[PS]The North Rankin Gas Field, Carnarvon Basin, Australia—Late Authigenic Pyrite Evidence of Early Oil Entrapment and Oil-Charged Fluid Flow*

Grant K. Ellis[1]

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[1]Eni Australia Limited, Perth, WA, Australia (grant.ellis@eniaustralia.com.au)

Abstract

The multi-TCF North Rankin gas and condensate field in Early Jurassic to Late Triassic sandstone reservoirs is one of numerous gas-dominated hydrocarbon accumulations on the Rankin Trend of the Dampier Sub-basin in the Carnarvon Basin. However oil shows in Late Cretaceous carbonate and early Tertiary sandstone above these gas-bearing reservoirs and oil shows below the gas-water contact indicate a more oil-dominated past. The presence of extensive late authigenic pyrite cementation in the reservoirs of the North Rankin Field provides further compelling evidence of a large palaeo-oil accumulation that has leaked and/or has been displaced by subsequent gas charge. The pyrite cementation developed in these reservoirs by reduction of formation water sulphate in the presence of migrating and/or entrapped oil followed by the reaction of iron with the resultant hydrogen sulphide. Sulphate reduction is considered to be most likely by sulphate-reducing microorganisms, which utilised hydrocarbons for their metabolism. Development of pyrite cementation in the sandstone was therefore dependent on the presence of sulphate- and iron-rich formation water. In the North Rankin A-18 well thick zones of abundant pyrite cement within the present gas column are interpreted to indicate significant sulphate reduction at both stable oil-water contacts and through the reservoir during oil charge. This late authigenic pyrite is disseminated, in fractures and in solution fronts and provides a fingerprint of the mechanisms involved in oil-charged and sulphate- and iron-rich fluid migration into and through the reservoirs. The shear abundance of pyrite points to an external source of iron with fluid migration inferred to have been at least in part vertically via dilated fractures into the reservoir. Late authigenic pyrite in conjunction with oil shows is therefore considered to provide evidence of the presence of a large North Rankin palaeo-oil field and a more oil-dominated hydrocarbon charge of the Rankin Trend structures in the past. Furthermore the pyrite provides a new methodology to understand and identify one mechanism of oil charged fluid flow into a structure.

The North Rankin Gas Field, Carnarvon Basin, Australia - Late Authigenic Pyrite Evidence of Early Oil Entrapment and Oil-charged Fluid Flow

Grant K Ellis, Eni Australia Limited, Perth, Western Australia, grant.ellis@eniauatralia.com.au.

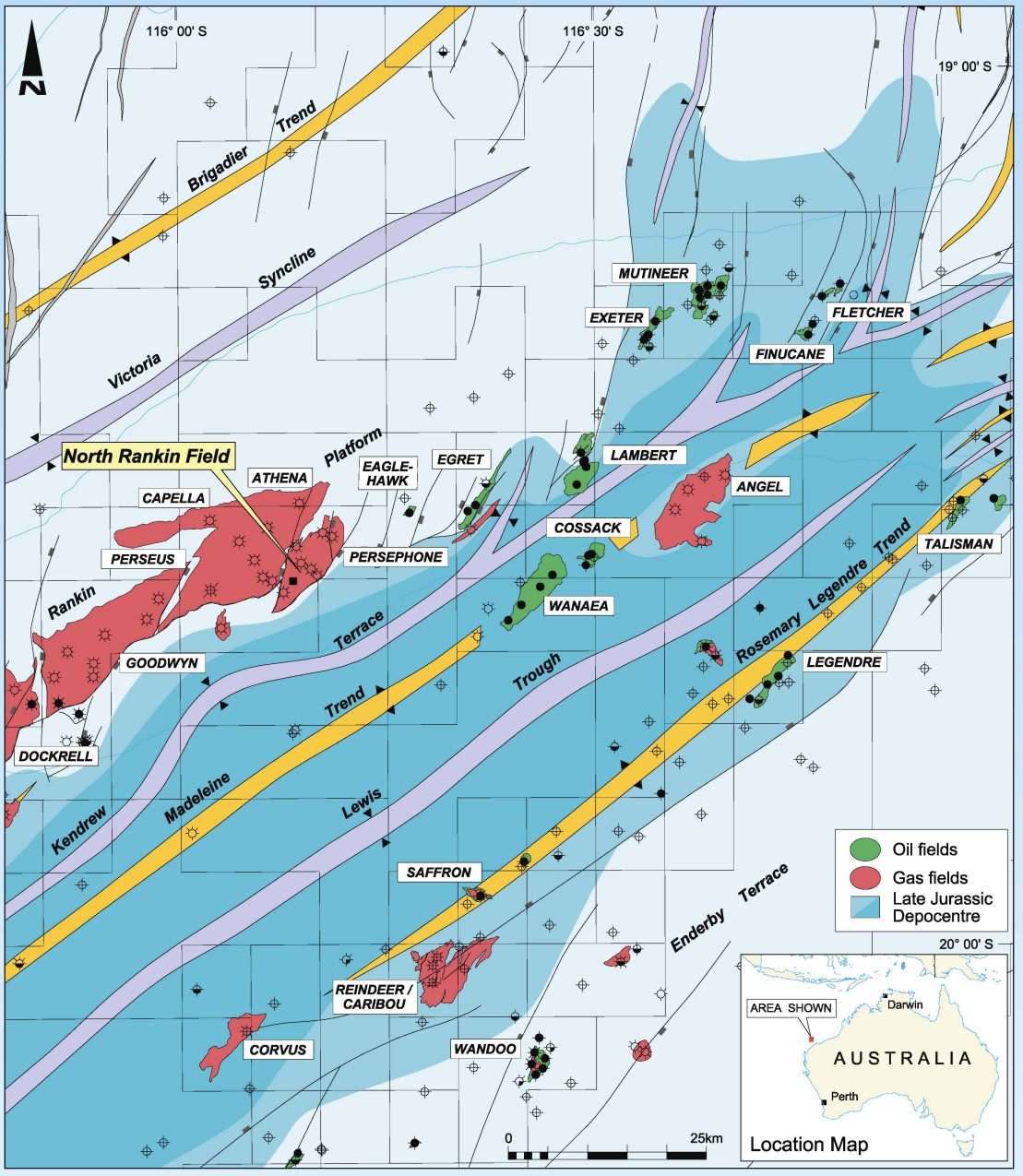
Abstract

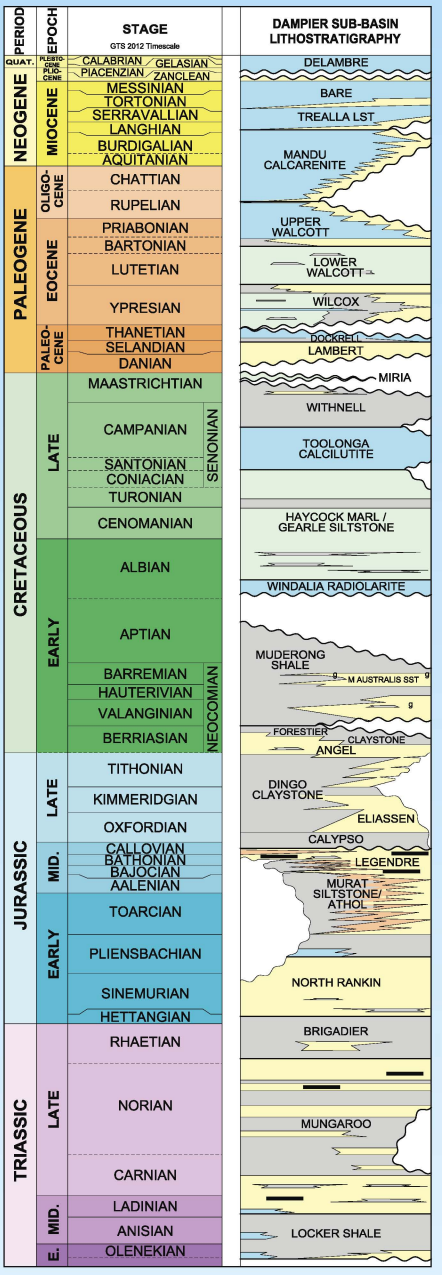
The multi-TCF North Rankin gas and condensate field in Early Jurassic to Late Triassic sandstone reservoirs is one of numerous gas-dominated hydrocarbon accumulations on the Rankin Trend of the Dampier Sub-basin in the Carnarvon Basin. However oil shows in Late Cretaceous carbonate and early Tertiary sandstone above these gas-bearing reservoirs and oil shows below the gas-water contact indicate a more oil-dominated past.

The presence of extensive late authigenic pyrite cementation in the reservoirs of the North Rankin Field provides further compelling evidence of a large palaeo-oil accumulation that has leaked and/or has been displaced by subsequent gas charge. The pyrite cementation developed in these reservoirs by reduction of formation water sulphate in the presence of migrating and/or entrapped oil followed by the reaction of iron with the resultant hydrogen sulphide. Sulphate reduction is considered to be most likely by sulphate-reducing microorganisms, which utilised hydrocarbons for their metabolism. Development of pyrite cementation in the sandstone was therefore dependent on the presence of sulphate- and iron-rich formation water.

In the North Rankin A-18 well thick zones of abundant pyrite cement within the present gas column are interpreted to indicate significant sulphate reduction at both stable oil-water contacts and through the reservoir during oil charge. This late authigenic pyrite is disseminated, in fractures and in solution fronts and provides a fingerprint of the mechanisms involved in oil-charged and sulphate- and iron-rich fluid migration into and through the reservoirs. The shear abundance of pyrite points to an external source of iron with fluid migration inferred to have been at least in part vertically via dilated fractures into the reservoir.

Late authigenic pyrite in conjunction with oil shows is therefore considered to provide evidence of the presence of a large North Rankin palaeo-oil field and a more oil-dominated hydrocarbon charge of the Rankin Trend structures in the past. Furthermore the pyrite provides a new methodology to understand and identify one mechanism of oil charged fluid flow into a structure.





Conclusions

Extensive, common to abundant late authigenic pyrite cementation in wells in the North Rankin Gas Field in the Dampier Sub-basin provides an excellent case history to better understand oil migration and entrapment processes as the pyrite leaves a fingerprint of the oil-charged fluid flow and the evolving biological and chemical reactions in the reservoir. It furthermore reveals an oil-dominant past for the North Rankin structure overshadowed by the present large gas and condensate accumulation

The general increase in the concentration of pyrite cementation within the sandstone of Unit NE of the Late Triassic Mungaroo Formation from North Rankin-6 in the north of the field, well below the present gas column, to the extensive and abundant pyrite cementation in North Rankin-A18 in the south of the field, within the gas column, is interpreted to indicate focussed migration in Unit NE of oil-charged, sulphate- and iron-rich fluid from the north up-dip to the south. Dormant sulphate-reducing bacteria resident in the reservoir reduced this sulphate resulting in pyrite precipitation in the presence of oil. The shear abundance of pyrite cementation in Unit NE in these wells, and particularly in North Rankin-A18, indicates input of iron from an external source and likely input of this oil-charged, sulphate- and iron-rich fluid into Unit NE via vertical migration up dilated faults from a deeper fluid source. The massive and extensive pyrite cementation in North Rankin-A18 represents the terminal area of the solution fronts close to the southern truncation of Unit NE.

The extent of the resultant palaeo-oil column is defined by the extent of the pyrite cementation, although the palaeo-oil/water contact is somewhat obscured by the inter-play of the oil-charge solution fronts and the evolving oil column. The lack of significant pyrite cementation in the upper part of the Mungaroo Formation sandstone in North Rankin-5 and North Rankin-A18 is interpreted to indicate a palaeo-gas column above the palaeo-oil column.

The presence of oil shows in cuttings and sidewall cores in the Cretaceous section overlying the Mungaroo Formation in North Rankin-5 and elsewhere in the North Rankin Field indicates subsequent leakage of this palaeo-gas column and partial leakage of the palaeo-oil column. Subsequent input of the current gas column displaced the palaeo-oil column. The presence of oil shows in conventional core indicate that a thin oil column was present below the gas column but has subsequently been lost

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North Rankin A18

Late authigenic pyrite cementation is developed in Unit NE of the Late Triassic Mungaroo Formation in North Rankin-A18 from 2968 to 3151 m. The pyrite cement developed as a result of reduction of formation water sulphate associated with oil-charged, sulphate- and iron-rich fluid migration into the reservoir and development of a dynamic oil column during the first phase of hydrocarbon entrapment. The lack of significant pyrite cementation in the upper part of the Mungaroo Formation Unit NE sandstone from 2873 to 2968 m is interpreted to indicate a palaeo-gas column above the palaeo-oil column.

Within the zone of pyrite cementation, abundant pyrite is concentrated in the lower part of two sandstone intervals from 3035 to 3057 m and from 3117 to 3151 m, as evident by the high density and PEF log response and the reduced resistivity response in the gas-saturated sandstone. This concentration of pyrite is interpreted to indicate oil migration, in conjunction with extremely high concentrations of sulphate- and iron-rich fluid, as a solution front with precipitation of significant volumes of pyrite as a result of bacterial reduction of formation water sulphate in the presence of the migrating oil.

The presence of oil shows in cuttings and sidewall cores in the Cretaceous section overlying the Mungaroo Formation in North Rankin-5 indicates subsequent leakage of the palaeo-gas column and partial leakage of the palaeo-oil column.

Subsequent input of the current gas column displaced the palaeo-oil column.

Grain Density (g/cc)

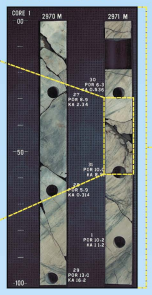
2970 - 2972m



Pyrite cement filling fracture.

2.66

2.67



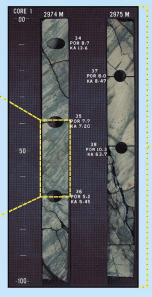
2974 - 2976m



Extensive disseminated pyrite concentrated along cross-bed laminations in the sandstone.

2.80

3.06

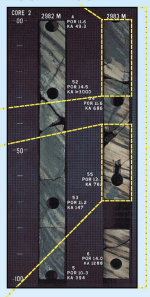


2982 - 2984m



Extensive concentration of pyrite-cemented sandstone in solution front.

2.85





Pyrite concentrated along cross-bed laminations in the sandstone.

Nodular and/or framboidal pyrite in sandstone.

2.71

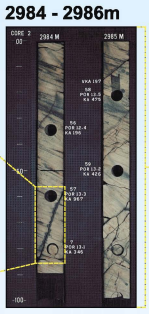
2984 - 2986m



Pyrite cement concentrated in and adjacent to fracture.

2.65

2.62



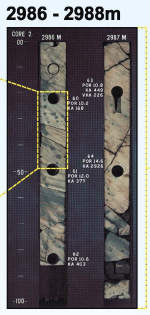
2986 - 2988m



Nodular and/or framboidal pyrite in sandstone.

2.66

2.67



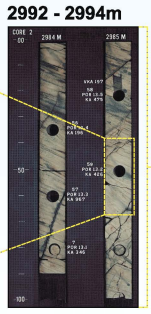
2992 - 2994m

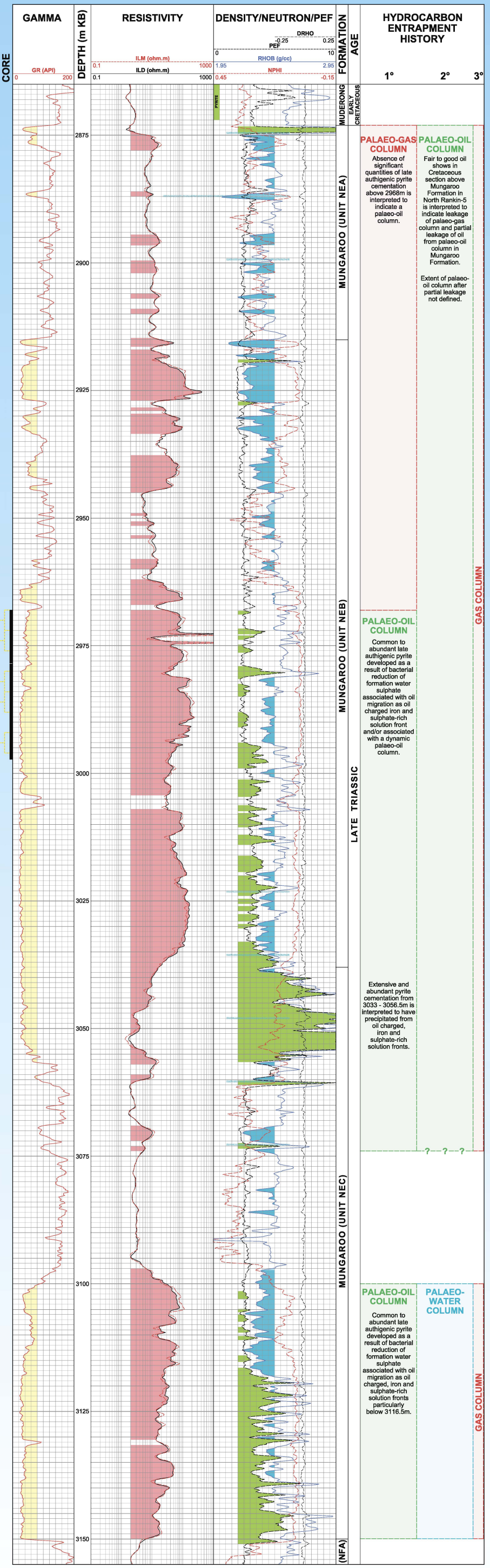


Pyrite cement concentrated in and adjacent to fracture.

2.65

2.69





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North Rankin 5

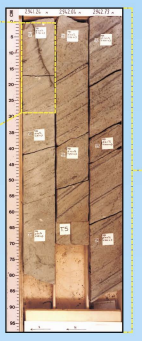
Late authigenic pyrite cementation is developed throughout Unit NE of the Late Triassic Mungaroo Formation in North Rankin-5 from 2849.5m down to 3161m in the uppermost sandstone of Unit NF. The pyrite cement developed as a result of reduction of formation water sulphate associated with oil-charged, sulphate- and iron-rich fluid migration into the reservoir and development of a dynamic oil column during the first phase of hydrocarbon entrapment. The lack of significant pyrite cementation in the upper part of the Mungaroo Formation sandstone from 2679 to 2849.5m is interpreted to indicate a palaeo-gas column above the palaeo-oil column.

The presence of oil shows in cuttings and sidewall cores in the Cretaceous section overlying the Mungaroo Formation indicates subsequent leakage of the palaeo-gas column and partial leakage of the palaeo-oil column.

Subsequent input of the current gas column displaced the palaeo-oil column. The presence of oil shows in conventional core indicate that a thin oil column was present below the gas column but has subsequently been lost.

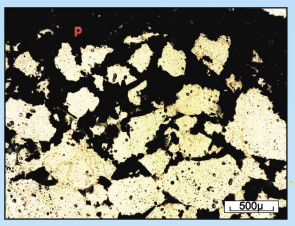


Pyrite filled fracture.

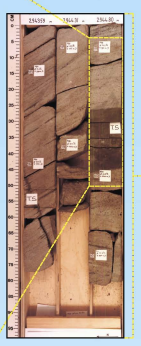




Pyrite-rich zone
2945.08-2945.28

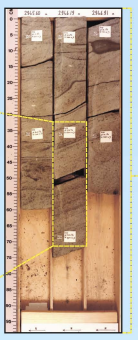


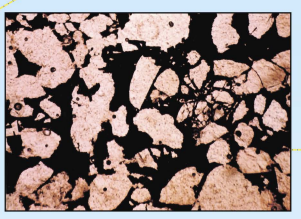
2945.15m Pyrite (p) filling pores and replacing detrital grains. "The formation of pyrite is the latest major diagenetic event and pyrite is replacive with regard to all detrital grains and previous cements" (Brown et al.,1977)





Pyrite on foreset planes.

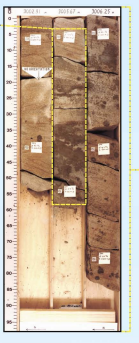




2998.69-2998.86m Pyrite cementation and corrosion of grains (black) in a subarkose. (x200) (von Sanden, 1977, photo 3)

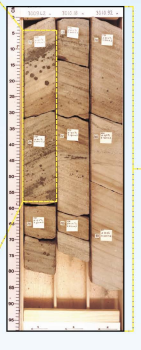


Large pyrite nodules.



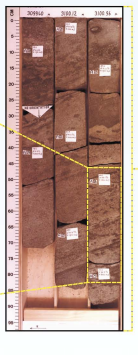
2cm diameter pyrite nodules.

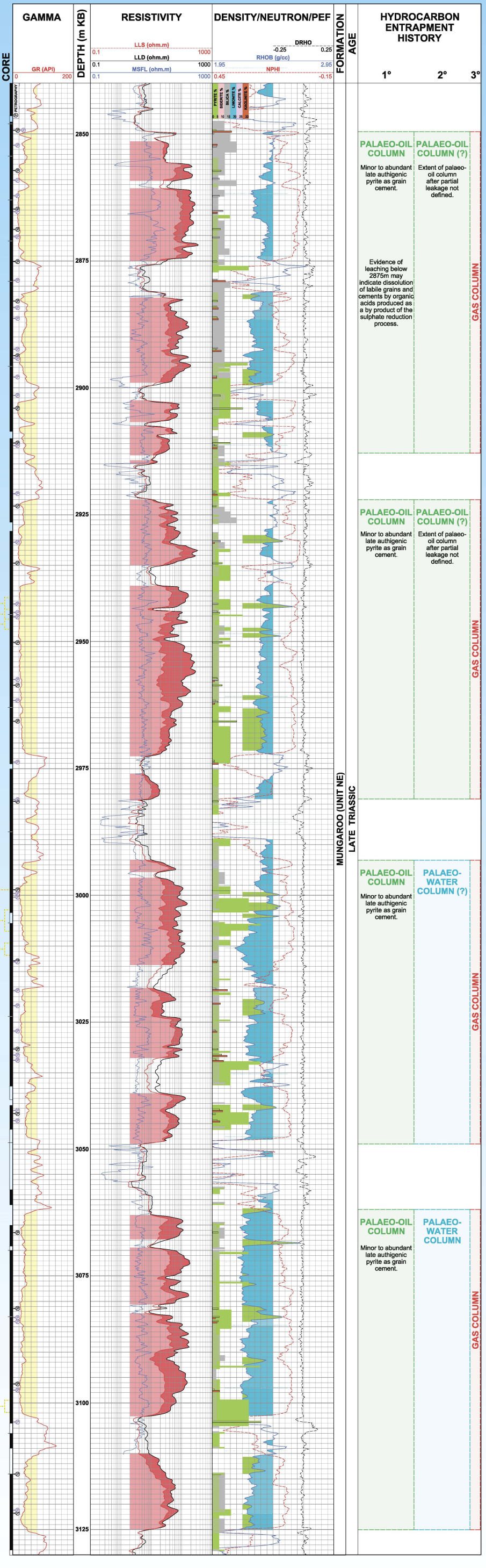






Pyrite on bedding planes (10% pyrite)





North Rankin 6

Late authigenic pyrite cementation is developed throughout the North Rankin Formation in North Rankin-6 from the top of the sandstone reservoir down to 3243.5m. The pyrite cement developed as a result of reduction of formation water sulphate associated with oil charge and development of a dynamic oil column during the first phase of hydrocarbon entrapment.

In the lower part of the interpreted palaeo-oil column more concentrated pyrite cementation is developed as solution fronts observed in conventional core, indicating input of iron- and sulphate-rich fluid with the oil charge into the reservoir.

The present extrapolated temperature is 110°C. During oil entrapment it is likely that the reservoir temperature would have been sufficiently below 100°C for bacterial sulphate reduction to be the most likely mechanism.

Grain Density (g/cc)

3193.6-3193.8m Solution front with sandstone containing up to 20% pyrite cement.

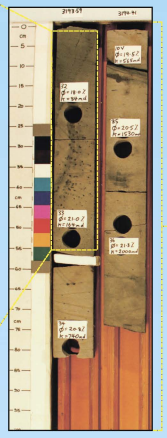


2.81

Small pyrite nodules throughout.

2.63

3193.57 - 3195.16m



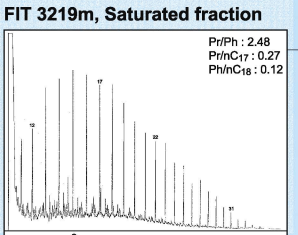
Palaeo-oil column (3196-3224m)

Fair to poor oil shows in conventional core and sidewall core at 3223m.

Slightly elevated resistivity interpreted to indicate residual oil saturation (Sw=80%) down to 3224m and FIT at 3219m recovered 33.6°API oil

Previous palaeo-oil column displaced by later gas input into the reservoir and trapped temporarily as thin oil column below the gas column.

FIT 3219m, Saturated fraction

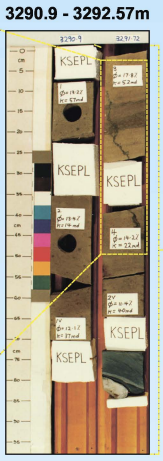


1.5 ft³ gas, 150cc oil (33.6°API)
9,800cc water



2.74

3290.9 - 3292.57m



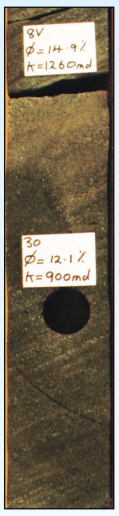
2.73

Pyrite fracture fill



Pyritic sandstone containing 25% pyrite cement.

3.01



2.61

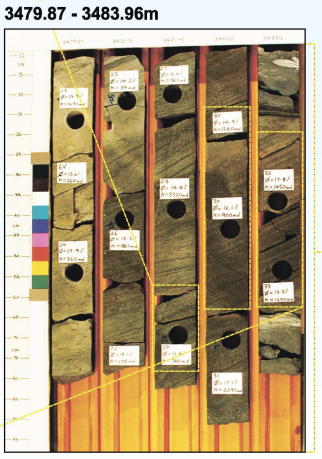
Non-pyritized sandstone section adjacent to pyritized solution front.

2.87

Palaeo-oil Migration Pathway (3458.5 - 3497.5m)

Pyrite is interpreted to have precipitated as a result of bacterial reduction of formation water sulphate associated with concentrated oil-charged, sulphate- and iron-rich fluid migration as solution fronts focussed preferentially through this sandstone interval of Unit NE of the Late Triassic Mungaroo Formation.

3479.87 - 3483.96m

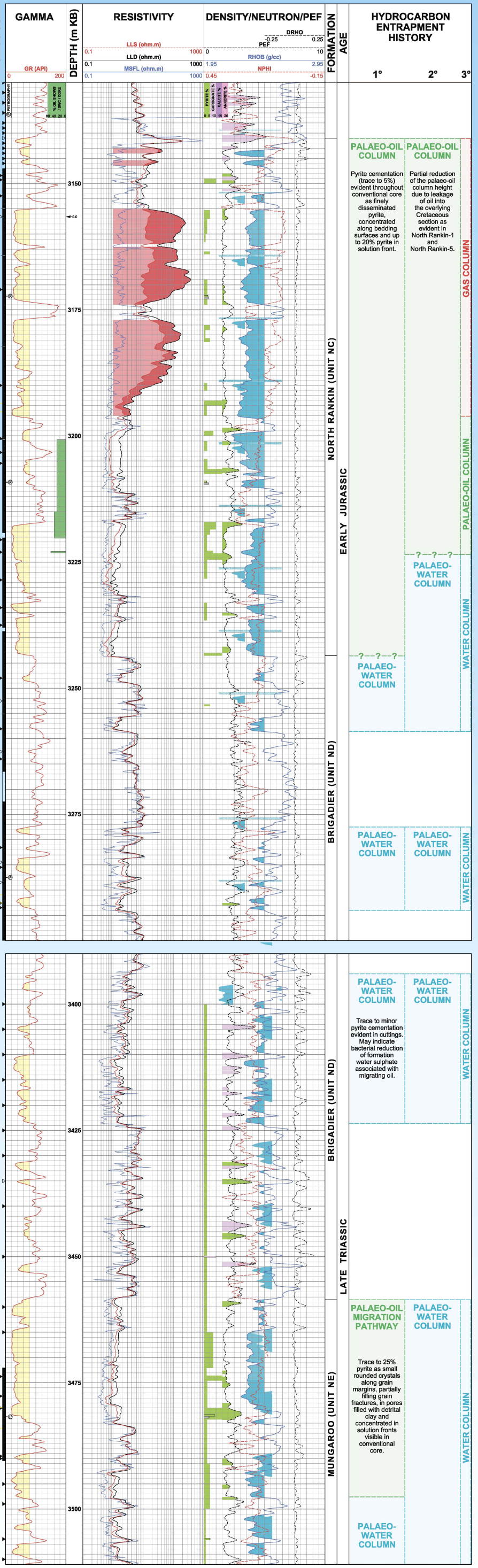




2.54

Non-pyritized sandstone overlying pyritized sandstone.

2.80



Oil Migration and Entrapment Mechanism
North Rankin Field

South

North

North Rankin A18

North Rankin 5

Unit NE

Sulphate-, Iron- and oil-rich solution front

Fair oil shows in cuttings in Early Cretaceous Windalia Radiolarite indicating partial vertical leakage of initial palaeo-oil column.

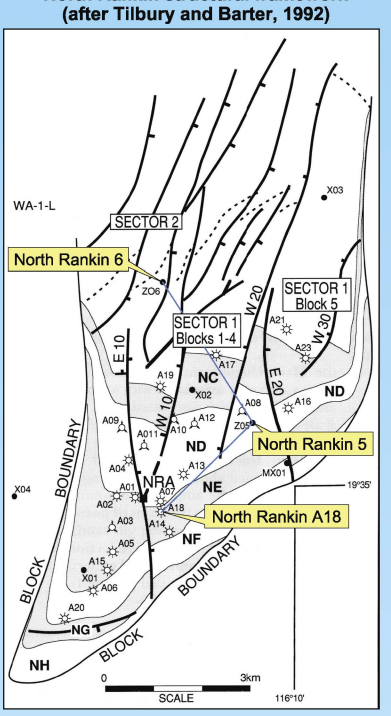
Palaeo-gas/oil contact of gas cap associated with initial oil charge

Palaeo-oil/water contact associated with initial oil charge

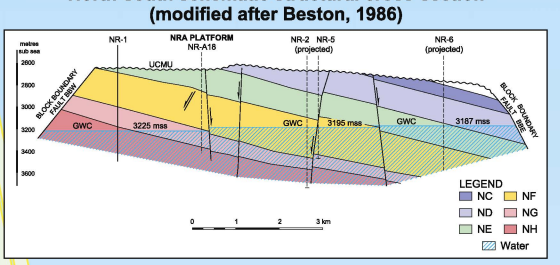
Gas/water contact

Palaeo-oil/water contact

North Rankin structural framework (after Tilbury and Barter, 1992)



North-south schematic structural cross-section (modified after Beston, 1986)



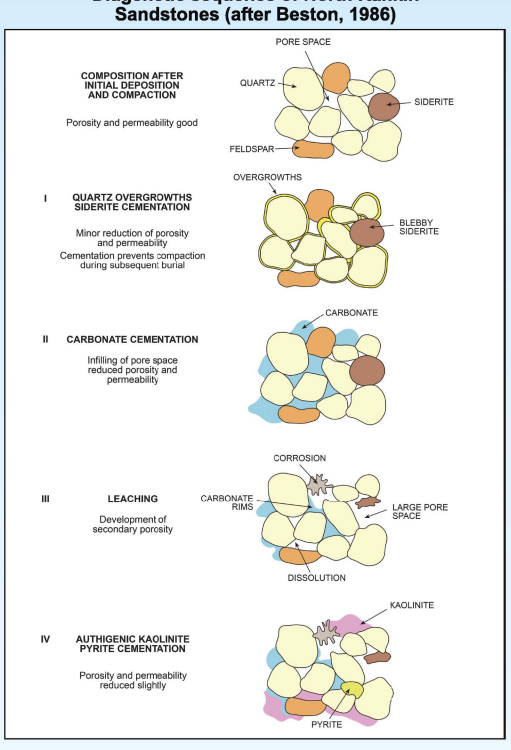
Late Authigenic Pyrite Cement Distribution

Strong development of pyrite cement close to the termination of the migrating oil-charged, sulphate- and iron-rich solution front.

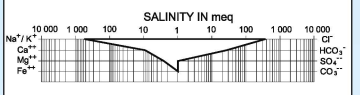
Strong development of pyrite cement due to lateral migration of oil and sulphate- and iron-rich formation water as a solution front with pyrite cement throughout the sandstone.

Weaker development of pyrite cement during lateral migration of oil and sulphate- and iron-rich formation water, with pyrite cement concentrated adjacent to the boundaries of the sandstone intervals.

Diagenetic sequence of North Rankin Sandstones (after Beston, 1986)



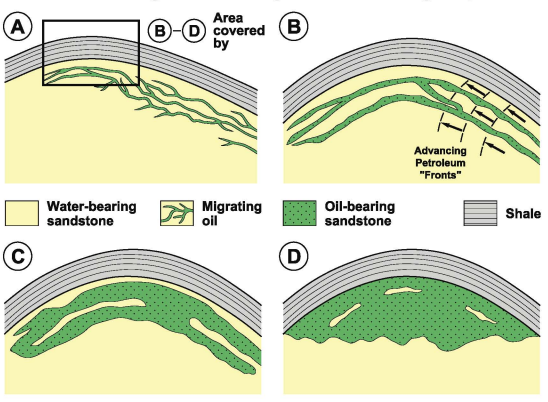
North Rankin 5 - DST 1 3233-3236m Mungaroo Formation



	meq	mg/l		meq	mg/l
Na^+	387	8900	Cl^-	363.2	12881
K^+	4.7	185	HCO_3^-	26.4	1607
Ca^{++}	9.0	180	SO_4^{--}	0.9	43
Mg^{++}	1.7	21	CO_3^{--}	-	-
Fe	0	0.12	NO_3^-	0.1	6
Sum of Ions = 23,817 mg/l			pH = 8.2		

Formation water from the Mungaroo Formation with very low levels of sulphate, possibly indicating sulphate (SO_4^{--}) depletion as a result of bacterial sulphate reduction. Elevated level of bicarbonate (HCO_3^-) has possibly resulted from CO_2 produced in the sulphate reduction process in the presence of hydrocarbons.

Schematic diagram showing reservoir-filling sequence



Modified after Figure 20 of England et al. (1987).

Pyrite-cemented sandstone in solution front in North Rankin-A18 conventional core. (Inverted to illustrate updip migration of solution front).



The increase in the concentration of pyrite cementation within the sandstone of Unit NE of the Late Triassic Mungaroo Formation from North Rankin-6 in the north of the field, well below the present gas column, to the extensive and abundant pyrite cementation in North Rankin-A18 in the south of the field, within the gas column, is interpreted to indicate focussed migration in Unit NE of oil-charged, sulphate- and iron-rich solution fronts from the north up-dip to the south. The shear abundance of pyrite in Unit NE in these wells, and particularly in North Rankin-A18, indicates input of iron from an external source and likely input of this oil-charged, sulphate- and iron-rich fluid into Unit NE via vertical migration up a dilated fault from a deeper fluid source. The massive and extensive pyrite cementation in North Rankin-A18 represents the terminal area of the solution fronts close to the southern truncation of Unit NE.

This focussed pyrite distribution is indicative of the preferred migration pathway of initial oil-charged, sulphate- and iron-rich fluid entering the trap as an advancing front via layers with the largest pores, as described by England et al. (1987). Subsequent fluid will be forced into smaller and smaller pores. However unlike the England et al. (1987) model, the presence in the fluid of sulphate, iron and sulphate-reducing bacteria contributed to the development of diagenetic or solution fronts as originally recognised in roll-front uranium ore bodies.

In North Rankin, oil-charged sulphate- and iron-rich fluid migrating through individual sandstone intervals activated resident sulphate-reducing microorganisms resulting in sulphate reduction and subsequent pyrite precipitation at the diagenetic front. The continuing input of oil-charged sulphate- and iron-rich fluid resulted in further pyrite precipitation. However the input of Fe+++ and sulphate, which are both strong oxidizing agents, also oxidized the pyrite and mobilized Fe++ in solution resulting in a dynamic solution front advancing through the sandstone unit.

North Rankin 6

Sulphate-, Iron- and oil-rich solution front

Vertical migration via dilated fault of oil-charged, sulphate- and iron-rich fluid from a deeper source into the Unit NE in the northern part of the North Rankin Field.