From Culprit to Hero: The evolving story of Methane Flux in Hydroelectric Reservoirs

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Abstract

Results of recent measurements of methane in stable interior parts of Brazil, where subsurface strata have very little organic matter, are found to be compatible with the hypothesis of its deep crustal origin. Analysis of observational data indicates that seepage through submerged fault systems contribute to methane flux in hydroelectric reservoirs. The main conclusion is that hydroelectric reservoirs impede, rather than promote, natural flow of methane of mantle origin. Consequently, supposed impacts of global warming by methane flux in hydroelectric reservoirs are unfounded.

Introduction

Methane is now recognized as one of the primordial gases of widespread occurrence in many planets of the solar system. In the case of Earth, much of the observational evidences gathered to date point to methane flux along continental margins. Experimental difficulties have prevented acquisition of representative data for interior parts of continental regions and vast stretches of deep oceanic regions. However, there are indications of continuous escape of methane through fault and fracture systems, in both continental and oceanic regions. Results of satellite measurements (Figure-1) point to quantities of methane in atmospheric over continental regions that cannot entirely be considered biogenic in origin.

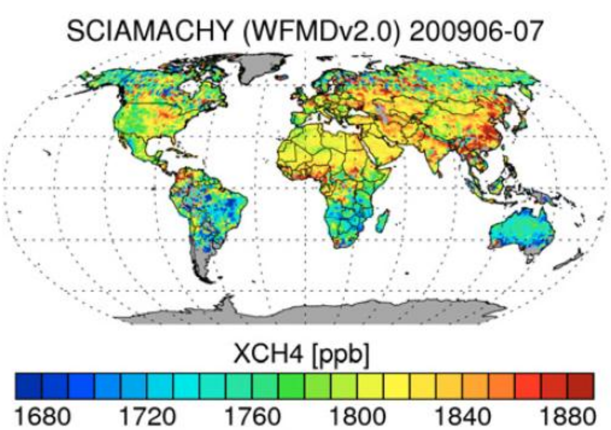

Figure (1) Satellite measurements of methane over air columns in continental margins (Buchwitz et al, 2005).

According to the abiogenic theory of hydrocarbons widespread seepage of methane from mantle beneath sedimentary basins is responsible for the formation of oil and gas deposits. Recent measurements in stable interior regions of Brazilian Highlands indicates that methane flux is not limited to sedimentary basins but also occur in Precambrian regions, generally devoid of organic matter. Clearly, fault systems act as convenient paths for escape of methane of deep crustal origin. Observational data indicate that methane flux is significant in water logged areas. In the present work we explore the implications of this observation for understanding methane flux through fault systems, submerged beneath hydroelectric reservoirs in Brazil.

Methodology employed in Field Measurements

Two different experimental setups are usually employed for measurements of methane flux. Measurements In water logged areas, in man-made reservoirs and in natural lakes are carried out using a floating chamber device (Alvalá, 2000). The instrumental setup used is illustrated in Figure (2), which is suitable for measurements of natural (diffusive) flux of methane.

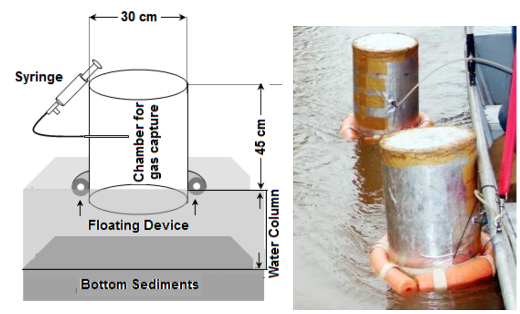

Figure (2) Setup for methane flux measurement in RF Lake in Rio de Janeiro.

Portable detectors are more convenient for localities in land areas where methane flux is focussed. For example, water wells are good sites as these intercept subsurface fracture systems and focus methane flux. Examples of field operations in wells using a portable detector are illustrated in Figure (3).

Figure (3) Measurements of methane concentrations in water wells.

Sources of Data discussed in the Present work

a) Hydroelectric Reservoirs: According to public domain information provided by ELETROBRÁS 512 hydroelectric reservoirs were in operation by the year 2000. Rosa et al (2000) reported results of methane flux measurements in nine of these reservoirs. The locations of these reservoirs are indicated in the map of Figure (4).

Figure (4) Locations of Hydroelectric reservoirs with measurements of methane flux.

Rosa et al (2000) reported data sets obtained in two stages. and refer to methane emission by diffusion and bubble release processes. Measurements were made at elapsed times varying between 1 and 37 years. A summary of their results is reproduced in Table (1).

Table (1) Results of methane flux measurements in hydroelectric reservoirs. (Extracted from Rosa et al, 2000)

Reservoir	Area (km^2)	Methane Flux ($kg/km^2/d$)	Elapsed Time (yr)
Miranda	50.6	154	1
Tres Marias	1040	196	37
Barra Bonita	312	22	36
Segredo	82	9	6
Xingó	60	38	4
Samuel	559	104	9.6
Tucuruvi	2430	112	14
Serra de Mesa	1784	51	5
Itaipu	1549	21	20

b) Natural Lakes: Methane flux measurements have been reported for water logged areas in the Amazon region (Maleck et al, 2004) and Pantanal (Alvalá and Kirchoff, 2000). Recently, Braz et al (2011) reported results of natural (diffusive) methane flux at eight different localities in Rodrigo de Freitas Lake, in Rio de Janeiro (Figure 5). A summary of data obtained is given in Table (2). As pointed out by Braz et al (2001) values of diffusive flux in this lake are comparable to those found for water logged areas. However, mechanical perturbation of bottom sediments of this lake leads to release of significant quantities of adsorbed methane and consequently much higher values of induced flux.

Figure (4) Locations of measurements in Rodrigo de Freitas Lake (Rio de Janeiro).

Table (2) Natural (diffusive) and induced methane flux in Rodrigo de Freitas lake, Rio de Janeiro.

Locality / Flow Type	Methane Flux ($mgm^{-2}d^{-1}$)		
	Mean	**σ**	**Median**
1 (Diffusive)	57,41	12,72	55,96
2 (Diffusive)	22,39	3,89	22,06
3 (Diffusive)	27,66	8,53	29,45
4 (Diffusive)	34,65	9,16	31,18
5 (Diffusive)	58,77	12,15	63,95
6 (Diffusive)	59,16	13,64	66,14
7 (Diffusive)	75,29	2,91	75,29
8 (Diffusive)	80,12	38,90	78,87
Mean Diffusive Flux	49,81	23,78	46,35
9 (Induced)	*4330*		
10 (induced)	*4362*		
Mean Induced Flux	4346		

c) Man-Holes in the urban area of Rio de Janeiro: Measurements of methane concentrations were also carried out in more than 50 man-holes in the urban area of the city of Rio de Janeiro. Values of methane concentrations of greater than 5% were observed in several localities overlying local fault zones. Unfortunately most of the results obtained were found to be contaminated by leakage of natural gas from underground pipe lines, and hence unsuitable for purposes of the present work.

d) Water Wells: Recently methane concentrations were measured in several different localities in the Paleozoic and Precambrian regions of the Brazilian Highlands. Because of obvious experimental difficulties land measurements were carried out in wells drilled for groundwater. The main advantage of this approach is that water wells, which usually intercept multiple fracture

systems in the subsurface layers of fractured continental areas, act as convenient paths for up flow of methane.
The geological characteristics of the sites selected are determined by such structural units as the Central Brazilian Shield, southern border of Guiana Shield, East Brazilian Fold Belt, Amazonas basin and Parnaiba basin. The localities of the measurements are indicated in the maps of Figure (6).

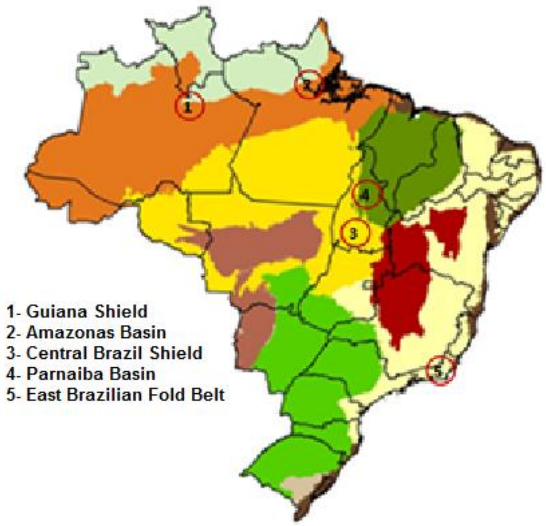

Figure (6) Locations of methane measurements in Paleozoic and Precambrian areas of Brazil.

The results of measurements in water wells are presented in Table (3). Here methane concentrations have been converted to equivalent values of methane flux based on the empirical correlation reported by Devol et al (1988). The results are considered representative of natural diffusive methane flux in respective geological units. Note that the range of values of methane flux in this case are comparable to those observed for water logged areas, reported for the Amazon region (Maleck et al, 2004) and Pantanal (Alvalá and Kirchoff, 2000). This is rather surprising since very little organic matter is present in subsurface strata of Precambrian continental regions, at localities of water wells.

Table (3) Estimated ranges of methane flux at one meter depth in water wells. The numbers in brackets of the first column refer to number of localities of water wells.

Locality	Well Depths (m)	Methane Flux ($mgm^{-2}d^{-1}$)
Guiana Shield (3)	80-100	5 - 40
Central Brazilian Shield (7)	100 - 300	5 - 40
East Brazilian Fold Belt (24)	100 - 200	10 - 50
Parnaiba Basin (4)	100 - 300	10 - 50
Amazonas Basin (3)	100 - 200	5 - 50

Source of Methane in Hydroelectric Reservoirs

Analysis of data gathered in the present work indicates that methane flux is significant in hydroelectric reservoirs but its presence is also quite widespread in continental regions. It is customary practice in environmental biological and studies (Whiting and Chanton, 1993; St. Louis et al, 2000) to assume that methane in reservoirs is of biogenic in origin, brought in by the local fluvial system with dissolved organic matter. This argument cannot however be extended to methane encountered in basement rocks of continental regions, which are usually devoid of organic matter. In this latter case methane has to be abiogenic, probably of mantle origin. The paths for up flow of methane have to be the extensive networks of fault and fracture systems in the crust, which have sufficient permeability to allow for seepage. It is reasonable to argue that methane flux also takes place through submerged faults beneath water logged areas. In the following sections we examine the spatial and temporal characteristics of the relevant observational data that can provide clues as to the origin of methane flux in hydroelectric reservoirs.

Relation between Methane Flux and Fault Length

One of the convenient methods of extracting information on the source of methane in hydroelectric reservoirs is to examine the dependence of methane flux on lengths of submerged fault systems. A positive correlation between the two is a strong argument in favor of the hypothesis that seepage through fault systems contribute to methane flux in reservoirs. The main problem in addressing this issue has been the limited availability of information on submerged fault systems. Nevertheless, an approximate estimate of the integrated fault lengths can be obtained from analysis of near linear features (derived from shape files) of reservoirs. A summary of the relevant data is given in Table (3) for the nine reservoirs considered in the work of Rosa et al (2000), along with the respective values of methane flux. Note that the estimates of integrated fault lengths vary considerably. However, these do not appear to bear strict correspondence with either the area extents or the power generation capacities of the reservoirs.

Table (3) Methane flux and estimated lengths of submerged faults in nine hydroelectric reservoirs.

Reservoir	Integrated Fault Length (km)	Methane Flux ($kg/km^2/d$)
Miranda	300	154
Tres Marias	600	196
Barra Bonita	40	22
Segredo	30	9
Xingó	60	38
Samuel	300	104
Tucuruvi	500	112
Serra de Mesa	100	51
Itaipu	20	21

The variation of methane flux with integrated fault length is illustrated in Figure (7). Note that there is a substantial near linear increase in methane flux for fault lengths of up to about 400km. This initial increase is followed by an asymptotic approach to a limiting flux value of about 200 kg/km^2/d for fault lengths in excess of 600 km. The curve in this figure refers to the fit, assuming a quadratic relation. Notwithstanding the obvious limitations of the data set the observed correlation maybe considered as indication that seepage through fault systems contributes to methane flux in hydroelectric reservoirs. On the other hand, if methane is entirely of biogenic origin, and brought into the reservoir by river flow, there is no reason to expect correlation with fault length.

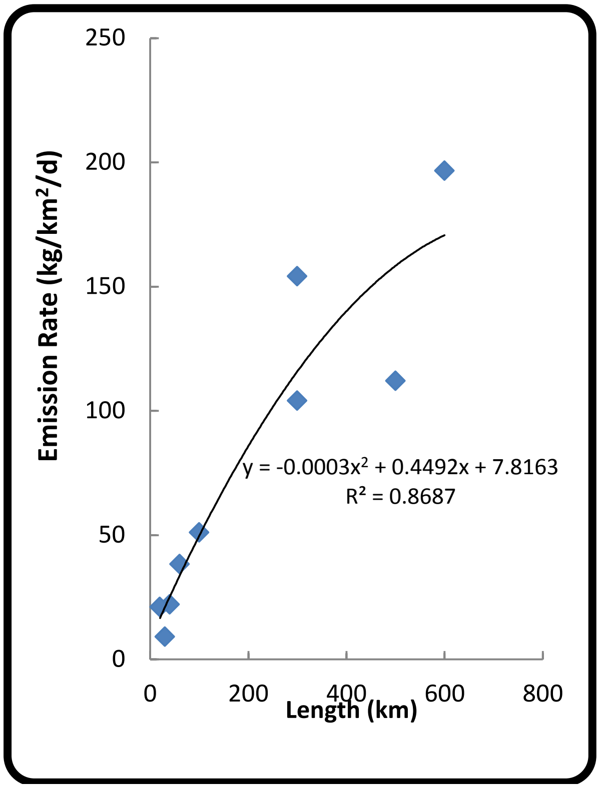

Figure (7) Variations of methane flux with lengths of submerged fault systems, for nine hydroelectric reservoirs considered by Rosa et al (2000).

Temporal Evolution of Methane Flux

Information on temporal evolution of methane flux is also capable of providing additional clues as to the source of methane in hydroelectric reservoirs. It is well known that much of the particulate material brought in by rivers is deposited at the bottom of reservoirs. Steady growth in the thickness of this sediment cover leads to the formation of a relatively impermeable blanket over the submerged fault systems. As a result one may expect a gradual reduction in methane flux for the period following the time of impoundment of the reservoir. In other words, temporal evolution of methane flux in reservoirs should reveal a systematic trend of decreasing values. The form of decay trends depend on such factors as the rate of influx of particulate matter and the rate of deposition. A summary of observational data on temporal evolution of methane flux in the nine hydroelectric reservoirs is presented in table (4).

Table (4) Temporal evolution of Methane flux in hydroelectric reservoirs (Data from Rosa et al, 2000).

Reservoir	Year of Impoundment	Elapsed time (Yrs)	Methane flux (kg/km^2/d)
Miranda	1996	2	154
Tres Marias	1959	39	196
Barra Bonita	1962	36.5	22
Segredo	1991	7	9
Xingó	1995	4.5	38
Samuel	1987	10.5	104
Tucuruvi	1987	12	112
Serra de Mesa	1996	1	51
Itaipu	1977	21	21

Note that methane flux is lower for reservoirs with large impoundment times. The forms of variation of methane flux with elapsed time are illustrated in Figure (8). Naturally not all reservoirs are likely to have identical trends. Hence the trends identified in this figure have been considered as indicative of three distinct groups. The first one is formed by reservoirs (Segredo, Xingô and Serra de Mesa) with relatively low methane flux. The second one is formed by reservoirs (Miranda, Barra Bonita, Samuel, Tucuruví and Itaipú) with intermediate values of methane flux. The data for the Três Marias reservoir does not fit with groups 1 and 2 and hence has been considered as pertaining to a third group. In all cases the trends are indicative of substantial decreases in methane flux with elapsed time after impoundments of reservoirs. On the other hand, if methane is entirely of biogenic origin, and brought into the reservoir by river flow, there is no reason to expect temporal variations in methane flux.

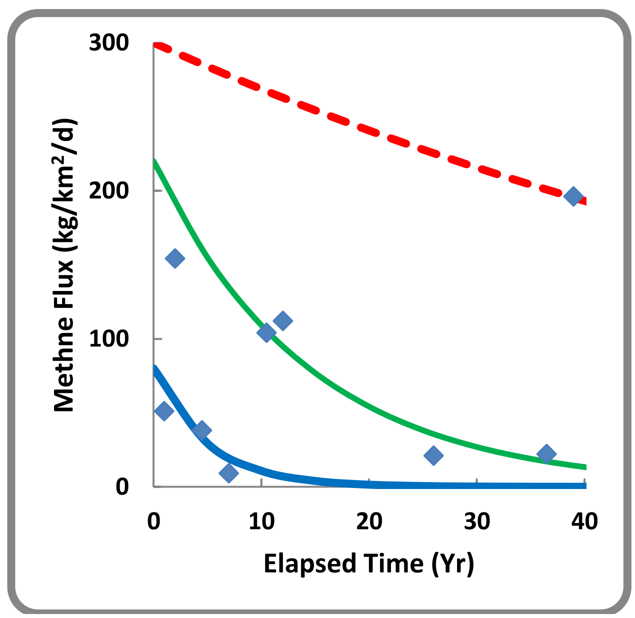

Figure (8) Temporal evolution of Methane flux in hydroelectric reservoirs (Data from Rosa et al, 2000).

Discussion

The argument that part of methane flux observed in hydroelectric reservoirs is abiogenic is based on the assumption that submerged fault systems in hydroelectric reservoirs allow seepage of methane of deep crustal origin. Induced seismicity associated with the great majority of reservoirs is indication that submerged faults are active and hence permeable for gas flow.
In this context it is convenient to explore briefly implications of some of the related observations. Foremost among these are the results of isotope studies, progress obtained in identifying the geologic control of river beds and conduit compression models for gas flow.

a) Isotope Variations: Analysis of isotope variations can principle be used for identifying the source of origin of methane. Biogenic methane has $\delta^{13}C$ values in the range of -50 to $-80^{0}/_{00}$, which overlap with the ranges for atmospheric and thermogenic methane. Correlated variations of $\delta^{13}C$ and $\delta D\text{-}CH_4$ may also be used as diagnostic tool. However, isotopic studies lose their resolving power in cases where mixing has taken place. For example, waters of hydroelectric reservoirs contain both biogenic (derived from organic matter) and abiogenic (derived from deep crustal sources) methane. In this context it is perhaps significant that waters of Tucuruvi and Samuel reservoirs have relatively high values of $\delta^{13}C$ (Lima, 2002). In the present case isotopic analyses of waters in reservoirs have not been carried out.

b) Geologic Control of River beds: It is well known that drainage patterns of fluvial systems on the land surface are in many cases determined by the folds and fault bounded subsidence of basement rocks (Twidale, 2004). Recent advances in morphotectonic analysis based on digital elevation models have contributed to significant advances in our understanding of features that determine the courses of rivers. Examples presented by Twidale (2004) illustrate the influence of regional scale faults on the courses of rivers and in Western Australia. In the present case results reported by Silva et al (2007) demonstrate clearly the roles of folds and faults in controlling drainage pattern in the Amazon region.

Conclusions

The main conclusions of the present work are:

1- Results of recent measurements of methane in the stable interior parts of Brazil (where subsurface strata have very little organic matter) are compatible with the hypothesis of its deep crustal origin;
2- Variation of methane flux with lengths of submerged faults reveals a significant positive correlation. This correlation has been considered as indication that seepage through fault systems contributes to methane flux in hydroelectric reservoirs. On the other hand, if methane is brought into the reservoir by river flow there is no reason to expect its correlation with fault length;
3- Reservoirs with large impoundment times are found to be characterized by relatively low values of methane flux. Such inverse correlation has been considered as arising from gradual sealing of fault systems by deposition of sediments. On the other hand, if methane is entirely of biogenic origin, and brought into the reservoir by river flow, there is no reason to expect temporal variations in methane flux;
4- Seepage of abiogenic methane through submerged fault systems contribute to observed flux of methane in hydroelectric reservoirs;
5- Hydroelectric reservoirs impede, rather than promote, natural flow of mantle methane;
6- Reported impacts of global warming by methane flux in hydroelectric reservoirs (Fearnside, 2008) are unfounded

Acknowledgements

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References

Alvalá, P.C.; Kirchhoff, V.W.J.H., 2000, Methane fluxes from the Pantanal floodplain in Brazil: seasonal variation. In: J. van Ham et al. (Eds.) Non-CO2 Greenhouse gases: scientific understanding, control and implementation. Amsterdam: Kluwer Academic Publishers, p. 95-99.

Braz, L., Ferreira, W.J., Batista, G.T., Targa, M.S., Alvalá, P.C. and Hamza, V.M., 2011, Caracterização Da Emissão De Metano Para A Atmosfera Na Lagoa Rodrigo De Freitas, RJ, XIX Simpósio Brasileiro de Recursos Hídricos.

Buchwitz, M., de Beek, R., Noel, S., Burrows, J.P., Bovensmann, H., Bremer, H., Bergamaschi, P., Korner, S. and M. Heimann, 2005, Carbon monoxide, methane and carbon dioxide columns retrieved from SCIAMACHY by WFM-DOAS: Year 2003 initial data set, Atmos. Chem. Phys., 5, 3313– 3329.

Devol, A.H., Richey, J.E., Clark, W.A., King, S.L. and Martinelli, L.A., 1988, Methane emissions to the troposphere from the Amazon flood plain. J. Geophys. Res., 93, 1583 – 1592.

Fearnside, P.M., 2008, Hidrelétricas como “fábricas de metano”: o papel dos reservatórios em áreas de floresta tropical na emissão de gases de efeito estufa. Oecol. Bras., 12 (1): 100-115.

Lima, I.B.T., 2002, Emissão de metano por reservatórios hidrelétricos amazônicos através de leis de potência. Ph.D. Thesis, Centro de Energia Nuclear na Agricultura, Univ. São Paulo, Piracicaba, 108p.

Marani, L.; Alvalá, P.C., 2007, Methane emissions from lakes and floodplains in Pantanal, Brazil. Atmospheric Environment, v. 41, n. 8, p. 1627-1633.

Melack, J.M., Hess, L.L., Gastil, M., Forsberg, B.R., Hamilton, S.K., Lima, I.B.T., Novo, E.M.L.M., 2004, Regionalization *of methane emissions in the Amazon basin with microwave remote sensing.* Global Change Biol., v.10, pp. 530-544.

Moura, J.M.S., 2010, Fontes demetano em florestas tropicais da Amazônia: Análise da composição isotópica e uso de técnicas indiretas para determinação de balanços gasosos nesses ecossitemas. Ph.D. Thesis, Centro de Energia Nuclear na Agricultura, Univ. São Paulo, Piracicaba, 107p.

Rosa, L.P., Sikar, B.M., Santos, M.A. and Sikar, L.M., 2000, Emissões de dióxido de carbono e de metano pelos reservatórios hidrelétricos brasileiros, Relat;orio Final, Centrais Elétricas Brasileiras S.A., DEA, DEAA, Eletrobrás, Rio de Janeiro.

Silva, C.L., Morales, N., Costa, A.P., Costa, S.S. and Jiménez-Rueda, J.R., 2007, Analysis of tectonic-controlled fluvial morphology and sedimentary processes of the western Amazon Basin: an approach using satellite images and digital elevation model. Annals of the Brazilian Academy of Sciences, 79(4): 693-711.

St. Louis, V.L., Kelly, C.A., Duchemin, E., Rudd, J.W.M. and Rosenberg, D.M., 2000, Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate, BioScience, 50, 766–775.

Twidale, C.R., 2004, River patterns and their meaning. Earth-Science Reviews, 67, 159–218

Whiting, G.J., and Chanton J.P., 1993, Primary production control of methane emission from wetlands, Nature, 364, 794– 795.