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Short Paper

Rapid late Pleistocene/Holocene uplift and coastal evolution of the southern Arabian (Persian) Gulf

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ABSTRACT

The coastline along the southern Arabian Gulf between Al Jubail, Kingdom of Saudi Arabia, and Dubai, UAE, appears to have risen at least 125 m in the last 18,000 years. Dating and topographic surveying of paleo-dunes (43–53 ka), paleo-marine terraces (17–30 ka), and paleo-marine shorelines (3.3–5.5 ka) document a rapid, >1 mm/a subsidence, followed by a 6 mm/a uplift that is decreasing with time. The mechanism causing this movement remains elusive but may be related to the translation of the coastal area through the back-basin to forebulge hinge line movement of the Arabian plate or, alternatively, by movement of the underlying Infracambrian-age Hormuz salt in response to sea-level changes associated with continental glaciation. Independent of the mechanism, rapid and episodic uplift may impact the design of engineering projects such as nuclear power plants, airports, and artificial islands as well as the interpretation of sedimentation and archeology of the area.

Introduction

The Arabian–Eurasian plate boundary is marked by an along-strike tectonic transition from continent–continent collision in the Zagros Mountains to ocean–continent convergence and subduction at the Makran Trench (Fig. 1a). Much of the deformation and seismicity responsible for the high-relief topography of the Zagros Mountains and northeastern margin of the Arabian (Persian) Gulf can be explained within the context of active tectonics associated with plate convergence. In contrast, the aseismic low-relief coastal regions along the southern margin of the gulf are widely considered to be a tectonically quiescent region (U. S. Geological Survey, 2011). Consequently previous studies in this area have focused on sea-level changes to explain Pleistocene and Holocene shoreline landscape evolution (Evans et al., 1969; McClure and Vita-Finzi, 1982; Lambeck, 1996; Evans et al., 2002; Williams and Walkden, 2002). We speculate here that, although sea-level fluctuations played a role in this landscape, regional tectonic activity was influential in the late-Pleistocene/Holocene coastal evolution.

Approach

We measured age and elevation of paleo-shorelines, paleo-terraces, and near shore paleo-dunes at four locations separated by nearly 500 km, along the southern Arabian Gulf of UAE and Saudi Arabia. These values were compared to known changes in sea level over the same time interval to separate sea-level variations from changes caused by tectonics. A detailed discussion of the methods and expanded data sets are available in the online supplement.

Results

New ages on emergent landscape features

A large number of barrier islands, protected lagoons, peninsulas, and shoals (National Atlas of the UAE, 1993) are consistent with regional emergence of land in the UAE costal area. Holocene-age, laterally extensive shorelines consisting of coarse-grained beach deposits of shells and shell fragments are intermittently preserved along the sabkha between Abu Dhabi City to Al Jubail, Kingdom of Saudi Arabia (Figs. 1b and 2b). Dating of aragonite Cerithiidae gastropod shells from a paleo-shoreline area approximately 60 km west of Abu Dhabi City (Figs. 1b and 2b) yielded progressively younger ages and lower elevations toward the current shoreline. The oldest sample,

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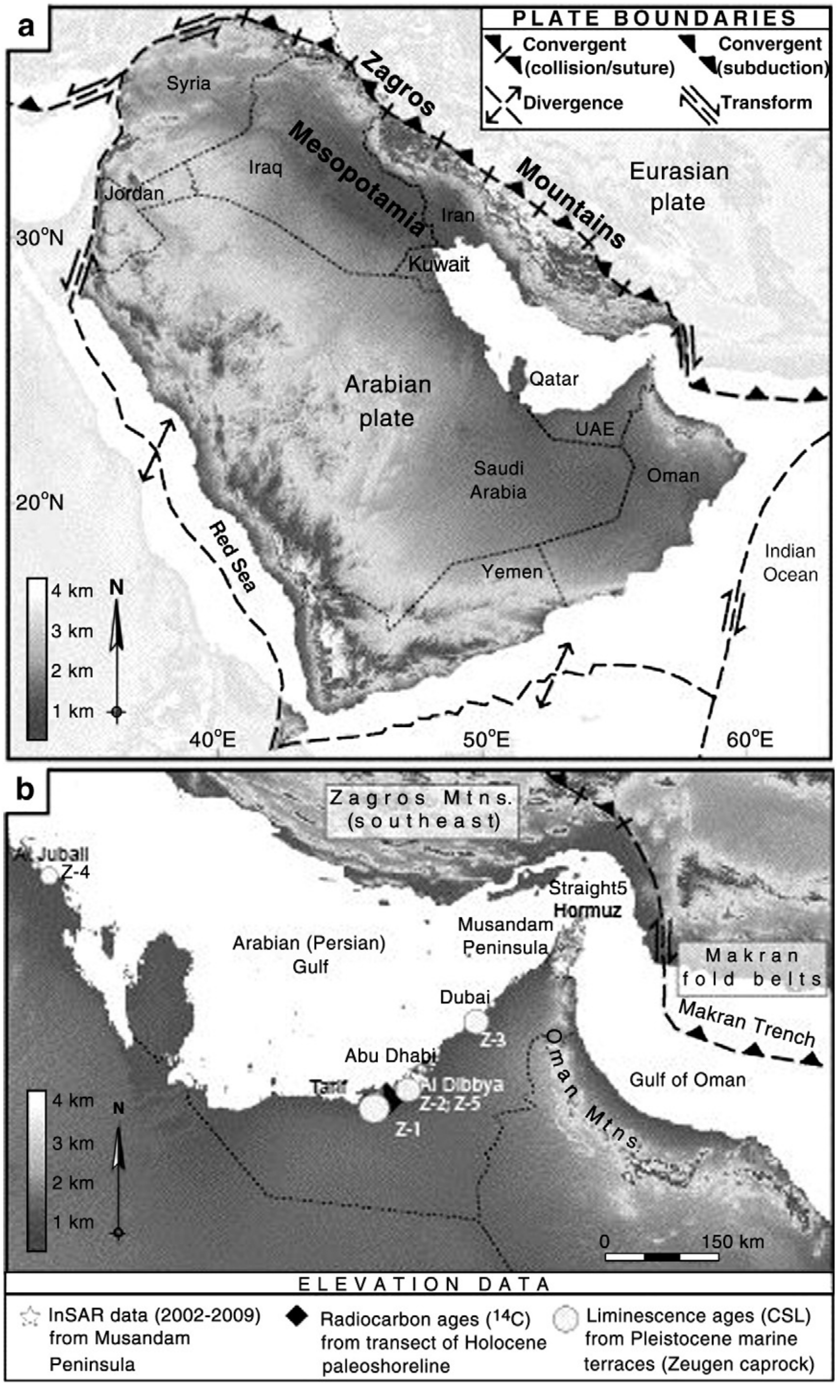

Figure 1. a. — Regional elevations of Arabian tectonic plate and relevant adjacent areas showing topographically subdued areas adjacent to the Arabian (Persian) Gulf foredeep, collisional, subduction, and transverse boundaries. b.– Sampling and cultural locations discussed in the text.

3.00 km from the current shore and 4.16 m above sea level, yields a marine calibrated (Hughen et al., 2004) radiocarbon age of 5.55 ± 0.030 cal ka BP. The youngest sample collected 2.19 km from the current shore, 3.57 m above sea level, is 3.32 ± 0.025 cal ka BP (Fig. 2b; Table 1; On-line supplemental information). These dates are consistent with those obtained from paleo-shorelines elsewhere on the coast (Evans et al., 1969; Ridley and Seeley, 1979; McClure and Vita-Finzi, 1982).

Remnants of a thin near-shore, marine carbonate deposit (Fuwayrit Fm.) that appears to have extended at least 500 km along the coast (Fig. 1b), are now represented by occasional isolated Zeuge. The caprocks on these Zeugen are composed of fossilliferous recrystallized low-magnesium micritic calcite containing 10 to 20% entrained eolian quartz grains. They are typically less than a meter thick, and are currently 3.9 to 6.1 m above sea level. $^{238}U/^{234}U$, $^{87}Sr/^{86}Sr$, $\delta^{18}O$, and $\delta^{13}C$ isotopes (Table 1) and fossil assemblage of gastropods, mollusks, coralline algae, foraminifera, ooids, barnacles, and micritic peloids are consistent with a shallow, near-shore marine origin. OSL (Optical Stimulated Luminance) (see On-line supplemental information) dating of entrained eolian quartz of the marine Fuwayrit Fm. provides estimates of sea level between 17.2 and 30.3 ka (Table 1). These OSL ages are consistent with the one

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Table 1
Location, elevation, U, Sr, O, and C isotopes, luminescence and carbon-14 dates, and elevations of Zeugen and paleo shorelines.

Field name	Elev.	Distance	Description	OSL age	^{14}C	^{14}C calibrated	Uplift rate	$\delta^{13}C$ ‰	$\delta^{18}O$ ‰	$^{86/87}Sr$	$^{234/238}U$
Zeugen	m AMSL	m, from gulf		ka	^{14}C ka BP	cal ka BP	mm/a	VPDB	VDBP		
					Error 1σ	Error 1σ					
Z-4-1 Al Jubail	3.9		Caprock	30.3 ± 3.5			3.4 ± 0.2	3.47	4.82	0.70920	1.106 ± 0.005
Z-4-2 Al Jubail	3.5		Underlying dune	43.5 ± 6.2							1.106 ± 0.005
Z-1-1 Tarif	5.0		Top, caprock	19.5 ± 2.9			6.4 ± 0.6	0.10	2.02	0.70914	1.137 ± 0.003
Z-1-2 Tarif	4.7		Bottom caprock	17.2 ± 3.0							1.060 ± 0.005
Z-1-3 Tarif	3.5		Underlying dune	51.6 ± 6.4							1.059 ± 0.003
Z-5-1 Al Dibb'iya*	~5		Caprock	28.0 ± 4.4	23.584 ± .181	29.000 ± .200	3.4 ± 0.3				
Z-3-1 Dubai	6.1		Caprock	21.1 ± 3.4			6.2 ± 0.6	1.86	3.28	0.70904	1.132 ± 0.006
Z-3-2 Dubai	4.4		Underlying dune	53.2 ± 6.2							1.082 ± 0.005
Paleo-shoreline											
S-RVD1	3.57	2190	Paleo shoreline		3.432 ± .025	3.320 ± .030	1.4 ± 0.1	3.39			
S-RVD2	3.61	2270	Paleo shoreline		3.554 ± .035	3.432 ± .030	1.3 ± 0.1	3.12			
S-RVD3	3.88	2385	Paleo shoreline		3.546 ± .030	3.422 ± .025	1.4 ± 0.1	3.11			
S-RVD5	4.04	2525	Paleo shoreline		4.058 ± .030	4.097 ± .033	1.3 ± 0.1	5.55			
S-RVD4	4.16	3010	Paleo shoreline		5.173 ± .030	5.548 ± .027	1.1 ± 0.1	3.55			

* No surviving elevation or isotope data, access to site is no longer possible.

radiocarbon date we collected (Table 1) and from dates on coral, red algae, and barnacles collected from Zeugen caprock at five coastal locations near site Z-5 (Fig. 1) that yielded calibrated ^{14}C dates ranging from 29.3 to 33.4 cal ka BP (Williams and Walkden, 2002).

A near-shore origin of carbonate-cemented terrestrial aeolian dunes is suggested owing to well-developed foreset beds containing a high proportion of detrital carbonate shell particles and occasional mangrove rhizoliths. These dunes unconformably underlie the Fuwayrit Fm. (Fig. 2c), are OSL dated between 43 ± 6.2 and 53 ± 6.2 ka (Table 1) and are consistent with the 42 ka date determined by Glennie (2005) for these features. Recent unpublished work by British Geological Survey found a similar range of ages for these features (Andrew Farrant, personal communication, 2011). These dunes overlie undated apparent coastal sheetwash deposits of similar composition (Fig. 2c).

Uplift and dynamic topography

Dating of paleo-shorelines suggests that the sabkha is prograding into the gulf (Evans et al., 1969), consistent with the geochemistry and hydrology of the sabkhat (Wood et al., 2002). As sea level has generally been rising over the late Holocene sabkha progradation requires coastal uplift. Rohde's (2011) composite Holocene global sea-level curve was used owing to complexity in establishing a local sea-level curve (Milne and Mitrovica, 2008). Lambeck's (1996) analyses of the Holocene gulf shoreline assumed the gulf was dry during the last glacial maximum and, thus, may need revision, as our Zeugen data indicate marine deposits in the gulf during this interval. The composite curve suggests the uplift rate of paleo-shorelines in this sequence ranges from 1.1 to 1.4 mm/a (Table 1). The discrete individual paleo-beaches of well-sorted clean fossils and declining elevation with time in the sequence suggest that uplift may be episodic rather than originating from storm surge (Fig. 2b). Acknowledging the possibility that sea level may have been ~2 m higher than present at 5 ka (Bird et al., 2010) and the observation that our paleo-shorelines are 4 m above sea level, suggests that the area had been uplifted ~2 m. Under this assumed condition, the uplift rate would be reduced to ~0.4 ± 0.1 mm/a. The preservation of paleo-shorelines at several locations at ~4 m elevation suggests the lack of major tsunami or severe cyclones within the last 5.5 ka. These features also document reduced erosion consistent with the beginning of the current hyper-arid climate ~5.5 ka as older paleo-shorelines have not been identified

During development of Fuwayrit Fm. (17.2–30.3 ka) sea level was significantly lower than present (Shackleton, 1987; Lambeck, 1996; Rohling et al., 2009) (Fig. 3). The caprock at site Z-4-1 has an age of 30.3 ± 3.30 ka (Table 1), at which time sea level was approximately ~100 m below the present elevation (Fig. 3). The caprock at this site is currently 3.9 m above current sea level, thus the area must have risen ~104 m, giving a time averaged uplift of 3.4 ± 0.3 mm/a; Zeuge Z-1-1 has a time-integrated uplift rate of 6.4 ± 0.6 mm/a; and Z-3-1 of 6.2 ± 0.6 mm/a (Table 1).

Rapid subsidence is inferred from the presence of near-shore eolian dunes underlying the Fuwayrit Fm. It is generally recognized that sea level declined ~15 m between 43 ka (youngest dune) and 30 ka (oldest Zeuge) (Fig. 3). Thus, the near shore dune surface on which the Fuwayrit Fm. was deposited must have subsided more rapidly than declining sea level (~1 mm/a) to become submerged prior to deposition of the Fuwayrit Fm. The near-shore occurrence of these dunes provides a conservative estimate for subsidence.

The rate of change of uplift is apparently declining with time as indicated by the rate of ~3.4 mm/a (28 ka) for the Zeugen to ~1.3 mm/a for shorelines in adjacent locations near site Z-5 (Table 1; Fig. 1). Analyses of younger (0.68–0.69 ka) intertidal deposits near this site suggest a further decrease in progradation rate of the sabkha (Lokier and Steuber, 2008). We interpreted this decrease to represent a decrease in uplift rate, as sea level is known to have risen between 1.3 and 1.8 m during the last thousand years (Nydick et al., 1995). No elevations were provided with the intertidal dates; thus, the absolute rate of change of land surface elevation cannot be ascertained. As with the paleo-shorelines, the discrete changes associated with the intertidal deposits appear to be episodic.

Conceptual models

Uplift in tectonically quiescent regions such as the southwestern margin of the Arabian gulf may be attributed in some part to a wide range of mechanisms including flexure due to the topographic load of the Zagros Orogenic Belt (DeCelles and Giles, 1996), subduction in the Makran Trench (Rodgers and Gunatilaka, 2002), possible “slab break-off” beneath the Zagros Mountains (Molinaro et al., 2005), or small-scale convection in the sublithosphere (Petersen et al., 2010). Similarly, paleo-monsoon related erosion (5.5–9.5 ka) (McClure, 1976) and removal of material from the upper lithosphere might have contributed to isostatic uplift. Flexural response to Late Cretaceous (~90 Ma) obduction and loading of a thick slab of dense ophiolite onto the Arabian plate, however, seems unlikely related to current uplift as mantle equilibrium occurs on the order of tens of thousands of years (Ali and Watts, 2009). Erosion of the ophiolite

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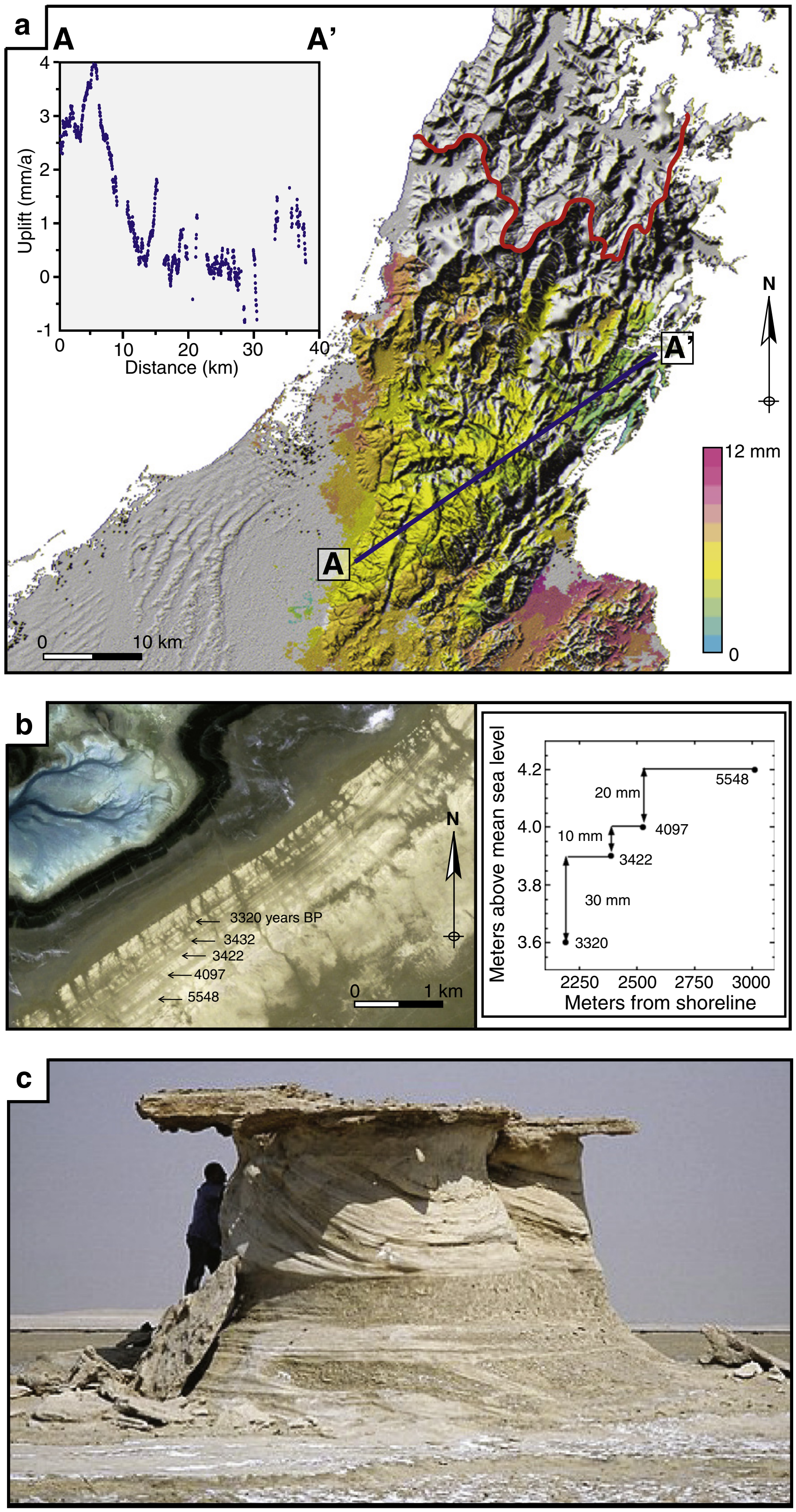

Figure 2. a) InSAR (Interferometric Synthetic Aperture Radar) images of Musandam peninsula acquired from European Envisat radar satellite during 2002-2009. Drown topography is clearly evident along both coasts and uplift on either side the mountain core is as much as 12 mm/a. b) Sequence of white paleo-shorelines each 10 m to 15 m wide against the yellowish brown of the intermediate sandy areas (Google Earth) "Insert illustrated elevation changes with time (cal yr BP) and distance from the current shoreline.". c) Typical Zeuge with caprock unconformably overlying terrestrial aeolian deposits with well-developed foreset beds composed of largely of fine quartz and detrital carbonate that in turn overlies a sandy/silty sheet wash deposit of unknown age.

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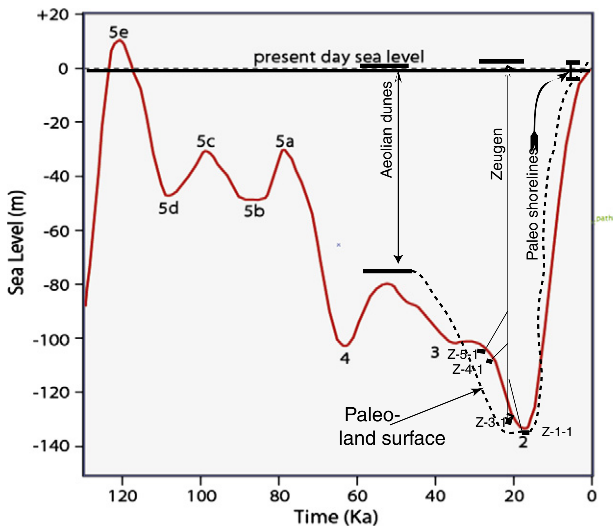

Figure 3. Land surface elevation, for the last 53 ka, superimposed on sea level. Modified from Shackleton, 1987.

may, however, reduce the total vertical stress and contribute isostatic uplift to the current tectonic uplift in the Oman Mountains. The Arabian plate is distant from Pleistocene continental glaciers and, thus, is unlikely to have been directly affected by ice loading and subsequent rebound. There could, however, be lower crustal flow induced by loading and unloading owing to changes in water levels in the gulf analogous to those observed in NW Europe (Westaway, 2002).

One scenario to account for the observed changes from subsidence to uplift is the translation of the coastal area through the backbasin to forebulge hinge line by the movement of the Arabian plate relative to that of the Eurasian plate. That is, assuming a fixed relation between the plate collision zone and large-scale features of foredeep, forebulge, and backbasin on the Arabian plate, movement of the plate with time would superimpose these structural features onto the coastal area and thus, provide the observed movement from subsidence (backbasin) to uplift (forebulge). The hinge line between these features is an especially sensitive area in which relative small horizontal movement may translate into large rates of changes in the vertical rate (see for example of current tectonic conditions of an analogous forebulge/foredeep area of the Musandam Peninsula, insert Fig. 2a). The episodic character of the uplift is believed to reflect the episodic strain relief imposed by movement of the Arabian plate and the declining uplift rate reflects movement of sedimentary features from forebulge toward the foredeep in response to plate movement.

A second scenario relates to salt tectonics of the region. The rise and fall of coastal land surface parallel that of sea level (Fig. 3) thus, the changing mass of water in the gulf associated with the Pleistocene sea-level changes may have caused movement of the underlying Infracambrian-age Hormuz salt. This salt, 1.5 to 4 km thick, is present throughout much of the Zagros basin (Edgell, 1996) and is known to induce rapid, but highly localized, uplift of 5–6 mm/a (Bruthans et al., 2006). We envision a non-linear model in which a drop in sea level reduced the total vertical stress on the floor of the Arabian Gulf and underlying sediment. This change in vertical stress generated pressure gradients that caused upward movement of the underlying salt, most likely along the topographically deepest areas of the gulf. Conservation of mass dictates that the area adjacent to this axis must have declined as the salt moved toward the basin axis, resulting in the observed land subsidence on the basin edge. As the sea level rose after the glacial maximum, the total vertical stress in the basin increased and salt was displaced to the adjacent edge areas resulting in the observed uplift the current coastal area. This conceptual model is analogous (substituting salt for lower crustal rock flow) to that proposed by Westaway (2002). The slowing of uplift with time reflects establishment of a new equilibrium with current sea level and the basin sedimentation. The rise of sediments in the axis, associated with salt rise, was likely balanced by erosion from the paleo-Tigris/Euphrates river system. The episodic character of the uplift is believed to reflect the episodic strain relief of imposed salt stress.

Several salt domes have been identified on the UAE coastal margins, including Dukhan Anticline, the Halul Island, and the Shraouh Island in Qatar, and Das, Dalma, Qarnain Zirku, Arzanah, Abu Musa and Beni Yas islands and Jebal Dhanna and Jebal Ali domes on shore in the United Arab Emirates as well as the Dammam Dome of Kingdom of Saudi Arabia and Jebel Dukhan dome of Bahrain. In addition most of the 60-plus anticlinal structures of the UAE are salt-related (Alsharhan and Nairn, 1997). The seismic profiles across the Arabian basin also portray a complex salt-thickness distribution in association with basement faulting resulting from the Arabian/Eurasian plate collision (Konyukhov and Maleki, 2006). The correspondence in elevation of similarly aged paleo-shorelines and the Fuwayrit Fm., assumed to have been continuous along hundreds of kilometers of coastline suggests regional, rather than local, diapiric salt movement. That is, we envision a band of marine sediments (Fuwayrit Fm.) that were deposited around the southern edge of the gulf ~30 to 18 ka.

Discussion

The above tectonic analysis clearly depends on the fossils, sedimentology, and isotopes, as being marine. We are confident of the OSL dates as they are consistent with our single radiocarbon date (Table 1) and the five radiocarbon dates of Williams and Walkden (2002), and are stratigraphically consistent (Table 1). An alternative marine origin of the Fuwayrit Fm. requires that a large segment of the Arabian gulf remained isolated and over 130 m above sea level during the last glacial maximum, yet maintained its marine isotope and fossil signature. Although there might have been temporary blockage of the outlet in the Straits of Hormuz by some tectonic event, it seems unlikely that the unconsolidated Quaternary sediments of the gulf would be able to support the hydraulic head differential of 130 m between the gulf and the ocean. Furthermore, it is difficult to envision how the salinity, biology, and isotopic composition would have remained similar to sea water or how this entrapped sea would have maintained the critical balance between inflow from the paleo Tigris and Euphrates rivers and evaporation for the 12,000 years during which the Fuwayrit Fm. was deposited.

Salt rheology is a function of salt viscosity, salt pressure, and overburden brittle strength (Jackson et al., 1994). Its movement is also a function of the density contrast with overburden sediments and applied horizontal stress. The Hormuz Salt, deposited directly on Precambrian igneous rocks, is buried 8 to 10 km below the surface. We know little of moisture content or grain size of the salt on which the viscosity is highly dependent. We know, however, that the temperature gradient is 26°C/km (Gumati, 1993), and thus the salt must have a temperature between 270 and 370°C. As viscosity is inversely dependent on temperature we would expect the salt to be extremely fluid. Additionally, with a salt density of ~2165 kg/m^3 vs. ~2700 kg/m^3 for overburden, and in an active compressive stress field, the salt is likely to be extremely mobile and exhibit sensitivity to slight perturbations in the stress field and thus, forms the basis of our conceptual model.

Evidence of contemporary stress changes in portions of the Musandam Peninsula was obtained using multiple InSAR images from the European Envisat radar satellite acquired during the years 2002–2009 (Fig. 1b). An average contemporary deformation map (Bernardino et al., 2002) was produced and a NE/SW profile was constructed perpendicular to the assumed hinge line between foredeep and forebulge of the Zagros Orogenic belt/Makran accretionary

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prism (DeCelles and Giles, 1996). This profile suggests uplift of 3–4 mm/a on the rising limb of the hinge line of the forebulge and subsidence of ≥1 mm/a on the falling limb of the foredeep (Fig. 2a). Movement identified by InSAR is likely related to the forebulge of the Makran Trench subduction zone and provides a model for what may have happened along the southwestern area of the Arabian Gulf during the late Pleistocene through Recent. It also provides evidence of contemporary horizontal stress on the Hormuz salt.

Conclusions

Dating of paleo-dunes, paleo marine terraces, and paleo-shorelines with different methods over different time scales suggested rapid surface-elevation change rather than sea-level changes as an explanation to the evolution and origin of many of the features. Two conceptual tectonic models (plate tectonic and salt dynamics) are proposed to account for the observed rapid subsidence (greater than ~1 mm/a) followed by a rapid rise (1–6 mm/a) and declining rate of rise in elevation. The mechanism responsible for this movement, however, remains elusive.

Regardless of the mechanism, design engineers concerned with natural hazards might wish to consider ramifications of the observed tectonics (uplift of 125 m over last 18 ka and current uplift of ~1 mm/a) to coastal projects such as nuclear power plants, airports, and artificial islands. The recent, relative large, vertical movements also have important ramifications on sedimentation, as this is the prototype "carbonate factory" and on archeology as this area is on the proposed southern route of early man leaving Africa (Mellars, 2006). The implications of rapid recent uplift may require transient rather than steady-state analyses of fluid gradients of both groundwater and petroleum. Dates of the Fuwayrit Fm. (17–30 ka), previously identified as likely either 125 ka (marine oxygen isotope stage 5e) (Evans et al., 2002; Williams and Walkden, 2002) or Miocene (National Atlas of the UAE, 1993), and underlying eolian deposits (43–53 ka) will necessitate a re-evaluation of some paleoclimatic and stratigraphic interpretations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.yqres.2011.10.008.

References

Ali, M.Y., Watts, A.B., 2009. Subsidence history, gravity anomalies and flexure of the United Arab Emirates (UAE) foreland basin. GeoArabia 14, 17–44.

Alsharhan, A.S., Nairn, A.E.M., 1997. Sedimentary Basins and Petroleum Geology of the Middle East: Amsterdam. Elsevier. 843 pp.

Bernardino, P., Fornaro, G., Lanari, R., Sansosti, E., 2002. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. Institute of Electrical and Electronic Engineers, Transaction of Geosciences and Remote Sensing 40, 2375–2383. doi:10.1111/j.1365-246X.2008.03881.x.

Bird, M.I., Austin, W.E.N., Wurster, C.M., Fifeld, L.K., Mojtahid, M., Sargeant, C., 2010. Punctuated eustatic sea-level rise in the early mid-Holocene. Geology 38, 803–806. doi:10.1130/G31066.1.

Bruthans, J., Filippi, M., Geršl, M., Zare, M., Melková, J., Pazdur, A., Bosák, P., 2006. Holocene marine terraces on two salt diapirs in the Persian Gulf, Iran: age, depositional history and uplift rates. Journal of Quaternary Science 21, 843–857. doi:10.1007/s00254-007-0734-6.

DeCelles, P.G., Giles, K.A., 1996. Foreland basin systems. Basin Research 8, 105–123. doi:10.1046/j.1365-2117.1996.01491.x.

Edgell, H.S., 1996. Salt tectonism in the Persian Gulf basin. Geological Society, London, Special Publications 100, 129–151.

Evans, G., Schmidt, V., Bush, P., Nelson, H., 1969. Stratigraphy and geologic history of the sabkha. Abu Dhabi, Persian Gulf. Sedimentology 12, 145–159. doi:10.1111/j.1365-3091.1969.tb00167.x.

Evans, G., Kirkham, A., Carter, R.A., 2002. Quaternary development of the United Arab Emirates coast: new evidence from Marawah Island, Abu Dhabi. GeoArabia 7, 441–458.

Glennie, K.W., 2005. The Deserts of Southeast Arabia. Gulf PetroLink Manama, Bahrain. 215 pp.

Gumati, Y.D., 1993. Kinetic modelling, thermal maturation and hydrocarbon generation in the United Arab Emirates. Marine and Petroleum Geology 10, 153–161.

Hughen, K.A., Baillie, M.G.L., Bard, E., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, G., Manning, S., Bronk-Ramsey, C., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. Marine04 marine radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46, 1059–1086.

Jackson, M.P.A., Vendeville, B.C., Schultz-Ela, D.D., 1994. Structural dynamics of salt systems. Annual Review of Earth and Plant Science 22, 93–117. doi:10.1146/annurev.ea.22.050194.000521.

Konyukhov, A.I., Maleki, B., 2006. The Persian Gulf Basin: geological history, sedimentary formations, and petroleum potential. Lithology and Mineral Resources (English translation) 41, 344–361.

Lambeck, K., 1996. Shoreline reconstructions for the Persian Gulf since the last glacial maximum. Earth and Planetary Science Letters 142, 42–57. doi:10.1016/0012-821X(96)00069-6.

Lokier, S., Steuber, T., 2008. Quantification of carbonate-ramp sedimentation and progradation rates for the late Holocene Abu Dhabi shoreline. Journal of Sedimentary Research 78, 423–431. doi:10.2110/jsr.2008.049.

McClure, H.A., 1976. Radiocarbon chronology of late Quaternary lakes in the Arabian Desert. Nature 263, 755–756. doi:10.1038/263755a0.

McClure, H.A., Vita-Finzi, C., 1982. Holocene shorelines and tectonic movements in eastern Saudi Arabia. Tectonophysics 85, T37–T43. doi:10.1016/0040-1951(82)90099-3.

Mellars, P., 2006. Going east: new genetic and archaeological perspectives on the modern human colonization of Eurasia. Science 313, 796–800.

Milne, G.A., Mitrovica, J.X., 2008. Searching for eustasy in deglacial sea-level histories. Quaternary Science Reviews 27, 2292–2302. doi:10.1016/j.quascirev.2008.08.018.

Molinaro, M., Zeyen, H., Laurencin, X., 2005. Lithospheric structure beneath the south-eastern Zagros Mountains, Iran: recent slab break-off? Terra Nova 17, 1–6. doi:10.1111/j.1365-3121.2004.00575.x.

National Atlas of the United Arab Emirates, 1993. United Arab Emirates University, City, 164 p.

Nydick, K.R., Bidwell, A.B., Thomas, E., Varekamp, J.C., 1995. A sea-level rise curve from Guilford, Connecticut, USA. Marine Geology 124, 137–159.

Petersen, K.D., Nielsen, S.B., Clausen, O.R., Stephenson, R., Gerya, T., 2010. Small-scale mantle convection produces stratigraphic sequences in sedimentary basins. Science 329, 827–830. doi:10.1126/science.1190115.

Ridley, A.P., Seeley, W.M., 1979. Evidence of recent coastal uplift near Al Jubail Saudi Arabia. Tectonophysics 52, 319–327. doi:10.1016/0040-1951(79)90239-7.

Rodgers, D.W., Gunatilaka, A., 2002. Bajada formation by monsoonal erosion of a subaerial forebulge, Sultanate of Oman. Sedimentary Geology 154, 127–146. doi:10.1016/S0037-0738(02)00126-4.

Rohde, R.A., 2011. Composite Sea-level Curves. http://www.globalwarmingart.com 2011last accessed 26 Oct. 2011.

Rohling, E.J., Grant, K., Bolshaw, M., Roberts, A.P., Siddall, M., Hemleben, Ch., Kucera, M., 2009. Antarctic temperature and global sea level closely coupled over the past five glacial cycles. Nature Geoscience 2, 500–504. doi:10.1038/NGEO557.

Shackleton, N.J., 1987. Oxygen isotopes, ice volume and sea level. Quaternary Science Reviews 6, 183–190. doi:10.1016/0277-3791(87)90003-5.

U. S. Geological Survey, 2011. World Seismicity Maps, Middle East 1990–2006. http://earthquake.usgs.gov/earthquakes/world/seismicity/m_east.php 2011last accessed September 2011.

Westaway, R., 2002. Geomorphological consequences of weak lower continental crust, and its significance for studies of uplift, landscape evolution, and the interpretation of river terrace sequences. Netherlands Journal of Geosciences 81, 283–303.

Williams, A.H., Walkden, G.M., 2002. Late Quaternary highstand deposits of the southern Arabian Gulf: a record of sea-level and climate change. Geological Society, London, Special Publication 195, 371–386. doi:10.1144/GSL.SP.2002.195.01.2.

Wood, W.W., Sanford, W.E., Al Habschi, A.R.S., 2002. The source of solutes in the coastal sabkha of Abu Dhabi. Bulletin of the Geological Society of America 114 (3), 259–268. doi:10.1130/0016-7606(2002) 114<0259:SOSTTC>2.0.CO;2.