



GEOLOGICAL SEQUESTRATION AND MICROBIOLOGICAL RECYCLING OF CO₂ IN AQUIFERS

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ABSTRACT

The world aquifers are estimated to have total storage capacity larger than three trillion tons of carbon dioxide. Systematic drilling survey for oil exploration suggests that the annual 70 million tons carbon dioxide injection is possible longer than 22 years in aquifers with anticlinal geological structures in and around Japan. The annual 70 million tons carbon dioxide injection separated from flue gas of fossil-fueled power plants into aquifers may reduce Japan's artificial carbon dioxide emission as much as 6% with annual cost of 420 billion yens that match 1,200 yens/c-ton carbon tax.

Extraction of methane dissolved in fossil groundwater squeezed out by the carbon dioxide injection makes possible to utilize low grade of natural gas resources. Hydrate-filled layers are formed under deep sea floor due to high pressure and cool temperature. Free natural gas tends to accumulate under gas-hydrate-filled layers and under permafrost layers, because the layers are perfect insulators of gas. Carbon dioxide injection is expected to stabilize gas-hydrate-filled layers and permafrost caps, because the carbon dioxide hydrate is stable at wider pressure-temperature range than methane hydrate and ice.

Carbon dioxide injection under gas-hydrate-filled layers or under permafrost layers may realize the greenhouse gas mitigation and recovery of unused natural gas. Autogenous sealing of carbon dioxide in deep and cool aquifers assures virtually complete and practically unlimited subsurface containment of carbon dioxide.

Chemoautotrophs fix carbon dioxide in deep aquifers even in the absence of sunlight. Thermophilic methanogens can convert the carbon dioxide into methane in anoxic and hot aquifers. Biogenic restoration of subsurface hydrocarbon deposits may be possible in CO₂-injected aquifers probably after tens or hundreds of years. Microbiological recycling of carbon dioxide in aquifers is an attractive possibility for energy-short countries such as Japan. Important key for underground CO₂ recycling is hydrogen supply, that is, energy sources from microbial decomposition of organic matter, from geochemical water-rock interaction and from deep geothermal activities. Wide diversity of underground microorganisms needs extensive search for favorable species and ecosystem.

EFFECTIVENESS OF GEOLOGICAL SEQUESTRATION OF CO₂ AS A MITIGATION OPTION

Japan emitted about 1.2 billion tons of CO₂ artificially in 1995, that is, already 8% larger than 1990 level. In the Third Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP-3) in Kyoto, 1997, Japan agreed to reduce greenhouse gas emission by 6% by the period 2008 to 2012 compared with 1990 level. It is very difficult for Japan to reduce the future greenhouse gas emission lower than 1990 level in spite of the best efforts for conservation of energy, development of new energy sources and the maximum boost in nuclear power generation. Then, only possible and quickly effective greenhouse gas mitigation option would be capture and storage of CO₂ from flue gas of fossil fueled power plants and factories to reduce greenhouse gas emission significantly below 1990 level.

Japan would be able to meet the COP3 target, if Japan takes immediately powerful action in geological sequestration of CO₂. It is assumed that 70 million tons of CO₂ would be captured in the early 21st century by chemical (amine) absorption method (90% efficiency) from flue gas of several new and powerful coal-fired power plants that would otherwise emit total 78 million tons of CO₂ in the air. As ocean sequestration of large amounts of CO₂ will be probably still unfavorable for protection of ocean environment, only feasible option that will be able to reduce CO₂ emission significantly, then, will be underground storage of CO₂ in unused aquifers.

Systematic fundamental drilling survey of geological structures for oil and gas exploration in and around Japan by Ministry of International Trade and Industry (MITI) - Japan National Oil Corporation found empty anticlinal structures that can store 1.5 billion tons of CO₂ (Tanaka et al., 1992), that is, enough capacity to accommodate 70 million tons of CO₂ annually longer than 22 years. Oil and natural gas reservoirs, too, can contain 2 billion tons of CO₂ (Tanaka et al., 1992). However, oil and natural gas reservoirs are available only when they become sufficiently depleted.

As energy, spent for capture, transport and underground injection, also causes emission of about 2 million tons of CO₂, net contribution of underground injection of CO₂ for reduction of CO₂ emission in the air is 68 million tons of CO₂

that is equivalent to 6% of artificial CO₂ emission of 1990 level in Japan. On the basis of preliminary cost estimation of Akai et al. (1993), geological sequestration would cost 424 billion yens for capture, transportation and underground injection of CO₂ to reduce 6% of artificial CO₂ emission of 1990 level. If this cost for geological sequestration of CO₂ is directly surcharged on the electric power generation cost of the CO₂-source fossil-fueled power plants, electricity charge would soar high. However, all users of fossil fuel energy should bear evenly expenses for geological sequestration of CO₂, because it contributes to reduce Japan's total artificial emission of greenhouse gas to meet COP3 target. If the expenses for geological sequestration of CO₂ were paid by carbon tax, carbon tax would be enough at a reasonable rate of 1,200 yen per 1 tons of carbon, that is, 0.13 yen per 1 kWh of electricity or 0.8 yen per 1 liter of gasoline.

Fossil fuels have been main energy source for human activities since the Industrial Revolution and would be the most important energy source in the world in the foreseeable future. Especially, coal has great potential as world's energy source but also is blamed as the worst CO₂ emitter. Koide et al. (1992) estimated that the storage capacity of saline aquifers is 320 billion tons-CO₂ in the world. However, this estimation is too much conservative as they assumed that CO₂ is dissolved at groundwater in 300m thick aquifers in only 1% area of world aquifers. It seems better to revise the storage capacity of world aquifers to 3 trillion tons-CO₂ at least. Zero emission fossil-fueled power plants with geological sequestration of CO₂ are feasible option for reduction of greenhouse gas emission. Positive sides of geological sequestration of CO₂ are discussed in the following sections.

AUTOGENOUS SEALING OF CO₂ IN AQUIFERS

Natural gas-hydrate-filled layers are often found under deep sea floor due to high pressure and cool temperature. Natural gas tends to accumulate under the gas-hydrate-filled layers and under permafrost layers, because the layers are virtually perfect insulators of gas. It is feared that global warming may be accelerated by emission of trapped methane due to dissolution of permafrost layers and hydrate layers by global warming. Injection of CO₂ under permafrost (Fig.1) and methane hydrate caps (Fig.2) with counter extraction of trapped methane prevent acceleration of global warming, because injection of CO₂ strengthen permafrost and methane hydrate caps with CO₂ hydrate that is stable at higher temperature than ice at high pressure and than methane hydrate (Koide et al., 1997a). CO₂ injection under methane hydrate layers and under permafrost layers may realize the greenhouse gas mitigation and recovery of unused natural gas at the same time.

CO₂ injection into deep aquifers may form CO₂ hydrate-filled layers under about 300m water column under deep and cool sea floor (Fig.2, Koide et al., 1997b). Autogenous sealing of CO₂ in deep and cool aquifers assures virtually complete and practically unlimited subsurface containment of CO₂. Autogenous sealing is very safe, because every crack shall be automatically filled even if earthquakes form gaps in cap rocks (Koide, 1997).

Intrusion grouting of calcium hydroxide solution is expected to induce similar sealing effects, because precipitation of calcium fills gaps in rocks when calcium hydroxide meets CO₂. Sealing of drill holes by calcium hydroxide is important to prevent leakage of CO₂.

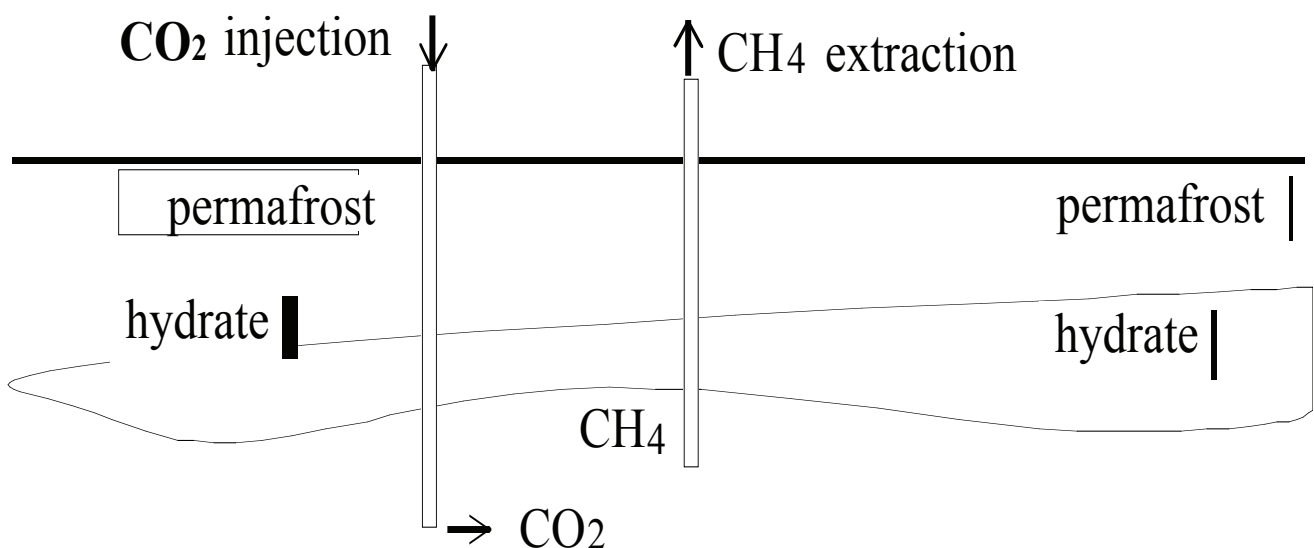


Fig.1 Injection of CO₂ under permafrost layer and extraction of methane.

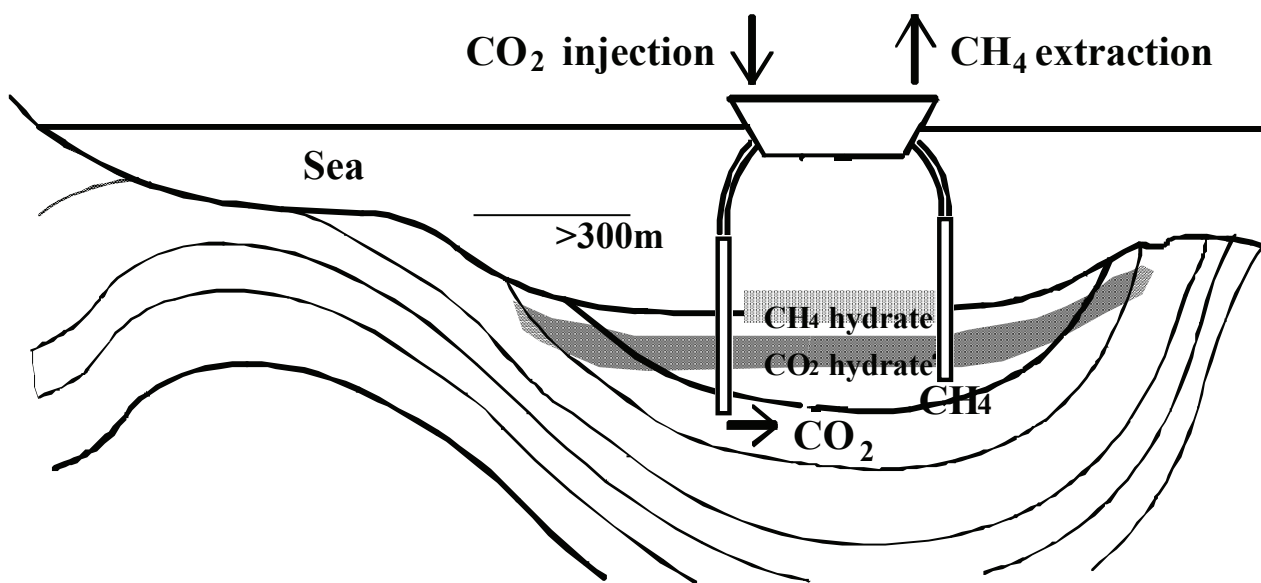
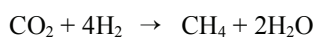


Fig.2 Injection of CO₂ under methane hydrate layer and extraction of methane.

UNDERGROUND MICROBIAL CO₂ FIXATION AND RESTORATION OF HYDROCARBON DEPOSITS

Saline fossil groundwater in sedimentary basins is often saturated with methane. Fossil groundwater is pumped up and natural gas dissolved in groundwater is separated and commercially used in a few sedimentary basins such as Kanto basin in Japan, although methane-dissolved groundwater is found in most of sedimentary basins. Dissolved natural gas deposits are not usually economically rich. Exploitation of natural gas deposits in Tokyo area has been prohibited generally, because pumping up of groundwater often caused subsidence. Underground injection of CO₂ can prevent subsidence owing to upholding of groundwater pressure in aquifers. Underground injection of CO₂ and counter extraction of groundwater realize recovery of methane dissolved in pumped up fossil groundwater to utilize low grade of natural gas resources while preventing subsidence (Koide et al., 1992).

Nakai(1960) made carbon isotope measurements on several dissolved natural gas deposits in Japan and found that carbon in CH₄ has isotopic values ranging from -65.5 to -74.8 per mil deviated from P.D.B. standard, while carbon in CO₂ has isotopic values from +2.0 to -12.2 per mil. He concluded that an isotopic equilibrium between CH₄ and coexisting methane indicates that bacterial processes formed these aquifers saturated with methane. Extremely light isotopic compositions of carbon in CH₄ suggest that methanogens formed some of dissolved methane deposits in Japan. Anaerobic chemoautotrophic methanogens belong to Archaea that are similar to early microorganisms that evolved in anoxic harsh environments on the primitive Earth. Methanogens have wide diversity. Many of them can survive in extreme environments such as high temperature, high pressure and high salinity. Most of methanogens form CH₄ from CO₂ and H₂ and gain energy.



Thus, bacterial methanogenesis is made without help of sun light. Methanogens are blamed for greenhouse gas emission as they produce methane in bowels of cows and termites and in rice paddy, as they are abundant in such anoxic habitats. Anaerobic microorganisms are abundant and active even in deep aquifers. Accumulations of methane-rich natural gas of bacterial origin have been found in many sedimentary basins in the world (Rice and Claypool, 1981). Stevens and McKinley (1995) found that methanogens are active in aquifers deeper than 1000m in the Columbia River Basalt Group, U.S.A. Bacterially formed methane are formed even in the depth of 4,500m in the Po basin, Italy (Mattavelli et al., 1983).

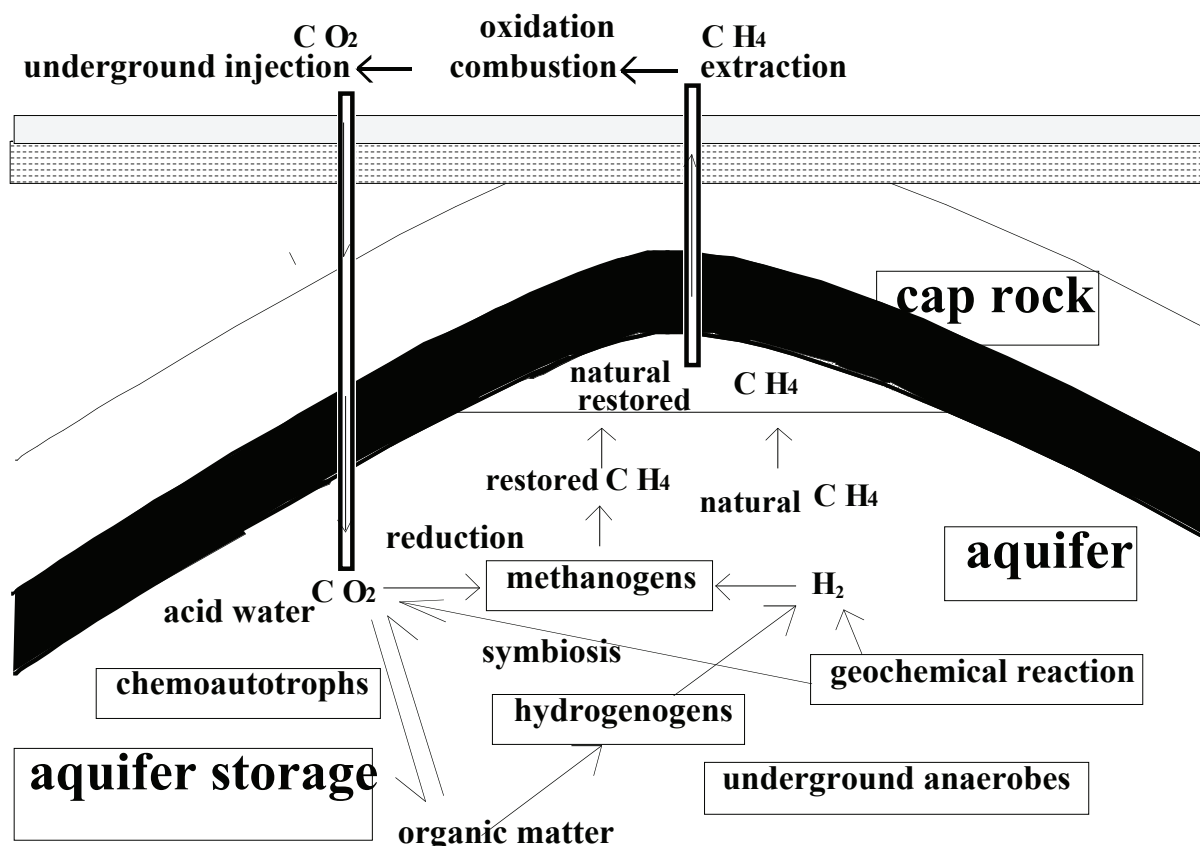


Fig.3 Geological sequestration of CO₂ and microbial restoration of methane deposit.

If CO₂ is injected into aquifers and dissolved in groundwater in which methanogens are active, methanogens reduce CO₂ into CH₄ as long as H₂ is available. Methane is less soluble in water and lighter than CO₂. Therefore, methane tends to be separated from water and migrate upward. If there exist no traps, methane is emitted finally into the air to accelerate global warming. Methane is much more efficient greenhouse gas than CO₂. However, if the aquifer has geological trapping structure, methane tends to accumulate at the top of reservoir under cap rock and may revive natural gas deposits (Fig.3). Chemotrophic methanogenesis is usually much slower than photosynthesis. However, appreciable amounts of biogenic methane probably form during tens or hundreds of years of CO₂ storage in aquifers at adequate conditions.

Deep aquifers are usually at high temperature, at high pressure and often at high salinity. Some kinds of methanogens, belonging to Archaea, are active at extreme conditions such as high pressure, high temperature and high salinity. As metabolism is faster at higher temperature, warm aquifers are favorable for fast methane production unless temperature is too high. Thermophilic methanogens such as *Methanobacterium thermoautotrophicum* and *Methanococcus jannaschii* are possibly suitable for fast brew of methane. Extensive search for favorable species is needed as methanogens have wide diversity.

Hydrogen H₂ supply into CO₂-dissolved groundwater is key to biogenic restoring of methane deposits, because hydrogen is energy source for methanogenesis. Stevens and McKinley (1995) pointed out that basalt - water reaction supplies hydrogen to induce active methanogenesis in deep basalt aquifers. Hydrogen is supplied by deep water-rock interaction in active geothermal regions. Anaerobic hydrogenogens produce H₂ from organic matter. Symbiosis of methanogens and hydrogenogens is favorable for active production of methane, as hydrogenogens are active when methanogens consume H₂ for methanogenesis. Adequate set of methanogens and hydrogenogens should be searched to form suitable ecosystem for methanogenesis in aquifers. As many sandy aquifers are not rich in organic matter, organic materials should be enhanced for active fermentation by alternate injection of CO₂ and organic fluid waste or solution of organic matter that is otherwise to emit CO₂ and/or CH₄ finally into the air. Elimination or reduction of sulfate is important as sulfate reducers prevent methanogenesis (Lovley and Chapelle, 1995). The coordinated ecosystem may efficiently rejuvenate methane deposits during CO₂ aquifer storage.

Chemoautotrophs fix CO₂ into organic matter without help of sun light. A mixotrophic bacterium, a kind of *Pseudomonas* which was separated from an oil spill at Sagara oil field, Japan, converts CO₂ into medium-chain alkane and alkene anaerobically in the presence of H₂ (Morikawa and Imanaka, 1993, Morikawa et al., 1998). This finding suggest possibility of bacterial oil production in addition to chemoautotrophic fixation of CO₂ during aquifer storage of CO₂.

CONCLUSION

Geological sequestration of CO₂ is a technically and economically feasible option for mitigation of greenhouse gas emission. Autogenous sealing by hydrate formation and microbial fixation of CO₂ assure long-term containment and safety of CO₂ aquifer storage. During many years of aquifer storage of CO₂, injected CO₂ may be fixed into organic matter by chemoautotrophs and furthermore converted into methane by methanogens. Biogenetic restoration of subsurface hydrocarbon deposits is possible in CO₂-injected aquifers probably after tens or hundreds of years. Important key for underground CO₂ recycling is hydrogen supply, that is energy source, from microbial decomposition of organic matter, from geochemical water-rock interaction and from deep geothermal activities. Due to wide diversity of underground microorganisms and environments, extensive and careful search for favorable species and ecosystem is needed for microbiological fixation and recycling of CO₂.

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地中メタン生成古細菌による

カーボン・リサイクルの提案

Carbon recycling by subsurface microbial methanogenesis

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ABSTRACT:

There is an enormous amount of methane in subsurface formations in the world. Most of the natural gas resources, however, is hardly economically recoverable as the methane is adsorbed in coal seams, trapped in hydrate clathrate or dissolved in saline groundwater. Shallow accumulation of methane is even a hidden threat of explosive global warming. Enhanced gas recovery by subsurface CO₂ injection (CO₂-EGR) is a practicable solution for the greenhouse gas control with efficient use of potential energy resources.

Extremely light isotopic compositions of carbon in methane suggest that methanogens formed many subsurface accumulations of methane-rich natural

gas in the world. Chemolithotrophic methanogens, that belong to Archaea, form methane from CO_2 and gain energy without sunlight in anoxic circumstances. Methanogens are often blamed for greenhouse gas emission as they produce methane in bowels of cows and termites and in rice paddy. However, reapplication of CO_2 -EGR for subsurface biogenic methane that is converted from disposed CO_2 makes the carbon recycling possible.

Subsurface ecosystem is somewhat similar to archaic ecosystem that is adapted to anoxic CO_2 -rich atmosphere under high pressure and temperature. Bionic methanogenesis is active even in deep basaltic aquifers. Subsurface biogeochemical carbon recycling may realize greenhouse gas control with restoration of energy resources.

1. はじめに

将来、20世紀は「石油バブルの世紀」として記憶されることになるであろう。20世紀初頭に石油を燃料として実現した航空機や自動車の発達による交通革命が世界を小さくし、さらに石油化学の発達など産業技術の爆発的発展を石油が支えた。しかし、その一方で便利な石油資源の浪費と環境問題という負の遺産を残したことの方が後世の人類への影響が大きい。20世紀に続く21世紀は、石油資源の枯渇と地球環境問題により「バブル崩壊の世紀」になる恐れがある。破局を避けるために、省エネルギーや代替エネルギー開発など数多くの努力が進められている。しかし、石油は日本のエネルギー消費の55%、世界の39%を占めている中心のエネルギー源(1996年)¹⁾であるだけに、抜本的な改善は難しい。

様々な廃棄物問題が深刻になっていることから、リサイクルによってゴミの量を減らす努力がいろいろな分野でなされている。化石燃料の燃焼によって排出される CO_2 もリサイクルすることが出来れば、温室効果ガス排出削減の決め手になると期待される。しかし、炭化水素からなる化石燃料をカーボン・リサイクルすれば、化石燃料の内蔵するエネルギーのうち炭素の担っている分のエネルギーは理論的には利用出来ないことになる。ほとんど炭素からなる石炭の場合は、リサイクルすればエネルギー源としては利用していないことになる。したがって、カーボン・リサイクルを実現す

るには、化石燃料以外のエネルギー源を利用する必要がある。例えば、太陽電池や水力発電により得た電気で水を電解して水素を製造し、水素によって CO_2 もを化学的に還元して、メタンやメタノールを再生産する²⁾。あるいは、微細藻類等による光合成で有機物や水素を生産する生物的固定・有効利用する方法が研究されている³⁾。これらのカーボン・リサイクルの多くは、根本的には太陽エネルギーを利用しているため、広い面積の地表あるいは水面を必要とし、他の土地利用や水面利用と競合しやすい。

そこで太陽光を必要としない、地中嫌気性化学合成独立栄養微生物生態系を活用した、地表面や水面を用いない新しい生物的カーボン・リサイクルの方法を提案する。

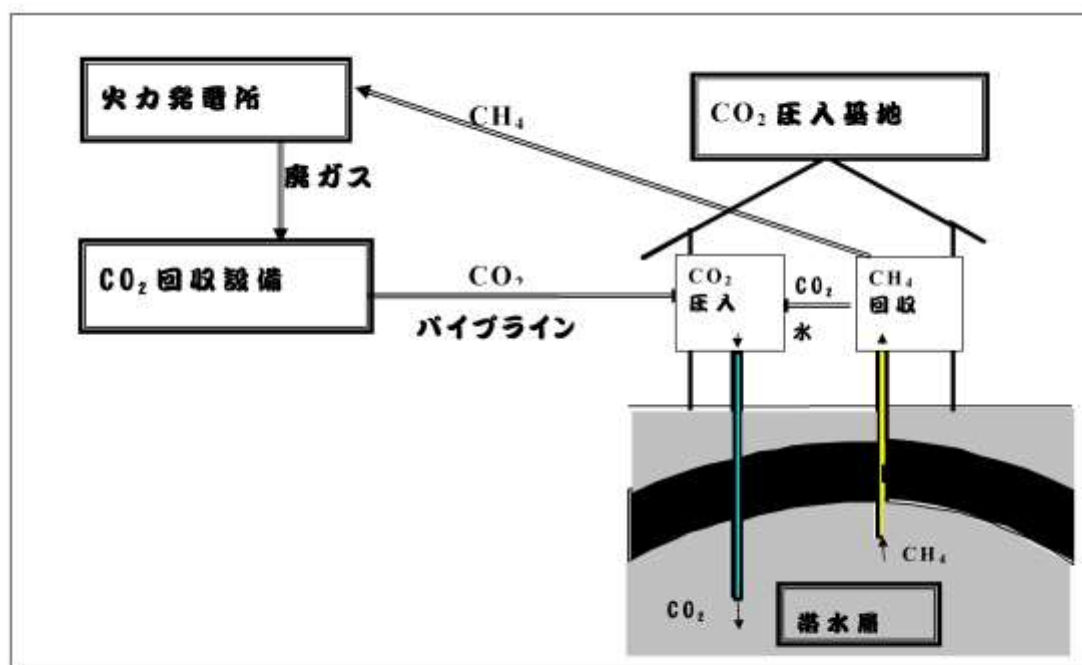


図7.火力発電所などの廃ガスから CO_2 を回収し、地下の帯水層（微細な空隙が多く、多量の地下水を含む岩層）中に圧入し、代わりに地下のメタン資源を回収する。

2. CO_2 地中圧入と未利用天然ガス回収

1996年からノルウェーで CO_2 地中貯留の実操業が開始された⁴⁾。また、米国などの産油国では原油増進回収のために CO_2 を地中に大規模に圧入している。 CO_2 地中貯留は既に実用技術になっていると言える。しかし、新しい技術であるだけに、地中における CO_2 の挙動がよく判っていないなど、重要な研究開発課題が多く残されている。安全性を高め、効率を高め、コストを低下させ、さらに貯留だけではない CO_2 地中圧入による積極的な利益を高めようとする研究が開始されている。

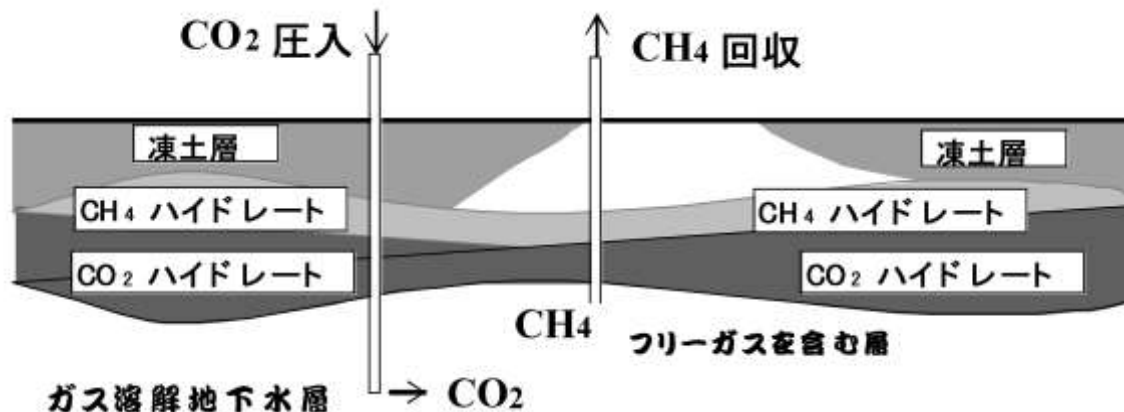


図 2. 凍土層・メタンハイドレート層下への CO₂ 圧入によるメタン回収とハイドレート層安定化

Koide ら⁵⁾は、CO₂ を地中圧入して、地盤沈下を防止しつつ水溶性天然ガスを回収する方法を提案した（図 1）。また、凍土層・メタンハイドレート層の下の帯水層に CO₂ を圧入して、凍土層・メタンハイドレート層の直下の岩層中に溜まっているフリーガスを回収する。凍土層・メタンハイドレート層の下には圧入した CO₂ が溜まるため、メタンハイドレート中のメタンを一部置換しつつ、メタンハイドレートの下に CO₂ ハイドレート層を形成する。CO₂ ハイドレートは、地下 300m 程度より深部では氷やメタンハイドレートより高温でも安定なため、地球温暖化によっても解けないので、封じ込められたメタンや CO₂ を大気中に放出しない（図 2）。このため凍土層・メタンハイドレート層の CO₂ ハイドレート化補強によって、懸念されている地球温暖化の爆発的進行を防ぐことができる。

米国のニューメキシコ州 San Juan Basin で世界最初の CO₂ 地中圧入によるコールマインガス増進回収法(CO₂-ECGR、図 3)のパイロットテストが実施され、3 年間で 75-100%生産を増加させることに成功した⁷⁾。1996 年以来 12 万トンの CO₂ を圧入したが、炭層に吸着されて CO₂ 漏出はほとんどなかった。San Juan Basin では、3700 億立方メートルのメタンを CO₂-ECGR により新たに回収でき、千立方フィートあたり 0.5 ドルの CO₂ 供給代を払っても利益が上がるとしている。

日本の炭層は、構造が複雑であるが、コールマインガス（メタン）の量は比較的に多いことが知られている。経済的に採掘の対象にならない深部の炭層や採掘跡の旧鉱でも、コールマインガスを採取できる可能性は大きい。コールマインガス増進回収技術（CO₂-ECGR）は、地球温暖化防止と未利用の非在来型天然ガス資源の開発が出来

る一石二鳥の技術である。

3. 地中メタン生成細菌によるメタン再生

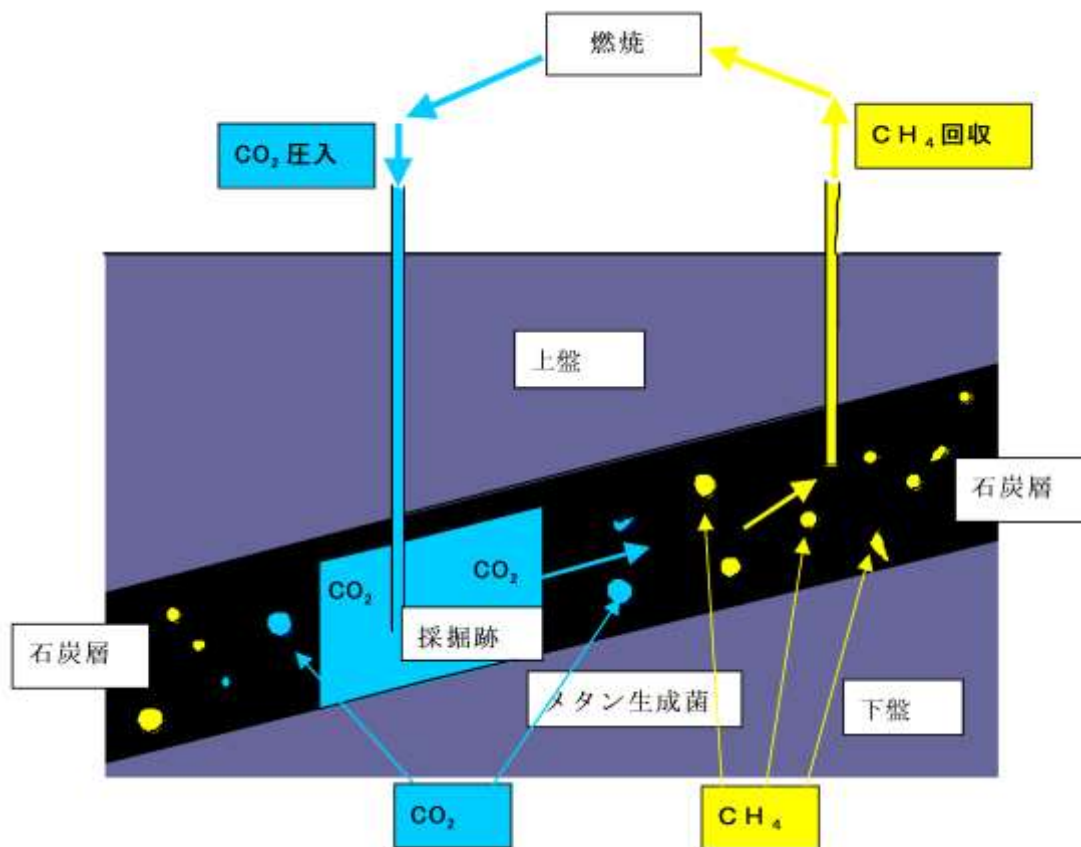


図3. CO₂ 圧入によるコールマインガス増産回収

水溶性天然ガス、コールマインガス、メタンハイドレート等の膨大な量のメタン資源が世界的に存在する。これらの地下の比較的浅所に存在するメタンを主成分とする天然ガスの多くが、メタン生成細菌によって生成されたことが、炭素同位体比の研究などから明らかにされている⁸⁾。最近、1000m以上の地下深部の玄武岩層からメタン生成細菌の活動が報告されている⁹⁾。メタン生成細菌は古細菌の一種で、酸素があると活動できない偏性嫌気性微生物で、CO₂と水素からメタンを合成することにより

表 1. CO₂ 固定をする生物

(1) 光をエネルギー源とし、CO₂を炭素源として利用する生物

: 光合成独立栄養生物(Photosynthetic autotroph)

好気性真核生物

- ・植物(plants)
- ・(藍藻類・原核緑藻類以外の)藻類(algae): 緑藻類、紅藻類等

好気性真正細菌

- ・シアノバクテリア(藍藻類)

嫌気性真正細菌

- ・緑色硫黄細菌、・紅色硫黄細菌

(2) 無機化合物の酸化をエネルギー源とし、CO₂を炭素源として利用する生物: 化学合成独立

栄養生物(Chemoautotroph)

好気性真正細菌

- ・一酸化炭素酸化菌、・硫黄酸化細菌、・硝化細菌・水素酸化細菌
- ・鉄細菌、・アンモニア酸化菌、・マンガン酸化菌

好気性古細菌

- ・高度好塩古細菌、・好熱好酸硫黄酸化古細菌

嫌気性真正細菌

(枠内は地下で CO₂ 固定可能)

- ・酢酸生成菌

嫌気性古細菌

- ・(硫黄依存) 超好熱性古細菌

(3) CO₂呼吸をエネルギー源及び炭素源とする生物



- ・メタン生成古細菌 methanogen
- ・硫酸還元好熱性古細菌 *Archaeoglobus*

エネルギーを得る。太陽光なしで、 CO_2 を有機物に固定化する化学合成独立栄養微生物である。深部の玄武岩層中では、熱水と玄武岩の反応で生成された水素とやはり地下深部に由来する CO_2 という無機起源の材料から、メタン生成細菌はメタンを合成してエネルギーを得て、生きていていると考えられる。すなわち、地熱をエネルギー源として CO_2 からメタンを生成する（表 1）。

玄武岩層は海洋底下に広範に広がっているので、メタン生成細菌の活動の場は膨大に存在する。生命が誕生して間もない頃の、高温高压で CO_2 に富み酸素に乏しい原始地球大気下にメタン生成古細菌は適応していたと考えられる。地下深部の塩水帯水層に CO_2 を圧入すると、原始地球の海洋に近い条件が成立し、メタン生成細菌が活動しやすい環境になり、 CO_2 からメタンが再生され、カーボン・リサイクルが実現する可能性がある。

堆積岩中には、砂や泥と共に多量の有機物が一緒に堆積している。したがって、堆積岩の帯水層中では有機物の嫌気性微生物による発酵によっても水素と CO_2 が供給される。水田土壤中でメタン生成細菌が活動して、大気中にメタンを放出することが、地球温暖化の要因の一つとされている。半地下式のメタン発酵槽は、メタン生成細菌と有機物を分解する嫌気性微生物の共生により有機廃棄物から効率的にメタンを発生、利用できる仕組みとして用いられている。堆積盆地の地下深部では、天然に有機物のメタン発酵が起こり、水溶性天然ガスや炭層ガスやメタンハイドレートのメタンを生成したと考えられる。

メタン生成細菌によって形成された天然ガスを回収した後の帯水層に CO_2 を貯留しておく、残存するメタン生成細菌の活動により、 CO_2 がメタンに変換される。トラップ構造を伴う帯水層であれば、再生されたメタンは帯水層中に集積され、大気中に逃げない。このメタンを回収すれば、カーボン・リサイクルが実現する（図 4）。

地下深部の酸素に欠乏し、太陽光の入らない環境下で CO_2 を有機物に固定する嫌気性の化学栄養独立合成微生物は多数の種類が存在する。日本の油田から、 CO_2 から石油成分になる炭化水素を合成する嫌気性細菌が採取されたことは特に注目される^{10,11)}。 CO_2 を地中に圧入して、石油を再生することも夢ではないかもしれない。最近では、メタン生成細菌と、それに水素を供給する通性嫌気性細菌の共生により真核生物が生じたとする説が有力になっている¹²⁾。地中微生物は嫌気性好熱性の古細菌および真性細菌であり、原始生命に近く、生化学的に極めて多様である^{13,14)}。未知の機

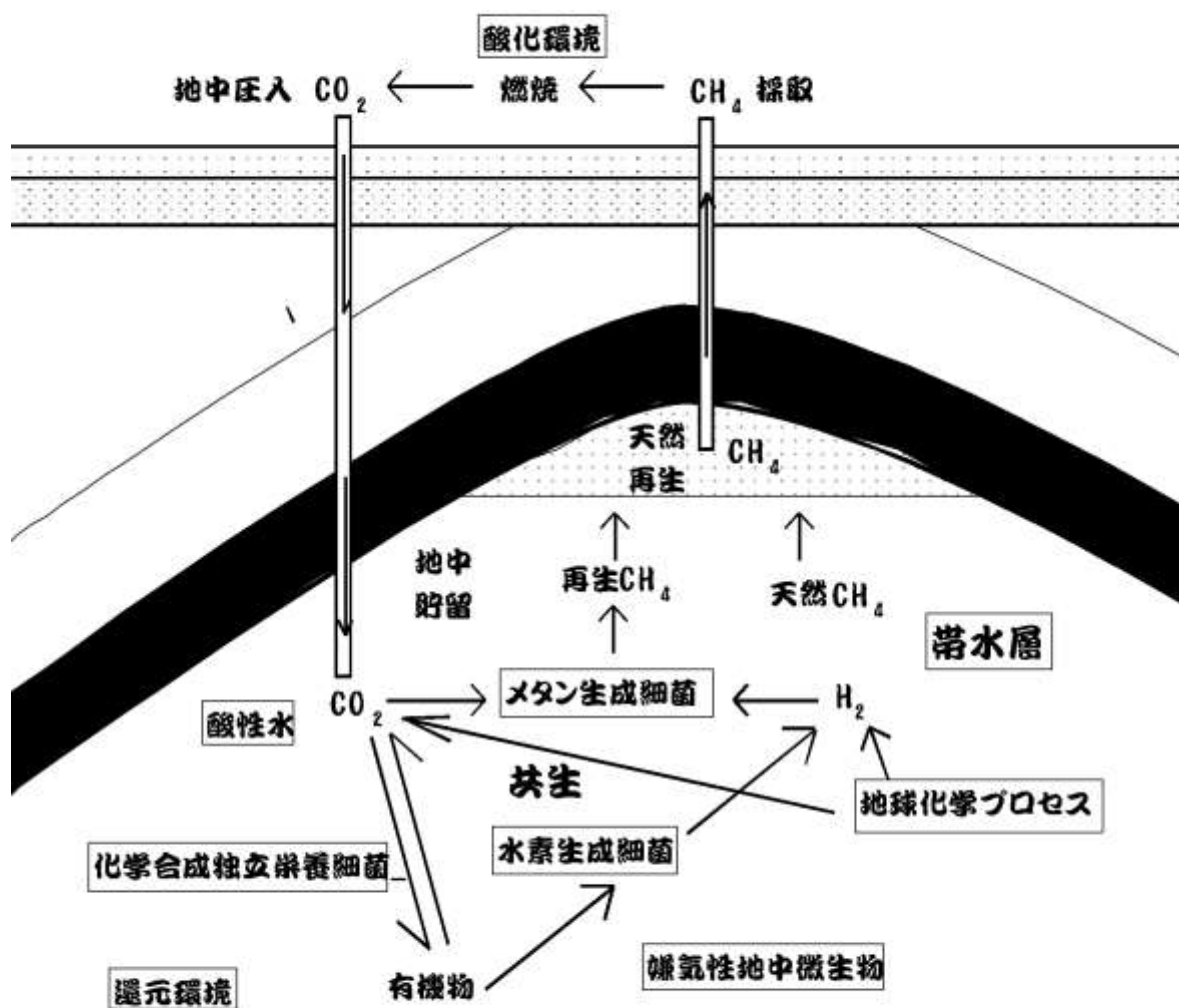


図4. 帯水層中のメタン生成細菌によるカーボン・リサイクル

能を持った微生物がなお地中に潜んでいる可能性は大きい。地下深部の石炭、低品位の炭質物、採取困難な深部の重質油、タールサンドやオイルシェールなども CO₂ と地中微生物の利用により回収可能になるかもしれない。CO₂ の固定に生命創成期の原始環境を利用できる可能性は大きく、今後の研究進展が期待される。

地中微生物により天然ガス鉱床が再生されれば、真のカーボン・リサイクルや栽培鉱業が実現し、資源問題と地球温暖化問題を一挙に解決できる可能性がある。しかし、地中の微生物探査は、多くの労力と費用を要するフロンティア探検に匹敵する事業であろう。地中微生物によるカーボン・リサイクルは、植林事業に匹敵する長期的視野による取り組みが必要と思われる。

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