Oil Charge Migration in the Peace River Oil Sands and Surrounding Region

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GeoConvention 2012:Vision

Summary

The oil source and alteration history of the Lower Cretaceous and underlying Mesozoic and Late Paleozoic reservoired oil fields of north-central Alberta (Peace River Arch area) were investigated using a very large database of public and in-house data, to produce the first high resolution model of oil-charge systematics for the oil sands. Bulk chemistry and stable isotopic analysis of oils, in combination with quantitative analysis of biodegradation resistant saturated and aromatic hydrocarbon molecular indicators of the Peace River oil-sands bitumen and surrounding oils revealed oil-charge from the Jurassic Gordondale (oil Family Z) in the west along the Montney and Gething formations, mixing with vertically migrated oil-charge from the Exshaw Formation east of the Debolt anhydrite facies pinch out. Most likely there is no significant Gordondale source contribution to the Exshaw source dominated Athabasca, Cold Lake and Lloydminster accumulations. The precursor oils to the Peace River, Athabasca, Buffalo Head Hills and Wabasca oil sands were the earliest expelled, lowest maturity petroleum from these source-rocks, with API gravities in the 20’s and with high initial viscosities. The complex vertical and lateral heterogeneity of fluid properties reflect variations in oil-charge maturity, migration pathways, and varying levels of biodegradation, conditioned by highly variable oil charging which explains why parts of the Peace River oil-sands fields are able to be cold produced whereas the dominantly Exshaw sourced oils are too highly degraded for cold production.

Introduction

The Alberta oil sands boast wide variations in heavy oil/bitumen fluid properties, which dictate the recovery strategies and market value of these viscous oils. The significant economic incentives to locate and produce the richest, best quality reserves from the three trillion barrels of heavy-oil and bitumen in the Western Canada oil sands has inspired geological and geochemical mapping to assess charge oil source facies, fluid quality controls and biodegradation of oils in the Lower Cretaceous reservoirs. Due to the high viscosity of the bitumen, primary production is only possible in some areas of the Peace River and Lloydminster oil-sands and these operations yield low oil recoveries (ca. 15 to 20%). Here we focus on the Peace River oil-sands, which host bitumen with viscosity values that straddle the primary oil production threshold (a dead oil viscosity of ~50,000 cP at reservoir conditions) and thus careful assessment of the resource fluid quality is required for choice of optimal bitumen recovery process.

In the Peace River region, there is a very wide range of oil properties (API gravities ranging from 7.0–45°API and sulfur content from 0.1 to approximately 9 wt% S), that are related to varying oil sources and their maturities and the levels of in-reservoir oil biodegradation. As summarized by Creaney et al. (1994), migration and mixing of oil from different source rocks can broadly explain these variations; however, local variations reflect complicated plumbing systems. Here, a regional study of oils in the Peace River area was undertaken to investigate the source of the Peace River oil sands bitumen and the regional oil geochemistry of western Lower Cretaceous oil fields to establish possible precursor oil compositions and map out migration routes. Comparison of the Peace River bitumen chemistry is made with other bitumen from Alberta oil sands deposits.

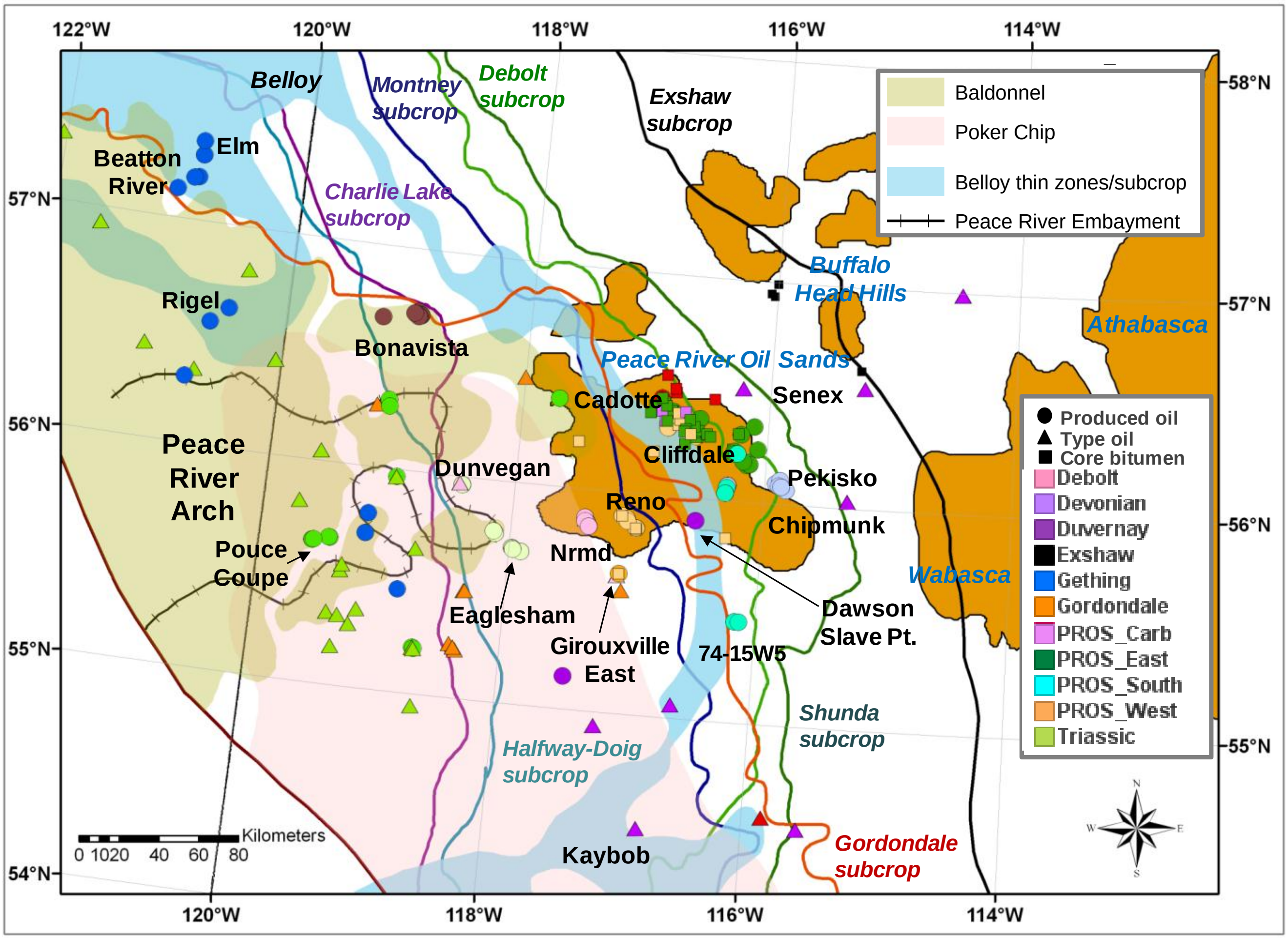

Figure 1: Location of study area showing produced oil and core bitumen sample locations. PROS stands for Peace River oil sands, Nrmd stands for Normandville.

Methods

Mapping the source contributions of the mixed oil-charges, especially highly biodegraded oils, is challenging due to the lack of detailed, regionally extensive, source-rock characterization data for an adequate number of samples, a paucity of effective universal, biodegradation resistant, source-related molecular parameters plus source maturity variation effects and the orders of magnitude concomitant variations in absolute concentrations of source diagnostic molecular markers seen in the charged oils. This work presents a regional case study of the Peace River area extending 200 km west from the eastern edge of the Peace River oil sands. For comparative purposes, a suite of 'type oils' that have been correlated with type source-rocks from across Alberta were also analyzed (Debolt, Exshaw, Duvernay, Gordondale, Doig and Upper Cretaceous sourced oils) from published work. The regional geochemistry of over 150 oils in the Peace River region is mapped using both produced fluids and core samples from the Bluesky, Gething, Triassic, and Pekisko and Debolt formations that can be subdivided into some geographic groupings:

1) Lower Cretaceous reservoired oil sands of the Peace River and Buffalo Head Hills oil sands.
2) Bluesky and Gething reservoired oils west of Peace River oil sands
3) Oils in the Charlie Lake and Montney Formation along their subcrop edges (west of the Peace River oil sands) at the sub-Cretaceous unconformity, sourced primarily from the Gordondale source-rock (Family Y and Z; e.g., Ejezie, 2006).

4) Debolt sourced and reservoired oils in the Belloy, Eaglesham, Dunvegan and Normandville fields (near the 6th meridian from township 76 to 81; Snowdon et al., 1998).
5) Exshaw sourced oils from southern Alberta and central Alberta (around 55W5) reservoired in the Banff (Family E; Creaney et al., 1994).
6) Triassic sourced type oils in the Charlie Lake, Baldonnel, Montney, Doig and Halfway reservoirs, found west of the Doig subcrop (Family X and Xi; e.g., Ejezie, 2006).
7) Duvernay sourced type oils from the Rimbey Meadowbrook trend, central Alberta Kaybob field (Swan Hills reservoirs) and northern Alberta Senex and nearby fields in the Granite Wash (between the Peace River and Wabasca oil sands) (Family D; e.g., Larter et al., 1996).
8) Upper Cretaceous Viking and Doe Creek type oils from central Alberta and the Progress field (78-08W6) respectively (Allan and Creaney, 1991).

All the oils were analyzed for bulk composition (SARA) by Iatroscan, molecular distributions of total saturated and aromatic hydrocarbons by quantitative GC-MS, bulk sulfur content and whole oil $\delta^{34}S$ isotopic composition. A subset of these oils was analysed for bulk $\delta^{13}C$ and δD composition, metals content and in some cases dead oil viscosity and API gravity. As part of regional oil-sands studies (Marcano et al., 2010; Oldenburg et al., 2010), a few samples were analysed for $\delta^{15}N$ and for high molecular-weight heteroatom compounds by FTICRMS.

Source Rock Contributions and Biodegradation Modeling

The bulk chemistry of this suite of produced oils and core bitumen (SARA; Figure 2) mimics the trends found in the API gravity and sulfur content data. The low API gravity, high sulfur Peace River oil-sands bitumen is depleted in saturated hydrocarbons and enriched in both aromatic hydrocarbons and polar compounds compared to the other oils found further west. This division reflects the level of biodegradation and geographically coincides with a SE-NW line on the eastern edge of the Peace River oil sands which is the limit of significantly biodegraded oils (Creaney et al., 1994; Adams et al., 2006).

The molecular chemistry of the Lower Cretaceous reservoired oil and bitumen show Gordondale sourced oils found in the Peace River oil sands located east of the zone where the overlying Poker Chip shale caps mature Gordondale source-rock, which may have focused S-rich, low biomarker content Gordondale oil to the east into the underlying Montney and then up into the Gething reservoirs. Mixing of Gordondale oils with Exshaw sourced oils only starts east of the Gordondale subcrop edge, with the bulk of the Exshaw oils trapped east of the pinch out of the Debolt anhydrite facies where there is also significant thinning of the Belloy Formation. Here, extensive vertical migration from the Exshaw source rock into Bluesky-Gething reservoirs was possible, as seen along a clear NW-SE mixing line on the western edge of the Cadotte field. Very thin or zero isopach areas in the Gething Formation and local faulting has localized Gordondale oil charge into reservoirs partially filled with Exshaw oil, resulting in some charge related compositional variations within oil columns in the central Cadotte field, overprinted by biodegradation gradients. The Exshaw sourced oils in the Peace River oil sands and further west seem to exhibit higher levels of biodegradation, related to both longer residence time in the reservoirs and likely, lower proportions of degradable hydrocarbons in the precursor non-degraded Exshaw oil.

The underlying Mississippian reservoired oils of the Peace River oil sands are more thermally mature and less degraded than the rest of the Peace River oil-sands bitumen, but most closely resemble pure central Alberta Exshaw sourced oil. These findings are consistent with the earliest Exshaw oil-charge being into the overlying Lower Cretaceous reservoirs with later back filling of the Pekisko and Shunda reservoirs. To the north and east, the Buffalo Head Hills and Wabasca reservoirs appear to be solely filled with even lower maturity Exshaw sourced oil than that in the Peace River oil sands, which likely migrated into Lower Cretaceous sand reservoirs along the sub-Cretaceous subcrop edge of the Exshaw Formation. These more easterly bitumens have been more highly degraded due to the shallower depth of burial of the equivalent Lower Cretaceous reservoirs. There is no evidence of contributions to the oil sands from the Triassic source-rocks and the Duvernay source rock system, except where extensive vertical faulting has uniquely locally allowed upward migration of oil (e.g., Normandville field).

Lower Cretaceous reservoirs charged in part with Exshaw sourced oil are scattered west of the Peace River oil-sands pasteurization line, controlled by vertical oil migration through faults (e.g. at the Progress and Spirit River fields). These reservoirs typically contain slightly biodegraded oil and/or have lower API gravities and high asphaltene contents compared to adjacent oil fields. Thermal basin modeling suggests that the Exshaw oils most likely charged these reservoirs around 110 to 80 Ma prior to paleo-pasteurization which is consistent with modeled oil expulsion timing of the Exshaw source-rocks and the low biodegradation levels seen. The limited or negligible amount of biodegradation in oils west of a NW-SE line passing through T85-R24W5 and T79-R22W5, is related to reservoir pasteurization near the 80ºC maximum burial isotherm in the Bluesky Formation.

A major unresolved issue for the origin of the oil sands is the volume of source-rock and associated oil-charge of the trillion barrels of viscous oils in place (Creaney and Allan, 1990), especially because of the large volume of oil postulated to have been removed by biodegradation (40 to 70% of OOIP according to Brooks et al., 1988). Some simple biodegradation models based on penecontemporaneous but variable, compound group degradation rates (Larter et al., 2003; 2006) of SARA fractions can assist in resolving these mass balance issues. Within each bulk SARA fraction, such as the saturated hydrocarbons, the most reactive (e.g., n-alkanes) and least reactive components (e.g., tricyclic terpanes or hopanes) would degrade at rates orders of magnitude apart, but the more reactive aromatic hydrocarbons degrade at intermediate rates while the high molecular-weight polar fractions degrade at rates many orders of magnitude more slowly. Figure 2 summarizes possible biodegradation scenarios with typical precursor bulk oil compositions sourced from the Triassic, Duvernay, Gordondale and Exshaw source-rock systems, assuming biodegradation of saturated hydrocarbons is five times faster than the aromatic hydrocarbons with no biodegradation of the polar compounds. Above, it was suggested that the precursor oils of the oil sands were the earliest expelled most immature oils from the Gordondale and Exshaw formations and might have been even more polar compound rich than the type oils considered here. This means that the modeled results predict a maximum level of biodegradation required to form the Peace River oil sands. The models assume that when 50 wt% of the original oil has been removed that the oil would be categorized as PM Level 5 (Larter et al., 2006), which is at best a rough approximation of current alteration levels.

This modeling, can be combined with oil sulfur contents, which is generally largely conservative during biodegradation to PM level 6 and even higher (Oldenburg et al., 2010). To account for the observed Peace River oil-sands bitumen sulfur contents, which can reach 10 wt% S in Gething reservoirs (Reno field T79-R20W5), its precursor non-degraded oil would have had sulfur contents ranging from 3–5 wt%, given estimates of hydrocarbon removal from Peace River bitumen by biodegradation of ca. 50–60 wt% (Adams et al., 2006). Based on the modeling, degradation of the low maturity Triassic (green squares) and Duvernay (purple squares) type oils to PM level 8 could explain the SARA compositions of the better quality Peace River oil-sands bitumen. However, given this hypothetical scenario, the sulfur contents of these biodegraded oils would still only be <1.4 wt%, which is substantially less than the observed sulfur contents(sulfur values are marked on Figure 2 at the PM level 5 dots). In the inset of Figure 2, the black bars indicate the sulfur content of each type oil assuming 50 wt% removal by biodegradation, showing that **only the Gordondale and Exshaw sourced oils** could account for the observed sulfur contents of the Peace River oil sands. The modeling shows that:

1. the Gordondale Family Z oil becomes too aromatic hydrocarbon-rich at PM level 5 (orange squares with solid line in Figure 2). However, if at PM level 3, we assume transition from 5:1 to 1:1 degradation of the two hydrocarbon types due to reduction in the concentration of saturated HC by PM level 3, then these simulations predict the SARA compositions and sulfur contents (7-

8.5 wt%) of the western Peace River oil-sands bitumen at PM level 5, as observed (orange squares with dotted line);

2. the Exshaw (white squares) biodegraded type oil becomes too polar rich by PM level 5 (Using the same transition from 5:1 to 1:1 biodegradation rate scheme at PM level 3). Geochemically this oil would most likely look like PM level 7–8, like the Athabasca oils. At PM level 4, the simulated oil compositions plot on the asphaltene-rich limit of measured Peace River bitumen.
3. the mixed Exshaw and Gordondale mixed oil (marked as black squares on the diagrams; applying the 5:1 and then 1:1 saturated to aromatic hydrocarbon biodegradation rates), which generates 6.3 wt% S oil at PM level 4–5, plots close to the eastern and carbonate Peace River oil sands samples.

Thus it seems likely the Peace River oils are a mix of varying proportions of Gordondale and Exshaw sourced oils, depending on geographic location of the reservoirs. These simulations shows that only a ~ 30 wt% reduction of the original precursor Exshaw or Gordondale oil by biodegradation is required to match the oil sands SARA compositions suggesting that initial charged volumes to the oil sands could be substantially less than the 2 to 3 times of original oil in place proposed elsewhere. This means that the mass balance calculations for the Exshaw and Gordondale source rock yields are much closer to the required volumes than previously thought. Albertan heavy oils start at low API gravity (ca. 22° API) and just get worse!

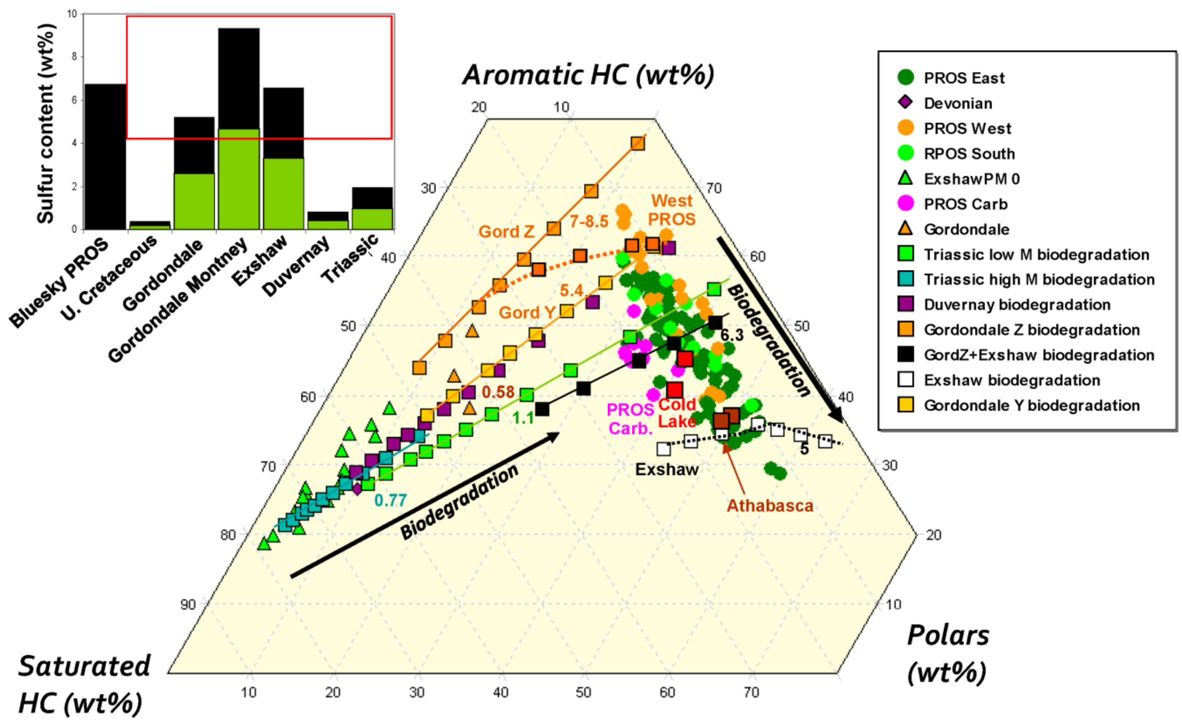

Figure 2: Modeled biodegraded oils based on typical precursor oil compositions sourced from the Triassic, Duvernay, Gordondale and Exshaw source-rock systems. Five times as many saturated HC as aromatic HC were removed by biodegradation in the model and the polars were not degraded. The Exshaw biodegraded type oil (white squares) and the Gordondale Z oil (dashed orange line) were degraded with the 5:1 saturated to aromatic hydrocarbons ratio until PM 3 and then 1:1 saturated to aromatic hydrocarbons ratio thereafter. This was due to the low level of saturated HC in the precursor oil and the assumed earlier onset of more intense biodegradation of the aromatic hydrocarbons. The squares in the biodegradation trajectories of each oil represent PM levels (0, 1, 2, 3, 4, 4.5, 5, 5.5, 6, 7, 8). Inset: Bluesky Peace River oil sands black column is the average measured sulfur content of Peace River oil sands produced oils (n=20; range from 4.5 to 8.7) and black columns above the source-rock oils represent the approximate sulfur content of this oil assuming removal of 50 wt% oil by biodegradation (a theoretical estimate for PM level 5; Larter et al., 2006). The red box indicates the range of sulfur contents in Peace River oil-sands bitumens.

Conclusions

The ubiquitous vertical and lateral oil compositional gradients seen at the regional, field, reservoir and even compartment scale of the Western Canada oil sands are the products of complex multiple source oil charges, spatially variable biodegradation effects and complex structural and stratigraphic relationships of source-rocks, migration pathways and reservoirs. Due to the extensive levels of biodegradation of the oils sands, oil-oil and oil-source rock correlations are most effective using oil bulk trace metal and sulfur content, and nitrogen, sulfur and carbon isotopic compositions, in combination with quantitative biodegradation resistant saturated and aromatic hydrocarbon molecular parameters. This work shows that, despite previously suggested common source-rocks and simple genesis models for the oil sands, the Peace River Arch area oil fields show substantial and complex mixing of Gordondale, Exshaw and to a lesser extent Duvernay sourced oils. The mixing is facilitated locally by faulting, thinning of seal facies (e.g. the Poker Chip shale and Debolt anhydrite member) above source-rocks and pinching out of migration pathways (e.g. the Montney and Gething formations) onto the base Cretaceous strata.

In general, the Peace River oil-sands bitumen is a mix of the earliest expelled low maturity Gordondale Z family oil and low maturity central/northern Alberta Exshaw sourced oils. The Exshaw sourced oils in the Peace River oil sands and further to the west seem to exhibit “higher levels of biodegradation”, related to both longer residence time in the reservoirs and likely, lower proportions of degradable hydrocarbons in the non-degraded precursor Exshaw oil. The portion of the Peace River oil sands that can be recovered by primary production correlates well with the areas that received significant oil-charge from the Gordondale source-rocks.

Further mapping of small scale lateral oil compositional variations may prove fruitful in identifying local higher quality fluids and production “sweet spots” in the oil sands. Better characterization of the molecular signatures of oil source facies within the both locally and regionally extensive source-rocks, using compositional kinetic approaches, will enable better oil-source-rock correlations and predictive models for fluid property variations in the oil sands. Translating compositional basin models down to the field and reservoir scale will facilitate assessment of quantitative charge timing and volume and mixing and in-reservoir alteration for targeted prospecting and field development.

Acknowledgements

The authors extend their appreciation to Joe Westrich and Cor van Kruisdijk for their support and constructive collaboration and Martin Fowler, Cynthia Riediger, Lloyd Snowdon and Steve Creaney for discussions. The following oil companies donated samples: Shiningbank Energy Ltd., Penn West Petroleum Ltd., Koch Petroleum, Bonavista Petroleum Ltd., Burlington Resources Canada Ltd., Blackrock Ventures Inc., Talisman Energy Inc., Tiger Energy Ltd., Shell Canada, Encana, Husky Canada, ConocoPhillips and Devon Canada. Funding for this project was provided by the Alberta Ingenuity Fund, Canada Research Chairs and NSERC. The Bacchus II sponsors (BP, Chevron, ConocoPhillips, AGIP ENI Hydro, Petrobras, Saudi Aramco, Shell, Statoil, Total, Woodside), the PRG Research Fund, CFI and CMC also provided financial support for part of this research.

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