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The Origin and Temporal Dynamics of Mercury in Gas Condensate Fields in Central Luconia Carbonate Province, Offshore Malaysia

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Why Mercury Matters in Hydrocarbon Fields

Mercury is a very high density, corrosive and hazardous element that occurs in nature in many forms

1. **Presence in Reservoirs:** It can be found in natural gas, condensates, and crude oil, often in particulate or dissolved forms.
2. **Operational Hazards**
    - Corrode Aluminium equipment, especially in cryogenic gas processing units like those used for LNG.
    - Forms amalgams with metals, weakening structural integrity and leading to costly failures in compressors, heat exchangers, and pipelines.
3. **Processing Challenges:** Specialized mercury removal units (MRUs) required.
4. **Regulatory and Economic Implications:** Strict mercury emission limits, especially in refining and LNG export.
5. **No definitive tool for Mercury Prediction.**
    - Mercury over time is uncertain and pose a significant challenge for facility design at FDP stage.
    - MRU planned for some of the gas fields were never used, while production deferred in few cases as mercury content exceeded the threshold limit, caused CAPEX sink and delayed cash flow.

Source, Transportation & Fixation of Mercury (Hg)

Mainly hydrothermal origin, typically found near organic-rich sediments (black shales), and in regions of recent volcanic activity.

Primary Source

- Inorganic minerals
  - Hydrothermal deposit
  - Vein deposit
  - Volcanic deposits – tuff, volcanic shale
- Hg deposit in coal basins
- Organic black shales having Hg content (1 -3 ppm)

Transportation

Isotopic and biological marker data support the hypothesis that all these components may have been derived from local sedimentary rocks in response to heating/cracking and subsequently transported to the site of deposition in a gas phase.

Fixation

The key fixation mechanisms for Hg in its source rocks are adsorption onto clay minerals, organic matter, and incorporation into the crystal structures of other host minerals, particularly sulphides (Moiseyev 1971)

Mercury Species in Petroleum

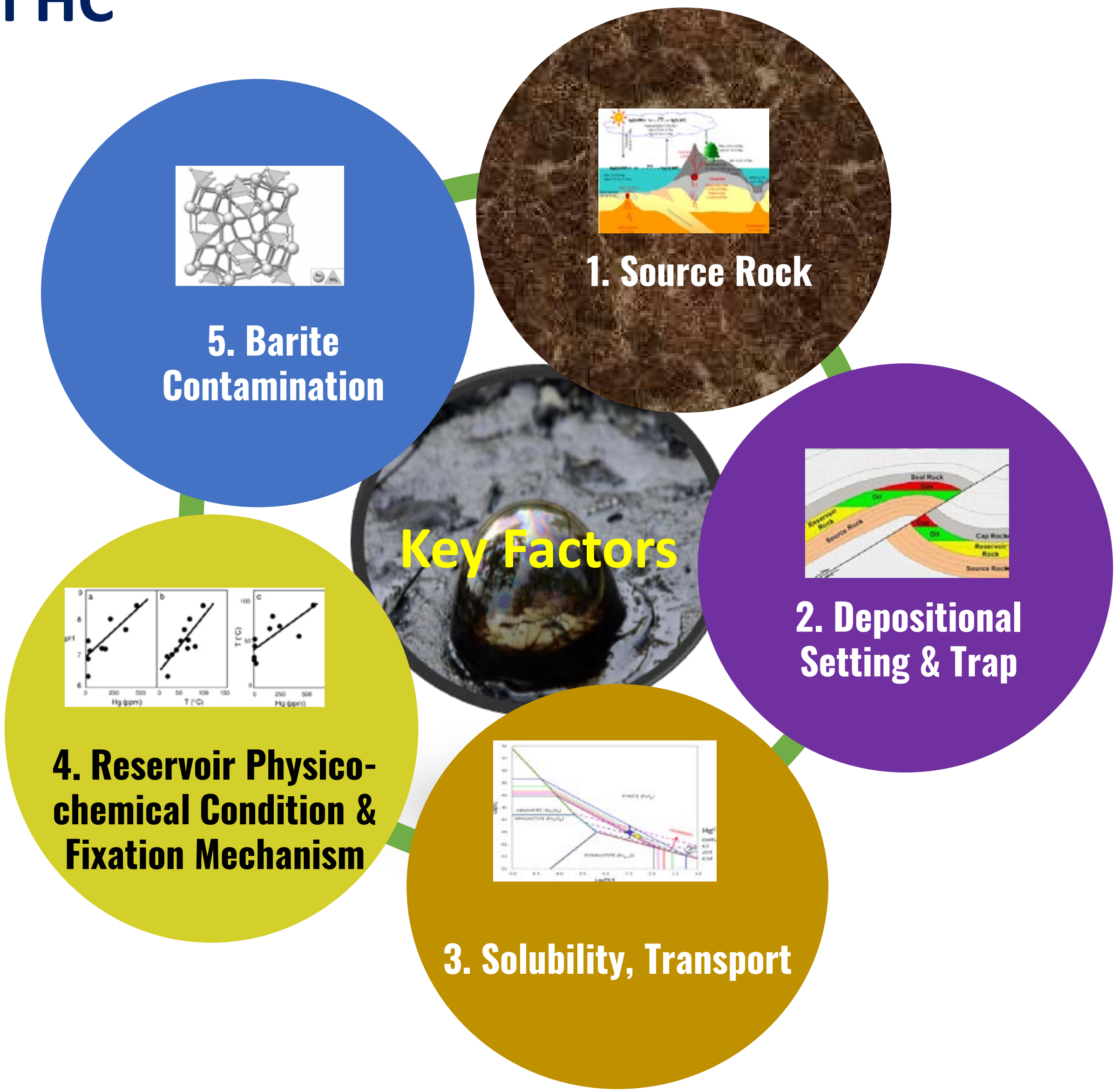
- Mercury occurs both in dissolved and particulate state in hydrocarbon and/or water.
- Six species identified as published by *Wilhelm & Bloom 2000, "petroleum system modelling results for CO_2 and Hg content trending analysis".*

Phase	Mercury Species	Description	*Potential sources
Dissolved mercury	Elemental mercury (pure)	**Volatile** and distributes between gas, liquified fractions and oil/condensate. ***Relatively insoluble in water***	• HC Source rock • organic shales • Coal shale • Hydrothermal
	Organic mercury	Highly soluble in crude oil, gas & condensate. ***Virtually insoluble in water.***	
	Organo-metallic	Typically, **non-volatile** and partition into the oil/condensate phase	
	Inorganic (ionic) mercury	Soluble in oil and gas condensate, but **preferentially partition to water phase.**	• Inorganic origin (**Mantle degassing?**) • Barite
Particulate mercury	Amalgamated mercury	Insoluble in liquids and **remain suspended** as solid fine particles. Examples include mercury sulphide (HgS)	• Presence could be due to barite mud contamination and/or HgS content in formation rock.
	Weakly adsorbed mercury	Mercury not dissolved, but rather **adsorbed** on inert particles such as sand or wax	

Factors Shaping the Hg Occurrence in HC

A detailed investigation into mercury occurrence in gas and condensate reservoirs identified five key influencing factors.

- Source Rock
- Depositional setting and trap
- Reservoir Physico-chemical condition
- Solubility, Transport
- Drilling mud composition - Barite



Thermodynamic Factors Governing Mercury Solubility

The solubility of mercury (Hg) in hydrocarbons is strongly influenced by both pH and temperature as evident from lab studies, EOS modelling and field data.

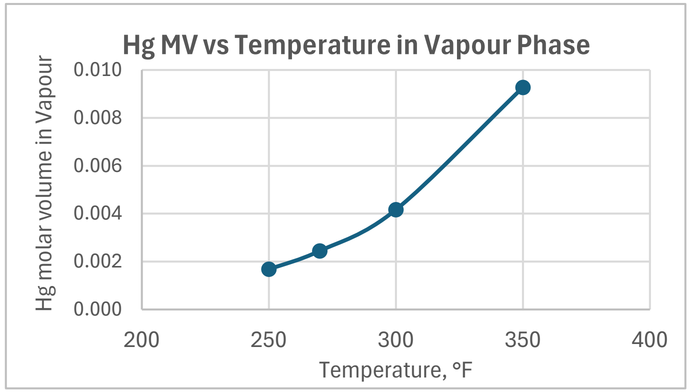
1. Equation of State (EoS) Modeling

A mixture containing hydrocarbon components (C1–C3), CO_2, H_2S, Hg, and 93% water was flashed at 5000 psia using an EOS application at five different temperatures: 250°F, 250°F, 270°F, 300°F, and 350°F. The results suggest that **Hg tends to vaporize into the gas phase as temperature increases.**

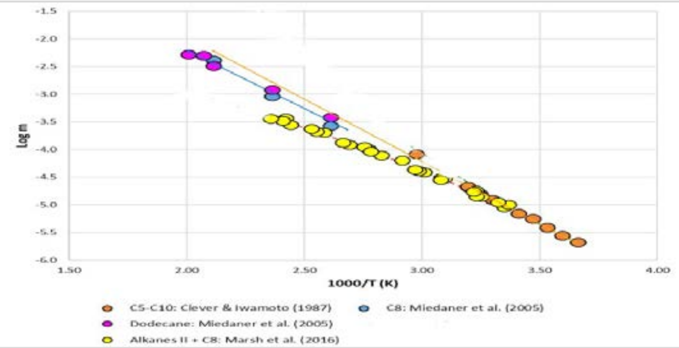
2. Laboratory Experimental Studies

Multiple studies have investigated the solubility of elemental mercury (Hg^0) in liquid hydrocarbons, with solubility measured in the C5–C7 range across various temperatures. These studies indicate that mercury solubility increases with temperature.

Hg in Vapour Phase -PVTSim



Hg^0 solubility - Experimental Data



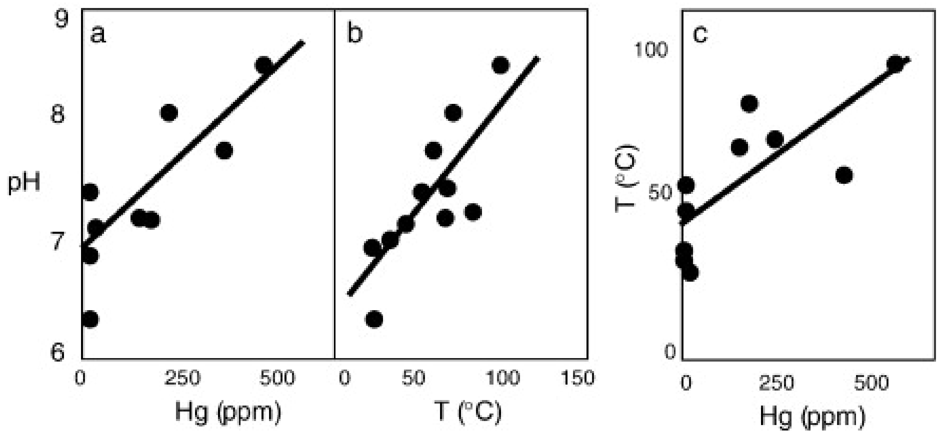
Solubility of Hg^0 in alkenes and alkane mixture from Clever & Iwamoto (1987), Miedaner et.al. (2005, Gallup and Bloom (2010 and Marsh et.al. (2016. (Source: modified picture from SPE-212271-pa)

Thermodynamic Factors Governing Mercury Solubility

The solubility of mercury (Hg) in hydrocarbons is strongly influenced by both pH and temperature as evident from lab studies, EOS modelling and field data.

Varekamp and Buseck (1984) reported that the solubility of aqueous elemental mercury ($Hg^0{}_{aq}$) in hydrothermal fluids is enhanced by elevated pH and temperature.

Hg^0 solubility in hydrothermal fluid

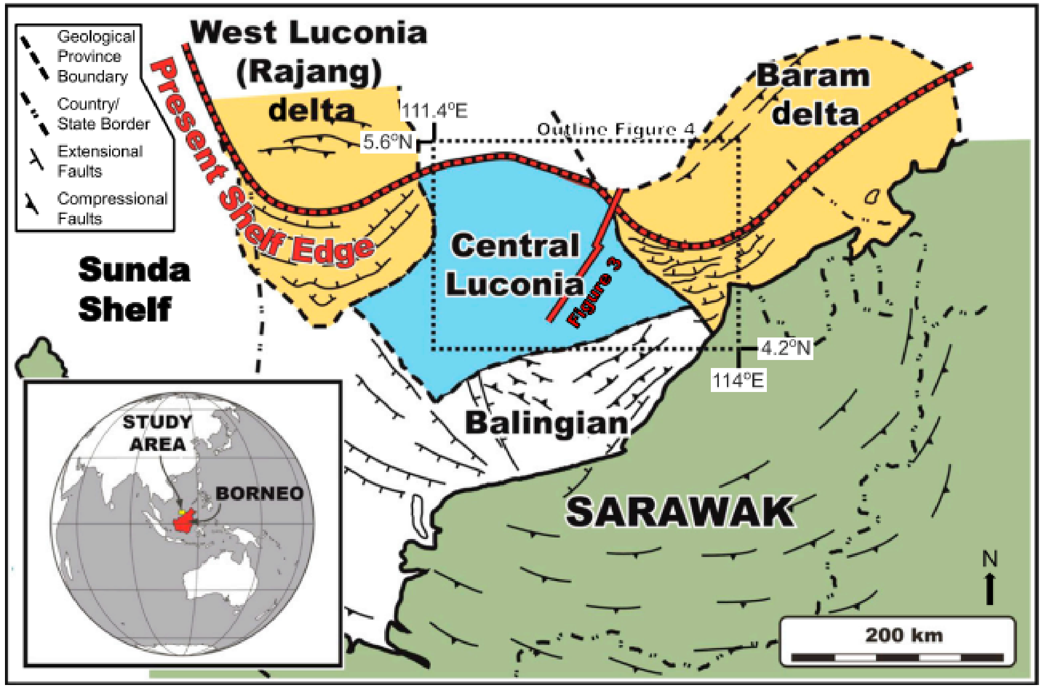


Varekamp and Buseck, 1984

Geological Setting of Central Luconia

- Central Luconia is in continental shelf of Sarawak offshore
- It is a most productive carbonate province for gas condensate reservoirs, contains about 65 trillion cubic ft of GIIP with minor contribution of oil rims.
- The geological structure of Central Luconia was deformed by tectonic regional extension following seafloor spreading in the South China Sea, resulting in several horst and graben structures over the region.
- Six regressive cycles observed in Central Luconia, (Hammad et.al. 2017).
- Carbonate deposition started during the early Miocene (Cycle III), but the mega-carbonate deposited during the middle to late Miocene (Cycles IV and V) time.
- Over 200 carbonate buildups grew during the Miocene period.
- Calcareous shale (Pre Cycle I) and coaly shale (Cycle I) are possible source rocks for hydrocarbon in Central Luconia.
- Hg frequently found in association with CO_2 and H_2S in gas, condensate and water (in some cases).

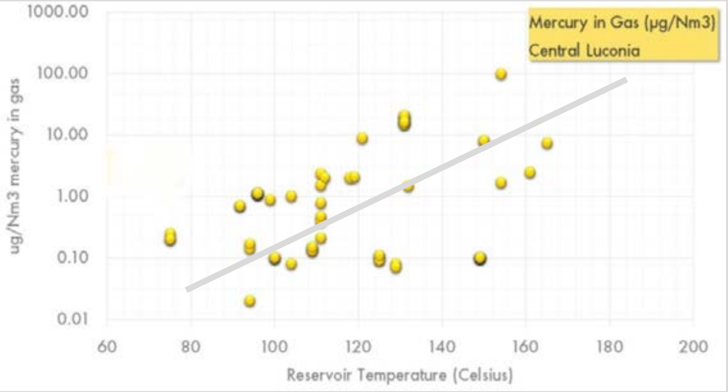
Geographical and geological location of the Central Luconia



Source: Article in AAPG Bulletin Marc 2019

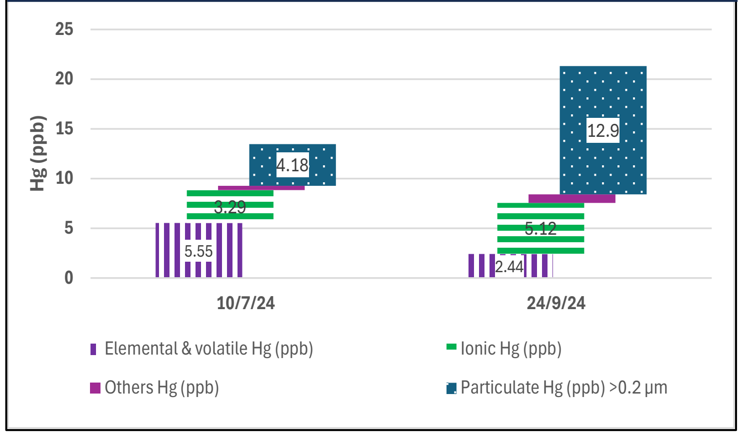
Mercury in Central Luconia Gas & Condensate Fields

Mercury in gas – Central Luconia



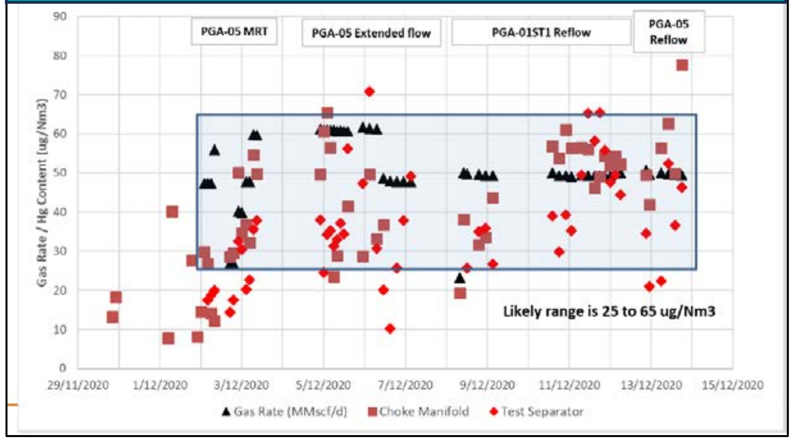
- Mercury in gas from several gas condensate fields in Central Luconia indicate that mercury concentration in the gas phase increases with reservoir temperature.

Mercury in gas – FGD vs FGD +3 months



- Mercury speciation analysis of the samples collected **"before PMC filter"** indicate increase in particulate Hg,.
- XRD analysis of solids produced during production indicates to be Barite in origin. It suggests particulate mercury could from Barite source and be attributed to wellbore clean-up.
- However, no major change in dissolved Hg is observed

Mercury concentration in gas



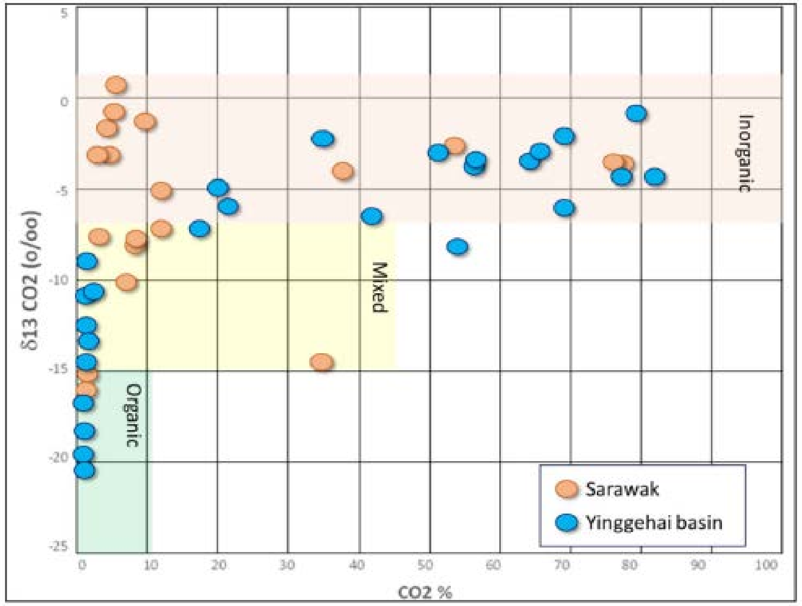
- The surface fluid samples collected both at choke manifold and separator indicated presence of mercury beyond threshold limit (gas 0.8 µg/Nm3, condensate 5ppb).
- The mercury found in all three phases (i.e. gas, condensate and water).
- No significant change in Hg trend during production.
- Production curtailment by 19 months to install of mercury removal unit (MRU).

Key Observation and Potential Source of Hg

Key Observations:

- Mercury is commonly associated with **H_2S and CO_2 in Central Luconia.**
- CO_2 gas concentration and isotopic cross-plot analysis (SPE 215443-MS) suggest **three distinct sources of CO_2 in offshore Sarawak.**
- Basin modeling and geochemical data indicate that the origin of CO_2 in the Sarawak Basin is linked to **calcareous shale (Pre-Cycle I), coaly shale (Cycle I), and magmatic activity.**
- Central Luconia is situated in a **moderately high-temperature region.**
- Results from PVT modeling, mercury solubility experiments, mercury speciation studies, and the thermodynamic conditions of Central Luconia reservoirs suggest that **mercury may be soluble in hydrocarbon gas.**

CO2 gas concentration and isotope cross plot*



*Source Rahim Masoudi, Nayak et.al, 2023, SPE215443-MS

Potential Source of Mercury in Central Luconia

1. Given that dissolved mercury species in the Central Luconia gas fields originate from both organic and inorganic sources, it is possible that **mercury shares a common origin with CO_2.**
2. Mercury may have originated from **sedimentary rocks subjected to thermal maturation and cracking and** was subsequently transported during hydrocarbon charging.

Summary and Conclusions

- Mercury content identified in Central Luconia are derived from both **organic and inorganic sources**.
- Solubility studies and EOS modelling indicate that mercury solubility in the gas and condensate phases **increases with temperature**.
- The EOS modelling also suggests that the presence of **even a small volume of water** can reduce the mercury content in the gas phase.
- Petroleum system modelling of CO_2 origin and mercury solubility in hydrocarbons suggests that the mercury in Central Luconia likely originates from **calcareous shale (Pre-Cycle I), coaly shale (Cycle I), and magmatic inputs**.
- A declining trend in particulate mercury in gas and condensate streams has been observed over time, with **Barite identified as the most probable source** of particulate mercury.
- Although mercury sampling and quantification during the pre-development stage is challenging—due to its **volatile and corrosive nature**—speciation studies is **crucial for facility design and Mercury Removal Unit (MRU) planning**.

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