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NEW DIMENSIONS IN STUDYING TRANSBOUNDARY AQUIFERS IN AFRICA: SEISMIC INDUCED HYDROLOGICAL CHANGES

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The interaction between volcanism, tectonic activities, and uplift results in aquifer compartmentalization, discontinuous groundwater flow, lower groundwater storage, and complex groundwater flow patterns. Hydrologic changes can occur in response to large earthquakes including (1) large drop of the water table in the mountainous areas; (2) rapid increase of discharge along active faults; and (3) change of chemistry of discharged water. Researchers have concluded that earthquakes offer a unique way to observe how hydrological systems behave, from small watersheds to transboundary aquifers which represent aquifers of large areal extent. Seismic events inducing hydrological changes have not received sufficient attention from most researchers although many parts of the African continent are located at the intersection of two seismically active tectonic belts. The proper management of transboundary aquifers in Africa should consider all factors to promote basin awareness by working to increase and exchange knowledge of groundwater units. Seismic events inducing hydrological changes is a new dimension that should be considered in studying shared aquifers in Africa.

INTRODUCTION

In attempts to optimize the future development of a transboundary basin, certain types of approaches should be sought preferentially, both by institutions dealing with transboundary water resources and by national water authorities themselves.

A convincing explanation of earthquake-induced hydrological and geochemical changes is that they are caused by changes in groundwater pressure due to the earthquake-induced changes in crustal volumetric strain (Wakita, 1975; Roeloffs, 1988; Kawabe, 1991; Muir-Wood and King, 1993).

Seismic waves shake aquifer materials and hence increase the permeability of rock to groundwater and other fluids. An earthquake emits its power in three waves of energy. Compressional or primary, or P-waves, are felt as a sudden jolt. Shear or secondary, or S-waves, arrive a few seconds later and are felt as a more sustained side-to-side shaking. Surface waves radiate outwards from the epicenter (Figure 1).

Seismic waves have two main types of effects on groundwater levels: oscillations, and “permanent” offsets. Muddy or turbid water at long distances from the epicenter are most likely an aftereffect of oscillations. Seismic waves cause expansion and contraction of the aquifer tapped by the well, in turn causing oscillatory pore pressure changes (Cooper et al., 1965). If the aquifer has high enough transmissivity, then these pressure changes cause flow into and out of the well. This implies that the pore pressure changes in the aquifer are about the same size as the water level fluctuations in the well. Offset produces permanent expansion and contraction of the surrounding rocks (Roeloffs, 1998). The offsets can be “instantaneous” (to the resolution of the water level sampling interval), or they can begin abruptly and take days to weeks to reach their maximum (or minimum) values.

Seismic waves at distant locations are transient, yet they can trigger seismicity that persists for days (or longer) or larger events that are more delayed (Roeloffs et al., 2002). It is known that increasing fluid pressure can trigger earthquakes (lab and induced seismcity studies), and the seismic wave induced fluid pressure offsets are effects that last much longer than the duration of the seismic wave train. It also appears that triggered seismicity preferentially occurs in hydrothermal areas, and that in these areas fluid pressure rises are more likely to be increases. The exact mechanism linking the fluid pressure changes and triggered earthquakes isn’t yet pinned down, but the circumstantial evidence for a connection is rather compelling.

Ultimately, the most obvious manifestation of an earthquake is the shaking from seismic waves that knocks down buildings and rattles people. Now researchers have established a more subtle effect of this shaking — it increases the permeability of rock to groundwater and other fluids (Stephens, 2006).

SEISMIC INDUCED HYDROLOGIC CHANGES

Hydrologic changes associated with earthquakes can be expressed as an induced change in both quality and quantity of groundwater. The interaction between volcanism, tectonic activities, and uplifting also results in aquifer compartmentalization, discontinuous groundwater flow, lower groundwater storage and complex groundwater flow patterns, in addition to high salinity as well as high fluoride, and above average content of trace elements.

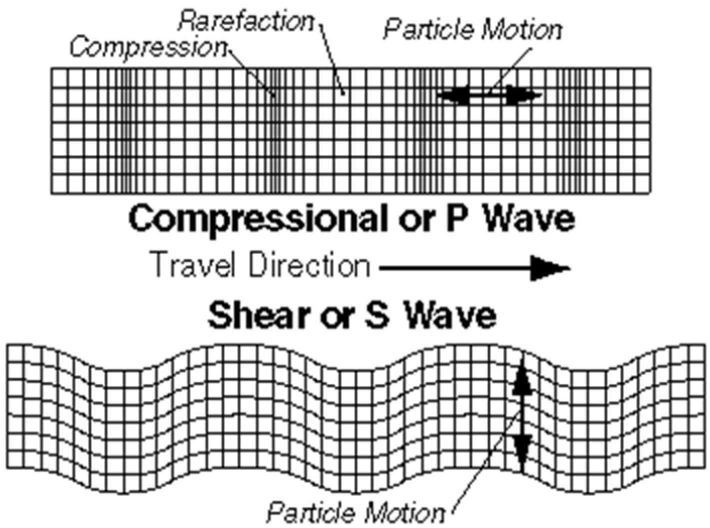

Figure 1. Compressional and shear waves impacted on aquifer's materials (Roeloffs, 1998).

CHANGES IN GROUNDWATER LEVEL

Four types of post-seismic responses may be distinguished (Shyu et al., 2008). In type 1, the groundwater level declined exponentially with time following a coseismic rise. This was the most common response in the study area (Chelungpu earthquake, Simoes et al., 2007) and occurred in unconsolidated sediments on the Choshui River fan. In type 2, the groundwater level rose exponentially with time following a coseismic fall as exemplified by the Landers earthquake (Figure 2). In type 3, the groundwater level continued to decline with time following a coseismic fall. This also occurred in the deformed and fractured sedimentary rocks near the ruptured fault as exemplified by the Northridge earthquake. Finally, in type 4, the groundwater level, following a coseismic rise, stayed at the same level or even rose with time before it eventually declined as exemplified by the Hector Mine earthquake (Figure 2) (Southern California Earthquake Data Center. Retrieved on 2007-11-4)

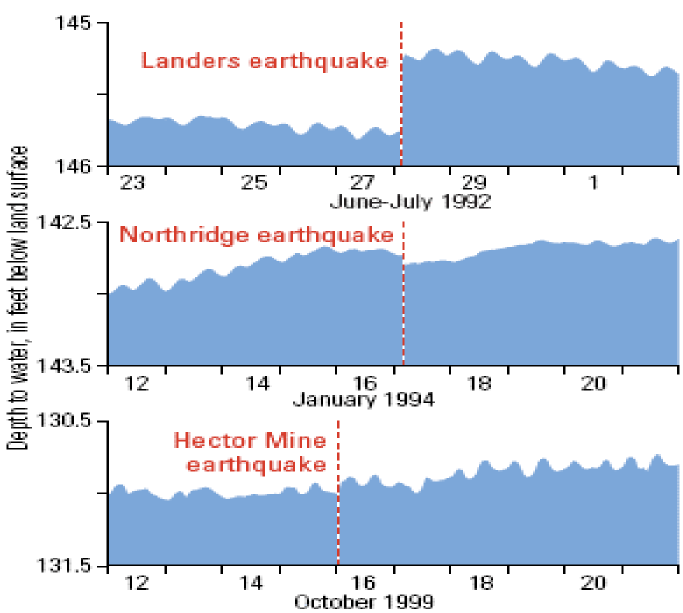

Figure 2. Earthquake induced groundwater level changes (Source: Southern California Earthquake Data Center. Retrieved on 2007-11-4).

Through the Cooperative Agreement with the U.S. Department of Energy, the Harry Reid Centre for Environmental Studies at the University of Nevada–Las Vegas (NCNSN, 1996) conducts ground water level measurements at selected boreholes near Yucca Mountain, and collects quarterly data from a network of 24 wells currently comprising the monitoring network. Most of these wells lie on the eastern flanks and along the crest of Yucca Mountain within Areas 25 and 29 of the Nevada Test Site (NCNSN, 1996). The plot of continuously monitored groundwater level changes due to the earthquake of Yucca Mountain is shown in Figure 3, while the quarterly ground water level changes are shown in Figure 4.

The Groundwater Research Group, Osaka City, Island of Awajishima, which is situated very close to the epicentre of Kobe earthquake, Japan, which occurred in January 17, 1995 (Figure 4), has reported repeatedly a dramatic decrease of groundwater level in the Kobe Earthquake. It has been reported by Sato et al. (1995) that groundwater levels started to drop soon after the earthquake (Figure 4), the water table in the central part of the Island before the earthquake was close to the topographic surface and dropped to more than 70m within 90 days after the earthquake.

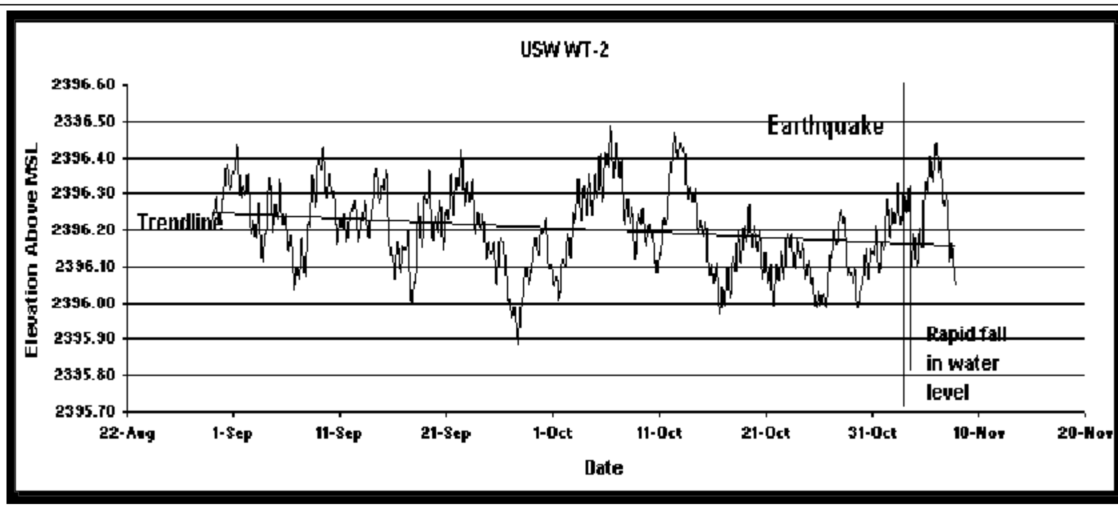

Figure 3. Plot of continuously monitored groundwater level changes, in meters showing effects of earthquake, Yucca Mountain, Nevada (NCNSN, 1996).

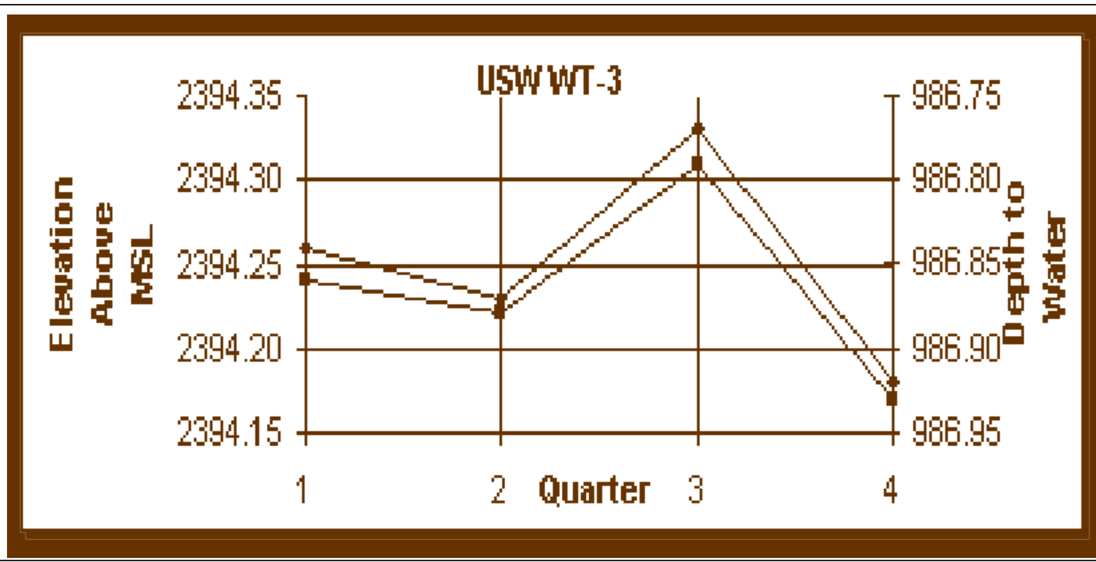

Figure 4. Plot of quarterly groundwater level changes, in meters, of earthquake, Yucca Mountain, Nevada (NCNSN, 1996).

RAPID INCREASE OF DISCHARGE ALONG ACTIVE FAULTS

The second earthquake induced hydrological change has included change of relative discharge as a function of time shown in Figure 5. Sato and Takahashi (1996) reported the volumetric change of discharge at six locations between May 1995 and June 1996. The overall discharge in June 1996 was 43% of that in May 1995. Although they did not measure the entire volume of discharge over the island, their locations are all situated at the major discharge points and also cover the studied area; thus, it can be assumed that the ratio of their measurements represents the ratio of the whole volume of discharge. Oshima et al. (1996) measured stream flow of four locations, located about 250 m from the coast, whose catchment areas extend about 500–600 m along the coast (Figure 5). They measured an overall discharge of 1.75 m3/min 290 days after the earthquake. This value is about 1.3–1.6 times larger than the steady state value (integrated over a 500–600m distance) obtained from the model which is described later, in the case where one-third of the annual rainfall is assumed to be the recharge rate. The increase of discharge also is significant compared with the annual fluctuations. Sato and Takahashi (1995) reported that the water level of one of the ponds, which is located where Oshima et al. (1996) measured discharge, increased very rapidly just after the earthquake even though no water existed there before the earthquake. Considering that the dam was artificially broken within a day after the earthquake to prevent it from overflowing, the increase of discharge must have been significantly larger than the annual fluctuations.

CHANGE OF CHEMISTRY OF DISCHARGED WATER

Earthquakes have imposed a drastic change in the chemistry of groundwater as a post seismic change in groundwater quality. In Awajishima Island, the change in chemical composition was observed after the earthquake of August, 1994 (Hake and Nishimura, 1994),the earthquake of Jan-Feb, 1995 (Sato et al., 1995), the earthquake of March, 1995 (Takamura and Kono, 1996) and the earthquake of October, 1996 in a well of 1205m depth as shown in Figure 6. The chemical composition of discharged water resulted in an increase in bicarbonate after the earthquake (Figure 6). The change of chemical composition can be explained either by the mixing of discharged water at steady state and the deeper water represented by the 1205m well or by the discharge of water that had been sidetracked into dead-end pores and/or slow pathways through relatively less

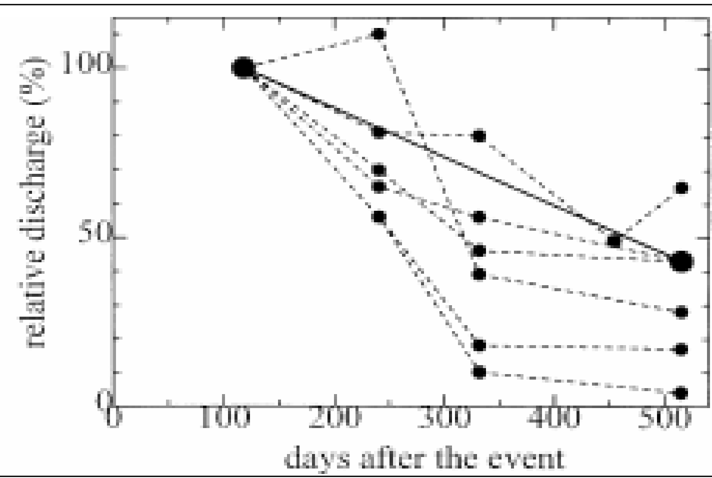

Figure 5. Change of relative discharge (normalized by that in May 1995) as a function of time. Small dots and dotted lines indicate each measurement and large dots and a line indicate the overall change between May 1995 and June 1996. Data after Sato and Takahashi (1996).

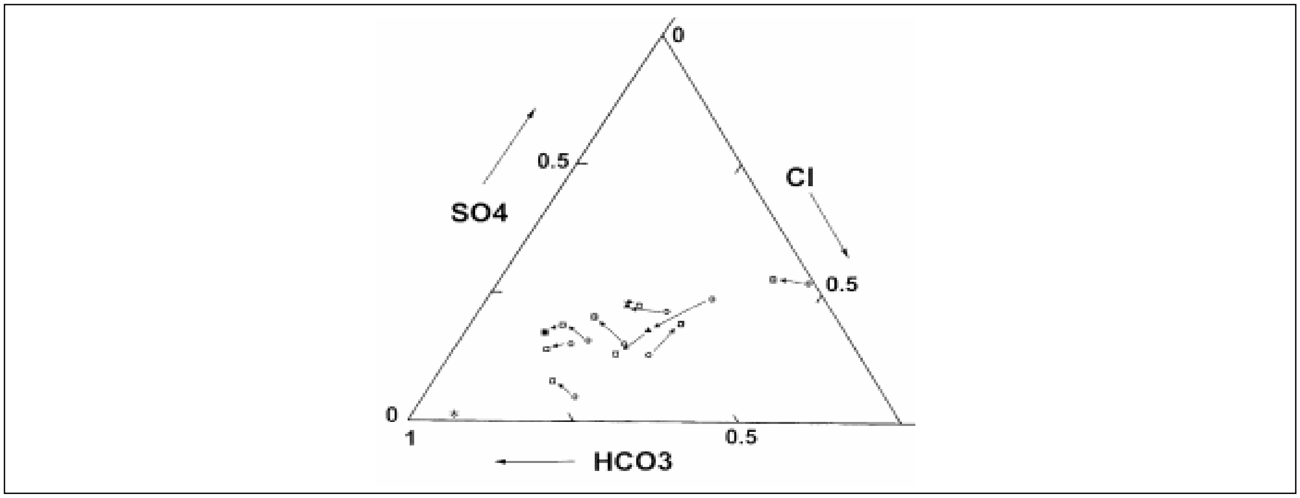

Figure 6. Change in groundwater chemistry due to earthquakes (Takamura, Kono, 1996).

permeable rocks due to possible earthquake-induced micro-fracturing, or some other reasons. A remarkable change in the concentration of radon in the groundwater was observed after the 1995 Kobe earthquake (Hashimoto et al., 1996) (Figure 7).

TRANSBOUNDARY (SHARED) AQUIFERS IN AFRICA

A consideration of case studies and other transboundary water resources (11 case studies representing the shared groundwater resources within the zone of action of the Sahel and Sahara Observatory (OSS) and 39 for all the African continent) (Figure 8) has shown that several factors with potential contributions to the optimal future development of transboundary basins are of frequent importance, but have received insufficient attention from most riparian (and at least some funding agencies) to date. Seismic event induced hydrological changes have received insufficient attention. Joint water management is a desirable objective in transboundary basins. However, the precise form that this should take varies considerably, according to a number of factors which are basin specific of which seismic events have not been considered yet within the framework of proper management. This issue is closely tied to the securitization - desecuritization scenario, which tends to prescribe the form of interface preferred by the basin states.

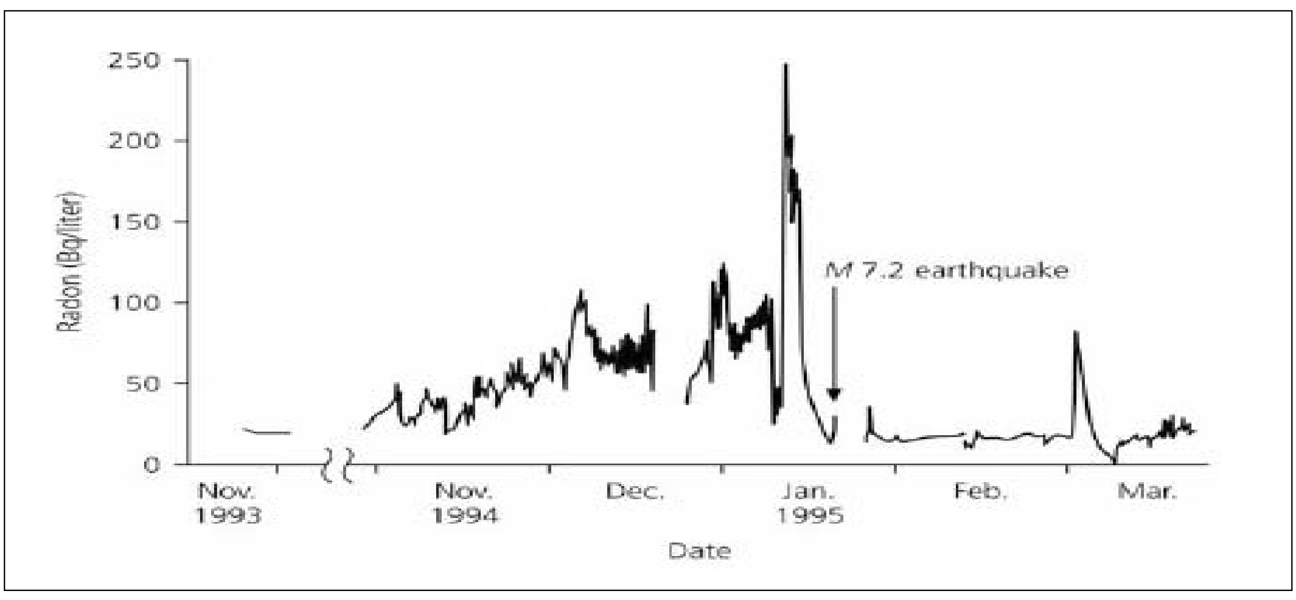

Figure 7. Radon emissions before and after the 1995 Kobe earthquake (Hashimoto et al., 1996).

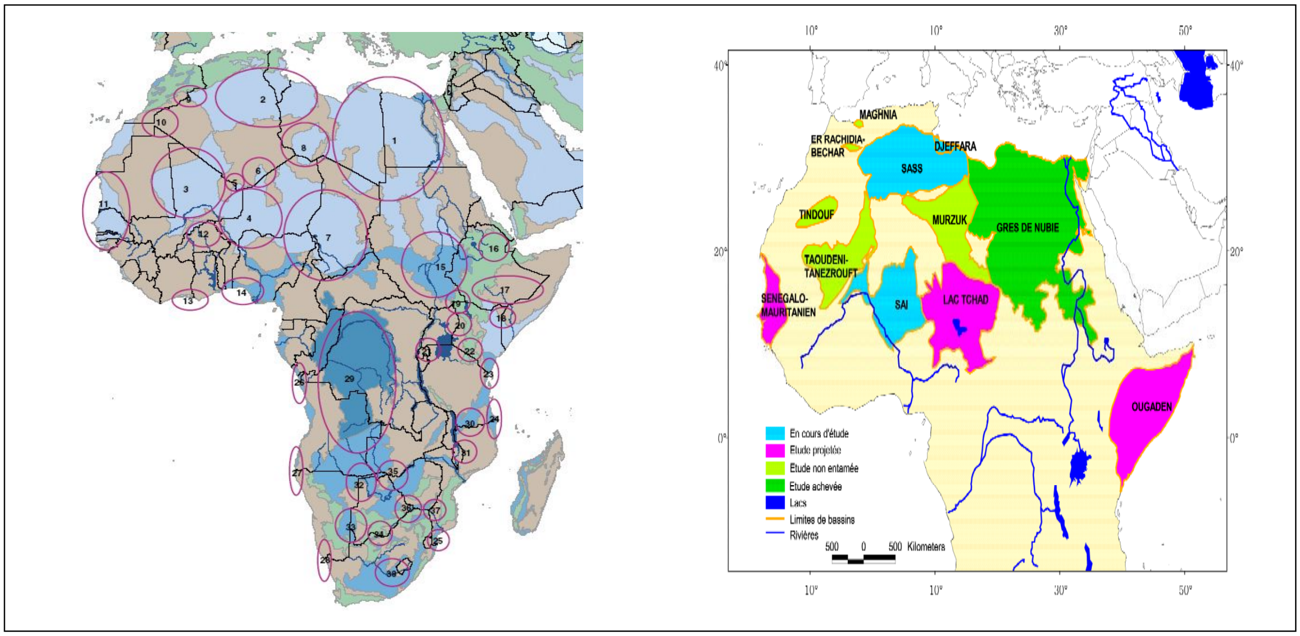

Figure 8. Transboundary aquifers in Africa (left) and within the zone of action of OSS (right).

THE TECTONIC SETTINGS OF AFRICA

The tectonic and geological history of Africa according to Irene et al., (2008) can be summarized and shown as Figure 9 which illustrates the most important tectonic features as described below.

Cameroon Rift

The Cameroon Rift is an extremely long and straight rift valley dating to the Cenozoic Era (65 million years ago). Its formation resulted in substantial volcanic activity in west and central Africa. The rift was caused by severe warping and uplifting of the craton (as much as 2,000 meters). The uplifting caused expansion of the crust and the resultant collapse of the arch crests along normal faults. The collapse formed the rift valley, and the breaks in the crust along the fault lines allowed magma to escape near the surface, causing increased volcanism. The rift is continued off of the Afro-Arabian Craton by a 2500 km long suboceanic ridge, the Guinea Ridge that terminates at St. Helena Island. It is possible that continued continental shifting may extend the rift as far north as the Mediterranean Sea, effectively splitting West Africa from Central Africa.

West African Mobile Belt

The West African Mobile Belt is a Cenozoic relict area where materials eroded from the Afro-Arabian Craton were deposited at the western continental margin. Much of this area was later uplifted by continental displacement. The Mobile Belt may have at one time been coterminous with the mobile belt along the eastern margin of North America that eventually gave rise to the Appalachian Mountains. The Belt dates to the Late Paleozoic (500-230 million years ago).

Cape Mobile Belt

The Cape Mobile Belt is a Cenozoic relict area where materials eroded from the Afro-Arabian Craton were deposited at the southern continental margin. Much of this area was later uplifted by continental displacement. This Mobile Belt was probably never coterminous with any of the other land masses of the period. The Belt dates to the Late Paleozoic (500-230 million years ago).

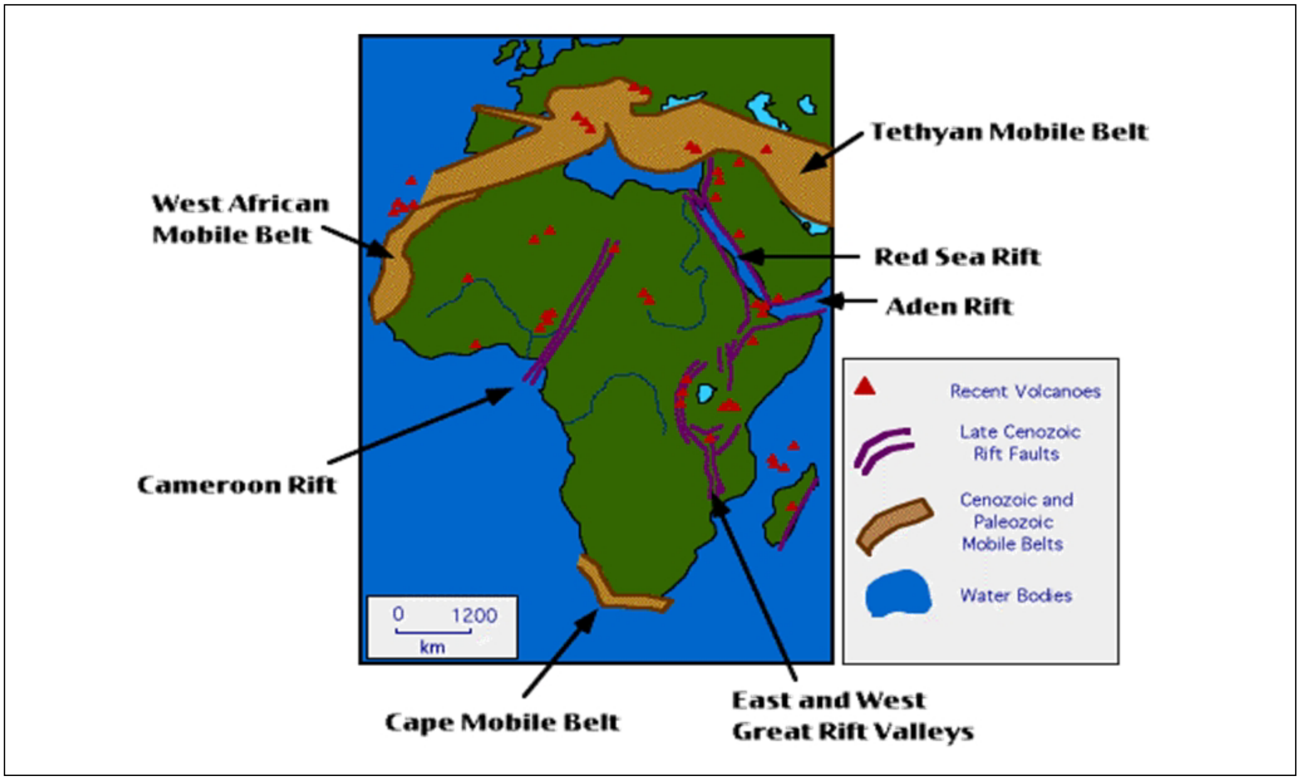

Figure 9. The tectonic setting of Africa (Irene et al., 2008).

Tethyan Mobile Belt

The Tethyan Mobile Belt actually extends from this area, across northern India, through the Himalaya Mountain Range, and finally terminates in the vicinity of Indonesia. This Mobile Belt was formed as the result of the deposition of erosional materials from the Afro-Arabian craton, the European craton, the Ural-Mongolian Mobile Belt, the Chinese craton, and the Indian craton. The belt dates to the Late Mesozoic-Early Cenozoic eras (100-25 million years ago). As you can see, most of the current landmass of southern Europe is built from this material.

Red Sea Rift

The Red Sea Rift began during the Miocene Epoch (about 25 million years ago) and continues today. Its formation is related to the formation of the Aden Rift. The two rifts have now effectively separated Africa from Arabia, although the two were once part of the same landmass, the Afro-Arabian craton. It has been suggested that the rifting was caused by Africa being displaced 200 kilometres south and west of its original position. Both Rifts attain oceanic depths (i.e. 2,000 meters below sea level) over most of their extent. It is possible that Africa is actually pivoting away from Arabia.

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East and West Great Rift Valleys

The East and West Great Rift Valleys of East Africa offer some of the richest beds of fossils dating from the Miocene and younger to be found in the world. With the exception of the South African cave deposits, all of the most important type fossils for Australopithecus and early Homo have been found within the Rift zone. The rifts were caused by severe warping and uplifting of the craton (as much as 2,000 meters). The uplifting caused expansion of the crust and the resultant collapse of the arch crests along normal faults. The collapse formed the rift valleys, and the breaks in the crust along the fault lines allowed magma to escape near the surface, causing increased volcanism. The rifts began forming during the Miocene Epoch (65 million years ago).

GROUND ACCELERATION IN AFRICA

Ground acceleration is a measure of how hard the earth shakes in a given geographic area. A Shake Map (ground acceleration map, Figure 10) is a representation of ground shaking produced by an earthquake. The information it presents is different from the earthquake magnitude and epicenter that are released after an earthquake.

Shake Map focuses on the ground shaking produced by the earthquake, rather than the parameters describing the earthquake source. So, while an earthquake has one magnitude and one epicenter, it produces a range of ground shaking levels at sites throughout the region depending on distance from the earthquake, the rock and soil conditions at sites, and variations in the propagation of seismic waves from the earthquake due to complexities in the structure of the Earth's crust (Wald et al., 2005). Accordingly, this parameter should be taken into consideration in modelling the response of any transboundary aquifer particularly if aquifer is located in tectonically active zone.

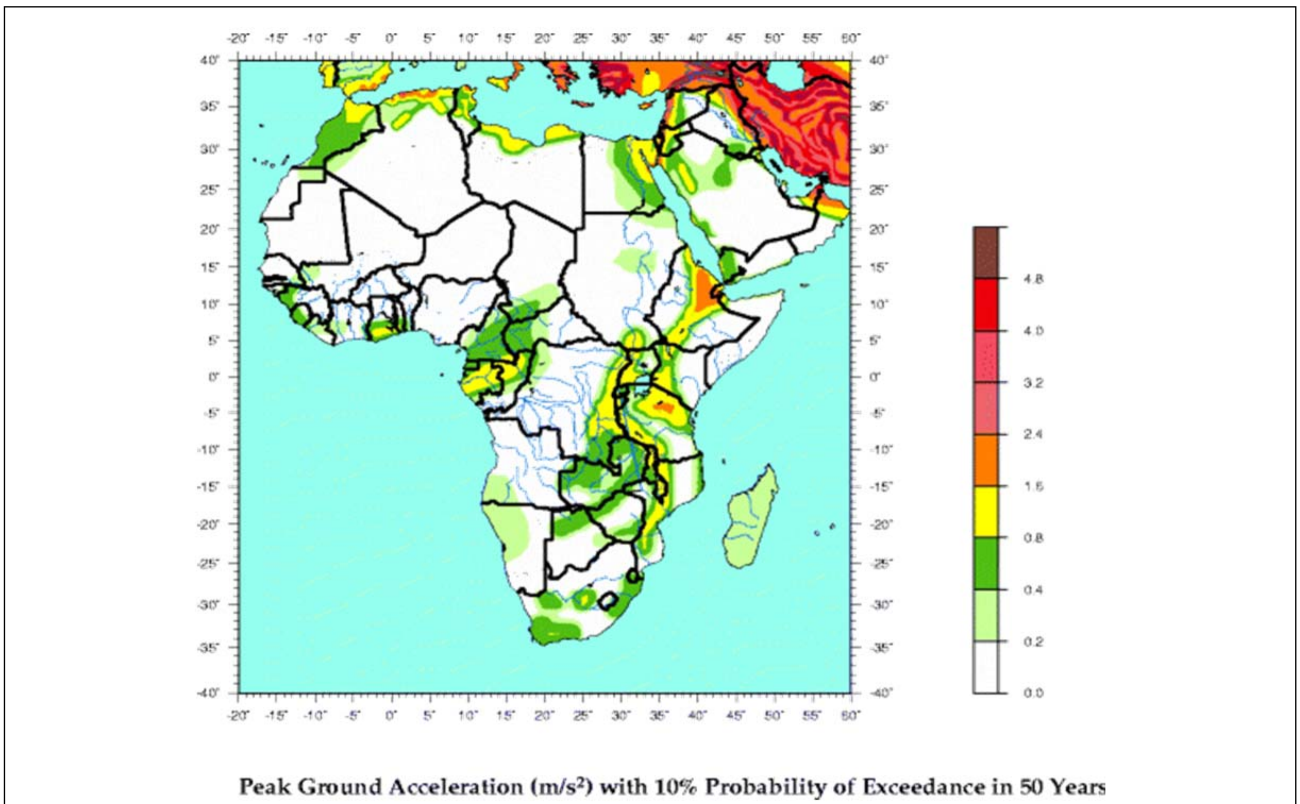

Figure 10. Ground Acceleration (m/s^2) map of Africa (Wald et al., 2005).

CONCLUSIONS

Researchers have concluded that earthquakes offer a unique way to observe how hydrological systems behave, from small watersheds to transboundary aquifers which represent vast aquifers or aquifers of large areal extent

Seismic events inducing hydrological change is a new dimension that should be sought preferentially in studying shared aquifers in Africa. This would improve the joint water management which is a desirable objective in transboundary basins. However, the precise form that this should take varies considerably, according to a number of factors which are basin specific.

Hydrologic changes occur in response to large earthquakes, and have included: (1) large drop of water table in mountainous areas; (2) rapid increase of discharge along active faults; and (3) change of chemistry of discharged water.

Many discharging waters appeared and several well water levels were lowered. This can be explained by permeability enhancement caused by the strong ground motion.

A convincing explanation of earthquake induced hydrological and geochemical changes is that they are caused by changes in groundwater pressure due to changes in crustal volumetric strain.

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