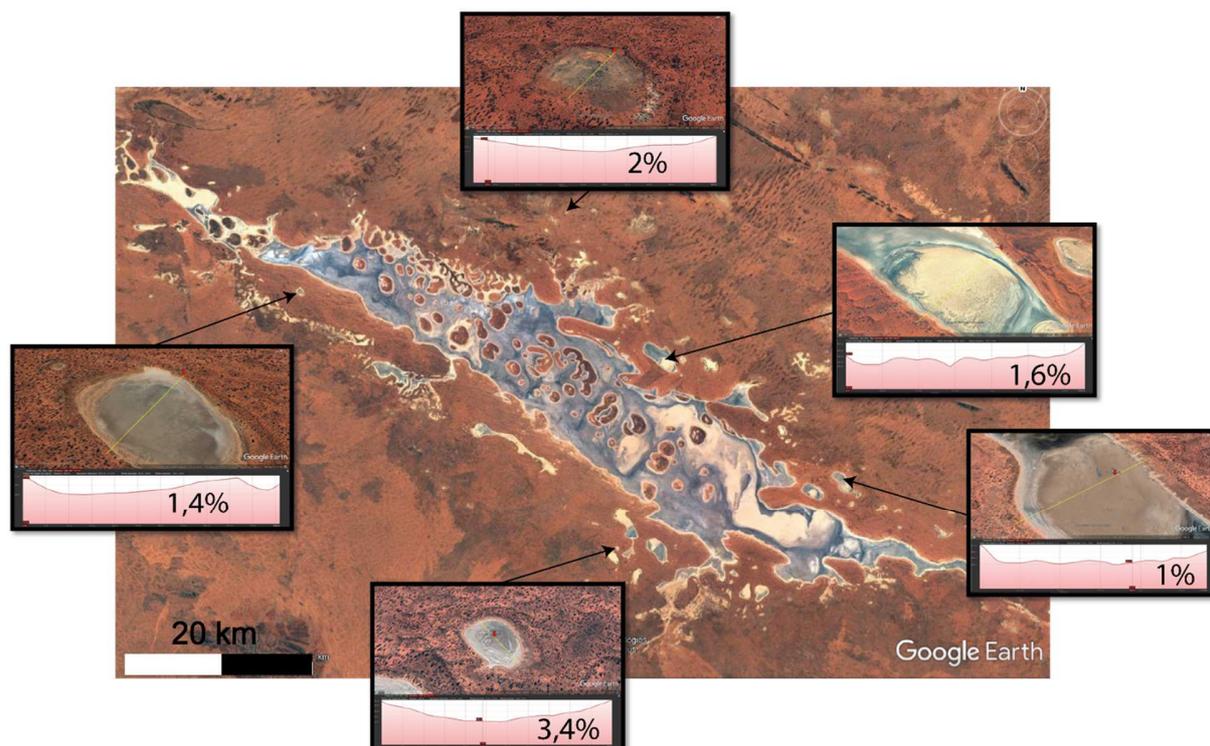
315 Three thin sections were prepared from the cutting and SWC samples retrieved from
 316 the 7 m thick Heavitree sandstones in Magee-1 well (Geotech, 1992). The cuttings were
 317 impregnated with araldite and blue dye to facilitate the visualization of pore spaces and

318 quantification of porosity. Additionally, the thin sections were stained with sodium
319 cobaltinitrite to identify feldspars.

320 4. Results

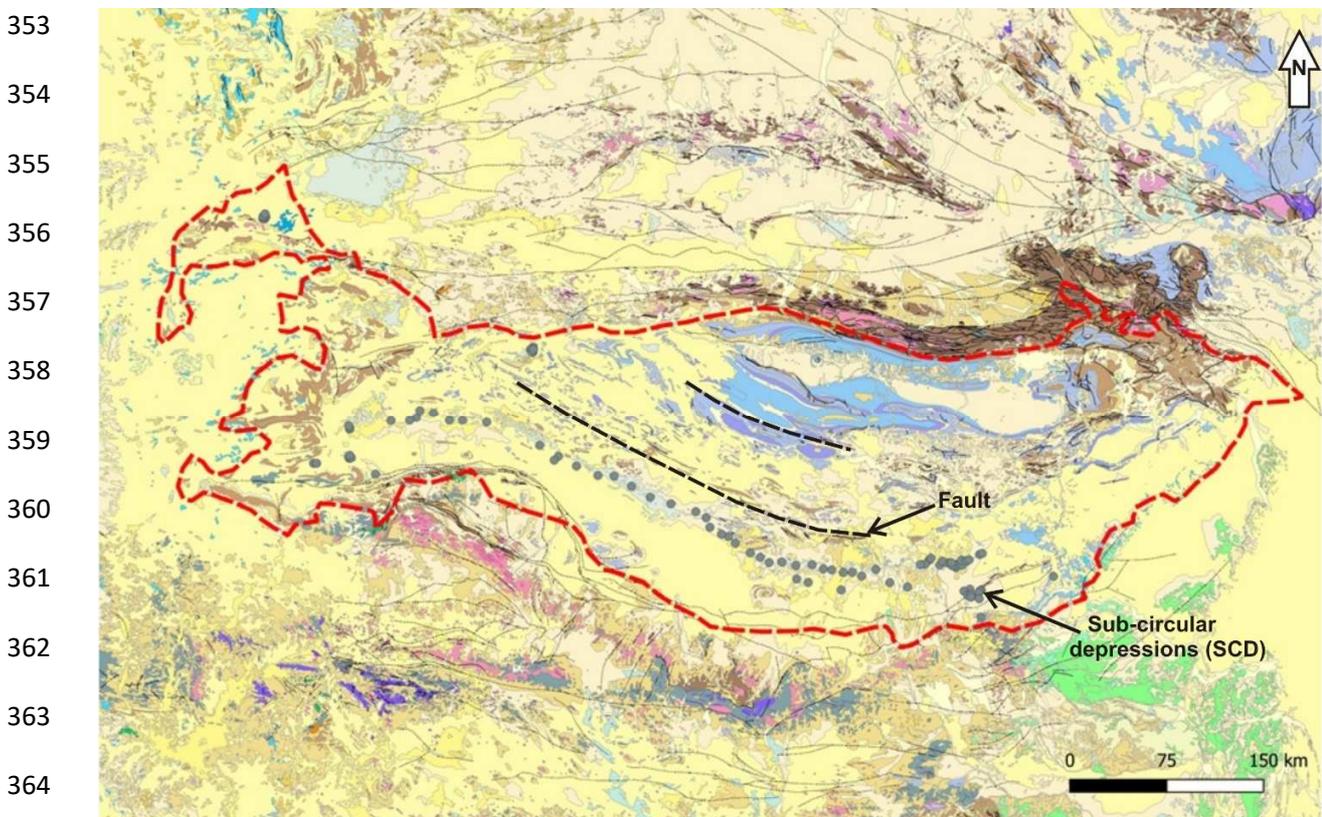
321 4.1. Surface emanations

322 Several sub-circular depressions (SCD) have been recognized from the satellite
323 images in the study area. The observed SCD are similar to those reported for surficial
324 H₂ emitting structures, the so-called fairy circles, as described in south and west
325 Australia (Moretti et al., 2021a; Frery et al., 2021, Geymond et al., 2022). High densities
326 of scattered, slightly elongated SCD are observed near the Amadeus Lake (Fig. 5). The
327 diameter of the SCD structures varies from several tens to hundreds of meters and
328 most of them have diameters greater than 400 m. The large SCD often display
329 concave-up elevation profiles with smooth topography, whereas the small depressions
330 (< 200 m diameter) have sharp, concave-up and irregular elevation profiles.



342 **Fig. 5.** Google Earth photographs illustrating occurrence of several aligned Sub Circular
343 Depressions in Amadeus Basin with variable depth/equivalent diameter ratios
344 highlighted in red.

345 The depressions also contain some local highs usually localized in the center. The
346 depth/equivalent diameter ratio of the SCD ranges from 1% to more than 3% (Fig. 5).
347 These values are very similar to the ones reported in other parts of Australia and in the
348 areas where H₂ emitting structures have been mapped (Moretti et al., 2021b, Geymond
349 et al., 2022). Moreover, a trend of SCD is observed to the south of the Amadeus Lake.
350 They are aligned in NW-SE direction parallel to the faults associated with Petermann
351 Orogeny (Fig. 6) suggesting a possible gas leakage along these faults similar to that
352 reported elsewhere such as in Russia (Larin et al., 2015).



365 **Fig. 6.** Map illustrating the distribution of the sub-circular depressions (SCD) in the
366 southern part of Amadeus Basin, grey dots. The depressions are aligned parallel to the
367 master NW-SE trending fault trends affecting the basin. One may note the highest
368 density of the SCD eastward near the wells that proven the presence of H₂.

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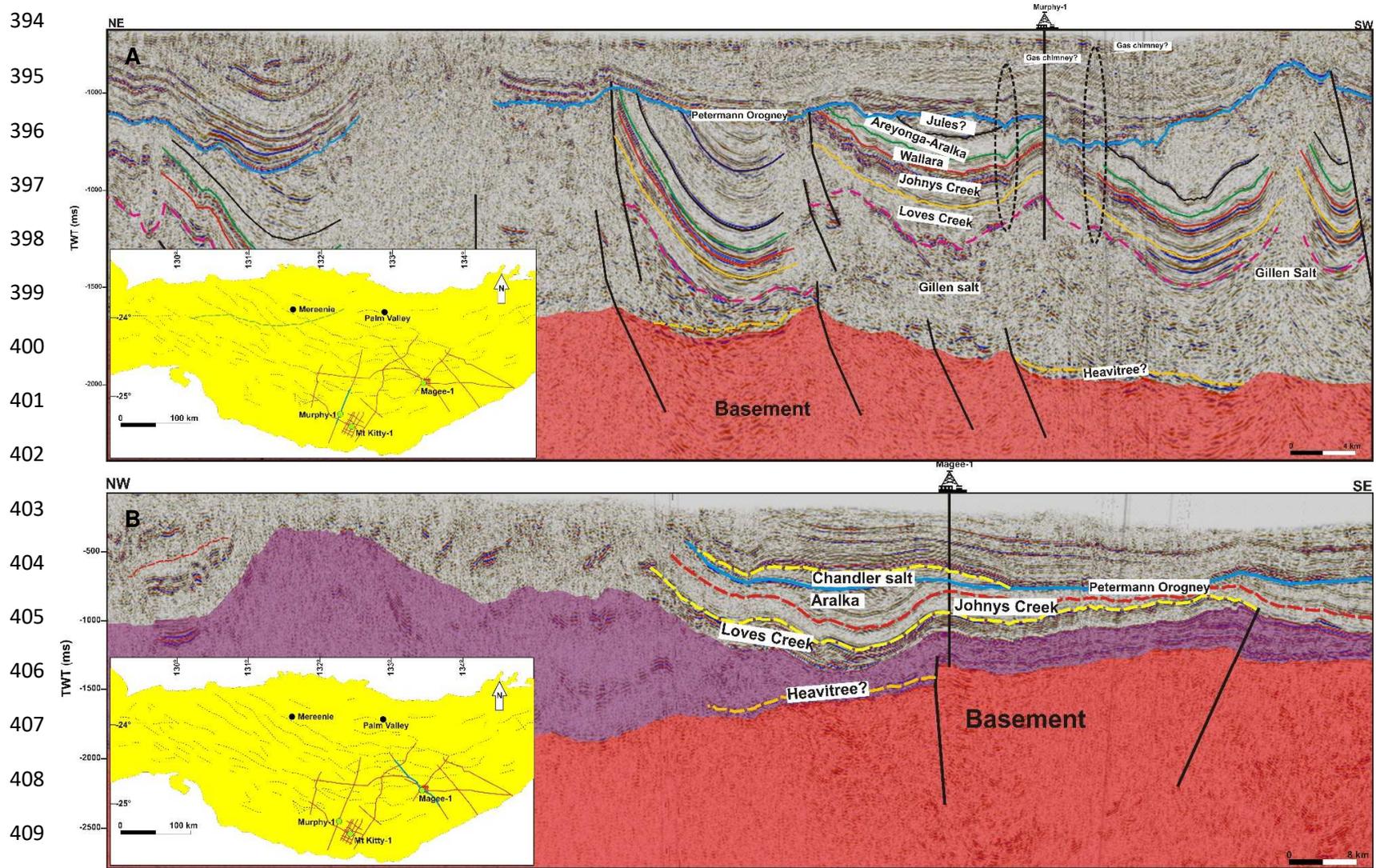
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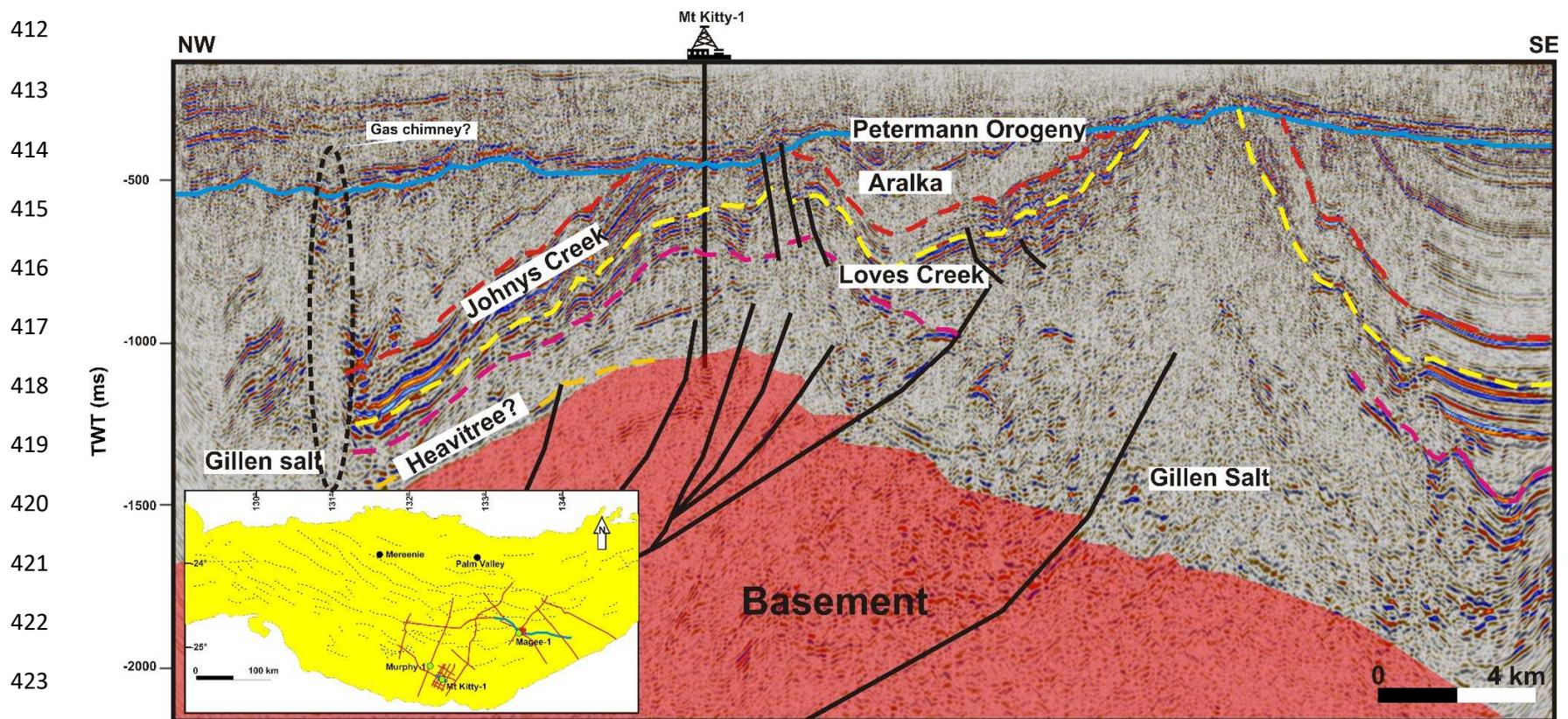
373 **4.2. Seismic interpretation**

374 The interpreted 2D seismic profiles delineate the complex structural elements that
375 influenced the stratigraphic architecture of the study region. The seismic profiles
376 illustrate chaotic and reflection free seismic reflections interpreted as crystalline
377 basement that are often dissected by large deep-sated faults (Figs. 7A, B and 8). The
378 basement is picked at relatively shallow depths (< 2000 millisecond two-way time ms
379 TWT), however several basement highs (< - 1700 ms TWT) are locally observed. The
380 basement top is defined by irregular, undulated non-conformity surface. Thin-skinned
381 deformation features probably associated with the Petermann Orogeny with major faults
382 detached within the basement and the overlying pre-salt and salt layers are identified as
383 the most prominent structural elements. The faults are mainly dipping westward with
384 displacements up to 300 ms TWT at the top of the Gillen Formation. The basement
385 faults were likely reactivated during Petermann Orogeny resulting in a formation of
386 multiple local antiforms associated with inverted basement blocks (Fig. 8).

387 The pre-salt Heavitree Formation is represented by discontinuous high amplitude
388 and reflectivity seismic reflections locally onlap the non-conformity surface topping the
389 basement (Fig. 7A, B). The Heavitree reflections are localized in the basement lows and
390 depressions adjacent to the deep faults (Fig. 7A), where they attained a maximum
391 thickness of less than 100 ms TWT. The basement is relatively deeper in the
392 southwestern part of the study area where its top is picked at more than - 2500 ms TWT
393 (Fig. 9A).



410 **Fig. 7.** Interpreted 2D seismic profiles showing the distribution of the different stratigraphic horizons and the major
 411 structural elements. Seismic location: green line on the map.



424 **Fig. 8.** Interpreted 2D seismic profile illustrating the main fault trends in Mt Kitty structure.

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428 The Gillen salt is characterized by very low amplitude, transparent to semi-
429 transparent chaotic reflections (Figs. 7A, B and 8). Lower Gillen reflections are less
430 chaotic with moderate amplitude and reflectivity, locally displaying discrete patches that
431 are localized in the basement highs (carbonate build-ups?). In some parts such as in
432 Magee-1 well area, these patches are followed by thin (~ 15 ms TWT), high amplitude
433 horizontal, continuous reflections interpreted as halite layers. The top of the Gillen salt is
434 picked at variable depths in the study area, however, it is relatively shallower and
435 thicker in the west than in the east (Fig. 9B). Loves Creek reflections are semi-
436 transparent and display low to moderate amplitude and reflectivity. They grade upward
437 into the parallel, high amplitude and reflectivity reflections of the Johnys Creek
438 Formation. The seismic reflections of the Bitter Springs Group are terminated against
439 Petermann unconformity characterized by high amplitude, continuous, and irregular
440 reflector erosionally-truncating the pre-Petermann reflections. The Petermann
441 unconformity is picked at greater depths in the eastern part of the study area (~ -1000
442 ms TWT, Fig. 10A). The Gillen salt has been mobilized possibly during the Petermann
443 Orogeny, and therefore its thickness varies greatly in the study region (Fig. 10B).
444 Reactivation of the basement faults during the Petermann Orogeny is more prominent in
445 the western part of the study area resulting in the inversion of the basement blocks
446 associated with formation of flower-like structures (Fig. 8).

447 Several forms of chaotic and disordered vertical disturbances have been observed
448 on seismic and were interpreted as gas escape structures (gas chimneys). They are
449 represented by vertically-aligned columnar features associated with an abrupt decrease
450 in the reflection amplitude and continuity (Figs. 7A, B and 8). The observed gas
451 chimneys often traced vertically from the basement to the Petermann unconformity
452 where they often disturb the overlying layers. They range in size on the horizontal scale
453 from several few tens of meters up to 500 m (Fig. 11). None of these features are
454 associated with pockmarks that often reflect entrapment of the migrated gases. In this
455 kind of salt-rich basin, some of these disturbances in seismic reflections may also be
456 induced from the mobilization of salt forming salt scars.

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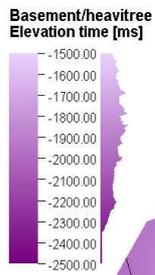
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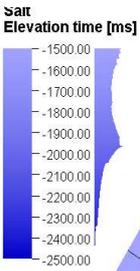
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A

Gas
chimneys ?

B

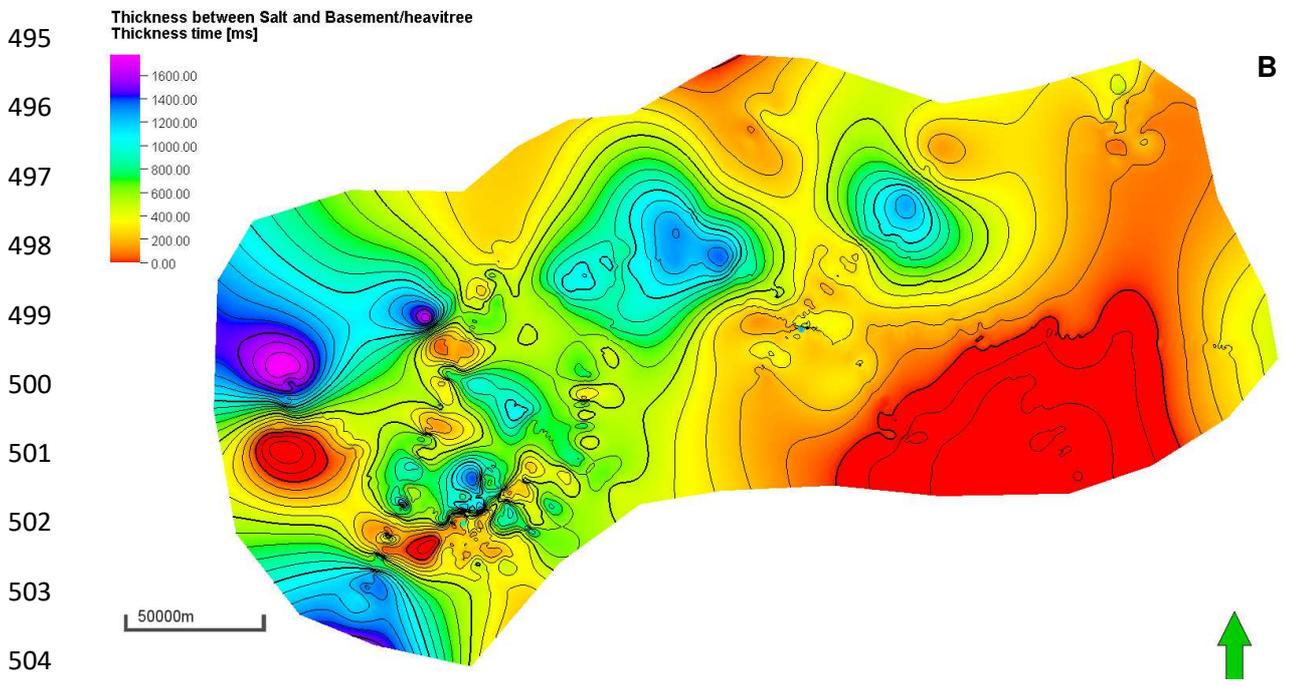
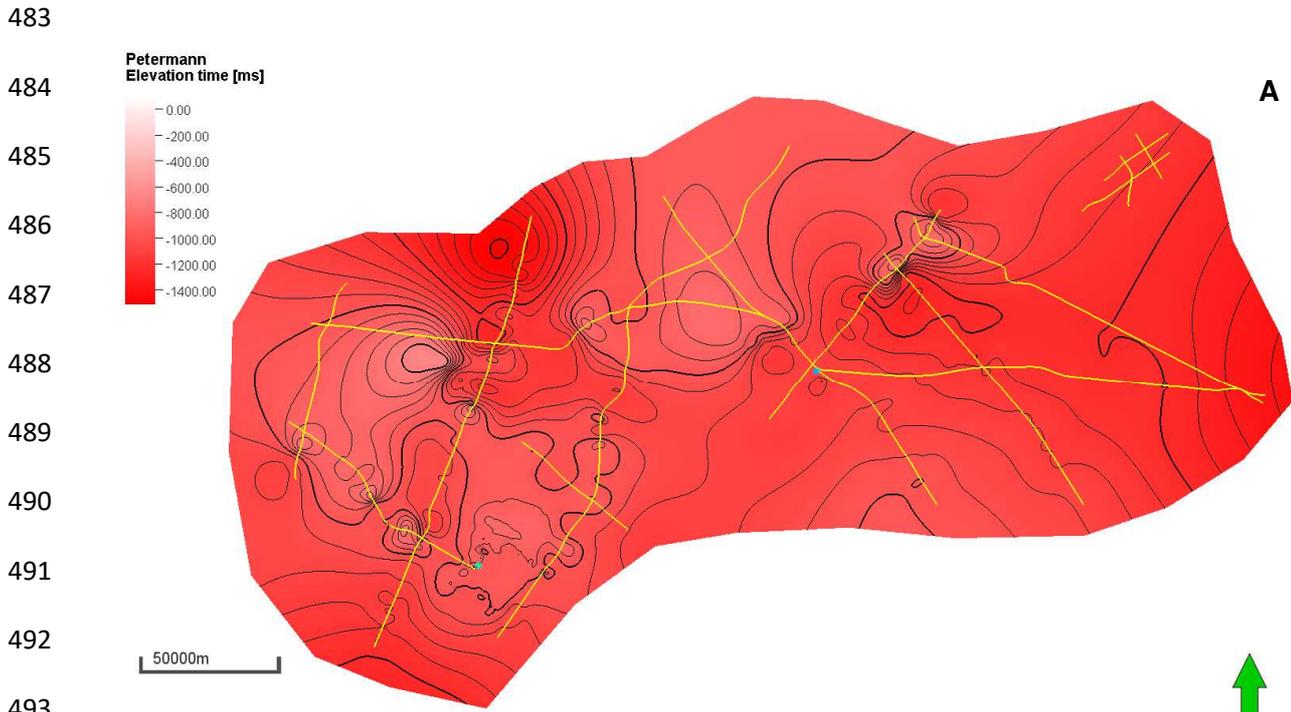
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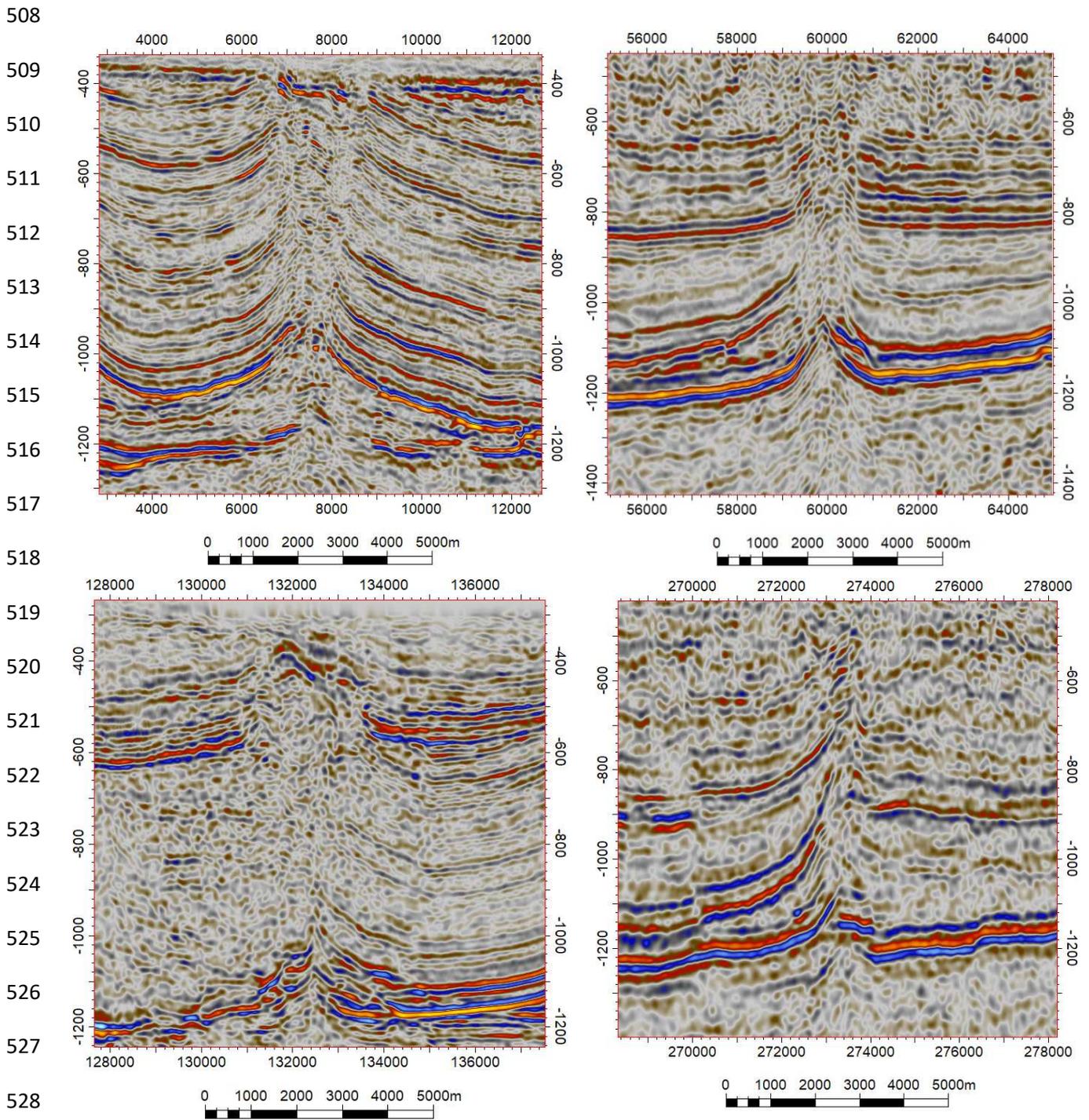
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Fig. 9. A) Depth contour maps at the top of Heavitree Formation/basement and Gillen Salt (B) illustrating relative deepening in the southwestern part of the study area. Projected gas chimneys often occur in the eastern part where the basement and salt are relatively shallow.



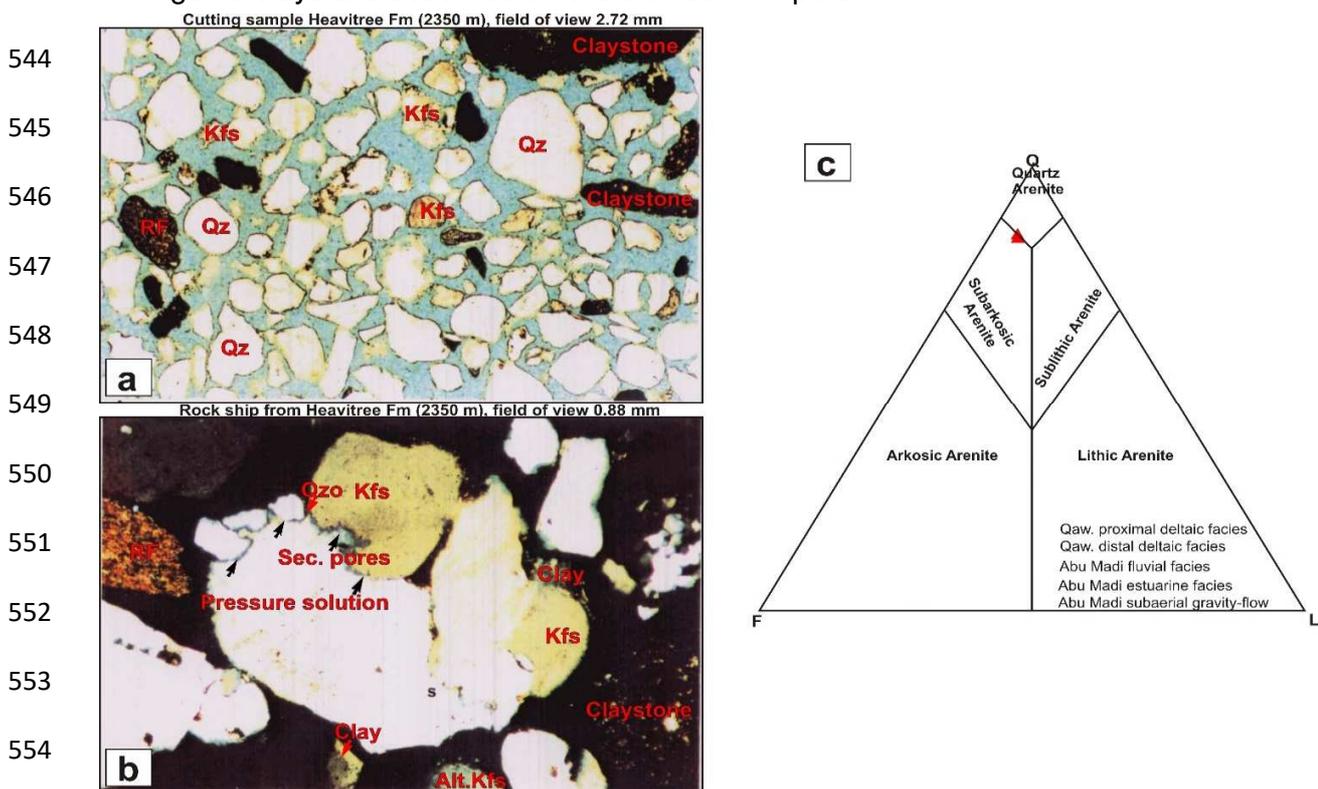
505 **Fig. 10.** A) Depth contour maps at the top of Petermann unconformity; B) Thickness
 506 map showing variations in salt distribution and its thinning in the eastern part of the
 507 study area.



529 **Fig. 11.** Local vertical disturbances in the seismic reflections possibly reflect occurrence
 530 of gas chimneys and/or salt scars.

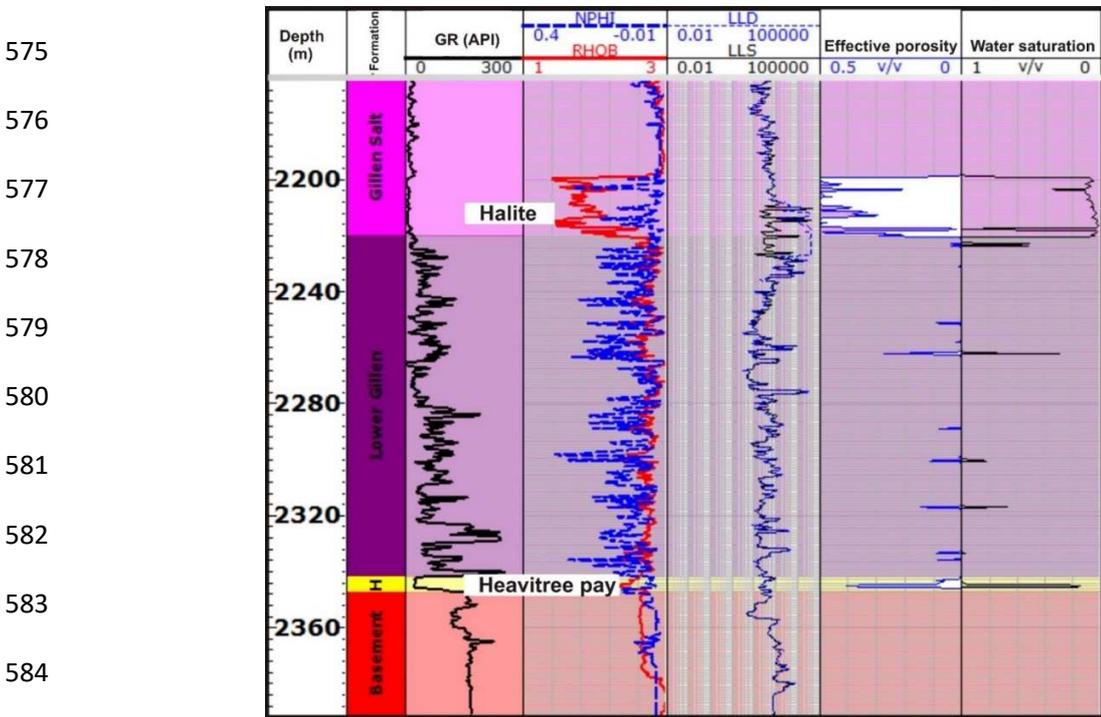
531 **4.3. Lithologic composition of Heavitree reservoir**

532 The Heavitree Formation consists mainly of quartzose sandstone with a framework
 533 composition dominated by quartz, feldspars and subordinate lithic fragments (Fig. 12A,
 534 B). The framework components are medium to coarse grained, poorly to moderately
 535 sorted and sub-rounded to sub-angular. The feldspars are fresh to partly altered and are
 536 mainly represented by K-feldspars (Av. 8%) with minor plagioclase (Av. 1%). The lithic
 537 fragments (Av. 5.5%) are mainly sedimentary (claystone) with minor igneous and
 538 metamorphic fragments. The sandstones have an average composition of Q₇₇F₁₅L₈, and
 539 are therefore classified as quartz to subfeldspathic arenite (Fig. 12C). The framework
 540 components are tightly-compacted and display sutured and concavo-convex grain
 541 contacts (Fig. 12B). Moreover, the feldspars are partly dissolved forming secondary
 542 pore spaces. Quartz overgrowths are often associated with the sutured grain contacts.
 543 Authigenic clays are observed on the altered feldspars.



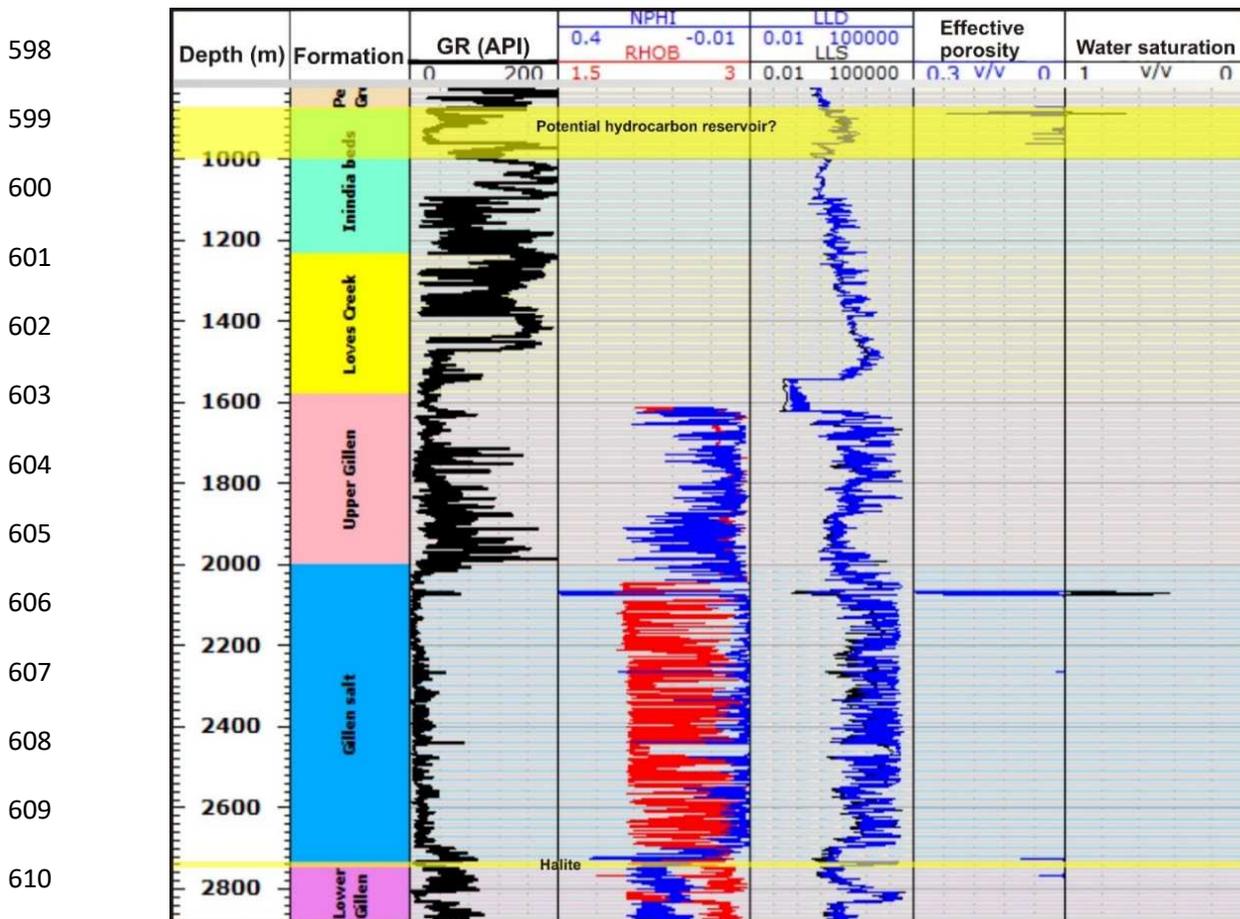
560 **4.4. Wireline log analysis**

561 Interpretation of wireline logs aids in the identification of different petrophysical
 562 parameters that determine the reservoir potential of the Neoproterozoic succession in
 563 the study area. In Magee-1 well, porous gas-bearing intervals are scarce and often
 564 localize above the basement at the base of the Gillen salt (Fig. 13). Heavitree pay (6 m
 565 thick) is characterized by a blocky gamma ray pattern with very low values (20-30 API).
 566 The Heavitree pay zone has an average clay volume of 17%, however, most of the clay
 567 materials are present in structural forms (claystone fragments, Fig. 12A) and therefore
 568 they do not adversely impact the porosity values (Av. 13%). The pay zone sandstones
 569 also display low water saturation values (Av. 34%) and a notable neutron-density
 570 crossover typifying the presence of trapped gas. Another porous, gas-bearing interval is
 571 observed above the Lower Gillen succession. This interval consists of approximately 20
 572 m thick halite layers characterized by very low gamma ray values (< 10 API). This halite
 573 interval is also traced in Murphy-1 well at the the base of Gillen Salt (Fig. 14). The halite
 574 beds have very high porosity (Av. 23%) and very low clay volume (< 5%) values.



585 **Fig. 13.** Vertical distribution of the different wireline logs data including the calculated
 586 values of effective porosity and water saturation in Magee-1 well.

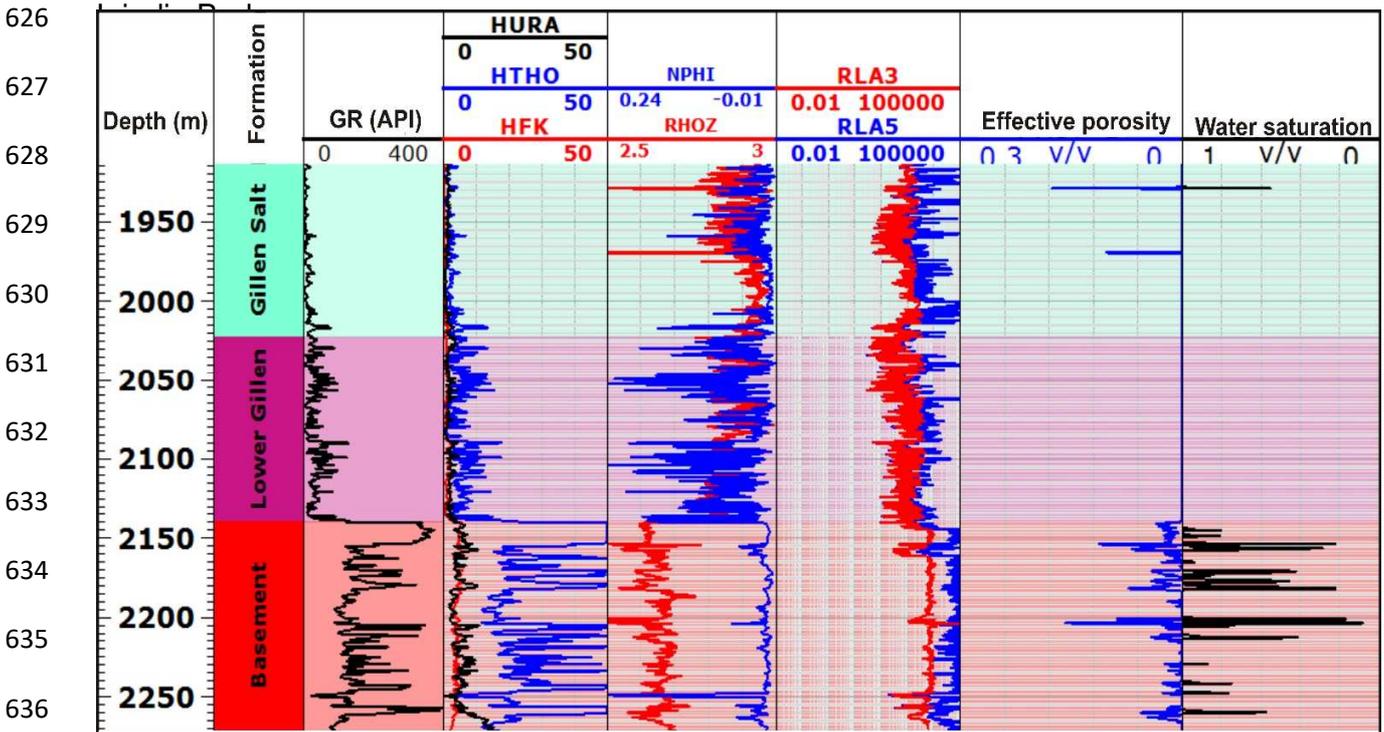
587 The abnormally high porosity of the halite possibly reflects a gas entrapment in the
 588 pore spaces during halite crystallization (Blamey et al., 2016). The elevated resistivity
 589 values (> 200 ohm.m) and the prominent neutron-density crossover coupled with the
 590 very low water saturation values (Av. 9%) are evidence for gas entrapment in the halite
 591 crystal lattice. In Mt Kitty-1 well, porous intervals are locally observed in the basement
 592 rocks where the effective porosity values are up to 13% with an average value of 4%
 593 (Fig. 15). The basement contains several fracture zones characterized by anomalously
 594 high resistivity values with a notable separation between shallow and deep resistivity
 595 curves characteristics for gas-filled fracture network (Sw < 50%). The fracture zones
 596 also display very low formation matrix density and high neutron values typifying a
 597 possible invasion of mud filtrate.



611 **Fig. 14.** Vertical distribution of the different wireline logs and calculated values of
 612 effective porosity and water saturation showing some potential above salt reservoir
 613 intervals in Murphy-1 well.

614 **4.5. Source rock characteristics**

615 The investigated shales from Lower and Upper Gillen have low TOC values < 1 wt%.
 616 Those of Lower Gillen have slightly higher TOC values (Av. 0.57 wt%) than the Upper
 617 Gillen samples (Av. 0.50 wt%). Elevated TOC values (however lower than 2 wt%) are
 618 observed in the shales of Inindia Beds. Most of the TOC content is attributed to the
 619 residual carbon (RC), whereas the pyrolyzed carbon (PC) values are very low (Table 1).
 620 The Rock-Eval S₁ values are low in the Lower Gillen and Inindia Beds shales (Av. 0.1
 621 mg HC/rock) and are comparatively higher in the Upper Gillen shale samples (Av. 1.5
 622 mg HC/rock). Rock-Eval S₂ values are lower than 1 in all the studied rocks. Similar to
 623 S₂, the Rock-Eval S₃ values are less than 1 with values ranging from 0.04 to 0.60.
 624 Additionally, the T_{max} values vary in a wide range in lower and Upper Gillen samples
 625 (393-445°C and 350-393°C, respectively), and they range between 433°C and 435°C in



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638 **Fig. 15.** Vertical distribution of the different wireline logs showing potential reservoir
 639 intervals only in the sub-salt basement of Mt Kitty-1 well.

640 The production index (PI) is high in the Upper Gillen samples with a maximum value
641 of 0.77, while it is relatively lower (< 0.4) in the Lower Gillen and Inindia beds samples
642 (Table 1). The generative potential (GP) is less than 1 except in one sample of the
643 Upper Gillen. The hydrogen index (HI) values are very low in Lower Gillen and Inindia
644 Beds shales (31-60 and 17-21 mg HC/g TOC, respectively) and are higher in the Upper
645 Gillen with values ranging between 90 and 159 mg HC/g TOC. Similarly, the oxygen
646 index (OI) values are very low in all the studied samples with values less than 50 and 5
647 mg CO₂/g TOC in the Lower Gillen and Inindia Beds, respectively, whilst elevated OI
648 values are only observed in the Upper Gillen samples (Table 1).

649 **4.6. Hydrocarbon and non-hydrocarbon gas analysis**

650 The Magee-1 well gases consist mainly of N₂ and CH₄ comprising approximately
651 75% of the whole gas composition. Other gas phases comprise He (6.20%) with
652 subordinate contents of C₂ and C₂₊ components (Table 1). The Magee-1 gas is
653 characterized by higher IC₅/nC₅ than IC₄/nC₄, and a dryness coefficient (DC) value of
654 0.80. Mt Kitty-1 gases are characterized by elevated N₂ contents that range from 61% to
655 approximately 100%. They contain variable contents of CH₄ (0.04-13.14%) with
656 subordinate quantities of He (0-9%) and H₂ (0-11.4%). C₂₊ phases are also significant in
657 Mt Kitty-1 gas samples where the DC values are often less than 0.75. Notably, Mt Kitty-
658 1 gases display much greater IC₅/nC₅ relative to IC₄/nC₄ (Table 1). In Murphy-1 gas
659 samples, the hydrocarbon gases mostly constitute CH₄ with variable contents of C₂₊
660 components. Murphy-1 gases also display a wide range of DC values between 0.79-
661 0.90 and show relatively elevated IC₄/nC₄ than IC₅/nC₅ values.

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4.7. Burial model

671 The burial model of Magee-1 well highlights five major tectonic phases that have
672 controlled the sediment distribution and architecture in the study region. These tectonic
673 events comprise: the earliest Areyonga rifting phase that is followed by four successive
674 younger compressional events. These are the Petemann, Bloodwood, Rodingan and
675 Alice Springs oroginies. The heat flow corresponding to these tectonic phases are
676 assigned as follows: 113, 75, 72, 70, and 65 mW/m², respectively. These tectonic
677 phases likely controlled the thermal maturity of the Lower Gillen organic-rich shales
678 (Fig. 16). The pre-rift sediments were subjected to a moderate subsidence which
679 created an accommodation space for the accumulation of the thick salt layers (Gillen
680 salt) and the massive white dolomite (Loves Creek) above the Lower Gillen sediments.
681 The syn-rift phase (Areyonga rifting) was characterized by a lithospheric stretching
682 coupled with elevated levels of heat flux. Contemporaneous to the post-rift thermal
683 subsidence (Cambrian-Ordovician), very thick sedimentary successions of post-rift
684 clastic facies were deposited. The post-rift thermal subsidence has been ended with the
685 onset of the successive compressive phases (Petemann, Bloodwood, Rodingan and
686 Alice Springs oroginies) during which the subsidence rate has significantly decreased
687 (Fig. 16). The top of oil window was reached at relatively shallow depths (~ 1350 m).
688 Additionally, the expulsion onset and the gas window maturity were observed at greater
689 depths (~ 2338 m) and higher temperatures (~ 117 °C, Fig. 17) compared to the oil
690 window.

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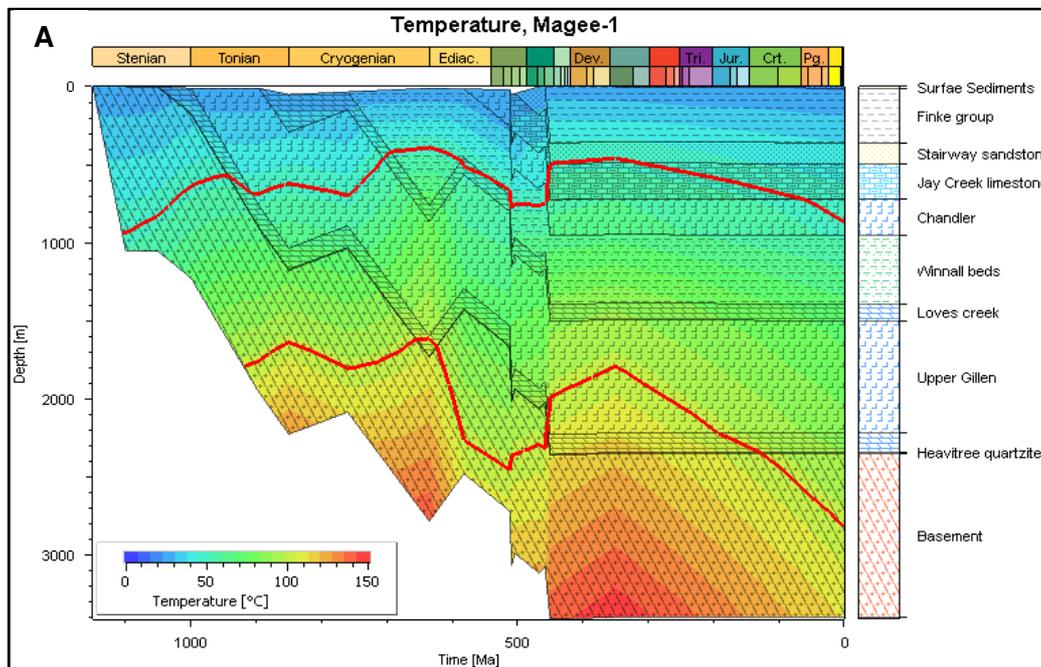
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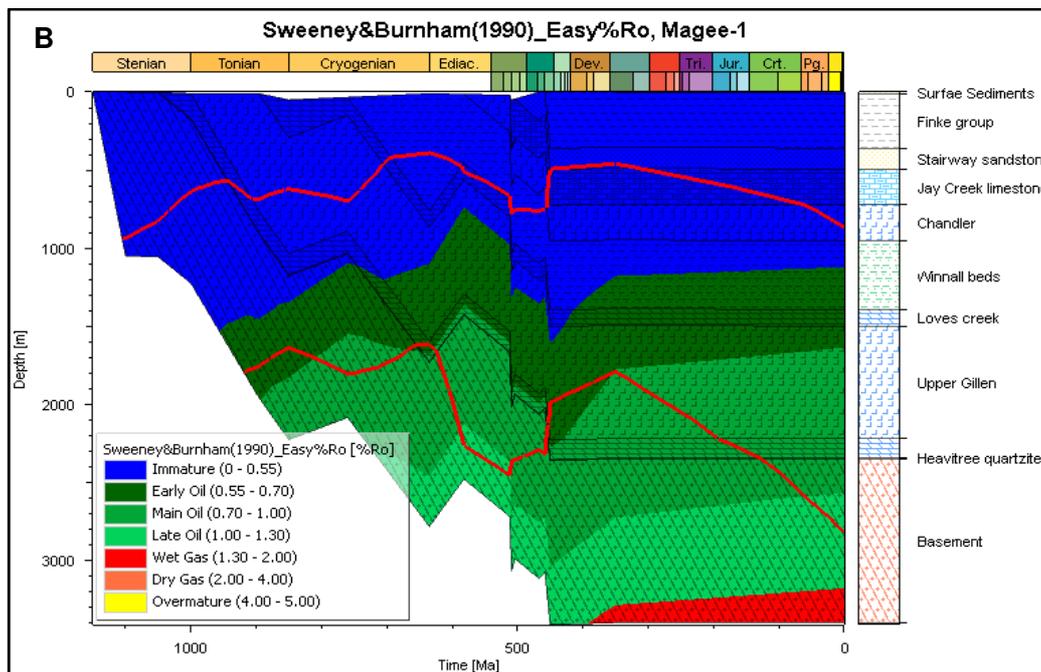
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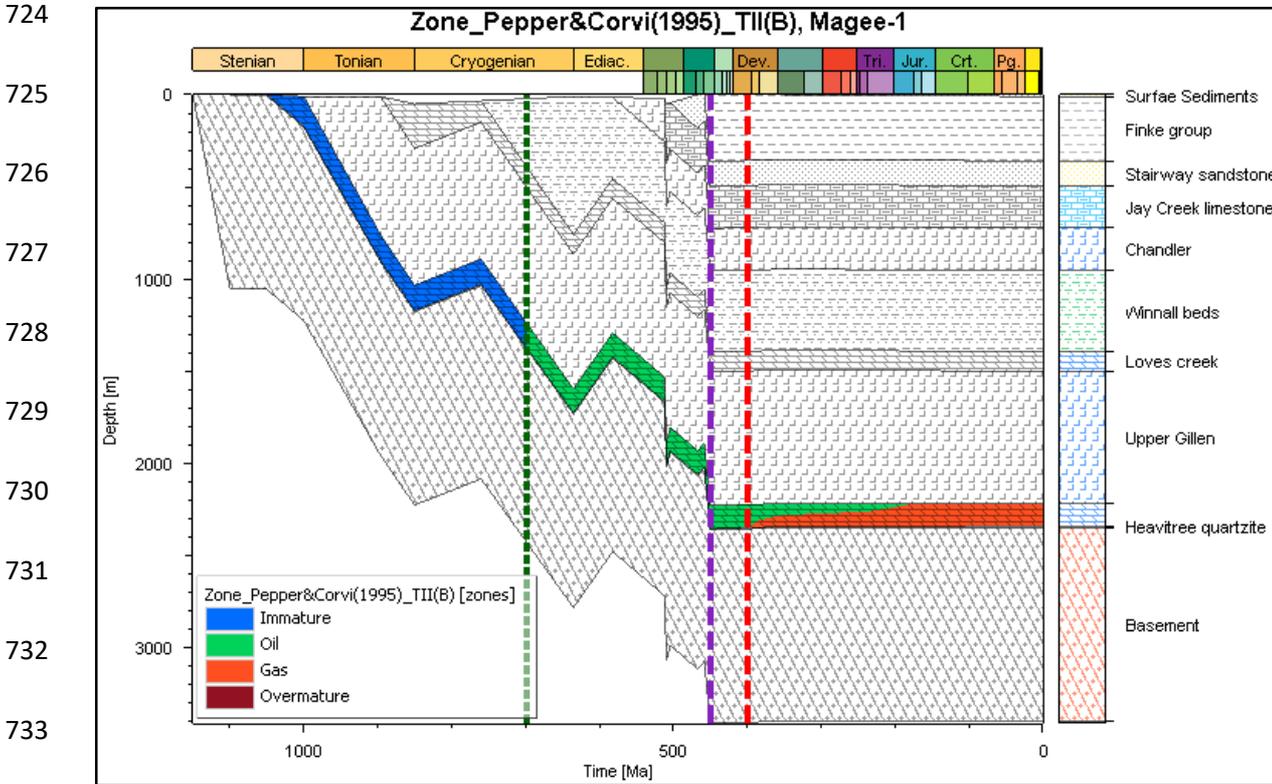
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719 **Fig. 16.** Illustrative burial models for the sedimentary succession in Magee-1 well. The
720 temperature overlay (A) is added to demonstrate the thermal history. The simulated
721 vitrinite reflectance maturity overlay (B) was deduced using the EASY%_Ro algorithm

722 (Sweeney and Burnham, 1990) as a function of time and space. The red lines
 723 represents the temperature intervals for 50, and 100°C.



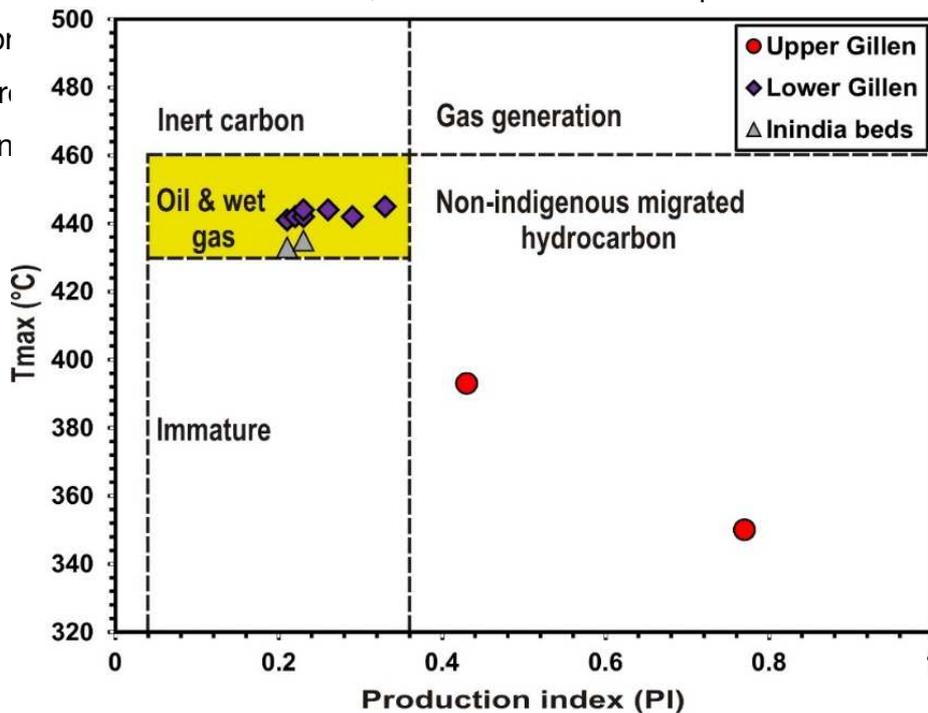
734 **Fig. 17.** The burial history chart of Magee-1 well with the hydrocarbon generation zone
 735 overlay according to TII-B kinetic model of [Pepper and Corvi \(1995\)](#) through geologic
 736 time. The vertical colored dashed lines represent the onset of oil generation at ~ 700 Ma
 737 (green dashed line), the vertical purple dashed line represents the expulsion onset at
 738 448 Ma and the red dashed line points to the gas generation window at 400 Ma.

739 **5. Discussion**

740 **5.1. Hydrocarbon gas origin, generation and expulsion**

741 The TOC and Rock-Eval pyrolysis results are frequently used to investigate and
 742 assess the capability of the organic-rich sediments to generate thermogenic
 743 hydrocarbons ([Peters, 1986](#); [Peters and Cassa, 1994](#), [Leila and Moscariello, 2017](#)).
 744 Based on the measured TOC values, Lower and Upper Gillen shales contain fair
 745 contents of organic matter, whereas the samples of Inindia Beds are richer in the
 746 organic content. However, the Rock-Eval S₂ values are below 0.8 that is often

747 considered as a lower limit to interpret the values in terms of generation potentiality,
 748 especially the T_{max} as valid for maturity assessment. The measured S_2 values in studied
 749 shales reflect their current poor potentiality to generate hydrocarbons upon thermal
 750 cracking of the kerogen. The poor S_2 values in all the shale samples are consistent with
 751 their depleted contents of pyrolyzed carbon (Pc), however, most of these samples may
 752 have had much higher initial TOC contents than that currently preserved. Based on
 753 measured present-day TOC, the initial TOC values were deduced following theoretical
 754 calculations proposed by Peters et al. (2005) (Table 1). The maximum initial TOC and
 755 HI values were theoretically deduced as 1.3 % and 500 mg HC/g TOC, respectively.
 756 Accordingly, potential source rock intervals that could have generated hydrocarbon
 757 gases are hosted in the Lower Gillen and Inindia Beds (Fig. 18). However, more data
 758 are required to better define the source rock in the deepest part in the drainage area of
 759 the drilled structures. In addition, no work has been published for such an old,



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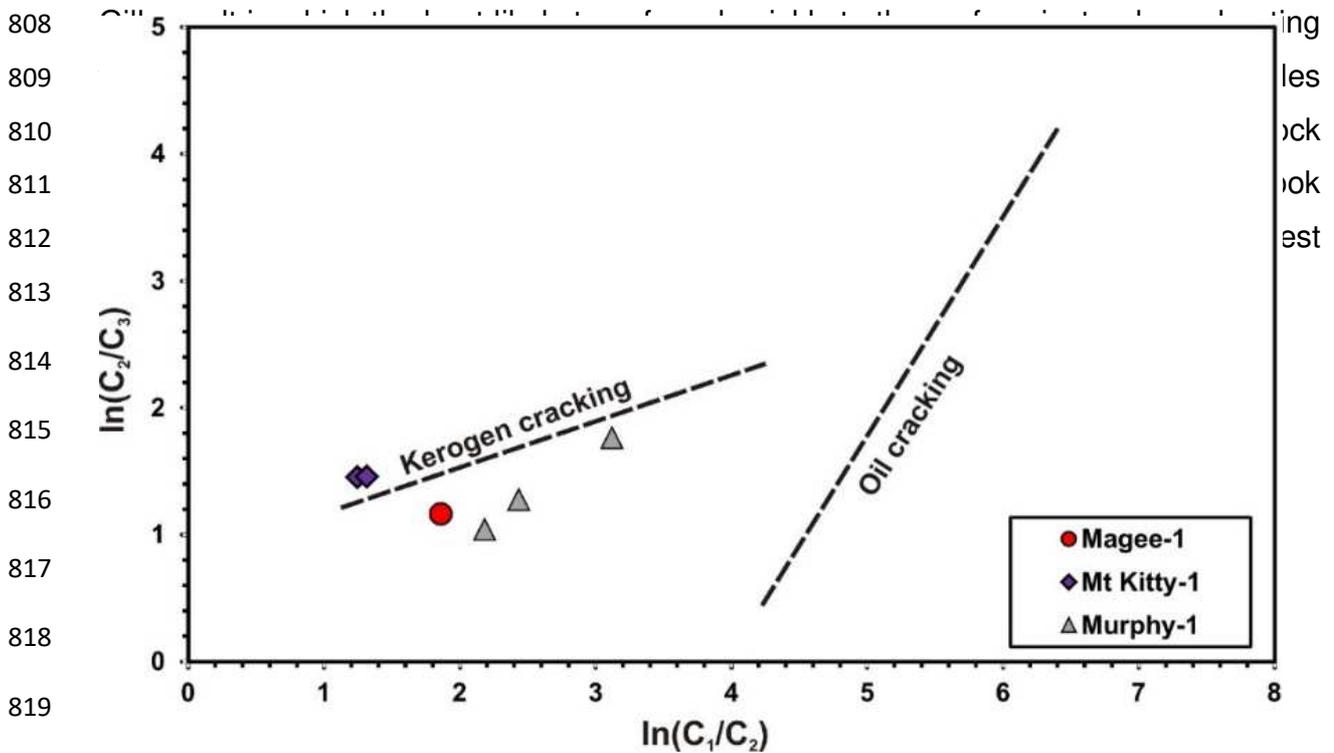
760 Precambrian
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774 **Fig. 18.** Production index (PI) versus Rock-Eval T_{\max} plot illustrating the potentiality of
775 some intervals in Lower Gillen and Inindia Beds to generate hydrocarbon gases. The
776 investigated shales of Lower Gillen Formation likely generated most of the hydrocarbon
777 gases in the basin.

778 Dominance of C_2 and C_{2+} gas phases in all the investigated HC gases points to a
779 prominent contribution from thermogenic sources (e.g. [Tissot and Welte, 1978](#); [Hunt,](#)
780 [1996](#)). Furthermore, the calculated dryness coefficient (DC) values for the HC gases are
781 less than 0.95 which is much lower than those reported for pure biogenic gases (~ 0.99 ;
782 [Radwan et al., 2022](#)), thus confirming a dominant thermogenic origin for the studied HC
783 gases ([Table 2](#)). Genesis of hydrocarbon gases via thermogenic cracking of organic-
784 rich kerogen is often associated with generation of wet gas components ($DC < 0.9$),
785 however, mixing with biogenic gas phases would increase the DC values to more than
786 0.9 ([Schoell, 1983](#); [Whiticar, 1999](#)). Accordingly, mixed biogenic and thermogenic
787 hydrocarbon gases are common in Murphy-1 well at different depths, whereas gases
788 collected from the other wells only contain thermogenic hydrocarbon gases. Occurrence
789 of some alkanes and their relative proportion such as iC_4/nC_4 and iC_5/nC_5 often infers
790 on the conditions of HC gas generation from mature kerogens ([Wang et al., 2017](#), [Qin](#)
791 [et al., 2018](#)). With increasing thermal maturity, the concentration of the less stable
792 isobutane decreases relative to the more stable n-butane ([Qin et al., 2018](#)). The good
793 correlation between the dryness coefficient and iC_4/nC_4 ($R^2= 0.75$) suggests generation
794 of studied HC gases via primary cracking of an organic-rich kerogen at the gas window.
795 The relationship between natural logarithms of C_1/C_2 and C_2/C_3 ratios commonly reflects
796 the mechanism of HC gas generation (primary versus secondary cracking).
797 Hydrocarbon gases generated via secondary cracking of liquid HC phases often display
798 a progressive increase in both C_1/C_2 and C_2/C_3 ratios ([Tao et al., 2014](#)). The studied
799 hydrocarbon gases show a slight increase in the natural logarithms of C_1/C_2 and C_2/C_3
800 ratios typifying their generation from primary cracking of a mature kerogen ([Fig. 19](#)).
801 This is consistent with our modelling results and the hypothesis of thermogenic cracking
802 of the Lower Gillen organic-rich intervals that have entered the gas window during the
803 earliest Mesozoic.

804 Burial modeling results point out that the Lower Gillen had reached the gas window
 805 about 200 Ma with a simulated present-day temperature of 86°C (Fig. 16). The initial
 806 rifting phase (850 Ma to 760 Ma) was characterized by high heat flow value; however, it
 807 did not contribute to the HC generation due to the high thermal conductivity of the Upper



825 **Fig. 19.** Plot of $\ln C_1$, C_2 and C_3 values typifying generation of the studied HC gas
 826 phases via primary cracking of the kerogen (Tao et al., 2014).

827 The transition from liquid to gaseous hydrocarbon generation was gradual with a
 828 generation phase of wet gases within the oil window. The 1D modeling results
 829 elucidated that the gas window occurred at a burial depth of 2340m in Magee-1 well.
 830 The first two tectonic events have induced a minimal impact on the hydrocarbon

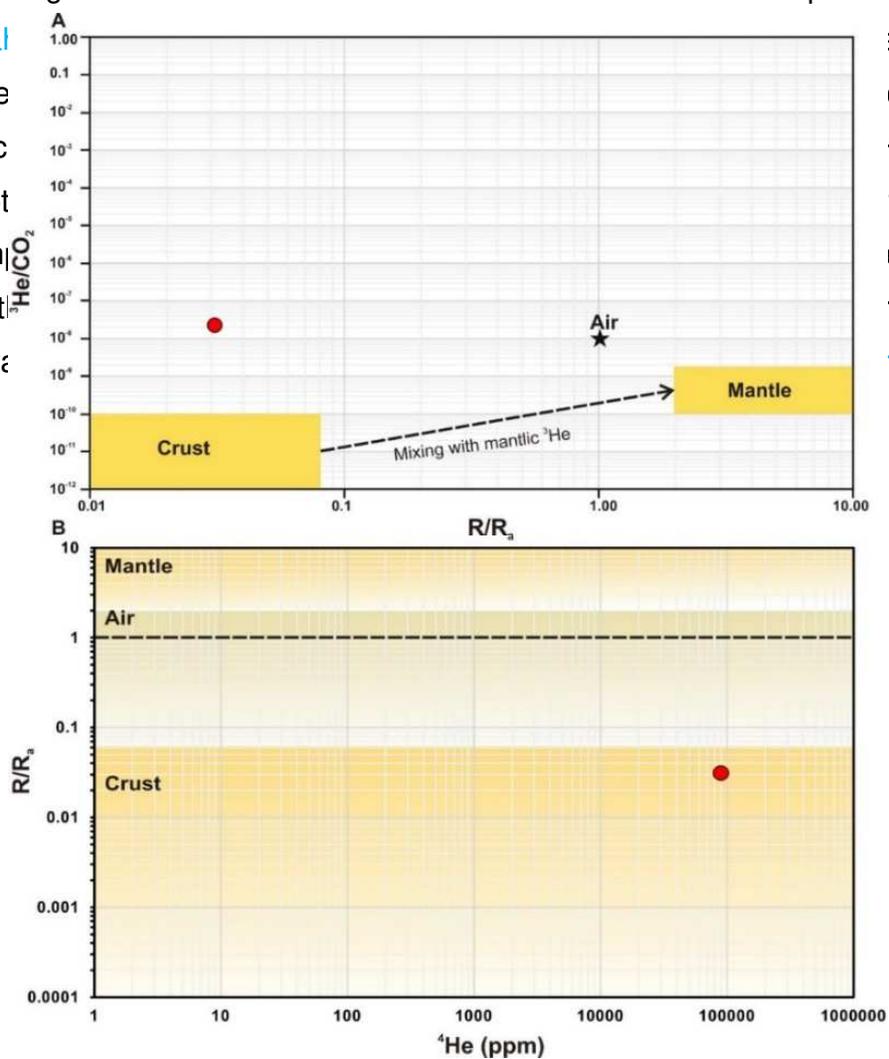
831 generation due to the cooling effect of the overlying Gillen salt layers. Despite the fact
832 that the burial temperature did not exceed 110°C and was even constant since the Late
833 Paleozoic, the prolonged exposure to this temperature resulted in a slow maturation of
834 the organic matter and kerogen transformation into hydrocarbons (e.g. [Loptain, 1971](#);
835 [Waples, 1980](#); [Wood, 2018](#)). We hypothesize that the kerogen type of the initial organic
836 matter, the interplay between burial temperature, exposure time as well as the cooling
837 effect induced by the Upper Gillen salt control the type and composition of the
838 generated hydrocarbons.

839 **5.2. Origin of H₂ and He**

840 Helium (He) occurrence in the study area with a maximum content of 9% in Mt Kitty-
841 1 well presents one of the highest recorded subsurface concentrations ever recorded on
842 Earth ([McInnes et al., 2017](#), [Boreham et al., 2018](#)). Furthermore, the He-rich gases are
843 mixed with a significant concentration of H₂ (~ 11%) as well as wet hydrocarbon gases
844 (C₁/C₂ ~ 3). This unusual gas blend reveals a complex interplay between various gas
845 generation processes in the subsurface. The occurrence of He in the subsurface is
846 often associated with either mantellic or crustal gases as well as the dissolution of
847 atmospheric gases in the groundwater ([Poreda et al., 1986](#); [Ni et al., 2014](#); [Moore et al.,](#)
848 [2017](#)). Except mantellic gases, all the other sources are associated with an enrichment
849 of ⁴He relative to ³He. Therefore, a useful tool to discriminate the origin of He-rich gases
850 is the relative proportion of He isotopic composition ($R = \frac{^3\text{He}}{^4\text{He}}$) relative to that in the
851 air ($R_a = 1.4 \times 10^{-6}$). For example, the He derived from the upper mantle displays
852 average R/R_a values between 2 and 8, whereas those from the lower mantle show
853 elevated R/R_a values up to 40 ([Ni et al., 2014](#); [Moore et al., 2017](#)). Helium derived from
854 the Mid-Ocean Ridge Basalt (MORB) displays high isotope ratios with an average
855 (R/R_a) value of about 8. On the other hand, atmospheric He dissolved in the
856 groundwater has an average (R/R_a) value of approximately 1, whereas the crustal-
857 derived He is largely depleted in ³He and therefore has an average value of 0.02 or less
858 ([Ballentine et al., 1991](#)).

859 The relative abundance of some elements such as uranium and thorium in the rock
860 forming minerals determines the extent of He generation from the crustal rocks and

861 hence controls its average R/R_a values (e.g. Poreda et al. 1986; Darrah et al. 2015;
 862 Moore et al. 2017). Pure crustal-derived He commonly shows R/R_a values greater than
 863 0.05 and mixing with mantle-derived He would increase the values up to 0.5 (Ni et al.,
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887 **Fig. 20.** (A) Plot of R/R_a ratio versus ³He/CO₂, (B) ⁴He versus R/R_a plot illustrating the
888 crustal origin of helium in the studied gases. Data are from [McInnes et al. \(2017\)](#).

889 The log-log plot of R/R_a versus ⁴He concentration ([Fig. 20B](#)) confirms the dominant
890 crustal origin of He in Mt Kitty-1 well. Thus, we hypothesize that He gas accumulation in
891 Mt Kitty-1 well is mostly derived from the sub-salt granitic basement rocks. The spectral
892 gamma ray logs typified that these rocks are rich in uranium and thorium ([Fig. 15](#)), thus
893 they are capable of generating helium via radiogenic reactions and radioactive decay
894 these elements. This crustal derivation of He is often coupled with a concomitant
895 generation of H₂ via a radiolytic dissociation of water (e.g. [Lin et al., 2005](#); [Warr et al.,](#)
896 [2019](#)). Alternatively, H₂ may also be generated by oxidation of iron rich materials but we
897 do not have data on the deepest layer mineralogy to discuss this hypothesis. Another
898 plausible mechanism for H₂ generation is the oxidation of hydrocarbons, however the
899 negative correlation between H₂ and hydrocarbon phases such as CH₄ (R²= -0.75) as
900 well as the complete absence of H₂ in the above-salt layers of Murphy-1 well may rule
901 out a significant H₂ input via oxidation of HC gases.

902 **5.3. Gas accumulation versus gas seepage**

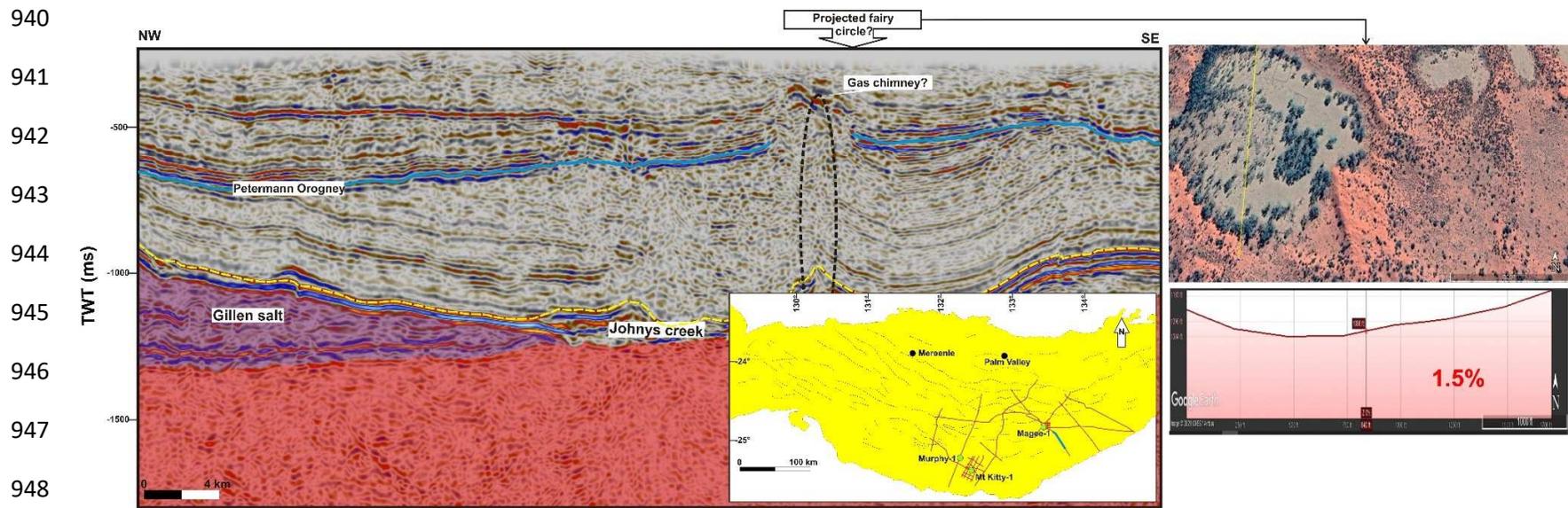
903 In the study region, the studied gases are reported from the sub-salt basement and
904 Heavitree Formation. Fractures in the granitic basement present the main gas-bearing
905 zones in Mt Kitty-1 well. Fractures are ubiquitous in the Proterozoic basement rocks
906 paving the base of the Amadeus Basin. The fracture network is commonly controlled by
907 the faults and the high porosities and permeabilities are often associated with the
908 tectonically induced fractures ([Heap and Kennedy, 2016](#)). Mt-Kitty-1 well is located in a
909 tectonically-high region due to the tectonic uplift of the faulted basement associated with
910 the fracture patterns and deep-seated faults which are commonly infilled with gases
911 (high resistivity zones) that are sealed beneath the thick Gillen salt layers ([Fig. 6](#)).
912 Therefore, gas accumulation in Mt Kitty-1 area are a classical structural trap sealed by
913 the thick salt layers.

914 The porous sandstones of Heavitree Formation present a potential gas pay zone in
915 Magee-1 well. Heavitree Formation has minimal contents of matrix and pore-filling
916 cements and therefore preserves a very good intergranular porosity. The intergranular
917 pores are well-connected and hence display a good effective porosity likely infilled with

918 gases (Fig. 11). But the Heavitree Formation is very thin in Magee-1 well (< 6 m), and
919 thus hindering any economic accumulation of gases. Moreover, economic gas
920 accumulations should occur in the western and southwestern parts of the basin where
921 the Heavitree Formation is believed to be thicker (Fig. 5B). Additionally, the thickness of
922 the Gillen salt layers also increases westward and southwestward and therefore will
923 provide effective seal for the trapped gasses in the Heavitree pay zone (Fig. 8B).

924 The above-salt reservoir intervals are scarce and the wireline log results reveal
925 occurrence of thick non-porous and impermeable intervals. However, thin porous and
926 permeable sandstone zones were observed in the Inindia Beds where the effective
927 porosity reaches up to 20%. These zones likely present potential reservoirs for the
928 gaseous hydrocarbons that were generated from the organic-rich zones in Inindia Beds,
929 however its low thickness may hinder any economic gas accumulations in this region.

930 Gas seepage zones such as SCD are correlated with distribution of the thin salt
931 layers. Observed discrepancies in the seismic reflections (gas chimneys) often coincide
932 with the regions where the thickness of the salt layers is minimal (Fig. 7). Thick
933 accumulation of salt layers commonly provides effective seal for fluids preventing their
934 leakage and hence allows the economic gas accumulation and entrapment in the
935 reservoir rocks (Grunau, 1987; Schlomer and Krooss, 1997). Furthermore, for gases
936 with a relatively small atomic radius such as He and H₂, thick impervious salt layers are
937 essential for to their entrapment in the reservoir. On the other hand, a clear link is
938 observed between the surficial SCD distribution and the subsurface gas chimneys (Fig.
939 22), and both are correlated with regions where thin layers of Gillen salt exist.



949 **Fig. 21.** Interpreted 2D seismic profile illustrating possible occurrence of gas chimneys where the Gillen Salt layers are
 950 thinning. The subsurface gas chimneys are well-correlated with SCD typifying continuous gas emanations.

951

952 **6. Conclusions**

- 953 • In the Amadeus Basin, hydrocarbon (HC) and non-hydrocarbon gas blend was
954 discovered in some exploratory wells. The gases range from HC-He-rich in
955 Magee-1 to HC-He-H₂ blend in Mt Kitty-1 well.
- 956 • The HC gases are wet gas with a significant share (> 10%) of C₂₊
957 components.
- 958 • Potential HC-source rock intervals likely occur in the Neoproterozoic Lower
959 Gillen shales, however, the Rock-Eval data revealed a remnant inert carbon
960 with minimal capability to generate HC gases.
- 961 • Modeling results shows that wet HC-gases may have been generated from the
962 Lower Gillen shales that had an initial organic carbon of at least 1.3 wt% and
963 entered the gas generation window during Late Devonian at the end of Alice
964 Springs orogeny. The temperatures remain rather low but the 400 years
965 allowed this gas generation.
- 966 • He-rich gases display a crustal signature with elevated ³He contents and R/R_a
967 value of 0.031 typifying their generation via radiolytic decay of the thorium and
968 uranium-rich basement potentially synchronous with H₂ generation from
969 radiolysis. Other source of H₂ by water reduction cannot be precluded.

970 The Amadeus Basin case study allows to open new horizons since the gas is very
971 likely a classical accumulation, in a structural trap sealed by a salt layer. The reservoir
972 has been charged by these three gases at different rates but probably all over hundreds
973 of millions of years since the He generation is a low process. The presence of this
974 mixture shows that the salt may retain these light gases for millions of years, which
975 opens new exploration perspectives.

976 **Acknowledgment**

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1223 2(1), 31.

1224 **Table 1.** Total organic carbon (TOC) and Rock-Eval pyrolysis results for the analyzed
 1225 shale samples retrieved from the studied wells in Amadeus Basin.

Well name	Formation	Depth (m)	TOC (wt%)	PC (wt%)	S1 mg/g	S2 mg/g	S3 mg/g	T _{max} (C°)	HI	OI	PI	GP
Magee-1	U. Gillen	1927	0.52	0.07	0.35	0.47	0.47	393	90	903	0.43	0.82
Magee-1	U. Gillen	2217	0.49	0.28	2.65	0.78	0.60	350	159	122	0.77	3.43
Magee-1	L. Gillen	2323	0.79	0.05	0.18	0.45	0.27	442	57	34	0.29	0.63
Magee-1	L. Gillen	2326	0.81	0.05	0.20	0.41	0.27	445	51	33	0.33	0.61
Magee-1	L. Gillen	2329	0.53	0.03	0.10	0.28	0.24	444	53	45	0.26	0.38
Magee-1	L. Gillen	2332	0.63	0.03	0.09	0.33	0.24	441	52	38	0.21	0.42
Magee-1	L. Gillen	2335	0.49	0.02	0.06	0.21	0.20	442	43	41	0.22	0.27
Magee-1	L. Gillen	2338	0.60	0.04	0.11	0.36	0.21	442	60	35	0.23	0.47
Magee-1	L. Gillen	2341	0.50	0.03	0.09	0.31	0.15	444	62	30	0.23	0.40
Magee-1	L. Gillen	2344	0.45	0.02	0.05	0.14	0.18	393	31	40	0.26	0.19
Murphy-1	Inindia Beds	1005	2.29	0.05	0.13	0.49	0.04	433	21	2	0.21	0.62
Murphy-1	Inindia Beds	1056	3.19	0.06	0.16	0.53	0.06	435	17	2	0.23	0.69

1226 *TOC = total organic carbon. S₁ = volatile hydrocarbon content (mg HC/g rock); S₂ = remaining*
 1227 *hydrocarbon generative potential (mg HC/g rock); S₃ = carbon dioxide yield (mg CO₂/g rock); T_{max} =*
 1228 *temperature at maximum of S₂ peak; HI = hydrogen index (S₂ × 100/TOC) (mg HC/g TOC); OI = oxygen*
 1229 *index (S₃ × 100/TOC) (mg CO₂/g TOC); PI = production index (S₁/ (S₁ + S₂)); GP = Generation potential*
 1230 *(S₁ + S₂) (mg/g).*

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1237 **Table 2.** Composition of the analyzed gas blend collected from the studied wells in Amadeus Basin. isotope gas analyses
 1238 are reported from [McInnes et al. \(2017\)](#).

Well name	Depth (m)	N ₂	Ar	He	H ₂	CO ₂	C ₁	C ₂	C ₂₊	IC ₄ /nC ₄	IC ₅ /nC ₅	DC	R/R _a	CO ₂ / ³ He	⁸⁴ Kr/ ³⁶ Ar	¹³² Xe/ ⁸⁴ Kr
Magee-1	2349	43.61	0.46	6.20	0.03	0.82	39.26	6.10	3.52	0.63	1.11	0.80	-	-	-	-
Mt Kitty-1	2144	79.62	-	4.23	5.05	0.33	7.29	2.10	2.85	0.41	8.00	0.71	-	-	-	-
Mt Kitty-1	2156	61.04	0.57	8.96	11.4	0.09	13.14	3.53	1.24	0.36	6.50	0.73	0.031*	4.46 x 10 ⁷ *	0.0062*	0.142*
Mt Kitty-1	2253	99.67	-	0.0	0.0	0.08	0.04	0.02	0.01	0	0	-				
Murphy-1	1647	-	-	-	-	-	1.18	0.01	0.31	0	0	0.79				
Murphy-1	1650	-	-	-	-	-	32.69	2.87	3.90	1.08	0.96	0.83				
Murphy-1	1653	-	-	-	-	-	72.61	3.21	0.99	1.10	0.25	0.94				
Murphy-1	1656	-	-	-	-	-	27.81	3.14	3.61	1.30	0.82	0.81				
Murphy-1	1764	-	-	-	-	-	1.48	0.08	0.16	0	0	0.90				

1239 *Dc is the dryness Coefficient (C₁/ΣC₁-C₃); * Noble gas data is from (McInnes et al., 2017).*

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