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Indications of a link between seismotectonics and CH_4 release from seeps off Costa Rica

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[1] Measurements of CH_4 concentrations in the bottom water during two discrete sampling periods in subsequent years above different cold seeps at the Pacific margin off Costa Rica indicate large-scale variations of CH_4 release. CH_4 is emitted from mud extrusions and a slide scar at 1000–2300 m water depth. Maximum CH_4 concentrations were found to be lower above all investigated sites in autumn 2003 than in autumn 2002 although seep sites are up to 300 km apart. Tidal and current changes were observed but found to apply only to individual seep sites. Increased seismic activity connected to the moment magnitude (M_W) 6.4 earthquake offshore Costa Rica in June 2002 could have had an impact on all seep sites and thereby caused an increase in CH_4 emission. This is supported by the largest variations of CH_4 concentration found above mud extrusions located above faults likely more strongly affected by tectonic movements. Even though our data indicate a relation between seismicity and CH_4 seepage, the relation is not proven, and future work is needed to comprehensively test this hypothesis.

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1. Introduction

[2] Natural CH_4 seeps of varying intensity are found along most convergent continental margins. Several of these sites have been investigated in detail, e.g., the Cascadian Margin [*Suess et al.*, 1999], the area offshore Peru [*Dia et al.*, 1993], and the Barbados accretionary prism [*Henry et al.*, 1996]. Convergent margins are crucial regions in terms of element recycling [*Moore and Vrolijk*, 1992]. Fluids and volatiles are mobilized due to the compaction of sediments that accrete in or subduct beneath margin wedges. CH_4 is one of the most frequent observed compounds migrating from various sediment depths toward the sediment-water-interface. Most of it becomes anaerobically oxidized in the near-seafloor sediments, leading to the precipitation of authigenic carbonates [*Han et al.*, 2004; *Kulm et al.*, 1986; *Teichert et al.*, 2005] and providing energy for vent-specific biota [*Sibuet and Olu*, 1998]. Only a fraction of CH_4 escapes into the water column, its extent depending on the fluid pathway, the efficiency of oxidation processes, and the rate of upward flow [*Linke et al.*, 2005; *Luff and Wallmann*, 2003]. A summary of cold seep activities with emphasis on CH_4 cycling is provided by *Boetius and Suess* [2004].

[3] Numerous cold seeps were examined in detail along the Costa Rican subduction zone over the past years [*Bohrmann et al.*, 2002; *Han et al.*, 2004; *Hensen et al.*, 2004; *Linke et al.*, 2005; *Mau et al.*, 2006]. Along the Costa Rican subduction zone, the Cocos Plate is subducted beneath the Caribbean Plate at a rate of nearly 88 mm/yr since late Oligocene/early Miocene offshore Costa Rica [*Kimura et al.*, 1997]. The subduction mechanism is proposed to be of erosive nature, that is not only the incoming crust and overlying sediments are subducted [*Saffer et al.*, 2000] but also material from the upper plate is removed [*Ranero and von Huene*, 2000]. The tectonic erosion leads to extension of the continental margin, as evidenced by observations of listric faults which lead to a landward tilt of blocks of the basement [*Meschede et al.*, 1999]. Some of the listric faults may penetrate the whole overriding plate down to the decollement [*von Huene et al.*, 2004]. All seep sites reported in this paper are located at this part of the continental margin in water depths ranging from 1000–2300 m.

[4] The seep sites are associated with mud extrusions and scarps (Figure 1). Mud extrusions are driven by buoyancy forces that arise from bulk density differences between undercompacted fluid-rich clayey sediments and denser overlying sediments [*Brown*, 1990]. All mud extrusions reported in this paper are associated with deep reaching fault zones. Off Middle America, submarine landslides can be triggered by seamount subduction, which leads to a temporary uplift of the continental wedge during passage of the seamount and causes landslides on the over-steepened seaward side of the uplift [*Ranero and von Huene*, 2000; *von Huene et al.*, 2000]. Several circular uplifts associated with slope failure structures have been identified along the continental margin of Costa Rica [*von Huene et al.*, 2000], and are here referred to as scarps. All of these different structures show the typical signs of active CH_4 seepage including chemosynthetic seep organisms and authigenic carbonates.

[5] The amount of CH_4 discharging from cold seeps is difficult to estimate because of the high variability in space and time [*Linke et al.*, 1994, 2005; *Tryon et al.*, 1999] in particular on longer timescales. We had the opportunity to measure CH_4 concentrations at several seep sites offshore Costa Rica in 2002 and approximately 12 months later (Figure 1). The temporal variability observed could have had several causes: seasonality, ocean current changes, tidal effects or differing seismic activity. In order to identify the most possible cause, we combined CH_4 concentration data with oceanographic and seismic data.

2. Methods

[6] CH_4 concentrations were measured in water samples collected with standard CTD/rosette equipment at four different cold seep sites offshore Costa Rica (Figures 1 and 2). Sampling took place in August/September 2002 aboard RV METEOR (M54-2/3) and in September 2003 using RV SONNE (SO173-3/4). For CH_4-analyses aboard a modification of the vacuum degassing method described by *Lammers and Suess* [1994] was used [*Rehder et al.*, 1999]. Replicate analysis of samples of a single hydrocast yield a precision of ±10% for samples with CH_4 concentration <2 nmol/L and ±5% for CH_4 concentration >2 nmol/L.

[7] Tidal data were obtained from http://www.costarica.com/Home/Weather/Tides documenting the sea level changes at the port of Puntarenas, Costa Rica. These data correspond with short-term records of pressure changes at Mound Culebra and Mound 12 (Figure 3). These variations in pressure were recorded by a MAVS 3-axis acoustic current

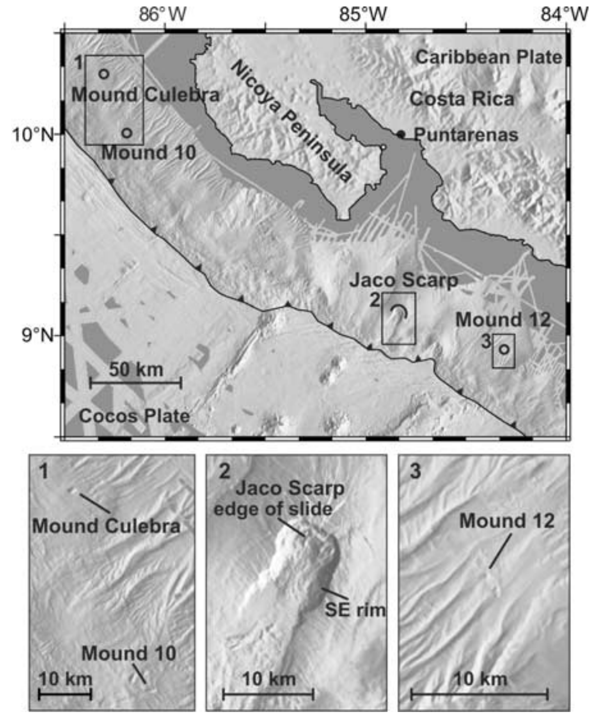

Figure 1. Bathymetry of a segment of the Costa Rica margin showing the sampled cold seep sites. Images 1, 2, and 3 are close-up views of map areas displaying the cold seep sites in more detail.

meter (NOBSKA) at Mound Culebra and a CTD (SBE16plus) at Mound 12 connected to a lander device [*Pfannkuche and Linke*, 2003] in 2002 (M54-2/3). Records of hydrostatic pressure exist from 16–23 September 2002 at Mound Culebra and from 23–24 September 2002 at Mound 12.

[8] Current measurements were obtained by upward looking ADCPs (Acoustic Doppler Current Profiler; RD Instruments) attached to different lander devices (Figure 4). ADCPs were located at Mound Culebra at 10°18.00′N/86°18.32′W in 1543 m water depth in 2002 and at 10°17.16′N/86°17.89′W in 1610 m water depth in 2003. Data from 20 m above the seafloor in 2002 and 2003 were used for comparison. At Mound 12 ADCPs were deployed at 8°55.87′N/84°18.85′W in 1020 m water depth in 2002 and at 8°55.61′N/84°18.40′W in 1023 m water depth in 2003. Data from 5 m above the seafloor in 2002 (1200 kHz ADCP did not cover a depth range as great as 20 m) and from 20 m above the seafloor 2003 were compared.

[9] Earthquakes located in the area of Figure 1 were selected from data provided by the Red Sismológica Nacional, Costa Rica (RSN: ICE-UCR). Earthquakes located by less than 5 stations and with a traveltime error of >0.6 s (root mean squared residual) were excluded. The energy released by earthquakes was calculated using the Gutenberg-Richter formula [*Gutenberg and Richter*, 1954]: $\log E = 11.8 + 1.5\,M_L$, where E is energy in TJ (Terra Joule) and M_L is local magnitude. Only earthquakes with a $M_L \geq 3$ were included in the calculation because of the limited magnitude detection level of the seismological network, especially offshore where no stations are situated.

3. Results

[10] Variations of CH_4 concentration were observed at cold seep sites investigated along the continental slope of Costa Rica between the sampling campaigns in 2002 and 2003, i.e., 11 to 12 months later. At all sites, the maximum CH_4 concentration was lower in September 2003 compared to the maximum CH_4 concentrations found in August/September 2002 (Figure 2 and Table 1). The values above the NW flank of Mound Culebra dropped from 42 nmol/L in August 2002 to 2 nmol/L in September 2003 (i.e., close to the regional background CH_4 concentration, Figure 2b). At the summit of Mound Culebra, the CH_4 concentration decreased from 24 nmol/L to 4 nmol/L between the investigations in 2002 and 2003 (Figure 2a). The values above Mound 10 and Mound 12 indicate the same trend (Figures 2c, 2f, and 2g). CH_4 concentrations in Jaco Scarp are more variable not only in time but also in space. The CH_4 profiles of 2003 show partly decreasing and partly increasing CH_4 concentrations compared to the profiles of 2002 depending on water depth. Still, maximum CH_4 concentrations at the upper edge of the talus apron decreased from 178 nmol/L in August 2002 to 64 nmol/L in September 2003 in 1850 m water depth (Figure 2d). Measurements at the SE rim of Jaco Scarp indicate a drop by 30% from 2002 to 2003 in 1700 m water depth (Figure 2e). The investigations indicate a general change to lower CH_4 concentrations that is more obvious above the mud extrusions than in the scarp within a time frame of approximately one year.

4. Discussion

[11] The large areal extent of the observed CH_4 concentration decline suggests a regional mechanism responsible for that change within this

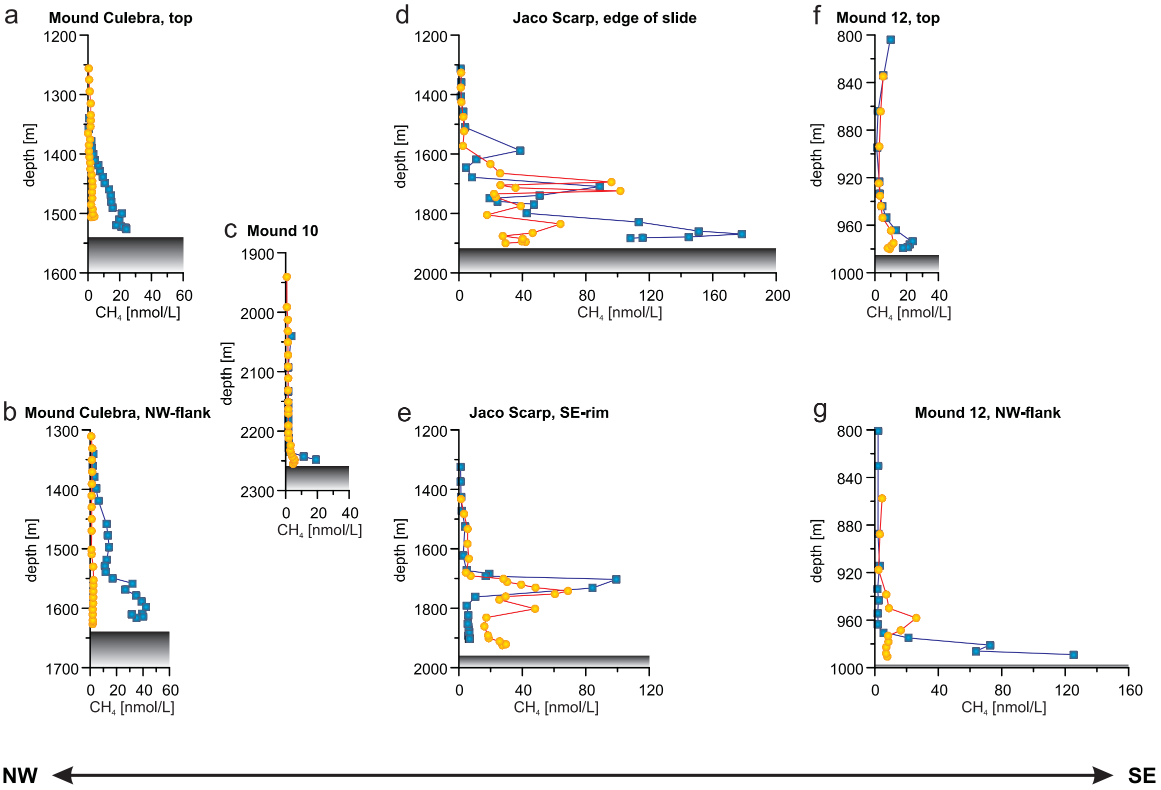

Figure 2. CH_4 concentration versus depth in the water column above the various seep sites starting with the NW-most site (left) proceeding to the SE-most site (right, note arrow). Blue squares, sampled in August 2002 (Mound Culebra and Jaco Scarp) and September 2002 (Mound 10 and Mound 12); yellow points, sampled in September 2003 (all locations). Sampling at the top of the mounds refers to sampling water above the highest elevation of the morphological hills, and sampling at the flank refers to sampling water above the slope of the hills. The black-to-white shaded boxes represent the seafloor.

11–12 month period between sampling. One possible change could have been seismic activity. The seepage sites are situated above a convergent plate boundary, an area of pronounced and continuous seismic activity. *Protti et al.* [1995] reported that the central Costa Rican margin, historically the most seismically active region on the margin, can generate earthquakes up to M_S 7.0 over a short recurrence interval. The segment offshore Nicoya Peninsula has also the potential for large M_S 7.7 earthquakes and a recurrence interval of 50 years [*DeShon et al.*, 2003].

[12] Temporal changes in concentration of chemical components of groundwater on land have been reported before many large earthquakes [*King*, 1986] going back to the 1960s when scientific studies in this field started. Such geochemical anomalies are thought to be driven by stress-induced crustal deformation, which affect the permeability of rocks [*Favara et al.*, 2001; *Italiano et al.*, 2001] and, in turn, fluid flow [*Montgomery and Manga*, 2003; *Trique et al.*, 1999]. A natural laboratory in the French Alps was used by *Trique et al.* [1999] to investigate this relationship. They showed that high water levels in lakes induced accelerated loading of the ground (deformation of the ground) suggesting enhanced fluid transport and causing the associated recorded radon emanation. Furthermore, *Montgomery and Manga* [2003] summarized reported observations of hydrological response to earthquakes and could even show that the maximum distance of changes in water levels in wells is related to earthquake magnitude. Recently, the connection between CH_4 seepage and seismic activity was hypothesized in marine settings by *Obzhirov et al.* [2004] and *Shakirov et al.* [2004] on the basis of CH_4 data and earthquake events in the Sea of Okhotsk. For parts of our research area at the continental margin off Nicoya Peninsula, Costa Rica, *Brown et al.* [2005] suggest that observed transient fluid flow events are linked to small scale seismic signals resembling tremors.

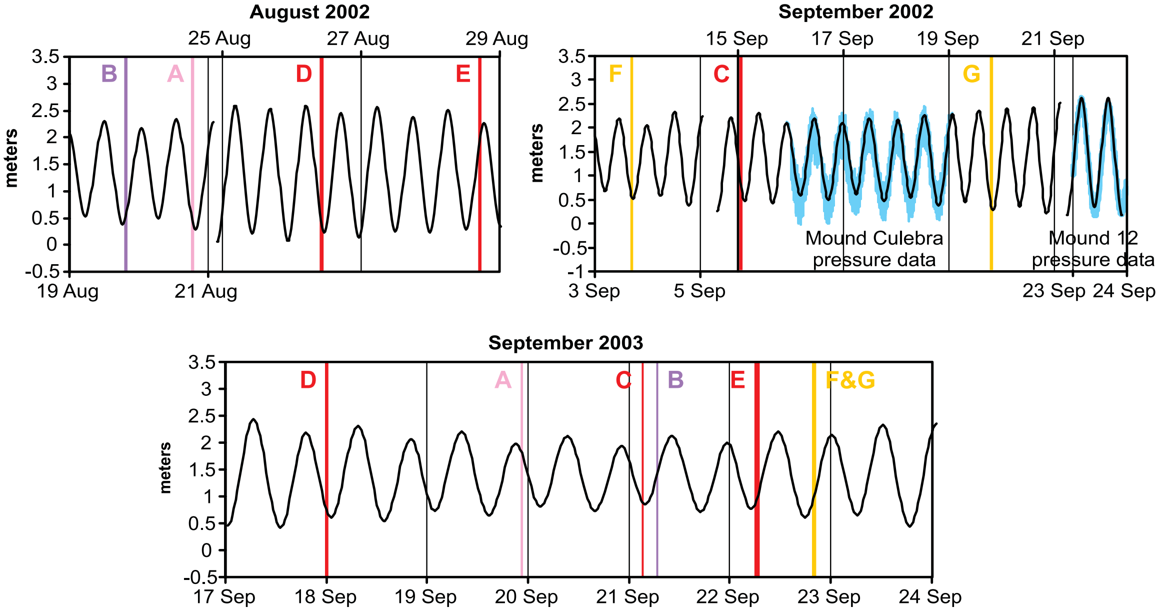

Figure 3. Tide height recorded at the port of Puntarenas (Figure 1) and times of sampling at the various seep sites. A, Mound Culebra, top; B, Mound Culebra, NW flank; C, Mound 10; D, Jaco Scarp, edge of slide; E, Jaco Scarp, SE rim; F, Mound 12, top; G, Mound 12, NW flank. The graph of September 2002 includes pressure data (unit: db, indicated by blue color) measured at Mound Culebra and Mound 12 subtracting 1523 db and 1015 db, respectively. This demonstrates a negligible phase shift between tides at the port of Puntarenas and the sampling sites at Mound Culebra and Mound 12.

Overall, a relationship between seismic activity and fluid flow is supported by observations on-land as well as, to a smaller extent, in marine tectonic settings.

[13] To identify a possible relationship of CH_4 seepage and seismic activity off Costa Rica, we used preliminary earthquake data of 2002 and 2003 provided by the Red Sismológica Nacional, Costa Rica. The data cover only earthquakes with local magnitude ≥ 3. Thus we could only investigate a possible effect of seismicity of higher intensity on CH_4-seepage. Tremor-related variations could not be studied. The earthquake record shows that CH_4 concentrations in 2002 have been measured 2–3 month after increased seismic activity (Figure 5). This increase may be the consequence of a M_W 6.4 earthquake that occurred near the plate interface on 16 June 2002 [*DeShon et al.*, 2003]. In contrast, CH_4 concentrations obtained in 2003 have been sampled after a period of less frequent, low magnitude earthquakes (Figure 5). Hence different seismic activities before sampling could have affected CH_4-emission over a regional scale.

[14] Most of the epicenters of earthquakes recorded by RSN are located SE of Nicoya Peninsula, 200–300 km away from Mound Culebra and Mound 10 (Figure 6). This raises the question, whether CH_4-emissions at these mounds could have been affected by these earthquakes. *Montgomery and Manga* [2003], who compiled reported observations of water well responses to earthquakes, found that an earthquake of magnitude 3 can have an impact on well levels in a radius of ~20 km, an earthquake of magnitude 4 on wells in a radius of roughly 50 km. By extrapolation of their model the M_W 6.4 earthquake in June 2002 could have had a possible effect on hydrology in a radius of up to 500 km. The areas potentially influenced by the earthquakes offshore Costa Rica monitored by RSN are shown in Figure 6, illustrating that only the major event in June 2002 could have affected all the investigated seep sites. Apart from Mound 10, the other seep sites could have also been influenced by other earthquakes lower in magnitude, but we suggest that the increasing stress accumulation that resulted in the final slip along the plates recognized as the M_W 6.4 earthquake could have caused a general increase of the CH_4 output into the water column.

[15] The decline in CH_4 concentration is more pronounced at the mud extrusions than at Jaco

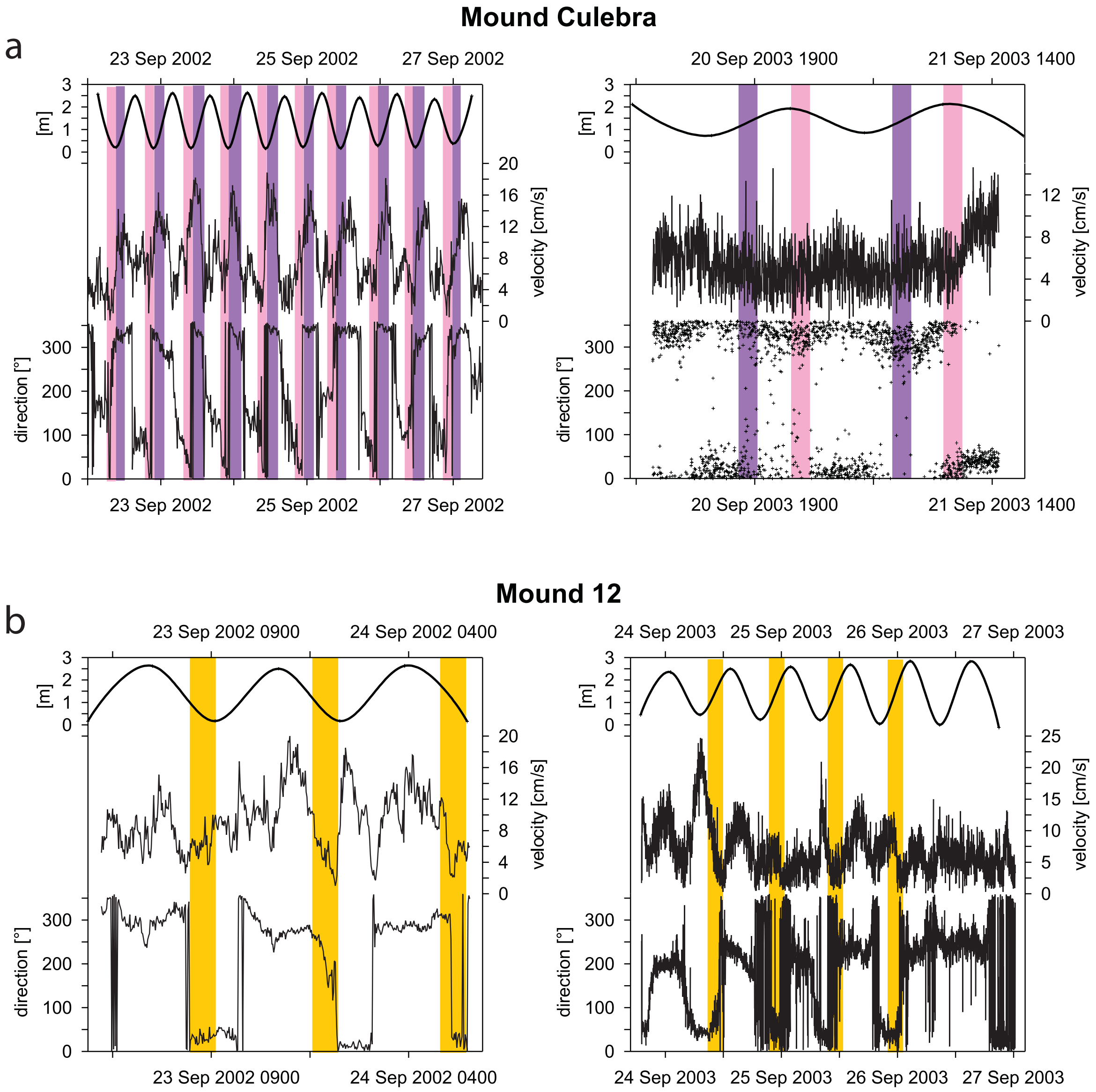

Figure 4. Tide height measured at the port of Puntarenas, current speed and direction recorded at (a) Mound Culebra and (b) Mound 12 versus time. Colored fields mark same phase of tidal cycle during which samples at Mound Culebra and Mound 12 were collected. Refer to Figure 3 for the color code: pink, Mound Culebra top; purple, Mound Culebra NW flank; yellow, Mound 12 top and NW flank.

Scarp. The maximum concentrations observed above the mud extrusions in September 2003 never reach 50% of the maxima in the year before and are in some cases lower by an order of magnitude, whereas the maxima at the scarp reach at least 55% of the values of the previous year (Figure 2). In contrast to the scarp, mud extrusions are situated above deep-seated faults. *Hensen et al.* [2004] showed that one end-member of the fluids expelled from mud extrusions originates from 10–15 km depth, i.e., from the subducted sediments, migrating most likely upward along faults. Ascending fluids push the zone of anaerobic oxidation of CH_4 into shallow sediment depth or even through the sediment-water interface. Thus higher fluid discharge results in enhanced CH_4 seepage [*Luff and Wallmann*, 2003]. Active faults are weak parts of the crust and it is not surprising that gases and fluids escape along this zones of least resistance [*Favara et al.*, 2001; *King*, 1986]. Tectonic strain may be greatly amplified at active faults [*King*, 1986], and so the influence of seismic activity on

Table 1. CH_4 Concentrations at the Different Seep Sites

Data 2002			Data 2003		
Station	Depth, m	CH_4, nmol/L	Station	Depth, m	CH_4, nmol/L
M54-2 Mound Culebra Top 20 Aug 2002	1526	24.2	SO173-3 Mound Culebra Top 21 Sep 2003	1506	2.0
	1524	23.8		1505	4.0
	1522	20.8		1500	3.1
	1520	17.9		1493	3.0
	1510	19.8		1485	1.9
	1500	21.4		1474	2.7
	1490	15.4		1464	2.6
	1481	14.7		1454	2.9
	1470	14.5		1446	2.7
	1460	13.2		1435	2.3
	1449	10.6		1425	1.5
	1439	9.3		1415	1.4
	1429	7.5		1405	0.9
	1419	6.5		1395	0.6
	1410	4.2		1385	0.6
	1400	3.3		1375	1.3
	1390	2.4		1365	0.0
	1379	2.0		1354	1.6
	1358	0.6		1344	1.7
	1340	0.6		1334	1.8
				1315	1.7
				1295	1.1
				1275	0.7
				1256	0.5
M54-2 Mound Culebra NW flank 19 Aug 2002	1616	35.1	SO173-4 Mound Culebra NW flank 22 Sep 2003	1627	1.9
	1611	40.2		1626	1.9
	1614	40.2		1623	2.1
	1610	39.4		1620	2.0
	1599	42.3		1611	2.0
	1589	39.1		1602	2.0
	1579	34.8		1592	2.3
	1569	26.6		1582	2.3
	1558	32.0		1571	2.4
	1549	17.1		1561	2.5
	1539	11.8		1553	2.6
	1530	11.2		1530	2.3
	1519	12.4		1509	1.1
	1498	14.3		1501	1.0
	1478	13.5		1470	1.2
	1458	12.3		1450	1.2
	1420	6.3		1430	1.2
	1399	4.4		1411	1.1
	1379	3.0		1391	1.3
	1360	1.9		1371	1.5
	1341	2.5		1350	1.3
				1331	1.6
				1311	0.8
M54-3a Mound 10 15 Sep 2002	2248	19.2	SO173-3 Mound 10 22 Sep 2003	2255	4.7
	2243	11.4		2252	5.5
	2239	5.4		2249	5.7
	2234	2.2		2247	5.3
	2228	2.1		2243	4.2
	2222	2.1		2238	3.4
	2217	1.9		2232	2.9
	2214	1.8		2224	3.1
	2202	1.8		2212	1.9
	2191	1.8		2203	1.7
	2183	1.8		2191	1.7

Table 1. (continued)

Data 2002			Data 2003		
Station	Depth, m	CH_4, nmol/L	Station	Depth, m	CH_4, nmol/L
	2173	1.7		2170	1.6
	2165	1.7		2163	1.6
	2153	1.7		2151	1.6
	2134	1.6		2131	1.5
	2111	1.3		2111	1.6
	2093	1.6		2092	1.5
	2041	3.5		2072	1.5
				2051	1.4
				2032	1.4
				2013	1.4
				1991	0.8
				1941	0.8
M54-2	1884	108.2	SO173-3	1901	29.3
Jaco Scarp	1881	115.9	Jaco Scarp	1896	42.1
Edge of slide	1879	144.8	Edge of slide	1894	39.7
26 Aug 2002	1869	178.5	19 Sep 2003	1885	40.2
	1860	151.1		1876	27.6
	1829	113.4		1866	46.5
	1800	42.7		1835	64.0
	1769	47.4		1805	17.7
	1759	24.3		1775	39.0
	1749	19.2		1745	23.2
	1739	51.0		1734	22.1
	1710	88.7		1724	101.8
	1678	8.4		1714	35.7
	1647	4.6		1705	26.1
	1619	10.9		1694	96.1
	1588	38.5		1665	26.0
	1510	3.7		1634	19.8
	1458	2.6		1573	2.5
	1359	1.6		1475	2.8
	1311	1.1		1425	1.5
				1377	1.2
M54-2	1904	6.9	SO173-4	1924	27.4
Jaco Scarp	1902	6.6	Jaco Scarp	1921	29.7
SE rim	1892	5.8	SE rim	1911	25.7
28 Aug 2002	1882	6.5	23 Sep 2003	1901	18.8
	1872	6.2		1891	18.4
	1862	6.1		1861	16.1
	1852	5.7		1831	17.4
	1822	5.9		1802	48.0
	1792	4.9		1771	25.5
	1762	10.4		1760	29.5
	1732	84.2		1752	60.5
	1703	99.3		1742	68.8
	1692	16.9		1731	48.3
	1683	18.9		1721	39.3
	1673	4.9		1712	30.5
	1623	2.8		1701	28.1
	1524	3.8		1691	7.5
	1474	2.0		1680	4.5
	1425	1.3		1633	6.3

Table 1. (continued)

Data 2002			Data 2003		
Station	Depth, m	CH_4, nmol/L	Station	Depth, m	CH_4, nmol/L
	1375	1.2		1583	5.4
	1326	1.1		1533	5.6
				1483	3.2
				1433	1.3
M54-2	968	15.8	SO173-4	980	9.3
Mound 12	966	15.2	Mound 12	979	8.1
Top	963	14.9	Top	977	10.4
3 Sep 2002	960	7.7	24 Sep 2003	975	11.7
	950	4.4		965	10.1
	940	2.7		954	4.8
	930	2.1		944	3.8
	920	2.5		935	3.2
	909	2.3		925	2.5
	880	1.6		894	2.8
	850	1.8		864	3.6
	820	1.4		835	5.2
M54-3a	989	125.2	SO173-4	991	7.9
Mound 12	986	63.9	Mound 12	988	7.0
NW flank	981	72.5	NW flank	983	7.2
19 Sep 2002	975	21.2	24 Sep 2003	978	8.5
	970	5.2		973	8.3
	964	2.1		969	16.3
	954	1.8		958	26.1
	943	2.3		950	8.9
	934	1.8		938	7.2
	914	2.9		918	2.3
	888	2.0		888	3.2
	830	2.0		858	4.6
	801	2.1			

fluid pathways connected to these geological structures is expected to be high. In contrast, the influence of tectonic activity is less pronounced at Jaco Scarp, where gas and fluid escape is mainly a result of exposed deeper sedimentary layers, hosting reduced geochemical compounds at elevated pore pressures. Thus CH_4 concentration vary less at seep sites related to the scarp.

[16] Our interpretation suggests an influence of major earthquakes on fluid flow/CH_4 discharge. However, it is based on data from only two field campaigns during similar time slots of subsequent years. The study complements the work by *Brown et al.* [2005] relating small scale seismic events (tremors) to transient fluid flow events. They found fluid flow anomalies near the trench whereas we investigated fluid seepage in the mid-slope of the continental wedge where mud extrusions are near deeply penetrating faults. Earthquakes affect hydrology in various ways, e.g., expulsion of fluids from the seismogenic zone, increased permeability due to shaking of surface deposits or bedrock fractures, decreased permeability resulting from consolidation of surficial deposits [*Montgomery and Manga*, 2003]. Possibly different mechanisms apply near the trench, in contrast to further upslope. Most of the dewatering is believed to take place near the trench, where faults and stratigraphic layers have approximately equivalent permeabilities. Landward, stratigraphic conduits decrease in permeability, but faults maintain high permeabilities [*Moore and Vrolijk*, 1992]. The sensitivity of different dewatering structures to seismicity is not well constrained.

[17] The variations in water column CH_4 concentration could also be caused by seasonal changes, tidal influence or changes in ocean currents, but we found these possible factors less satisfactory. Concerning the seasonality, we determined the CH_4 concentration during the same season in each year (in August/September 2002 and September 2003). Also, the CH_4 emitting sites have been

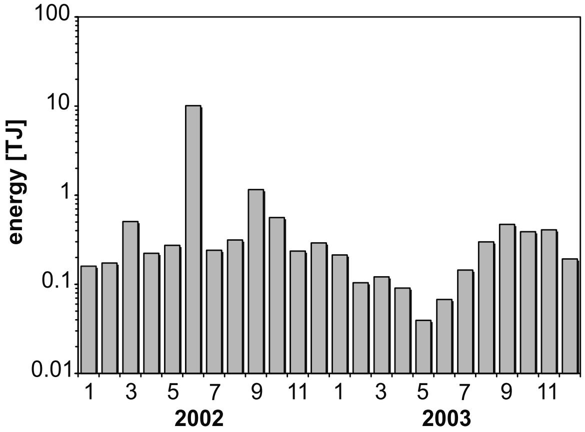

Figure 5. Energy released per month by earthquakes of magnitude ≥ 3 in the area of Figure 1. Energy was calculated from local magnitude using the Gutenberg-Richter magnitude-energy relation. Note logarithmical energy scale.

thoroughly investigated and are caused by subsedimentary fluid flow rather than degradation of young organic matter [*Hensen et al.*, 2004; *Soeding et al.*, 2003].

[18] Tidal control on fluid seepage as a result of changing hydrostatic pressure has been shown to be a factor for fluid seepage sites at Coal Oil Point, California [*Boles et al.*, 2001] and at Hydrate Ridge, Oregon [*Torres et al.*, 2002]. Yet, four of the seven sites were sampled in the same part of the tidal cycle either during high or low water level (above and below the mean tide height, respectively), i.e., high or low hydrostatic pressure (Figure 3). At Mound Culebra and the eastern rim of Jaco Scarp a partial influence cannot be excluded. However, a general trend toward measuring intervals near low tide/decreasing water levels in 2002 and high tide/raising water levels in 2003 is not shown by our data.

[19] Changes in the oceanographic current regime are another potential mechanism which would produce lower concentrations even above constantly emitting seep sites. Current speed influences dilution of CH_4 and thus CH_4 concentration in the water column. Changes in directions could cause the same sample location to be upstream of the source in the one year and downstream in the next, thus causing concentration changes. Unfortunately, currents were not recorded during sampling and current data are only available for short time intervals at Mound Culebra and Mound 12. We approximated the current conditions during sampling at the mounds using the available current data at the corresponding phase of the tidal cycle. Comparison of the estimated currents indicates potential changes in current regime, but the inferred changes differ from site to site. For example at Mound Culebra top, direction turned from NE/SE to NW/NE (Figure 4a) whereas at Mound 12 currents changed from NW/NE to north/NE (Figure 4b). Current velocities in 2002 were higher than in 2003 at Mound Culebra NW flank (Figure 4a), thus lower CH_4 concentrations should have been measured in 2002 rather than higher CH_4 concentrations, as has been observed. Therefore, although changes in the oceanographic current conditions occurred at individual sites, a general change in current speed or direction, affecting all seep sites uniformly and causing the observed decline in CH_4 concentration, cannot be inferred from the data. It would be a very unlikely coincidence if the observed changes were toward lower concentrations at all seven sites that are 300 km apart.

5. Summary and Conclusion

[20] Maximum CH_4 concentration decreased significantly from autumn 2002 to autumn 2003 in the water column above mud extrusions and in the area of a scarp offshore Costa Rica, all known to be active sites of fluid emissions [*Bohrmann et al.*, 2002; *Mau et al.*, 2006]. Hydrostatic pressure changes due to tides and oceanographic variations could explain the changing CH_4 content at individual sites, but systematic changes in hydrostatic pressure and/or oceanographic variations affecting all sites have not been observed. The M_W 6.4 earthquake at the seismogenic zone of Central America in 2002 could have had an impact on all investigated seep sites, which could have lead to increased discharge of CH_4-rich fluids into the water column. Even though a continuous data set would be needed to verify a relationship between seismic activity and CH_4 seepage, the data support such a hypothesis. Knowledge of the influence of large to small magnitude earthquakes on the output of CH_4 at seep sites is thus likely to be required for the calculation of CH_4 emissions from seep sites over longer timescales. The observed changes of fluid flow patterns on land before an earthquake and potentially similar effects at the seafloor is surely of interest in the ongoing discussion of precursors of large seismic events. Long-term investigations of fluid seepage/CH_4 discharge at different areas (e.g., near the trench and further away) in correlation to environmental parameters

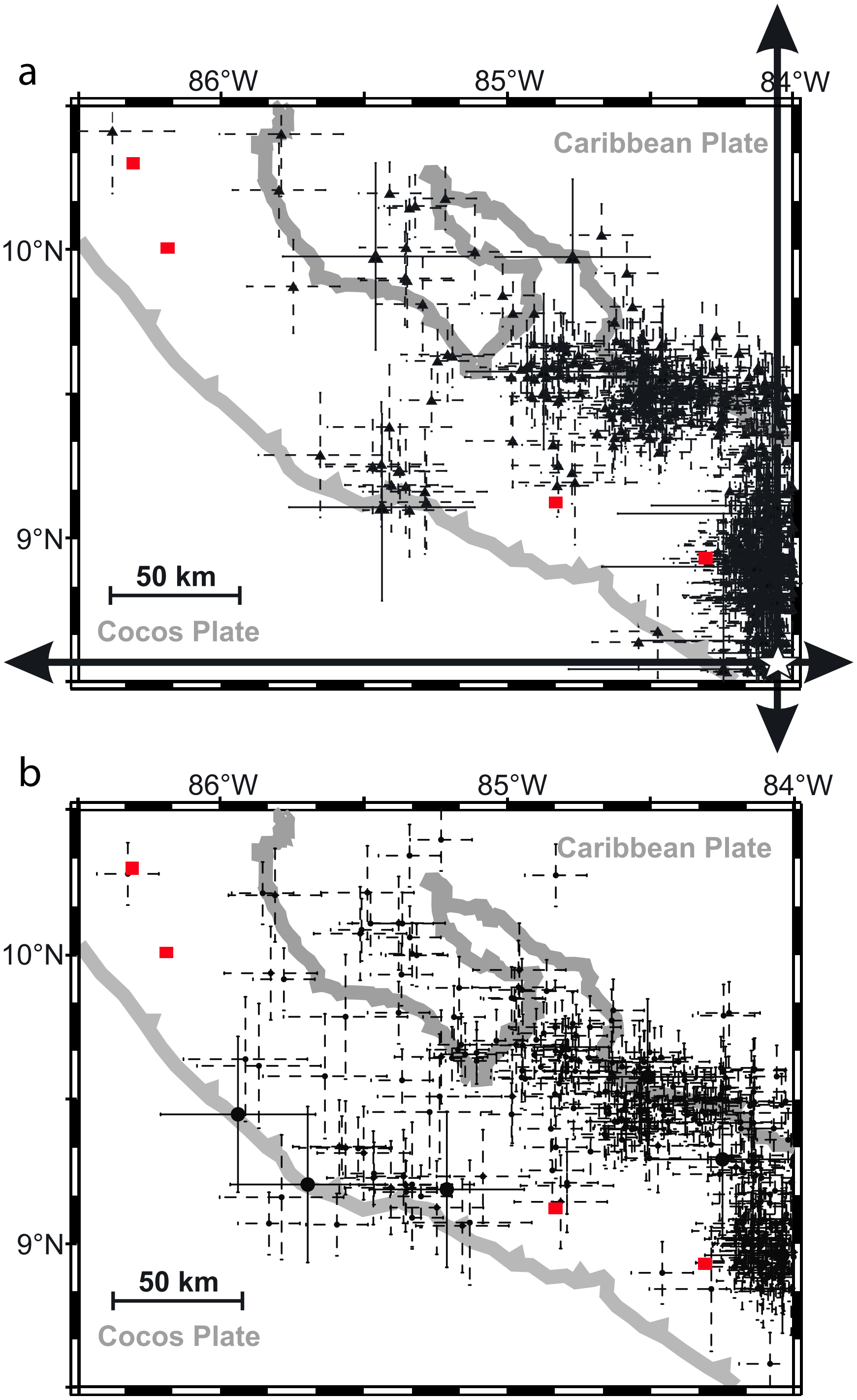

Figure 6. Epicenters of earthquakes in the area of Figure 1: (a) in 2002 and (b) in 2003. Crosses of dashed lines and crosses of solid lines indicate areas potentially influenced by earthquakes with magnitude <4 and ≥4, respectively. These areas were estimated on the basis of the relation between earthquake magnitude and distance to epicenter given by *Montgomery and Manga* [2003]. The star illustrates the epicenter of the M_W 6.4 earthquake on 16 June 2002, and thick lines with arrows show the area influenced by this earthquake covering a circumference of up to 500 km. This extends beyond the research area shown. Red squares show locations of seep sites.

and earthquake data are required to comprehensively address these questions.

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