The formation of low-carbon, N2-dominated helium gas fields

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Summary (All headings should be Arial 12pt bold, DELETE SECTIONS THAT ARE NOT USED)

Helium is a non-renewable natural resource essential for various scientific and industrial applications. To date, the helium discovery has been serendipitous during hydrocarbon exploration [1-3], and the market repeatedly faces a supply crisis. The radioactive decay of uranium and thorium produces helium at a slow rate, but the volume and age of continental crust provide a substantial helium generation capacity. The produced helium dissolves in porewater and can be transported diffusively or advectively to the overlying sedimentary units.

To form a viable resource, a subsurface gas phase is required to focus the dissolved helium from porewater. Helium concentration in groundwater is low compared with its solubility. The two most common gases observed that 'strip' helium from groundwater are CH_4 and CO_2 [4], which also chain helium to a high carbon footprint and dilute this primary deep crust gas. An alternative type of helium reservoir is nitrogen-dominated [5], and understanding such a system can significantly advance helium discovery while aligning with the Net Zero target.

Helium migration in sedimentary basin systems is simulated by considering flux from the crystalline basement, sediment deposition and compaction and basinal hydrogeological history [6]. In some deep sedimentary units, groundwater can be undisturbed over geological time, and dissolved gases diffuse following the concentration gradient. The transport of co-occurring nitrogen is modelled following the same diffusive principle; when its concentration exceeds solubility, a gas phase is generated, allowing helium to partition from the groundwater and concentrate in the gas phase [7].

This new reservoir forming mechanism predicts gas formation in the Williston basin, a classic intracratonic sedimentary basin. The model simulates the gas composition (^{4}He, ^{20}Ne, N_2) of a nitrogen-dominated helium reservoir discovered in the basal sedimentary lithology. The gas phase redistributes the helium budget in the sedimentary basin and reduces dissolved-gas diffusional flux into overlying strata. These findings provide quantitative insight to assess helium resource potential in similar intracontinental sedimentary basins worldwide.

Theory / Method / Workflow

The vertical transport of porewater dissolved gases is modelled from first principles. The model adds stratigraphic units sequentially and alters rock unit porosity as a result of compaction at the start of the formation age. It updates helium concentration as a function of depth at each time step. Both *in situ* radiogenic ^{4}He and ^{4}He flux from the Precambrian basement are considered as helium input into the sedimentary system. An illustration of the conceptual model is presented in figure 1 [6].

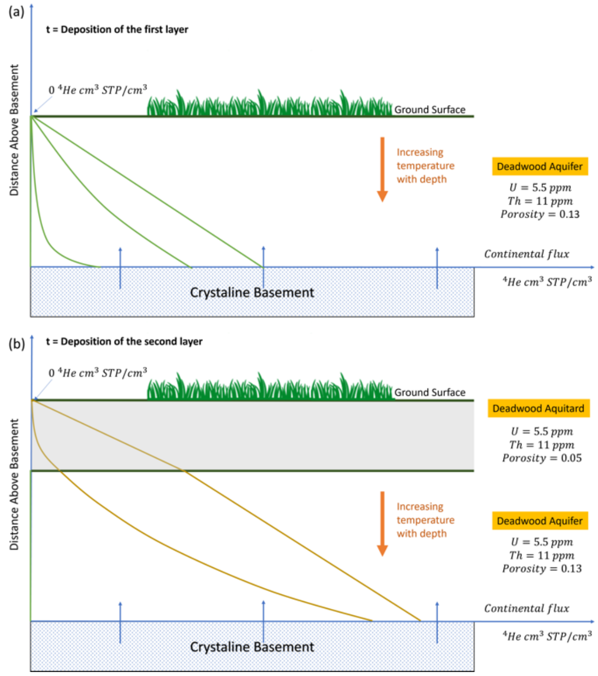

Figure 1. Illustration of helium diffusion conceptual model [6]. The concentration lines do not represent actual values but reflect the distribution trend. (a) The creation of the first, deepest, stratigraphic unit. (b) The creation of the second stratigraphic unit, overlying the first one. The concentration gradient is generated between the helium input (basal flux and in-situ production) and the atmospheric equilibrated groundwater (with extremely low helium concentration).

N_2 transport is also modelled with a basement flux and atmospheric-equilibrated groundwater at the surface. However, the upper limit of nitrogen concentration in the groundwater at depth is also controlled by its solubility, which is a function of temperature, pressure and salinity. Excess N_2 at depth dissolves to form a gas phase, partitions helium and forms a nitrogen-dominated-helium-rich system [7, figure 2]

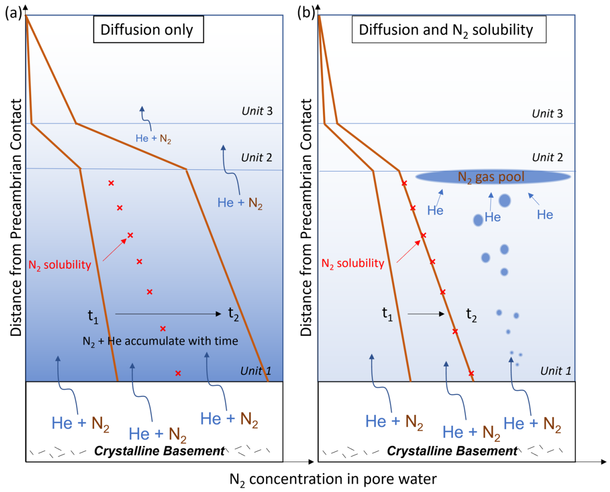

Figure 2. An illustration of conceptual model of diffusion-dissolution of N_2 and He [7]. (a) considering diffusion only and (b) showing gas phase formation caused when the nitrogen solubility limit is reached. N_2 concentrations are not to scale. The schematic concentration of helium at t_2 is illustrated with the background colour; the darker the colour the higher the concentration.

Results, Observations, Conclusions

Primary helium-rich gas fields, dominated by nitrogen gas, discovered at the Williston Basin in the sedimentary units in contact with the crystalline basement can be explained by a steady-state crustal degassing and appropriate basin architecture. The diffusion-and-exsolution model with typical He and N_2 continental basement flux predicts gas phase helium concentrations and gas composition matching those observed. The gas phase also redistributes the dissolved chemical budget in the subsurface by buffering any concentration gradient that controls upward diffusion into shallower units (figure 3). Gas phase formation time in the Williston Basin is estimated to be as early as ca 140Ma and sensitivity tests suggest that hydrogeological events earlier than 200Ma has little impact on the formation of the nitrogen gas phase. This work identifies a new helium reservoir forming mechanism that helps quantitatively assess the helium resource potential in a geological setting that has previously been overseen. It also indicates the important role of the sub-surface gas phase in controlling the transport and distribution of chemicals.

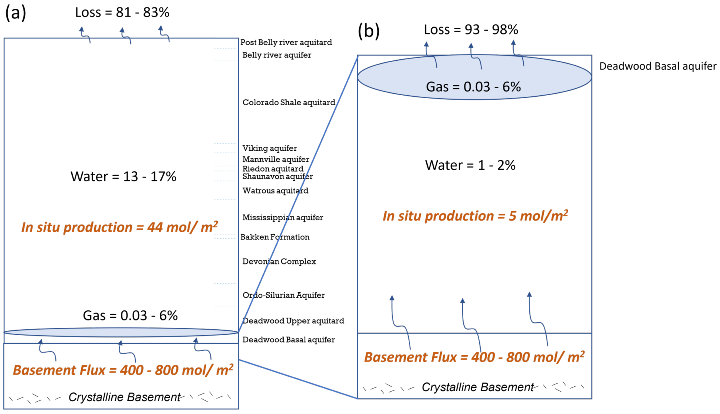

Figure 3. Mass balance of helium distribution in the sedimentary column assuming a constant basement flux between 0.8×10^{-6} to 1.6×10^{-6} mol ^{4}He/m^2 yr [7] and N_2/^{4}He flux ratio of 50 over 500Ma basin history [7].

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