

Origin and source characterization of methane in the shallow-water environment of Southern Lake Tanganyika Rift Basin, Tanzania

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Lake Tanganyika, located in the western part of Tanzania between 3°S and 9°S lat, harbours hydrocarbon and non-hydrocarbon gases in its northern and southern shallow-water environment. In this study, a geochemical analysis of stable carbon and hydrogen isotopes and an interpretation of individual gas molecular composition were done in order to determine the origin and composition of the naturally occurring hydrocarbon gases in Tanganyika Basin. Nitrogen, a non-hydrocarbon gas is a major component (76.69%–78.31%) by volume percentage followed by methane (11.68%–12.94%) and other higher hydrocarbons (0.16%–1.63%). The isotopic composition of carbon $\delta^{13}\text{C}_1$ and hydrogen $\delta\text{D}\text{C}_1$ ranges from -65.32‰ to -65.81‰ and -272.5‰ to -275.9‰ respectively. The isotopic compositions of ethane ($\delta\text{D}\text{C}_2 = -36.7\text{‰}$ to -35.2‰) and propane ($\delta\text{D}\text{C}_3 = -31.3\text{‰}$ to -27.5‰) reflect the thermogenic origin of these higher hydrocarbons. According to molecular characterization of carbon and hydrogen isotope ratios and δD -values, methane gas falls in the biogenic origin category and is formed by carbon dioxide reduction. The isotopic composition of CO_2 varies between -8.6‰ and -3.4‰ . CO_2 reduction is also regarded as a mechanism of biogenic methane formation based on carbon isotope fractionation factors (greater than 0.16).

Keywords: Biogenic origin, isotopic composition, methane, molecular characterization, shallow-water environment.

METHANE (CH_4) gas venting in Lake Tanganyika, Tanzania has drawn the attention of several researchers, debating on its origin and mechanism of occurrence. The origin, molecular characterization and maturity evaluation of hydrocarbon gases in lacustrine settings have long been propounded using hydrocarbon molecular content (methane/(ethane + propane); C_1/C_{2+} or $\text{C}_1/(\text{C}_2 + \text{C}_3)$; commonly termed the Bernard parameter) and isotope carbon composition ($\delta^{13}\text{C}_1$)^{1–5}. These gases are composed mainly of methane (C_1) with minor amounts of ethane (C_2), higher hydrocarbons (C_{3+}), nitrogen (N_2) and carbon

dioxide (CO_2). The gases can be produced through biogenic (microbially-derived) or thermogenic (petroleum-derived) processes⁶. The significant range in carbon and hydrogen molecular composition and stable isotope composition ratios of hydrocarbon gases render interpretative details regarding the gases and their concentration in lacustrine basins depending on environmental settings.

Globally, hydrothermally active regions are characterized by traces of gas anomalies in the freshwater/seawater (plumes) or in the sediments^{7–10}. Tropical lakes accumulate approximately one-quarter of the Earth's freshwater¹¹ and bear a substantial amount of hydrocarbons like methane and non-hydrocarbons like CO_2 (greenhouse gases). Most East African rift lakes are hydrothermally active and contribute an enormous amount of carbon in the lakes' water column. Till date, the contribution of these rift lakes of CH_4 gas to the atmosphere is unknown¹². The Ocean Drilling Programme in Middle Valley, Juan De Fuca Ridge, Leg 1391, East African rift lakes showed the presence of thermogenic gases in the area. The evidence for thermogenic hydrocarbons included elevated contents of higher hydrocarbons ($\delta^{13}\text{C}_1 = -30.0\text{‰}$ to -45.0‰) and based on the geologic setting, it is highly probable that the thermogenic gases were formed by hydrothermal processes. However, there is possible evidence of a bacterial gas component admixed with the thermogenic gases. The biogenic hydrocarbons in the free gas are concentrated below the thermocline where bacterial sulphate reduction has removed most or all of the dissolved sulphate³.

Schoell *et al.*¹³ discussed the origin of significantly-high methane gas concentration in Lake Kivu, north of Lake Tanganyika along the rift system, stating that methane gas (C_1) was formed by bacterial activity through acetate fermentation and CO_2 reduction. Further they mentioned that along Lake Kivu and the northern trough of Lake Tanganyika, thermal springs exist and gases vent through the water column, which is associated with both biogenic and hydrothermal origin^{13–18}. Climate variability, dry and hot conditions lead to decreased lake level by evaporation and changes in aqueous CO_2 concentration. This phenomenon coupled with increased pH and salinity led to reduced dissolved CO_2 concentration¹⁹.

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Botz and Stoffers⁷ suggested that active hydrothermalism occurs in the shallow-water environment of northern Lake Tanganyika. The major gaseous component of magmatic origin is carbon dioxide ($\delta^{13}\text{C} = -9.1\text{‰}$ to -3.8‰). Other variable light hydrocarbons were also detected. The isotopic composition of methane ($\delta^{13}\text{C}_1 = -58.0\text{‰}$ to -50.4‰ ; $\delta\text{DC}_1 = -199\text{‰}$ to -149‰) indicated both a bacterial and thermogenic source for the hydrothermal gas. The δDC_1 values, however, indicated that most of the bacterial methane is likely formed by CO_2 reduction. Rudd²⁰ also carried out significant work on methane oxidation in Lake Tanganyika.

Various researchers have developed different hypotheses to explain the origin of these gases. According to Deines²¹, Rohrbach *et al.*²² and Chung *et al.*²³, the carbon isotope ($\delta^{13}\text{C}$) composition of sedimentary organic matter in geologic age ranges between -35‰ and -20‰ . The carbon isotope composition of methane derived from the thermogenic decomposition of organic matter ranges between -50‰ and -20‰ , whereas abiogenic methane has $\delta^{13}\text{C}$ values between -110‰ to -50‰ (refs 3 and 5). The carbon isotopic compositions of methane and ethane, are used to determine the kerogen type of gas source rocks²⁴⁻²⁹.

Microbial hydrocarbons are usually generated from complex hydrocarbons, shallow-depth environments and reasonably low temperatures ($<80^\circ\text{--}100^\circ\text{C}$). Also, their stable carbon isotope composition ratios increase with increasing carbon number ($\text{C}_1\delta^{13}\text{C} < \text{C}_2\delta^{13}\text{C} < \text{C}_3\delta^{13}\text{C}$)^{30,31}. Further distinct characteristics of biogenic gases include low concentrations of higher C_{2+} hydrocarbons (low C_{2+}/C_1) and isotopically $\delta^{13}\text{C}$ light methane ($\text{C}_1 < -60\text{‰}$)^{32,33}.

In deep lakes like Tanganyika with anoxic bottom waters, methane oxidizes through a narrow zone in the upper boundary during water stratification. The methane oxidizers consume all the methane as it diffuses through the upper boundary. This phenomenon leads to low concentration in the oxic water layer and increase in the anoxic zone^{17,20}. Tanganyika rift basin also receives a large amount of terrestrial organic matter; therefore, the generation of abundant nitrogen gas from the decomposition of organic matter in the Lake Tanganyika is inevitable.

Comprehensive geochemical works have been carried out to determine the origin of methane in northern Tanganyika Basin^{7,13,34,35}. This study, therefore, focuses on gas samples collected in two different seasons in the southern Tanganyika Basin. An extensive and concise geochemical interpretation of individual gas molecular composition and isotopes will offer empirical evidence on the origin and composition of the naturally occurring hydrocarbon gases in the southern Tanganyika Basin.

Lake Tanganyika hydrology and geology

Lake Tanganyika, situated in the western region of Tanzania between 3°S and 9°S latitude at an altitude of about 773 m amsl, is a young (9–12 Ma), half-graben rift lake

within the western branch of the Eastern Africa Rift System. Among the rift system lakes, it is the deepest (~ 1.47 km) and the largest (34,000 sq. km) in terms of contained volume of freshwater in the world, after Lake Baikal in the south of Russia²⁰. The lake extends NW-SE and runs from north near Lake Kivu to the south near Lake Nyasa. The Lake borders with the Democratic Republic of Congo (DRC) on the west and Zambia on its southern shore.

The Lake is meromictic and below the depth of 150 m, the waters and sediments are permanently stratified, anoxic, containing hydrogen sulphide, ammonia and phosphates^{14,16,36}. The Lake water is chemically mildly alkaline with a pH of 9 (refs 35, 36). Below the thermocline, sulphate concentration is significant and favours the formation of a chemically appropriate environment for anaerobic oxidation of methane.

The Lake and the region around it experience a tropical climate (semi-humid). The late Pleistocene–Holocene sediment accumulation rates are estimated to be 0.4–0.5 mm/year for the deep waters (>600 m) basinal settings and could be less on structural highs¹⁶. This makes Lake Tanganyika a potential site for hydrocarbon explorations³⁷. Large amounts of organic-rich sediments have been deposited in this Lake for sufficient organic matter supply, deep water and anoxic condition. The biological precursors for organic matter are mainly diatoms³⁸. Stratified waters and organic-rich sediments in the Lake control the formation of high-potential source rocks^{15,36,39,40}.

Lake Tanganyika consists of several sub-basins with three main depositional basins, namely the northern basin also called the Rusizi sub-basin, the Kigoma sub-basin and the southern sub-basin, separated by the Ubwari and Kalemie horst blocks respectively. The basins consist of half-grabens, with border faults and an accommodation zone separating the north and south basins^{37,41}. The depositional basins are normally faulted with more than 4 km of sediments deposited in the deepest parts of the fault boundaries³⁷. The resultant tectonic setting defines discrete structural forms within the lake, such as border fault margins, littoral platforms, midlake structural highs and axial-deep basins^{42,43}.

Studies show that Lake Tanganyika continuously experiences an increase in gross and organic carbon (OC) sedimentation due to: (i) enhanced internal upwelling as a result of hydrological changes; (ii) increased terrestrial nutrient inputs caused by increased anthropogenic activities and/or (iii) modified internal food web^{36,44}.

Materials and method

The method employed in this study was developed after McAuliffe⁴⁵. The headspace equilibration method was modified to increase sensitivity and storage of samples prior to analysis. The method is designed for open-ocean surface water, freshwater lakes, rivers and groundwater samples collection.

Materials

Major reagents used were potassium hydroxide (KOH) and sodium hydroxide (NaOH) pellets. The 125 ml glass serum bottles used for the headspace equilibration were from the organic geochemistry laboratory of the China University of Petroleum. Black and blue thick butyl rubber stoppers (1 cm) that sealed the glass serum bottles were also from the University laboratory. The plastic syringes used were 3 ml, luer lock syringes. Stopcocks were all three-way, polycarbonate, Luer-fitted. Needles were 21G or 22G Precision Glide-type needles. The ultra-high purity grade helium gas, KOH and NaOH pellets were all of the analytical grade and purchased from Beijing Chemical Company in China.

Experimental procedure

Eleven gas samples were collected from shallow water (2–33 m water depth) in the southern Tanganyika Basin (Figure 1) and sampled using a rosette equipped with Niskin bottles. After retrieval, the bottles were subsampled immediately to minimize any equilibration of water contained in the Niskin bottles with air. Upon filling, the serum bottles were flushed at least two volumes of water to withdraw air bubbles, prevent contamination, and ensure that the water in the bottle was not exposed to air. Next, 0.5 ml of 8 mol l⁻¹ KOH solution was immediately added to the bottles using a 1 ml syringe inserted as far as possible in the bottle to avoid air bubbles and contamination and which contained no traces of methane. The KOH solution was prepared at least a day prior to insertion into the bottle to let it equilibrate with air. However,

it is advised to use KOH solution as opposed to adding KOH pellets directly to the sample to avoid contamination with methane. The bottles were then capped without headspace using butyl rubber stoppers probed with a needle connected to a 3 ml syringe to allow air and water to leave the bottle when the stopper was inserted. The residual water in the syringe blocked back-injection of air when the needle was withdrawn. This also allowed water to expand or contract as the temperature of the sample equilibrates to laboratory temperature.

Once all Niskin bottles were subsampled and the samples had attained room temperature, the needles and syringes were withdrawn and the stoppers secured with aluminium crimps. To prevent bottle cracking due to temperature variations, a 10 ml headspace of methane-free helium was added to the bottles using a 10 ml syringe, a 21G or 22G needle and a three-way stopcock. At the same time, 10 ml water was removed with a second syringe, needle and stopcock assembly. Once the headspace was added, the bottles were stored upside down to isolate gas from the stopper until analysis of the headspace methane. All the geochemical and stable carbon isotope composition analyses were performed using standard techniques as described by Schoell^{46,47}. The methane carbon isotopes were determined using the method of Malanotte-Rizzoli *et al.*⁴⁸, and results denoted in the common δ -notation relative to Vienna Pee Dee Belemnite (VPDB). The methane concentrations were determined on a gas chromatograph (Agilent, 6890). Standard deviation (SD) and standard error (SE) were calculated to determine the consistency of the results. The SD of sample measurements taken in December 2013 and March 2014 was 0.49 and 0.45, while SE was 0.22 and 0.19 respectively. When all datasets were combined, the SD and SE values were 0.47 and 0.14 respectively.

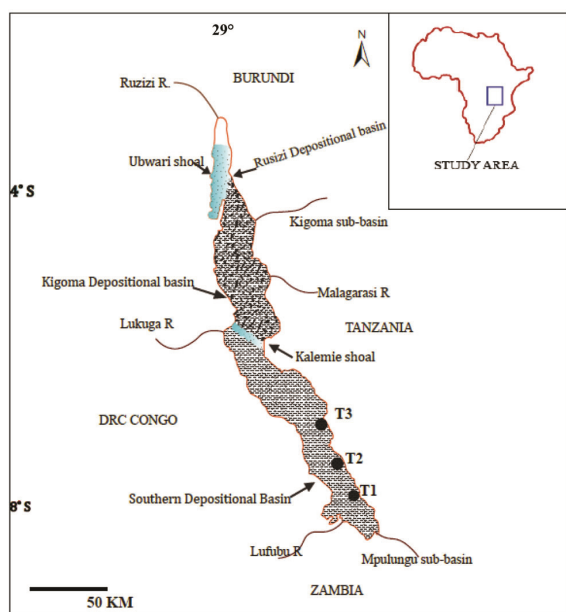


Figure 1. Schematic map of Lake Tanganyika showing the sampling sites T1, T2 and T3 in the southern depositional basin. Kigoma and Rusizi (Ruzizi) are the other depositional basins.

Results

Table 1 provides the location and approximate sampling depth for gas samples in the southern Tanganyika basin. Table 2 shows the results of the gas chromatographic analysis, which is the percentage of the various extracted gases (hydrocarbons and non-hydrocarbons) by volume assuming that the total is 100%. The stable isotope data indicate methane as the predominant hydrocarbon gas present. The percentage by volume of C₁ varies between 11.68 and 12.94, while the minimum amount of

Table 1. Locations (coordinates) and approximate water depths of gas samples in southern Tanganyika Basin

Station	Approximate depth (m)	Easting (UTM)	Northing (UTM)
T1	8	193,296	9,231,144
T2	15	238,020	9,147,091
T3	33	270,333	9,074,754

Table 2. Extracted gases percentage by volume in southern Lake Tanganyika

Sample ID	Percentage							
	Ar	O ₂	CO ₂	N ₂	C ₁	C ₂	C ₃	C ₁ /(C ₂ + C ₃)
T1-D-500-1	1.5	6.3	0.52	78.31	12.12	0.94	0.31	9.70
T1-D-500-2	1.6	6.4	0.54	77.53	12.64	1.05	0.24	9.80
T2-D-500-3	1.5	7.3	0.43	77.82	11.71	0.73	0.51	9.44
T3-D-500-2	1.6	7.1	0.52	77.85	11.68	0.84	0.41	9.34
T1-D-400-1	1.6	5.3	0.53	78.2	12.71	1.21	0.45	7.66
T1-D-400-1	1.52	6.55	0.55	77.12	12.94	0.98	0.34	9.80
T1-D-400-3	1.58	7.21	0.51	77.26	12.29	0.86	0.29	10.69
T2-C-200-1	1.53	6.95	0.49	76.69	12.9	0.79	0.65	8.96
T2-D-400-2	1.6	6.42	0.5	78.22	11.92	0.72	0.62	8.90
T3-D-500-1	1.48	7.1	0.55	77.84	11.95	0.92	0.16	11.06
T3-D-500-3	1.51	6.57	0.58	76.96	12.64	1.63	0.11	7.26

Ar, Argon; O₂, Oxygen; CO₂, Carbon dioxide; N₂, Nitrogen; C₁, Methane; C₂, Ethane; C₃, Propane.

Table 3. Isotopic composition of methane ($\delta^{13}\text{C}_1$, δDC_1), ethane ($\delta^{13}\text{C}-\text{C}_2$), propane ($\delta^{13}\text{C}-\text{C}_3$) and carbon dioxide ($\delta^{13}\text{C}-\text{CO}_2$) from southern Lake Tanganyika

Sample ID	$\delta^{13}\text{C}_1$ (‰ versus PDB)	δDC_1 (‰ versus VSMOW)	$\delta^{13}\text{C}-\text{C}_2$ (‰ versus PDB)	$\delta^{13}\text{C}-\text{C}_3$ (‰ versus PDB)	$\delta^{13}\text{C}-\text{CO}_2$ (‰ versus PDB)
T1-D-500-1	-65.40	-274.4	-35.4	-30.1	-8.3
T1-D-500-2	-65.46	-272.5	-36.6	-30.3	-6.8
T2-D-500-3	-65.75	-274.7	-35.2	-29.8	-5.7
T3-D-500-2	-65.73	-275.7	-35.7	-29.3	-3.4
T1-D-400-1	-65.77	-274.8	-35.3	-29.3	-4.7
T1-D-400-1	-65.32	-274.5	-35.2	-30.6	-8.6
T1-D-400-3	-65.57	-272.7	-36.1	-31.3	-6.1
T2-C-200-1	-65.45	-274.6	-35.8	-29.4	-4.7
T2-D-400-2	-65.48	-275.9	-36.7	-28.3	-3.8
T3-D-500-1	-65.60	-274.9	-35.9	-29.8	-4.1
T3-D-500-3	-65.81	-274.6	-36.6	-27.5	-3.7

VSMOW, Vienna Standard Mean Ocean Water – an isotopic water benchmark used for both hydrogen and oxygen isotopes; PDB, Pee Dee Belemnite – for carbon isotopes in organic matter.

higher hydrocarbons ethane to propane varies from 0.16 to 1.63. The gas ratios $C_1/(C_2 + C_3)$, i.e. methane/(ethane + propane) range from 7.26 to 11.06 (Table 2). The $C_1/(C_2 + C_3)$ ratio is an indicator of the origin of the gases and decreases with depth towards the Basin depocentres. Most researchers relate these trends to the deeper generation of thermogenic wet gases while at shallower depths, late-stage microbial gas is subject to meteoric recharge^{1,49,50}. The isotopic composition of carbon $\delta^{13}\text{C}_1$ and hydrogen δDC_1 ranges from -65.32‰ to -65.81‰ and -272.5‰ to -275.9‰ respectively (Table 3). The isotopic composition of carbon dioxide varies between -8.6‰ and -3.4‰ (Table 4), falling in the range of magmatic origin. However, thermogenic CO₂ should be less in carbon isotope as it is derived from decarboxylation reactions of organic matter^{2,13}.

Discussion

Methane, carbon and hydrogen isotope ratios

Natural gas, also called fossil gas, is found in a wide variety of environments. Methane is a major constituent

of natural gas, but the latter also contains heavier hydrocarbons (ethane, propane, butane), small amounts of nitrogen, carbon dioxide, hydrogen sulphide, rare gases and trace amounts of water. Natural gas can be generated through two processes, viz. microbial and thermogenic. The carbon $\delta^{13}\text{C}_1$ and hydrogen δDC_1 isotopes and molecular compositions are used to determine the methane gas origin and generation pathways. The most important parameters used to distinguish the gas types are their isotopic composition of stable carbon $\delta^{13}\text{C}_1$ and hydrogen δDC_1 along with the relative abundance of methane to other hydrocarbon gases^{2,3,5,33,47,51}. The different types of methane have characteristic carbon and hydrogen isotope compositions, which vary with source type and maturity in the case of thermogenic methane⁵. The carbon isotope compositions of methane derived from the primary thermogenic decomposition of organic matter ranges between -50‰ and -20‰ , whereas biogenic methane has $\delta^{13}\text{C}_1$ values between -110 and -50‰ and less than -60‰ for carbon dioxide reduction pathway^{3,5,49,52}. An intermediate methane carbon isotope composition between -50‰ and -60‰ may be interpreted as mixing origins between microbial and thermogenic gases^{49,53}. The combination of

carbon and hydrogen isotope analysis of natural gas is therefore an important approach to decipher the different origins of gases.

The hydrocarbon composition of methane can also be quantified in a number of ways, such that it is important to precisely distinguish between gas dryness and wetness. The ratio of methane to the sum of ethane and propane ($C_1/(C_2 + C_3)$) is extensively used to distinguish between microbial and thermogenic gases. The ratio of methane to the sum of ethane and propane greater than 1000 and less than 100 (wet gases analogous with oil show $C_1/(C_2 + C_3) < 50$) is an indicator of microbial and thermogenic gas respectively, when used in combination with methane carbon isotope composition^{3,49-51,54,55}. Table 3 shows the isotopic composition of methane ($\delta^{13}C_1$, δDC_1), ethane ($\delta^{13}C-C_2$), propane ($\delta^{13}C-C_3$), and carbon dioxide ($\delta^{13}C-CO_2$) from the southern Tanganyika Basin. The isotopic composition of carbon $\delta^{13}C_1$ and hydrogen δDC_1 ranges from -65.32‰ to -65.81‰ and -272.5‰ to -275.9‰ respectively. Various diagrams previously developed for the classification of natural gases, including the Schoell⁵ and Whiticar⁵¹ diagrams, have been used to determine the origin of methane. The most widely used is the Bernard diagram (modified after Bernard *et al.*⁵⁴), which compares the molecular ratio of $C_1/(C_2 + C_3)$ with $\delta^{13}C-CH_4$ to distinguish between microbial (biogenic) and thermogenic gases.

Figure 2 displays the $\delta^{13}C_1$ against δDC_1 plot comprising isotopic data for methane from southern Lake Tanganyika. According to the original diagram (refer to Whiticar⁵⁶), methane gas from Tanganyika Basin falls in the category of bacterial/biogenic origin.

Figure 3 shows the isotopic composition of biogenic methane within the isotopic fields of CO₂ reduction. Therefore, CO₂ reduction is a controlling mechanism of biogenic methane formation in Lake Tanganyika. However, according to the Bernard diagram (Figure 4), methane in southern Lake Tanganyika falls in the region of mixed origin (biogenic and thermogenic) which agrees with the relative amounts of higher hydrocarbons (C_2 and C_3) by comparing the molecular ($C_1/(C_2 + C_3)$) ratio with

the $\delta^{13}C-CH_4$ isotopic composition. Despite the presence of minimum amount of higher hydrocarbons, i.e. ethane, propane, etc. the source interpretation is confirmed by the Bernard diagram⁵⁴. The isotopic composition of ethane ($\delta DC_2 = -36.7\text{‰}$ to -35.2‰) and propane ($\delta DC_3 = -31.3\text{‰}$ to -27.5‰) reflect the thermogenic origin of these higher hydrocarbons. This makes it hard to rule out methane origin from thermogenic processes as well. The generation of N₂ and methane may have occurred by the process of thermal decomposition of humic organic matter, based on the quantity of N₂ gas, while the most important methane-producing pathways in lacustrine sediments are biogenic (methanogenesis from acetate) and CO₂ reduction⁵⁷.

The fermentation process in shallow deposited sediments contributes to the formation of biogenic methane in Lake Tanganyika and both processes (fermentation and CO₂ reduction) may be involved. Bacterial oxidation

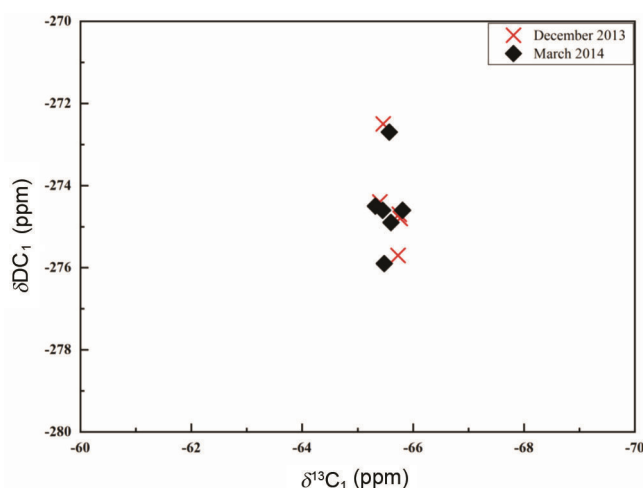


Figure 2. Plot of $\delta^{13}C_1$ versus δDC_1 showing the isotopic composition of methane in southern Lake Tanganyika.

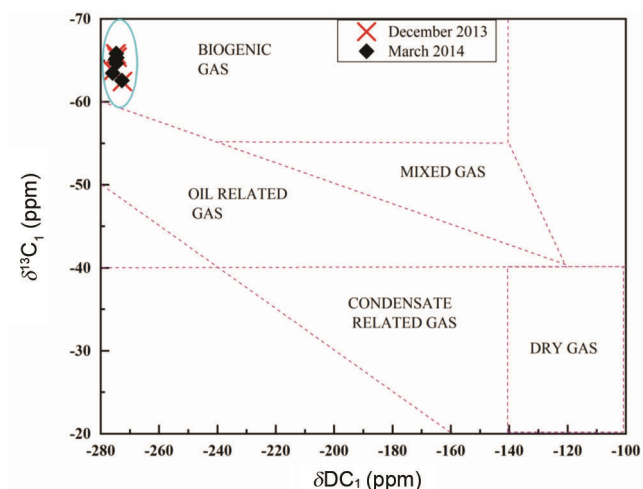


Figure 3. $\delta^{13}C_1$ against δDC_1 plot showing the isotopic composition of methane from southern Lake Tanganyika (modified from Schoell⁴⁷ and Whiticar⁵⁶).

Table 4. Isotopic composition of carbon dioxide from shallow waters in southern Lake Tanganyika

Sample ID	CO ₂ (%)	$\delta^{13}C-CO_2$ (‰ versus PDB)
T1-D-500-1	0.52	-8.3
T1-D-500-2	0.54	-6.8
T2-D-500-3	0.43	-5.7
T3-D-500-2	0.52	-3.4
T1-D-400-1	0.53	-4.7
T1-D-400-1	0.55	-8.6
T1-D-400-3	0.51	-6.1
T2-C-200-1	0.49	-4.7
T2-D-400-2	0.50	-3.8
T3-D-500-1	0.55	-4.1
T3-D-500-3	0.58	-3.7

significantly influences the production of methane rather than lighter hydrocarbons.

Carbon $\delta^{13}\text{C}_1$ isotopic characterization

Based on primary processes, the $\delta^{13}\text{C}_1$ isotopic characterization of natural gases is related to the three main stages of thermal evolution of organic matter in sedimentary rocks, i.e. metagenetic (-40‰ to -25‰), catagenetic (-55‰ to -40‰) and diagenetic (-90‰ to -55‰).

Carbon dioxide carbon isotope composition

The possible sources of CO_2 in lake waters and sediments may include microbial degradation of organic substrates, dissolved CO_2 from the atmosphere, magmatic/mantle origin, thermal decomposition of carbonates, and thermal maturation of kerogen^{49,58,59}. The best way to evaluate the origin of CO_2 is to assess the relationship between concentration and carbon isotopic composition. Gases with CO_2 content greater than 10 vol%, mostly have isotopic composition with $\delta^{13}\text{C}_1$ values between -3‰ and -10‰ , which fall in the range of CO_2 from geothermal (magmatic) systems and are predominantly of magmatic/mantle origin. Gases with CO_2 content less than 10 vol% display a wide range of $\delta^{13}\text{C}$ values. Gases with CO_2 content less than 10 vol% and isotopic composition in the inorganic range between -3‰ and -10‰ are probably thermogenic or mixtures and are affected by microbial degradation^{49,53}. In this study, the isotopic composition of carbon dioxide varies between -8.6‰ and -3.4‰ (Table 4), falling in the range of CO_2 from geothermal (magmatic) systems (Figure 5).

During methanogenesis, the covariance of $\delta^{13}\text{C}_1$ values of methane and carbon dioxide is presumed where

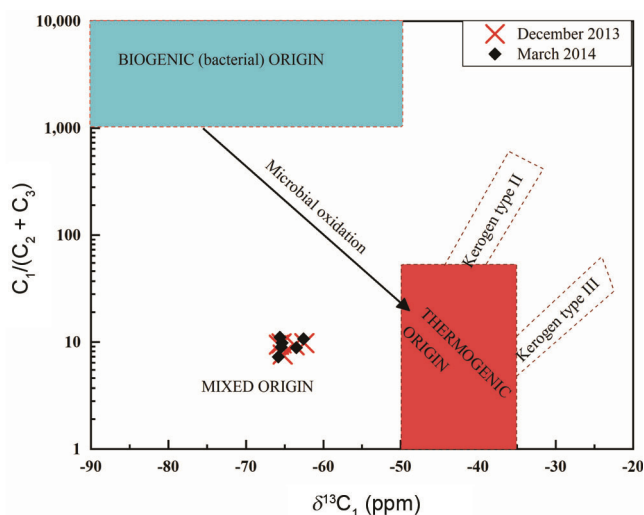


Figure 4. Schematic illustration of Bernard diagram for southern Lake Tanganyika gas samples modified from Schoell⁴⁷ and Bernard *et al.*⁵⁴.

methanogens utilize the CO_2 reduction pathway. The CO_2 and CH_4 isotopic composition values associated with carbonate reduction range from -49‰ to over -100‰ . However, the most frequently observed values fall between -60‰ and -80‰ . For acetate fermentation and methanogenesis utilizing methylated substrates, the CO_2 and CH_4 isotopic composition values are relatively low, with average values between -40‰ and -55‰ (refs 2, 49, 51 and 60). A plot of $\delta^{13}\text{C}-\text{CO}_2$ against $\delta^{13}\text{C}-\text{CH}_4$ values shows the carbon isotope fractionation lines for various methanogenic pathways, where $\alpha_{\text{CO}_2-\text{CH}_4} = (1000 + \delta^{13}\text{C}-\text{CO}_2)/(1000 + \delta^{13}\text{C}-\text{CH}_4)$ ⁴⁹. The carbon isotope fractionation values between 1.03 and 1.06, 1.06 and 1.09 are characteristic of acetate and methyl-type fermentation

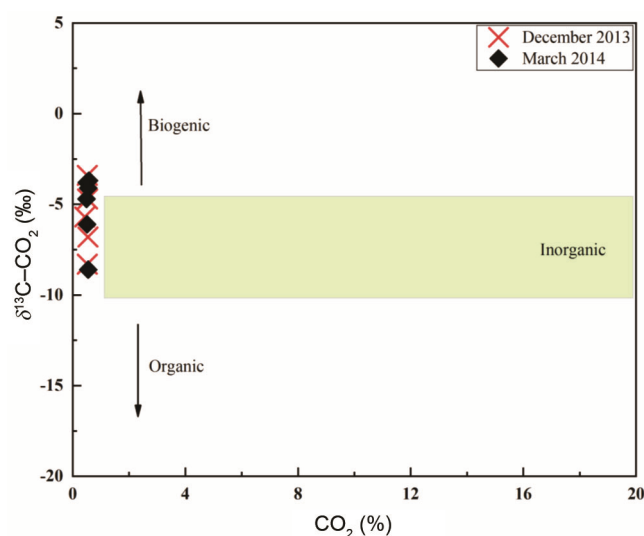


Figure 5. Carbon isotopic composition of CO_2 versus molecular percentage of southern Lake Tanganyika methane. Organic – from thermal decomposition of organic matter; biogenic – influenced by microbial activity and inorganic – from igneous input (magmatic systems).

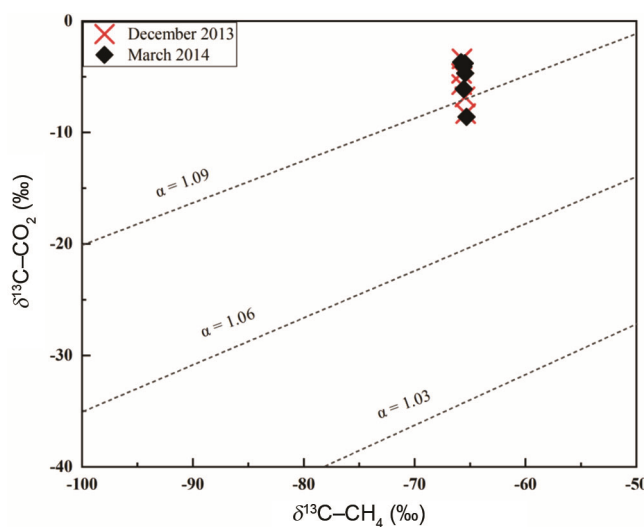


Figure 6. Plot of carbon dioxide $\delta^{13}\text{C}$ versus methane $\delta^{13}\text{C}$ values showing the carbon isotope fractionation lines for various methanogenic pathways in southern Lake Tanganyika.

and CO₂ reduction respectively^{49–51}. This demonstrates that the carbon isotope fractionation between CO₂ and CH₄ (Figure 6) may as well be used to depict and distinguish between gases of microbial and thermogenic origin (Figure 6). The isotope fractionation factors reveal that CO₂ reduction has been implicated in gas generation in Lake Tanganyika.

In this study, N₂ percentage volume is higher in all samples (Table 2) and presumed to be the major gas component (76.69%–78.31%) in the Tanganyika Basin. This significant quantity suggests fermentation of autochthonous organic matter and deposition of clastic sediments in shallow depths. Water-column stratification and upwelling are important processes that introduce ammonia (NH₃) to the upper southern end water surfaces and assumed to be assimilated by planktons. A large proportion of NH₃ introduced into the layer is lost either to the atmosphere or by oxidation to N₂ in solution³⁹. It can be concluded that thermocline and upwelling are significant processes for rapid oxidation to nitrogen in the southern Basin.

Conclusion

In addition to light hydrocarbon methane, southern Lake Tanganyika Basin contains sufficient quantities of other gases (N₂, O₂ and Ar). The isotopic composition of methane in Lake Tanganyika indicates biogenic origin with carbon $\delta^{13}\text{C}_1$ and hydrogen δDC_1 isotopic composition ranging from –65.32‰ to –65.81‰ and –272.5‰ to –275.9‰ respectively, while the gas ratios C₁/(C₂ + C₃) range from 7.26 to 11.06 of mixed origin. The isotopic compositions of ethane ($\delta\text{DC}_2 = -36.7\text{‰}$ to -35.2‰) and propane ($\delta\text{DC}_3 = -31.3\text{‰}$ to -27.5‰) reflect the thermogenic origin of these higher hydrocarbons. CO₂ reduction and fermentation are the processes for biogenic methane formation. The possible source of CO₂ in lake waters is magmatic/mantle origin and its isotopic composition varies between –8.6‰ and –3.4‰. Moreover, the isotope fractionation factor values which fall above 1.06 show that CO₂ reduction has been implicated in gas generation in the Tanganyika. There is evidence that more CH₄ is produced from enormous autochthonous (derived from aquatic plants and phytoplankton) organic matter present in the deep southern Tanganyika Basin than from allochthonous (derived from land plants) organic matter. A high organic matter supply rate and accumulation can stimulate significant sediment CH₄ formation and emission, especially for biologically reactive organic matter. Thermal decomposition of organic matter and oxidation of NH₃ to N₂ may have been the reason for N₂, CH₄ and CO₂ gases in the southern Tanganyika Basin.

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