An assessment of natural and man-made vibrations in Lake Kivu, Rwanda

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SUMMARY

This report overviews the general level of vibrational disturbance to which Lake Kivu, Rwanda has been subjected (e.g., shaking of approximately 10cm/s and 0.1g by recent earthquakes in the magnitude 6 range). These levels are compared to man-made sources, especially those of the exploration seismic community (air guns and sub-bottom sounders). The energy released by marine seismic sources is several orders of magnitude smaller than that of recent Rwandan earthquakes. Interest and concern relates to Lake Kivu because of its vast quantities of dissolved carbon dioxide and methane. Due to its thermohaline structure, the Lake is regarded as stable (although potentially vulnerable to extreme events). The sediments beneath the Lake could be host to hydrocarbons (similar to Lake Albert, Uganda). Thus, there are a number of compelling scientific, hazard reduction, and economic reasons to undertake seismic surveys on the Lake. However, because of the large population around Lake Kivu, potential environmental effects of a seismic survey must be considered. The energy and pressures involved in a seismic survey (using sub-bottom sounders and small airguns) are likely much smaller than those previously experienced in the depths of Lake Kivu. The seismic vibration estimates appear to be safely within Wüest et al.'s (2009) factor of safety and stability criteria.

INTRODUCTION

The East African Lakes (Figure 1) are fascinating as active records of continental rifting, climate variation, biological activity, and natural beauty. Lake Kivu, shared by Rwanda and the Democratic Republic of the Congo, is particularly interesting on account of its depth, salinity (Stoffers and Hecky, 1978), and gas content.

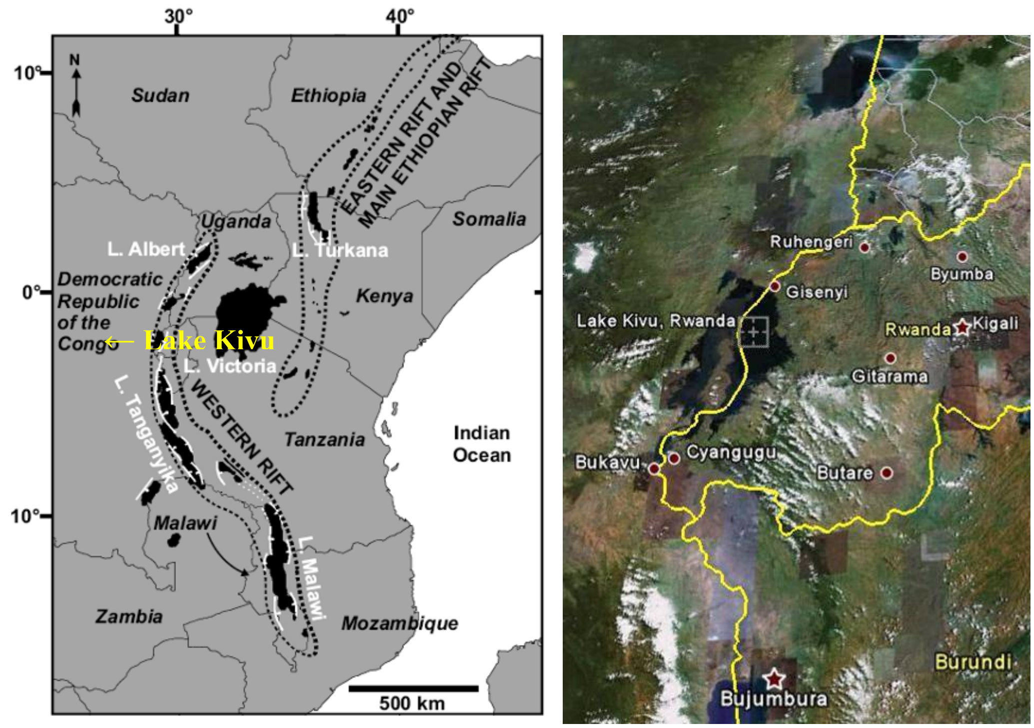

FIG. 1. Map of the East African Rift Zone and Lakes (from Karp et al., 2010) on the left and a satellite image (from Google Earth) on the right.

The natural gas (methane) in Lake Kivu provides both an opportunity for energy production as well as concern over its stability. The lake, with a surface area of 2,400 km2, is thought to contain some 55 km3 (at STP) of methane and 250 km3 of carbon dioxide (Sharife, 2009; Wüest et al., 2009). Lake Kivu is one of three gas-charged lakes in Africa (Kuhn, 2009) – the others being Lakes Nyos and Monoun in Cameroon. The source of the carbon dioxide in the Cameroon lakes, with their volcanic proximity, is likely magmatic (Kling et al., 1987; Kling et al., 2005). Lakes Monoun and Nyos were probably at the CO2 saturation level when they underwent limnic eruptions or out-gassing phases. Both tragic events gave rise to fatalities on account of flow of their dissolved gases into populated areas. The exact cause or trigger of the eruptions remains unknown, although lack of sediment disturbance in the deeper Lake Monoun and other factors argue against a volcanic injection. Lakes Nyos and Monoun have undergone controlled de-gassing of their carbon dioxide as a hazard remediation precaution.

The methane gas in Lake Kivu is probably the result of the activity of methane-producing bacteria in its waters and perhaps a deeper thermogenic source (Pers. comm., A. Bissada, 2010). Extraction of methane from the lake is proceeding, on a limited scale, for use as a power source in addition to mitigating the natural hazard (Kapchanga, 2009).

The Rwanda Energy Co., with its facility at Cap Rubona, is currently producing about 2MW of electricity from the lake-extracted methane (Figure 2).

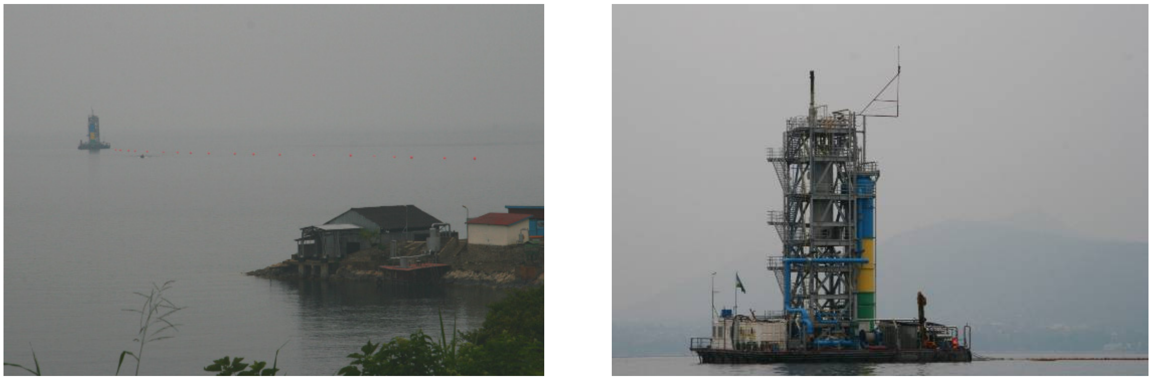

FIG. 2. Methane extraction facility (left) on Cap Rubona, Gisenyi on Lake Kivu and close-up (right) of extraction platform (R. Stewart photos).

The Braliwra Brewery uses methane, also extracted from the Lake, for its boilers (Figure 3). Several other extraction and power-production projects are underway.

FIG. 3. The Bralirwa brewery (left) uses methane from Lake Kivu for its operations Heavy transport vessels (right) operate on Lake Kivu near the Bralirwa brewery (R. Stewart photo).

The discovery of oil (Tullow, 2009; Sheehan, 2010) underneath Lake Albert, Uganda (Figure 4) - some 400km NNE of Lake Kivu - has generated interest in the possibility of hydrocarbons beneath Lake Kivu itself.

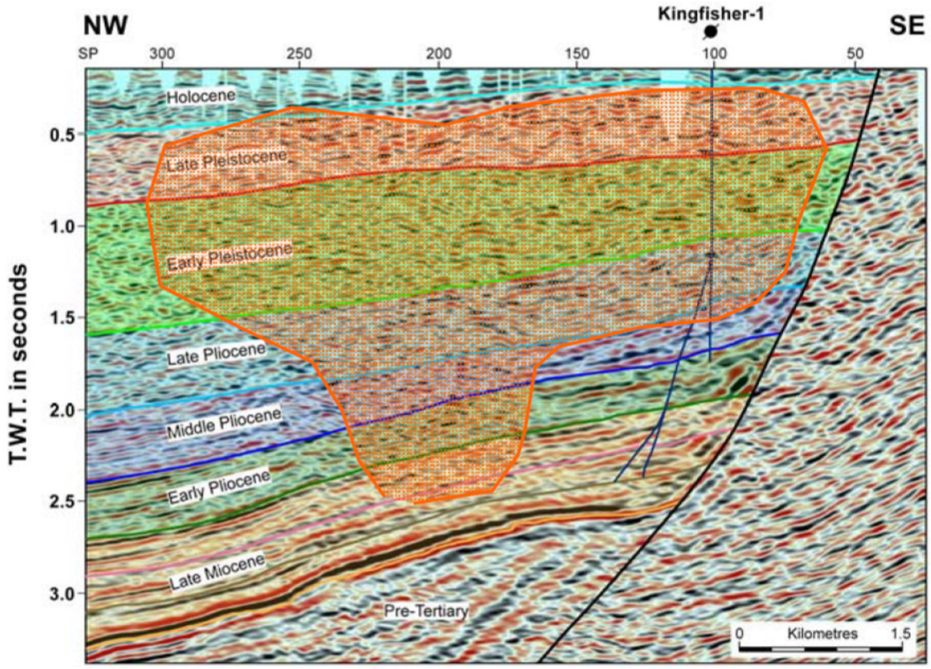

FIG. 4. Seismic line through the Kingfisher oilfield discovery with sediment ages annotated. Note the interpreted gas cloud, outlined in orange, above the reservoir (Logan et al., 2009).

There is likely over 4000m of sediments beneath parts of Lake Albert (Figure 5) as interpreted from reflection seismic data.

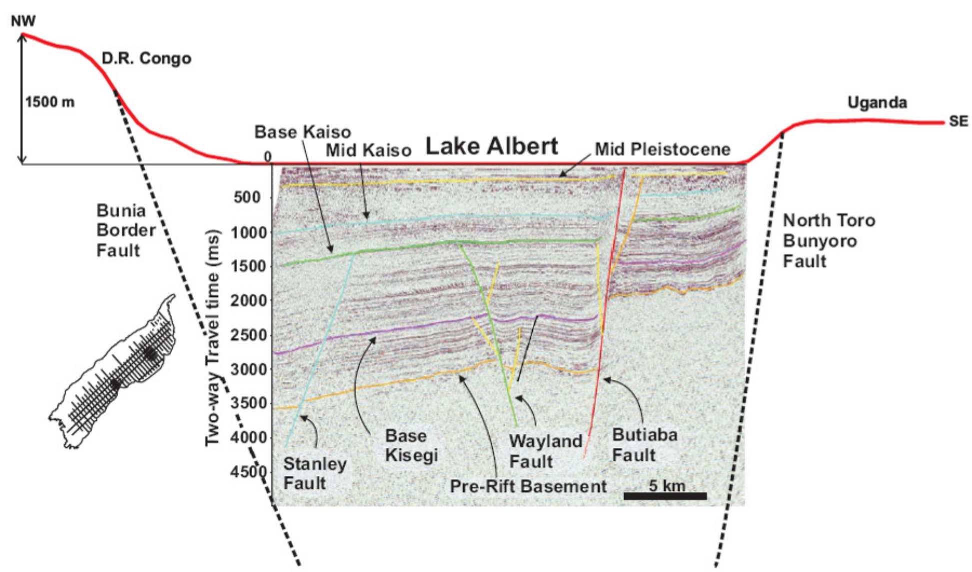

FIG. 5. Seismic section across Lake Albert, Uganda (from , 2010) indicating over 4000m (approximately corresponding to 4000ms of seismic traveltime) of sediments.

Perhaps correspondingly, recent gravity measurements over Lake Kivu suggest that there could be up to several kilometers of sediments (Figure 6) underlying parts of the Lake (PGW, 2008).

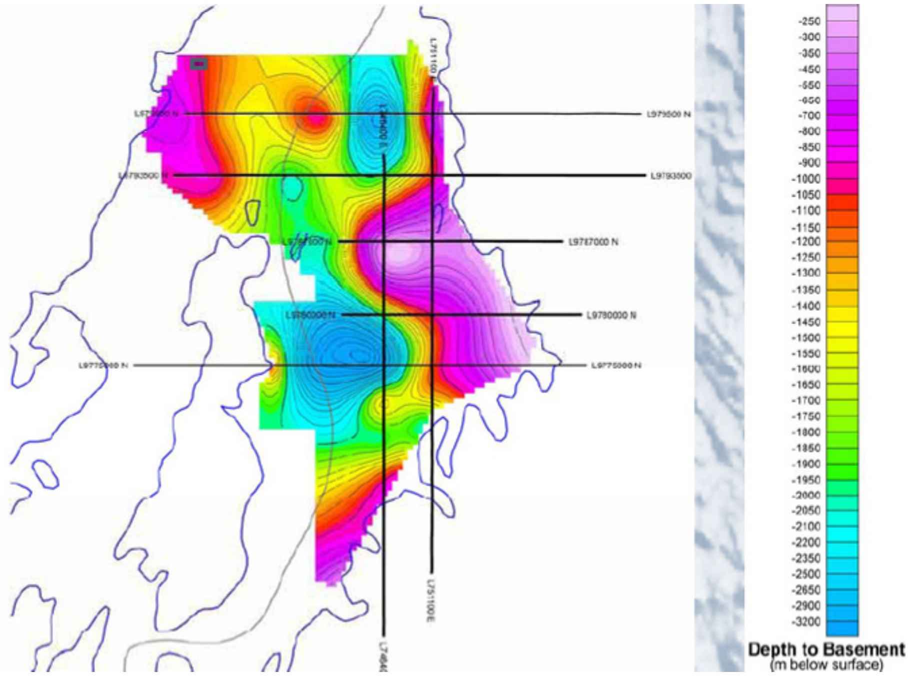

FIG. 6. Depth to the basement around northeastern Lake Kivu. Note that interpreted depths exceed 3000m (PGW, 2008).

Early seismic sections, acquired on Lake Kivu, were interpreted to indicate that generally less than 500m of unconsolidated sediments underlie the western part of the Lake (Figure 7). However, the coverage, data quality, and analysis of these early seismic measurements were limited.

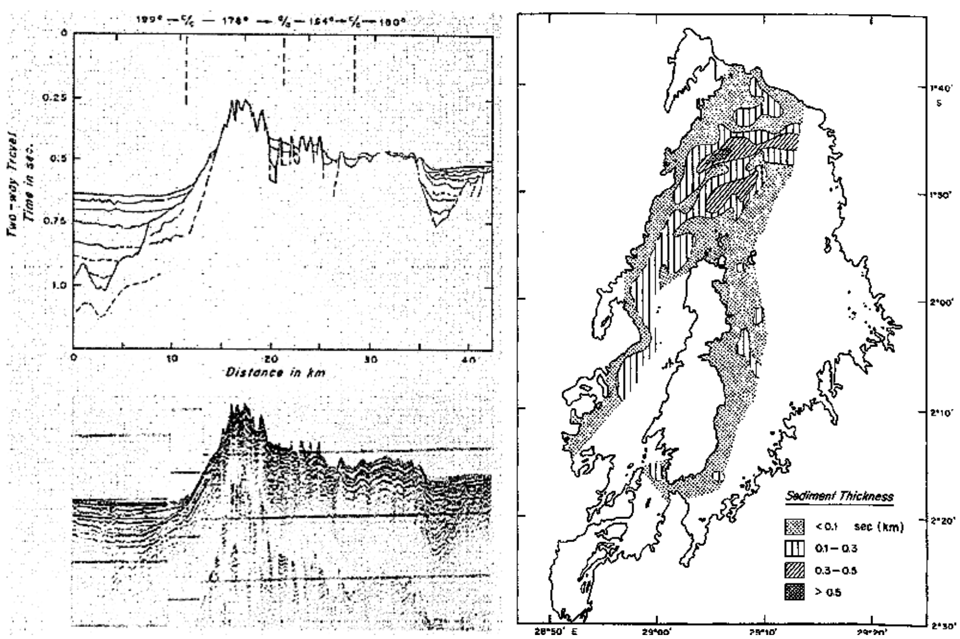

FIG. 7. An example seismic section (lower left) from seismic data acquired in 1971 (WHOI, 1971) and its interpretation (upper left) from western Lake Kivu. The resultant interpretation of sediment thickness over the survey area is displayed on the right.

Nonetheless, when we overlie an outline of zones of greater unconsolidated sediment thickness from Wong and Von Herzen (1974) which was interpreted from the Woods Hole studies, we find some correlation.

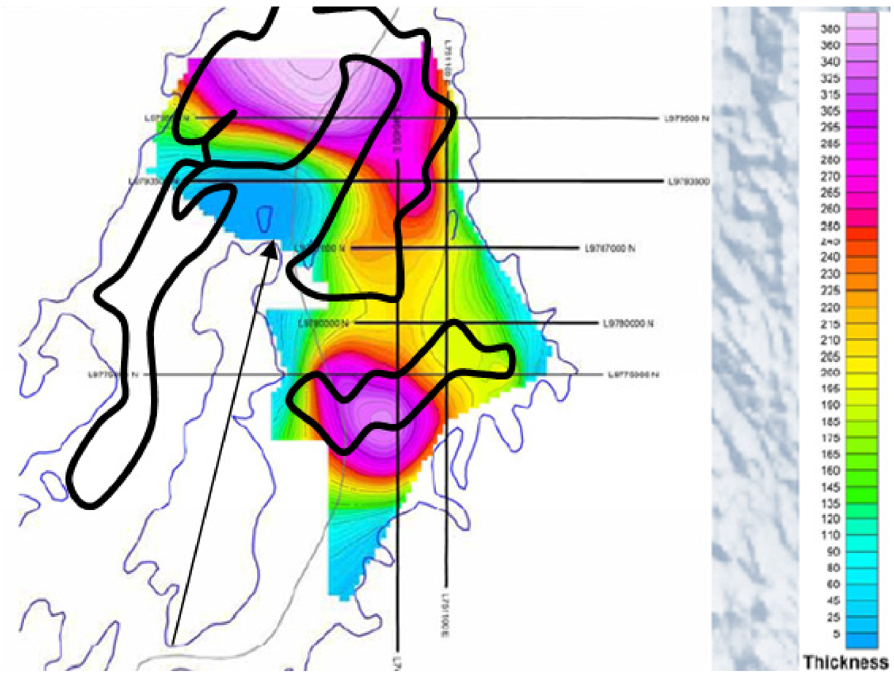

FIG. 8. The dark contours are from Wong and Von Herzen (1973) indicating their interpreted zones of greater unconsolidated sediment thickness. They bear some correlation with the estimated unconsolidated thickness from the airborne potential methods (GWP, 2008).

However, there is a clear need for deeper penetrating seismic data if the sedimentary structure and hydrocarbon potential of the strata underneath Lake Kivu is to be assessed. The concern is whether a seismic survey of this nature could somehow destabilize the lake. That is, could the vibrations induced in the lake water from a seismic source be an environmental issue? With a large population encircling Lake Kivu, caution is certainly warranted. The work discussed in this report follows two lines of investigation: 1) What levels of vibration has Lake Kivu already endured? And how do exploration seismic sources compare to these previous events? 2) What level of shaking or movement of deep lake waters could be destabilizing? And do exploration seismic sources approach these levels? Before this analysis though, it is useful to review the reasons for undertaking seismic surveys in the first place.

SEISMIC SURVEY RATIONALE

There are a number of reasons to undertake seismic surveys on Lake Kivu. They could be categorized as scientific, hazard reducing, and economic. All would be useful. Motivations for the surveys are to:

1. Scientifically study a modern tectonic rift zone

2. Understand the Lake's depositional history for climate change studies
3. Look for gaseous hazards in lake-bottom sediments
4. Look for fluid or gas injections into the Lake
5. Image previous slumps and landslides for future hazard assessment
6. Describe the record of volcanic eruptions as evidenced in the lake bottom
7. Image faults underneath and around the lake
8. Determine the stratigraphy beneath the lake
9. Estimate depth to basement
10. Map structures (traps) that could host hydrocarbons
11. Look for direct hydrocarbon indicators and estimate lithology (rock) type
12. Develop more detailed bathymetry for site surveys, moorings, structure
13.

VIBRATIONAL DISTURBANCES OF LAKE KIVU

The gases dissolved in Lake Kivu have been sampled a number of times and are thought to be in a stable containment state – that is, they are well beneath saturation (bubble point) pressures at their depth (Figure 9). Bubble formation (rupturing of the fluid or cavitation) occurs when ambient pressure falls below vapor pressure (Brennen, 1995). To cause de-gassing of the water would require a significantly disruptive event including lifting of the saturated water to a much shallower depth, considerably lowering the hydrostatic pressure, or greatly increasing the partial pressure of the gases. Could exploration seismic vibrations have these effects? We will explore this question in the following overview.

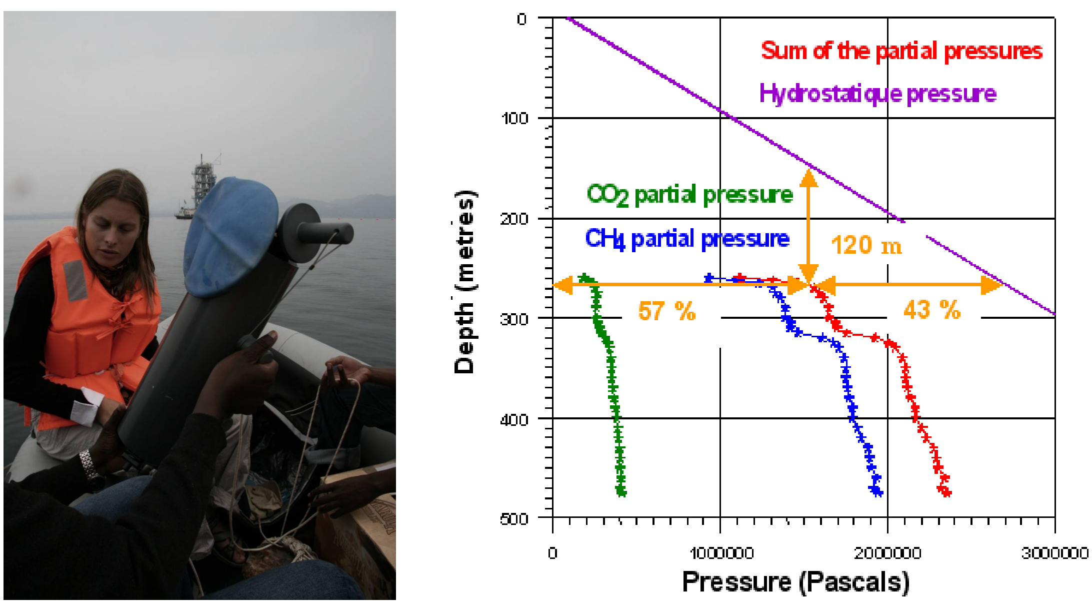

FIG. 9. Water sampling on Lake Kivu near the methane extraction facility (R. Stewart photo; January, 2010). Measurement of the gas partial pressures, total gas pressure, and hydrostatic pressure in Lake Kivu.

The general consensus at a recent workshop (Tropical Rift Lake Systems at Gisenyi, Rwanda, Jan. 13-15, 2010 sponsored by the US National Science Foundation) on the hazard assessment of Lake Kivu indicated that destabilization of the lake would likely need a major event such as a large earthquake, volcanic eruption close to or in the lake, or landslide. As volcanoes, for example, are often inherently unstable (Acocella, 2010), these are important concerns.

The Lake Kivu region (as part of the East African Rift Zone) has been subjected to significant earthquake activity (Figure 10).

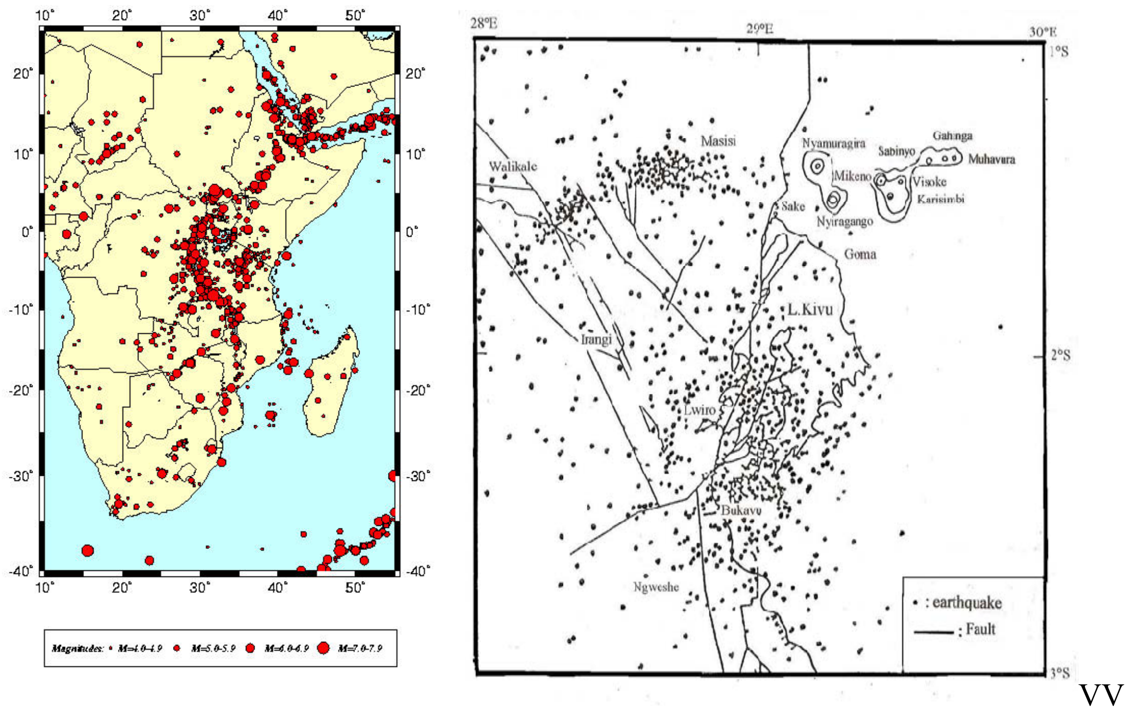

FIG. 10. Historical seismicity map of east Africa indicates considerable activity with significant earthquakes (left). A more detailed map of the seismicity of Lake Kivu basin for the period from Aug. 1979 to Dec. 1980. Most of earthquakes had Magnitude ≤ 3.5 (Wafula et al., 2009).

While many of the earthquakes are small, there have been several recent events that have had magnitudes in the 6 range (Figure 11). These have led to substantial ground shaking in excess of the 10cm/s and 0.1g range Other earthquakes, for example associated with the volcano Nyiragongo, have exceeded magnitude 5.0 (Shuler and Ekström, 2009). Appendix 1 provides a comparison of earthquake energies and man-made events.

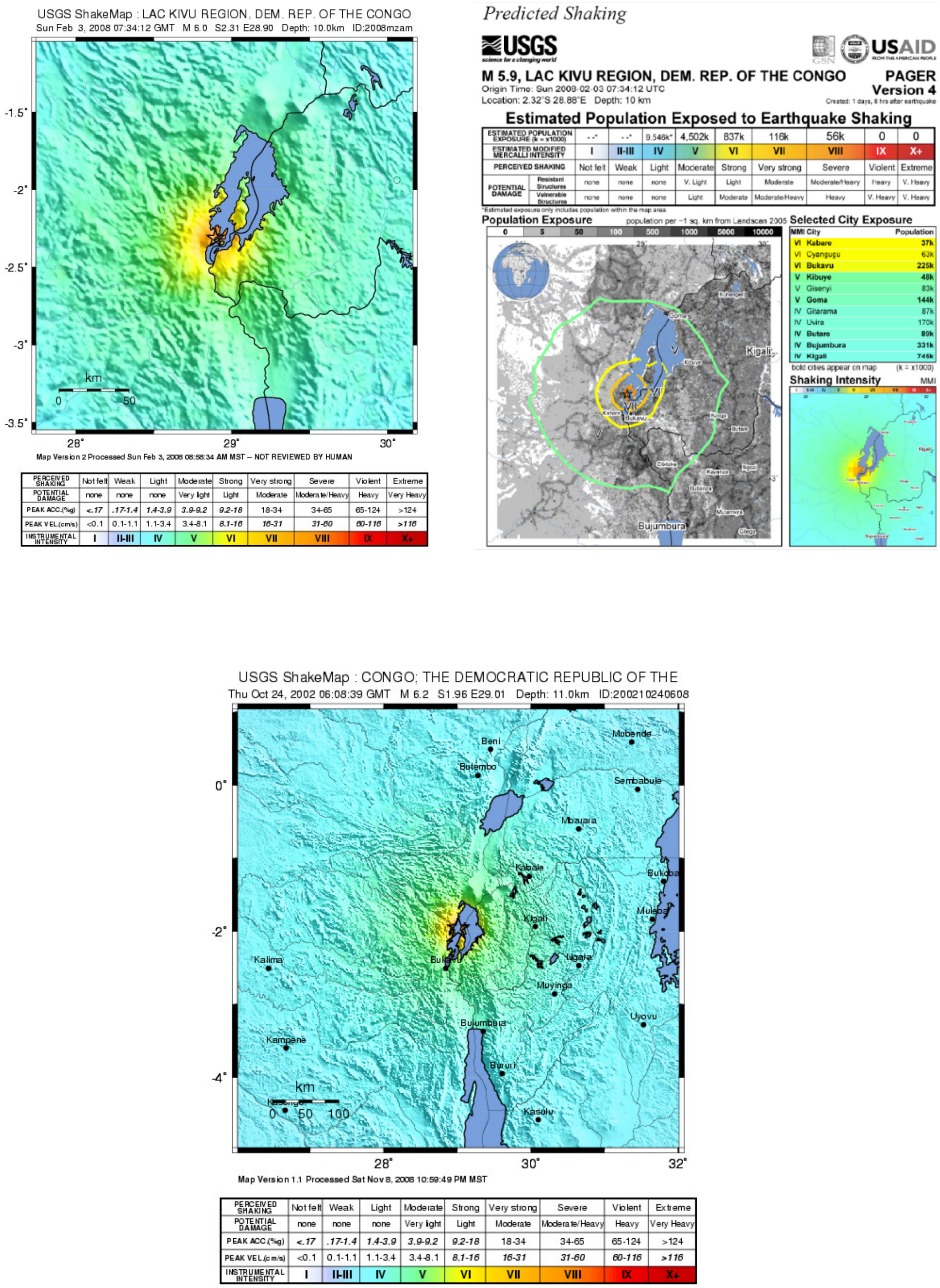

FIG. 11. Ground shaking maps for the 2008 (above left and right) and 2002 (above center) earthquakes (magnitudes 6.0 and 6.2, respectively) with epicenters at Lake Kivu from the United States Geological Survey. These shake maps indicate velocity values in excess of the 10cm/s and 10% g range.

In fact, due to the interaction of the lake bottom with the overlying water, the vibration in the lake could actually have been somewhat amplified (by 1.4 times) during the earthquakes – as indicated in the plot below (Figure 12). Note that we've estimated some of the material properties of the lake sediments using Gardner's relationship [a density of 2 gm/cc, from PGW (2008), gives a P-wave velocity of 1732m/s] and the mudrock line

$$Vp = 1.16Vs + 1.36, \qquad (1)$$

where Vp and Vs refer to P-wave velocity and S-wave velocity, respectively in km/s.

We calculate a Vs of 323m/s. The acoustic velocity of the water is dependent on temperature, salinity, and to a lesser extent depth (Appendix 2). We use a value of 1540m/s.

Wong and Von Herzen (1974) give unconsolidated sediment velocities from 1.5 km/s – 1.6 km/s. The associated Gardner density would be 1.95 gm/cc. They also provide a lower layer (consolidated sediment) velocity of about 2,700m/s. Again using Gardner's relationship, this indicates a density of 2.23g/cc. PGW (2008) used 2.4g/cc for the consolidated material in their modeling.

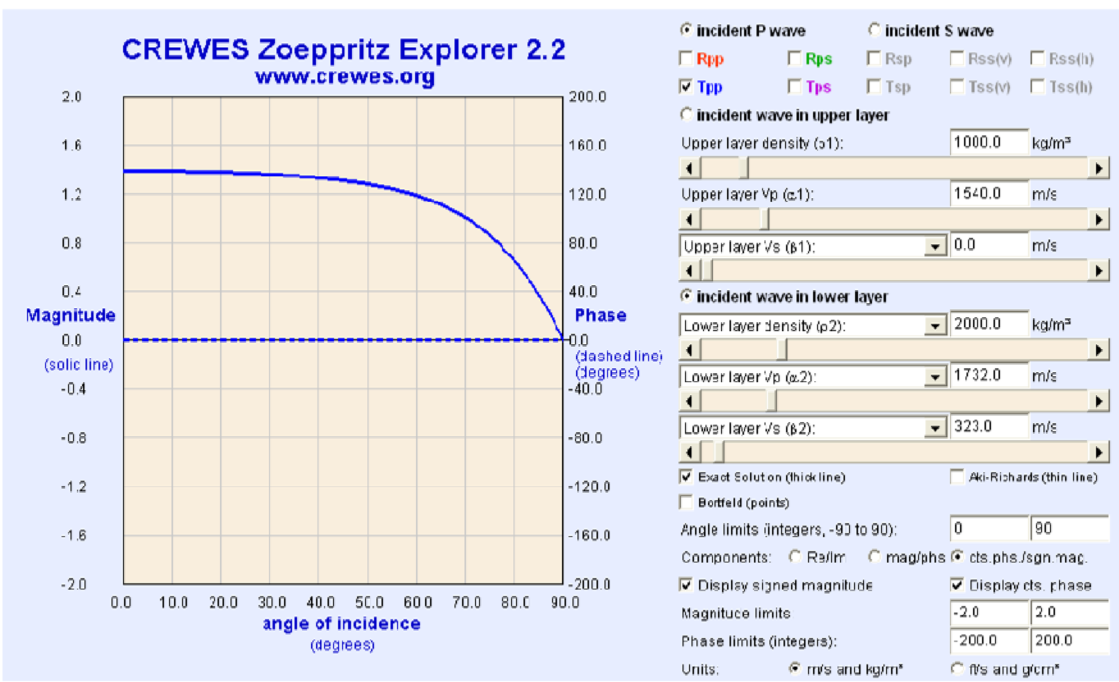

FIG. 12. A plot of the motion transmitted across a solid interface to overlying water. The upper layer is lake water while the lower layer is an estimate of the sediment properties. The CREWES (University of Calgary, Canada) motion simulator is used for the calculation.

Lava from the 2002 eruption of Nyiragongo (Figure 13) reached the Lake and possibly penetrated to a 100m depth (Lorke et al., 2004). This intrusion did not seem to cause significant warming, destratification, or disruption of the deeper layers of the lake.

FIG. 13. Nyiragongo volcano as viewed from the southeast (R. Stewart photo; January, 15, 2010) and an elevation map of the area (Google Earth).

The Lake is also subject to numerous other sources of vibration, such as boat traffic (Figures 3 and 14), aircraft noise, methane production, and storms. All of these sources cause vibrations in the waters of Lake Kivu (e.g., Gordienko and Gordienko, 2007).

FIG. 14. Water sports on Lake Kivu (left) from the Serena Hotel, Gisenyi and an airplane leaving Goma and flying over Lake Kivu (R. Stewart photos).

UNDERWATER ACOUSTICS

Vibrations and pressures in water are measured using a number of different units as given in Appendix 3. Sound pressure can be specified in the SI (mks) system with a Pascal (Pa), equivalent to a Newton/m2, or bar (105 Pa). Other units include an atmosphere (atm) - the approximate air pressure at sea level - and pounds per square inch (psi), where approximately 14.7 psi is equal to an atmosphere. Now, we also need to be able to convert pressures (p) into vibrational amplitudes (ξ) or particle velocities (v). This is accomplished by knowing the acoustic impedance (Z) which is the product of the water's density (ρ) and inherent sound speed (c). The acoustic or sound intensity (I) or pressure flux is given by the product of pressure and particle velocity. Then,

$$p = Zv = \rho cv = I/v, \tag{2}$$

where p is the pressure in the fluid in Pa; Z is the acoustic impedance, sound impedance, or characteristic impedance in Pa·s/m; v is the particle velocity in m/s; and I is the acoustic intensity or sound intensity, in W/m2.

Particle displacement (or particle amplitude) ξ, in m, is connected to pressure and frequency (f) of the motion by

$$\xi = v/2\pi f = v/\omega = p/Z\omega, \qquad (3)$$

where ω is the angular frequency.

Equivalently, sound pressure is related to particle motion by

$$p = \rho c\omega\xi = Z\omega\xi. \qquad (4)$$

When a pressure source excites its surrounding fluid, the energy spreads out in the fluid and the amplitude of the vibration decreases. Gausland (2000) provides a straightforward equation for the pressure variation with distance from the seismic source:

$$p(r) = p(s) - 20 \log10(r) - .002r, \qquad (5)$$

where p is the pressure at distance r (in meters). The very near source pressure output is given by p(s). He also takes the acoustic impedance of water to be 1.54 x 106 Pa•s/m. Close to the source acoustic pressures are often quite high, but they decay rapidly (Figure 15).

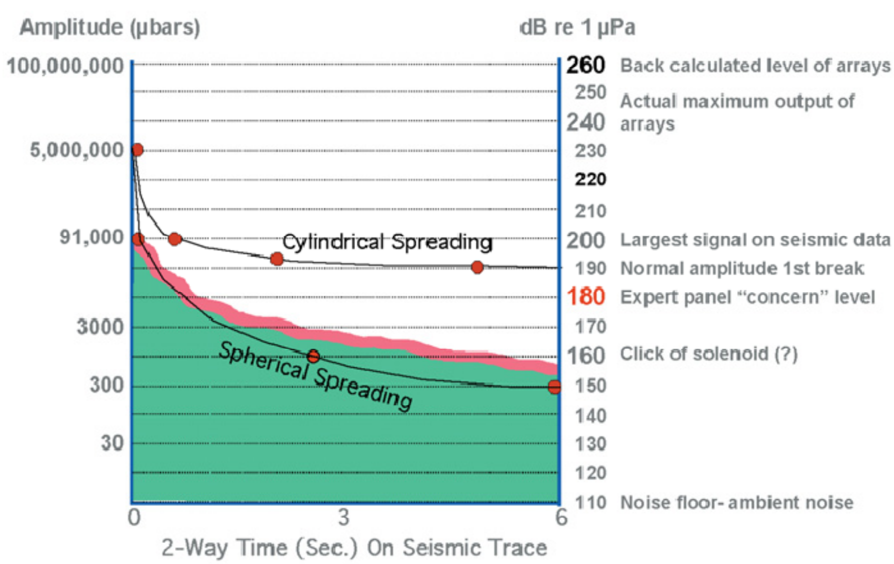

FIG. 15. Decrease of seismic energy from an airgun array as a function of two-way seismic traveltime (from Caldwell and Dragoset, 2000). Three seconds, on the horizontal axis, is equivalent to about 4500 m travel path.

MARINE SEISMIC SOURCES

In the seismic reflection method, a vibration is produced which propagates into the Earth and reflects or echoes from various subsurface interfaces. These minute vibrations are detected and recorded by sensitive motion sensors. There are a number of types of sources used to generate a vibrational disturbance as listed in Table 1. The most commonly used source for deeper penetration is the air gun. Marine vibrators and water guns have historically not been favored due to reliability or mechanical problems, operational complexity, low penetration ability, or reduced frequency bands (IAGC, 2002).

Table 1. Types of marine seismic sources and their operating frequencies (from Woods Hole Science Center, http://woodshole.er.usgs.gov/operations/sfmapping/seismic.htm).

Water gun	20-1500 Hz
Air Gun	100-1500 Hz
Sparker	50-4000 Hz
Boomer	300-3000 Hz
Chirp systems	500 Hz-12 kHz 2 - 7 kHz 4 - 24 kHz 3.5 kHz and 200 kHz

Marine seismic source output is often represented logarithmically relative to a very small pressure (1 μPa). That is, the pressure (p) at some point is described as a certain decibel value greater than 1 μPa:

$$\text{Output in dB} = 20 \log [p/(1\mu\text{Pa})] \tag{6}$$

Additionally, the pressure may be given at a distance (usually 1m) from the source itself. Further characteristics of various marine sources are given in Appendix 4. Airguns (often in arrays) used in the open ocean release large volumes of high-pressure air. There has been considerable concern that these exploration sources could injure fish, sea mammals, even crustaceans. Thus, extensive testing of marine sources has been reported. Wardle et al. (2001) discuss a case with a seismic triple G. airgun (three synchronised airguns, each gun 2.5 l and 2000 psi) was deployed and repeatedly fired. The guns were fired once/min for eight periods on four days at different positions. The structure and intensity of the sound of each triple G. gun explosion was recorded and calibrated. Peak sound pressure levels of 210 dB (rel to 1 μPa) at 16 m range and 195 dB (relative to 1 μPa) at 109 m range were measured at positions where the fish were being observed. The final position of the triple G. gun, at 5.3 m range, had a peak pressure level of 218 dB (relative to 1 μPa).

U.S. regulations indicate that sound pressure levels above 180 dB pose a risk of injury for whales and dolphins and beyond 190 dB for seals. Pressure levels associated with disrupting marine mammals’ behavior are some 70 dB lower (Tyack, 2009). Another airgun experiment gives maximum pressure levels of 200dB with respect to 1uPa for a 3190 cu in. 21 element airgun array and 177 dB µPa2/s maximum sound pressure exposure levels with measurement some 750 m from the seismic source array (Tashmukhambetov et al., 2003). Wilmut et al. (2007) report on a test with the primary sound source being a single 164 cm3 Bolt air gun that was deployed from the stern of the Tully and operated using a pressure cylinder on the ship. The air gun generated average sound exposure levels of 151 dB re µPa2s-1 at the ocean-bottom (sponge) location some 160 m away. Examples of air gun signatures are given in Figure 16. We note that the sound pressure is up to about 50 kPa for the largest air gun.

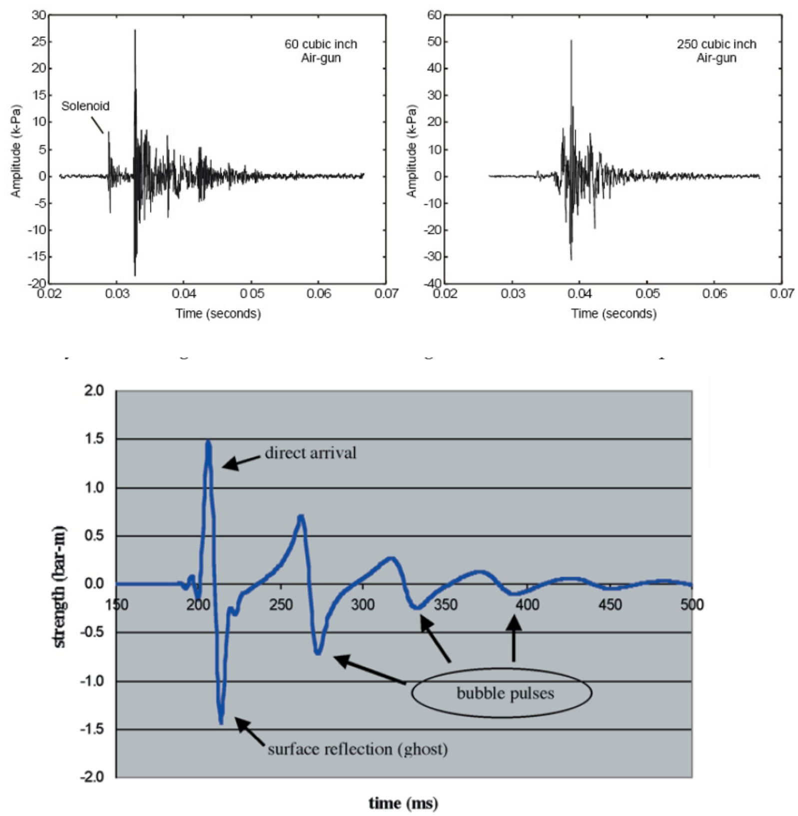

FIG. 16. Signature of marine seismic sources (above left and right) at 10 m from the source from http://www.iwcoffice.org/_documents/sci_com/SC58docs/SC-58-E30.pdf and a 40 cu. in. air gun signature measured at 300 m (above center) from Dragoset (2000).

PREVIOUS SEISMIC SURVEYS IN AFRICAN LAKES

There have been many 100s of kilometers of seismic data acquired on African lakes over the last decades: A survey was undertaken on Lake Bosumtwi to image the sub-bottom of this meteorite impact crater. A 35 cu. in. (0.57 l) air gun was used at a 10m depth (Meillieux et al., 2007). In addition, a 52 cu. in. (0.85 l) air gun was employed for wider-angle velocity analysis (Scholz et al., 2002). Coherent data to approximately 0.8s and an interpreted depth of about 450 m were found. Scholz et al. (2003) acquired more than 400km of seismic reflection data on Lake Tanganyika with a small airgun 10 cu. in. (0.16 l) giving data returns from more than 0.8 s two-way traveltime. Karp et al. (2009) used an array of three Bolt airguns, 0.66 l (40 cu in) each, and a 1200 m long digital streamer with 48 channels (25 m channels spacing) for work in Lake Albert. Shot spacing was 25 m, resulting in a 24-fold data set with a CDP spacing of 12.5 m. Source and streamer were generally towed at a depth of 3 m, but brought closer to the surface where the water was very shallow (< 10 m). The length of the recorded data is 6.144 s with a sampling rate of 1 ms. The results of this recording provided up to 3.5 s of interpretable reflection events (and up to 5km of sediments under the lake were interpreted). Seismic data have been acquired in a number of other Africa Rift zone lakes (Lake Malawi - Mortimer et al., 2007).

Lake Kivu itself experienced seismic surveys in the early 1970s (Wong and Von Herzen, 1974). Fugro OSAE (Offshore Survey and Engineering) GmbH posted note of a survey undertaken on Lake Kivu (with an SBP source ~ 220dB at 1uPa at 1m from 3.5kHz to 7.5kHz) in 1998 consisting of a surprising 14,000 line km of survey lines for Lahmeyer Intl. (http://www.fosae.de/refs_bathy.htm).

VIBRATION COMPARISONS

Let's now compare these seismic sources to other types of events. There are well established stand-off distances for seismic surveys on land – that is, prescribed separations from a seismic source to various structures which could suffer vibrational damages (Appendices 5 and 6). These distances are regarded as those that will prevent harm to nearby structures. For relatively large sources (4 kg of dynamite and vibrators), the distances can be up to 100m.

In terms of total energy, the sub-bottom sounder's output is in the 1 kJ range (Figure 16) and might produce around 120 dB pressures (relative to µPa at 1m) near the source. This is smaller than a magnitude 0.0 earthquake and fishing vessel, respectively. The energy release of dynamite is about 4.2MJ/kg. Thus, the sounder's energy release should be similar to a gram of explosive (1/1000 of a normal land source). To achieve a sense of an earthquake's energy (up to magnitude 6.2 near Lake Kivu), a one kT nuclear explosion is similar to a magnitude 4 earthquake. A 20 kT nuclear explosion is approximately equivalent to a magnitude 4.8 earthquake. Dorman and Sauter (2006) describe a new implosive marine source which can be used near the seafloor. They note that at 500m water depth, their 20 liter source is about equivalent to 0.5lb of dynamite. They also indicate that this corresponds to an earthquake moment magnitude of -0.9.

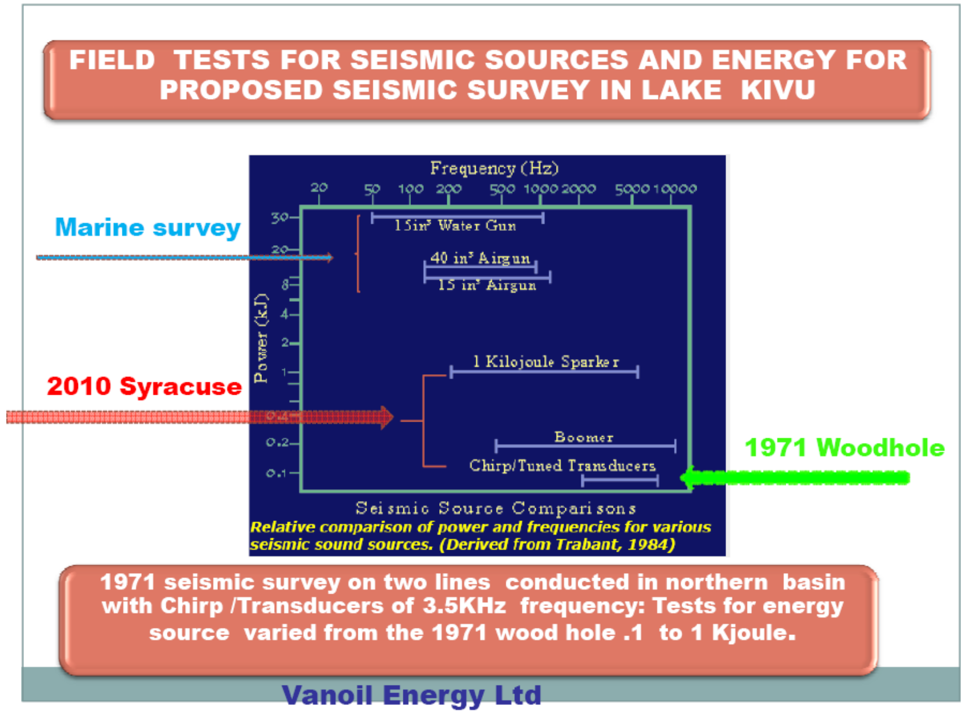

FIG. 16. Frequency range and power output of various small marine seismic sources (After Woods Hole Science Center, http://woodshole.er.usgs.gov/operations/sfmapping/seismic.htm).

A seismic air gun will produce higher energy output and pressures. The air gun might output about 200 dB wrt $1\mu Pa$ @ 100m with a resultant 104 Pa pressure oscillation. Comparing this to the pressure graph in Figure 9, we see that it is a small pressure variation compared to the 1000 kPa hydrostatic head. At 300m depth, a 0.01MPa pressure oscillation is also small compared to the total partial pressure/hydrostatic head differential (greater than 1 MPa).

If we have a pressure oscillation of 10 kPa (0.1 bar), then we expect a particle or shaking velocity of v=0.6 cm/s (with a water impedance of Z=1.54 x 106) which appears to be considerably smaller than the shaking velocities of recent earthquake events at Lake Kivu. The particle motion excursions could be estimated using a 25Hz signal in water with a velocity of 1540m/s. This gives a seismic wavelength of about 60m. If we have strains in the larger seismic range of about 10-5, then the particle displacement should be on the order of millimeters. Wave propagation particle motion should be quite small compared to destabilizing motions of 10s of meters.

Wüest et al. (2009) discuss a water column stability attribute – the Schmidt stability. This value gives the energy input (over a sq. meter) required to homogenize the stratification in the water column. They suggest that the value for Lake Kivu is greater than 300,000 J/m2. Fricke et al. (1985) give general energy flux values for air guns as ranging from 100 J/m2 to 10,000 J/m2. To achieve the kind of energy to create instability in the Lake, with seismic sources, would appear to require many airguns deployed every square meter over the Lake. The amount of energy in waves and currents due to the wind over Lake Kivu would compare to sparker sources placed at every square meter over the Lake (Figure 17).

	Pings /Survey	J /Ping	Duty Cycle	Peak Frq	Frq Range	Watts	Peak Pres re 1 µPa	Pulse Duration	Directionality sr/4pi	Source Depth	Tow Rate
Added noise:											
Airgun Array &	100,000	2.5 x 10^5	20 s	50 Hz	5-200 Hz@	8.3 x 10^6	256 dB	.03 s	0.25	3-12 m	4 kts
Silenced Airguns										3-12 m	4 kts
Marine Vibrators	Similar to airguns			10 Hz	6-100 Hz#	?	20-50 dB below airguns	6-10 s	omni	0-1000 m	0-4 kts
DTAGS	c20k		30s	650 Hz	220-850Hz			250ms	omni	0-6 km	2kts
Para-metrics	?	?	?	?	?	?	?	?	10 deg.	0-6 km	?
LISA			100%	10	5-500	20-200K	210@1m	continuous	variable	0-100m	0-4kts
Sparkers +	c20k	300	1 s	500 Hz	480-520 Hz	1.5 x 10^5	233 dB	2 ms	omni	0-6 m	
Boomers	c20k	280		600Hz	0.1-15 kHz			2-3 ms	omni	0-6 m	4 kts
LACS**				50 Hz	10-150 Hz		212 dB	8-100 ms			

FIG. 17. Marine seismic sources and their characteristics (Weilgart, 2009).

Wüest et al. (2009) also introduce the concept of a “safety margin”, that is the amount of energy per volume required to potentially destabilize deeper waters. They suggest that susceptible water would be deeper than 200m and have a safety margin of about 2000 J/m3. Sounder sources have relatively smaller energies released (1kJ) which will also be markedly decreased at 200 m depths. If we take an air gun array with a much larger 250 kJ output and imagine that this energy is distributed across a hemispherical volume 10 m thick (a wavelength) at 200 m, then its energy density would be on the order of 0.1 J/m3.

CONCLUSIONS

There have been and are a number of vibrational disturbances in Lake Kivu, Rwanda (e.g., earthquakes, lava flows, boats, aircraft, and storms). These have not caused known, serious disruptions of the Lake. There are scientific, hazard-reduction, and economic reasons to undertake seismic surveys on the Lake. However, these must be weighed against potential untoward environmental consequences. There have been seismic surveys previously conducted on Lake Kivu without known consequences. New proposed low-power (2010 Syracuse) and seismic (small air gun) surveys are likely to have considerably smaller energies and deep pressures than previous natural events and the pressure changes and energy charging required to directly effect hydrostatic stability.

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APPENDIX 1 – ENERGY RELATIONSHIPS AMONG EARTHQUAKES AND EXPLOSIONS

Richter Approximate Magnitude	Approximate TNT for Seismic Energy Yield	Joule equivalent	Example
0.0		63 kJ	
0.5	0.07kg (0.16 oz)	.35 MJ	Large hand grenade
1.0	0.43kg (0.95 lb)	2.0 MJ	Construction site blast
1.5	2.42kg (5.34 lb)	11.2 MJ	WWII conventional bombs
2.0	30 lb	63 MJ	Late WWII conventional bombs
2.5	168 lb	354 MJ	WWII blockbuster bomb
3.0	952 lb	2.0 GJ	Massive Ordnance Air Blast bomb
3.5	2.67 metric tons	11.2 GJ	Chernobyl nuclear disaster, 1986
4.0	15 metric tons	63 GJ	Small atomic bomb
5.0	476 metric tons	2.0 TJ	Seismic yield of Nagasaki atomic bomb (Total yield including air yield 21 kT, 88 TJ)
6.0	15 kilotons	63 TJ	Double Spring Flat earthquake (NV, USA), 1994
6.5	84 kilotons	354 TJ	Rhodes (Greece), 2008 Southeast of Taiwan (270km), 2010
7.0	476 kilotons	2.0 PJ	Java earthquake (Indonesia), 2009 2010 Haiti Earthquake
7.1	666 kilotons	2.8 PJ	Energy released is equivalent to that of Tsar Bomba (50 megatons, 210 PJ), the largest thermonuclear weapon ever tested 1944 San Juan earthquake
7.8	7.5 megatons	31.6 PJ	Tangshan earthquake (China), 1976 April 2010 Sumatra (Indonesia)

8.0	15 megatons	63 PJ	México City earthquake (Mexico), 1985 Gujarat earthquake (India), 2001
8.5	84.2 megatons	354 PJ	Toba eruption[citation needed] 75,000 years ago; the largest known volcanic event Sumatra earthquake (Indonesia), 2007
8.8	238 megatons	1.0 EJ	Chile earthquake, 2010
9.2	947 megatons	3.98 EJ	Anchorage earthquake (AK, USA), 1964
9.3	1.3 gigatons	5.6 EJ	Indian Ocean earthquake, 2004
9.5	2.67 gigatons	11.22 EJ	Valdivia earthquake (Chile), 1960

APPENDIX 2 – SPEED OF SOUND IN WATER (VERSUS TEMPERATURE AND SALINITY)

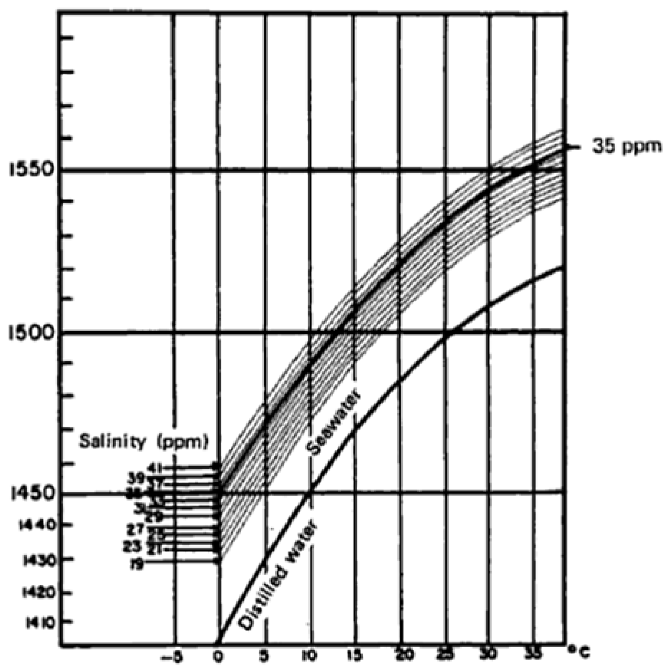


FIG. III.2.2. – Speed of sound in water (on the surface) in terms of temperature and salinity (according to Del Grosso).

$$V\,(\mathrm{m/s}) = 1{,}410 + (4.21\,t - 0.037\,t^2) + 1.105\,s + 0.018\,d$$

where:

t = temperature in degrees centigrade,
s = salinity in ppm,
d = depth of water in metres.

APPENDIX 3 – PRESSURE UNITS AND CONVERSIONS

The table below gives different pressure units and their conversions (from wikipedia - http://en.wikipedia.org/wiki/Pressure).

Pressure Units

	pascal (Pa)	**bar (bar)**	**technical atmosphere (at)**	**atmosphere (atm)**	**torr (Torr)**	**pound-force per square inch (psi)**
1 Pa	≡ 1 N/m²	10^{-5}	1.0197×10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	145.04×10^{-6}
1 bar	100,000	≡ 10^6 dyn/cm²	1.0197	0.98692	750.06	14.5037744
1 at	98,066.5	0.980665	≡ 1 kgf/cm²	0.96784	735.56	14.223
1 atm	101,325	1.01325	1.0332	≡ 1 atm	760	14.696
1 torr	133.322	1.3332×10^{-3}	1.3595×10^{-3}	1.3158×10^{-3}	≡ 1 Torr; ≈ 1 mmHg	19.337×10^{-3}
1 psi	6.894×10^{3}	68.948×10^{-3}	70.307×10^{-3}	68.046×10^{-3}	51.715	≡ 1 lbf/in²

Example reading: $1\ \text{Pa} = 1\ \text{N/m}^2 = 10^{-5}\ \text{bar} = 10.197\times10^{-6}\ \text{at} = 9.8692\times10^{-6}\ \text{atm}$, etc.

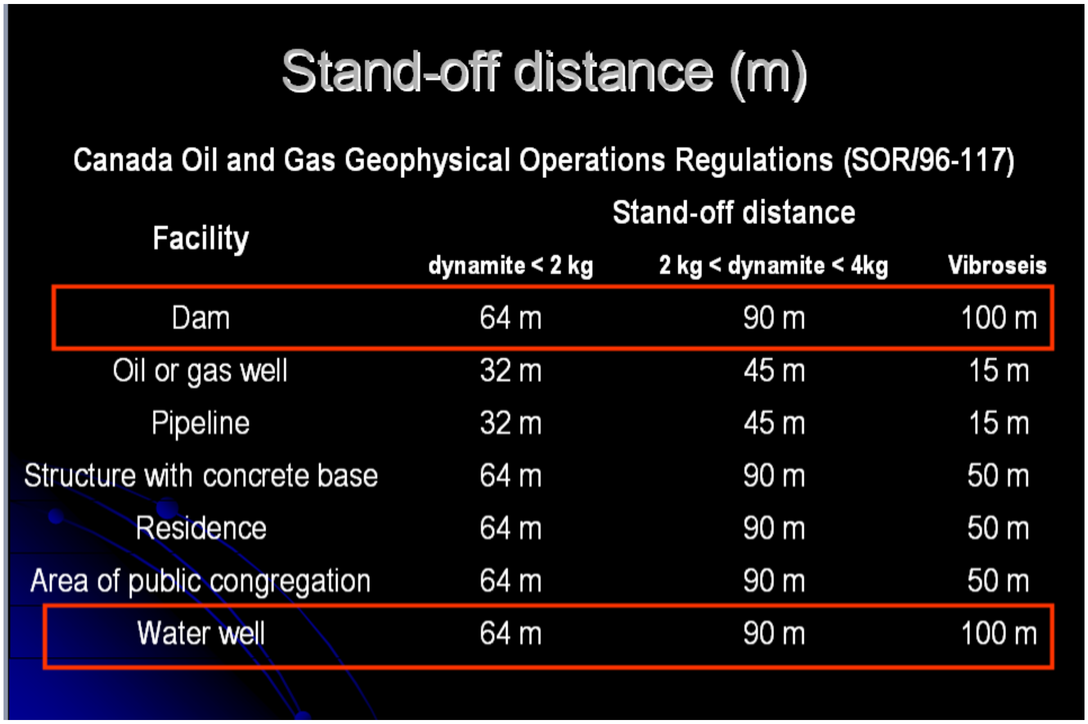
APPENDIX 4 – COMPARISON OF MAN-MADE UNDERWATER SOUND SOURCES

Sound Source	SPL dB re 1µPa @1m	Ping Energy (dB re 1µPa2*s)	Ping Duration	Duty Cycle (%)	Peak Frequency (Hz)	Band Width (Hz)	Direct-ionality
Underwater Nuclear Device (30 kilo-ton)	328	338	10 s	Inter-mittant	Low	Broad	Omni
Ship Shock Trial (10,000 lb TNT)	299	299	1 s	Inter-mittent	Low	Broad	Omni
Airgun Array 2000 psi and 8000 in3	256	241	30 ms	0.3	50	150	Vertical
Military Sonar (53C)	235	232	0.5 – 2 s	6	2,600-3,300	Narrow	Horizontal
Super Tanker 270 m long	198		CW	100	23	5-100	Omni
Research Sonar (ATOC Source)	195		20 minutes	8	75	37.5	Omni
Acoustic Harrassment Device	185	185	0.5 - 2 s	50	10,000	600	Omni
Multibeam (Echosounder Hull-mounted)	235	218	20 ms	0.4	12,000	Narrow	Vertical
Fishing Vessel 12 m long (7 knots)	150		CW	100	300	250-1000	Omni

CHARACTERISTICS OF SEDIMENT SOUNDERS

Manufacturer	EGG	ORE	EDO Western	Raytheon	CESCO	Thomson CSF
Type	Pinger probe 229	Sub-bottom profiling system : model 1,036	Model 515	RTT Transducer TC-7 1,000 Transceiver PTR 106 A	SONIA Mark I or II	TEF
Frequency	5 kHz	3,5-7 kHz	3,5-7 kHz	7 kHz	3 kHz	3,5-6 kHz
Power		10 kW	2 kW/10 kW	2 kW	10 kW	1 kW
Pulse duration	0.4 ms Energy = 0.4 J Firing rate = 20 pulses/s		0,5 ms	0,1-1 ms	0,4 ms	Adjustable from 0.1 ms
Transmission level (ref. : 0,1 Pa at 1 m)	98 dB	114 dB	112/116 dB			107 dB

APPENDIX 5 – STAND-OFF DISTANCES FOR LAND SEISMIC SOURCES AND INFRASTRUCTURE



Stand-off distance (m)

Canada Oil and Gas Geophysical Operations Regulations (SOR/96-117)

Facility	Stand-off distance		
	dynamite < 2 kg	2 kg < dynamite < 4kg	Vibroseis
Dam	64 m	90 m	100 m
Oil or gas well	32 m	45 m	15 m
Pipeline	32 m	45 m	15 m
Structure with concrete base	64 m	90 m	50 m
Residence	64 m	90 m	50 m
Area of public congregation	64 m	90 m	50 m
Water well	64 m	90 m	100 m

APPENDIX 6 – SAFE STAND-OFF DISTANCES OF A SEISMIC SOURCE FROM A MARINE VESSEL

No. of Guns	Air-Gun Source Type	Total Chamber Size (in.^{2})	Measured Peak Amplitude (bar-m)	Conservative Safe Distance Calculation (m)
1	Single gun	150	3.0	4.0*
2	Dual gun cluster	300	5.2	6.3
3	Triple gun cluster	450	6.7	8.1

* In all cases, 4.0 m is the minimum recommended distance for any source, regardless of the size of the air gun used.