Reports

Late Holocene Tectonic Activity Along the Margins of the Sinai Subplate

Abstract. *Remarkable folding and uplifting movements were active along the western margin of the Sinai subplate (the Bardawil Lagoon and its periphery) during the Upper Holocene. The coasts of the eastern margin (Gulf of Elat) were also uplifted during the same tectonic phase. The nature of this activity is discussed in relation to the regional tectonic framework.*

The purpose of this report is to suggest that the Sinai subplate was affected by tectonic movements some 2700 to 3000 years before the present (B.P.), as indicated by the dating of disturbances which occurred at approximately the same time on both its western and eastern borders. We also attempt to relate this movement to the regional tectonic framework. The evidence presented here is based on the findings of D. Neev and E. Oren for the Mediterranean border of the Sinai subplate and on those of G. M. Friedman for its eastern border (Fig. 1).

The evidence on the western border of the subplate comes from the vicinity of the Bardawil Lagoon (Fig. 2). The western half of the bar of this lagoon extends southwest to Qantara on the Suez Canal and beyond, as a low ridge composed of stabilized dunes. This ridge appears to be of tectonic origin as indicated by its straight and sharply lineated morphology (Fig. 2) and also by the elevated position of a few segments along it. One of these is the structural dome of Mount Casius (*1*), the uplifting of which is indicated by the high elevations (up to +30 m above mean sea level) of Flandrian-aged (about 6000 years B.P.) beds of a sequence containing friable rhythmic sands and shell fragments of marine or lagoonal origin. This sequence is overlain by a soil layer (light-brown loam with distinct $CaCO_3$ concretions of the B horizon). The genesis of the soil layer is closely related to the groundwater table. The oldest traces of human activity, which were found on top of this soil at Mount Casius, are pottery shards from the Persian period (about 2700 years B.P.) (*2*). Hence, it is assumed that this structural ridge was elevated to above the post-Flandrian sea level sometime prior to Persian times (that is, 2700 to 3000 years B.P.).

Another phase of tectonic activity along the same structural element took place during Mamluk times (about 500 years B.P.), but indications of tectonic restlessness, also during the first century A.D., were reported by Strabo (*3*). The northeastern limit of the Nile Delta forms a belt of subsidence (a synclinal trough) that has been known at least since Miocene times (*4*). This belt, which is about 40 km wide between the sites of Tenis and Pelusium (Tel Farameh) and has subsided and become partly submerged since Roman (Tenis) and Mamluk (Pelusium) times, was named the Pelusium Line (Figs. 1 and 2). The Bardawil Lagoon forms a second elongated synclinal trough, which is also stretched to the northeast and is parallel to the structural ridge of Mount Casius but is located on its southeastern flank (Fig. 2).

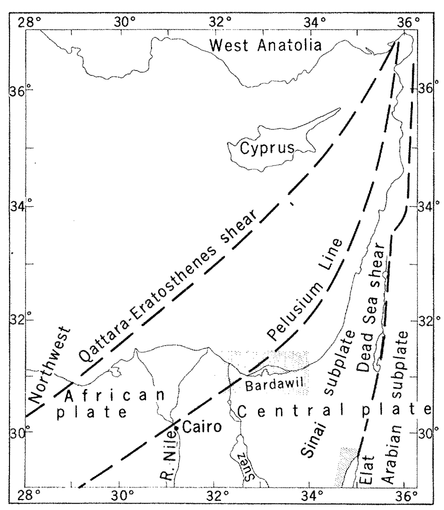

Fig. 1. Index map. (Stippled areas) The Bardawil Lagoon and the coastal segment close to Elat which are discussed in the text. Also shown are the three shears: (i) Qattara-Eratosthenes, (ii) Pelusium, and (iii) the Dead Sea, along all of which the Central plate has moved left laterally. Movements along the first and second shears occurred between late Paleozoic and late Oligocene times, after which the activity shifted to the third shear.

The submergence of the site of Ostrakina (which lasted from Roman to Mamlukian times) and a very high rate of deposition of the underlying pre-Persian-aged beach deposits indicate that this trough also has subsided in two phases in accordance with the uplifting of the adjacent structural ridge (*1*). The uplifting of another structural ridge which flanks the Bardawil trough on its southeast (Fig. 2) (*1*) is also believed to be associated with these movements, which can be related to the system of Israel and the Levant trending northeast to southwest and also to the tectonic activity along the Pelusium Line (*5*).

Until approximately the Persian period, the main (older) coastal route from Egypt to Syria and Mesopotamia (Fig. 2) extended from the site of modern Qantara, through Romani, and along the southern shores of the Bardawil Lagoon to Rhynocorura (the site of present El Arish) (*2*). The more northern route (Via Maris), from Tenis and Pelusium through Mount Casius and Ostrakina to Rhynocurura (Fig. 2), was used only between Persian and Mamluk times. The abandonment of the northern route in later times was due to the tectonic subsidence and partial submergence of the segments which coincided with the two synclinal troughs mentioned above. The correlation between the phases of human and tectonic activities is, therefore, obvious.

The evidence on the eastern border of the subplate is derived mainly from the radiocarbon dating of (i) an uplifted fossil reef (*6*) and (ii) *Cerithium*-rich lime muds and the overlying lagoonal facies algal mats.

The Gulf of Elat, which forms the southern segment of the Dead Sea Rift Valley, is so narrow (10 to 20 km) and steep-sided that Gregory (*7*, p. 17) described it as "a crevasse in the earth's crust." The submarine slopes of the gulf, as well as the onshore slopes, are fault-controlled and precipitous (*8*).

A fossil reef was found on the western shores of the northern gulf, about 1 m above sea level. Numerous patches of elevated beach rock terraces are found along these shores up to 3 m above mean sea level; these terraces were probably associated with the fossil reef. Radiocarbon dating of the reef yielded an age of 4770 ± 140 years B.P. (*6*). According to the curve of eustatic changes of sea levels during the Holocene (*9*), the ocean level during that time was somewhat lower than today. Hence, a tectonic uplifting of the fossil reef is implied. Inasmuch as the age records the time when the coral reef community was actively

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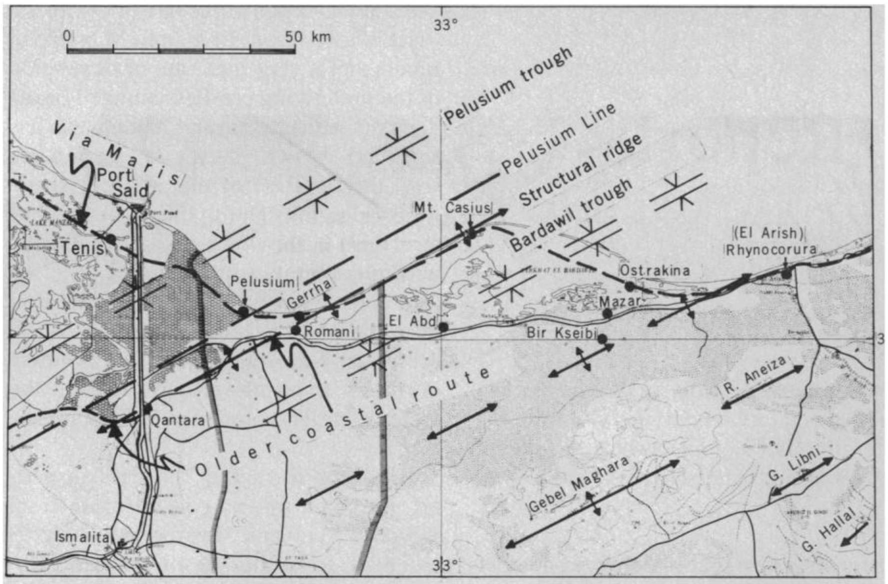

Fig. 2. Delineation of the main structural elements (trending northeast-southwest) of northwestern Sinai (the Pelusium trough and Pelusium Line, the Mount Casius structural ridge, the Bardawil synclinal trough, and two structural ridges that belong to the Gebel Maghara chain of structures), superimposed on the physiographic map. Also shown is a tracing of the two main traffic routes: (i) the older coastal plain route, which is still in use, and (ii) the beach route, Via Maris, which was used from about 2700 to about 500 years B.P., during the interval between the two phases of tectonic activity described in the text.

growing, the tectonic movement which elevated the reef occurred sometime more recently.

A second line of evidence for tectonic movement along the same shores has been obtained from radiocarbon dating of sediments that were sampled by cores drilled in an isolated sea-marginal, hypersaline pool named the Solar Pond, located about 20 km southwest of Elat (*10*). The cores drilled within the pool, close to the bar which separates it from the open gulf, reveal a succession of organic-rich, algal-mat sediments which are underlain by carbonate mud, rich in *Cerithium* gastropod shells. The algal-mat sediments typify a very shallow, restricted, hypersaline water environment similar in salinity to the present-day range of salinity of the waters in this pool (70 to 146 per mil). On the other hand, the *Cerithium*-rich sediments represent a littoral, open-sea environment. The compilations of the radiocarbon datings of these sediments (*10, 11*) indicate (Fig. 3) that the transition from the open marine environment (carbonate mud, rich in *Cerithium* gastropod shells) to the restricted, hypersaline lagoonal environment (algal-mat sediments) occurred sometime between 3405 ± 90 years B.P. (the youngest age of the *Cerithium*-rich samples analyzed) and 2465 ± 155 years B.P. (the oldest age of the algal-mat sediments analyzed). We believe that these changes of the environments (shoaling of facies and the separation of the lagoon from the open gulf) occurred as a result of the tectonic uplifting of the coastal zones. We also deduced from the compilation of the radiocarbon dating analyses [(*11*), figure 4] that another phase of tectonic activity occurred at this site sometime after 1910 ± 115 years B.P., that is, during Roman times. This phase, which involved mainly the subsidence of the pool's trough, is interpreted on the basis of cores that reveal an alternating sequence of algal mats and gypsiferous sediments. This alternating sequence indicated phases of subsidence of the pool's bottom, where it became too deep for the proliferation of algal mats.

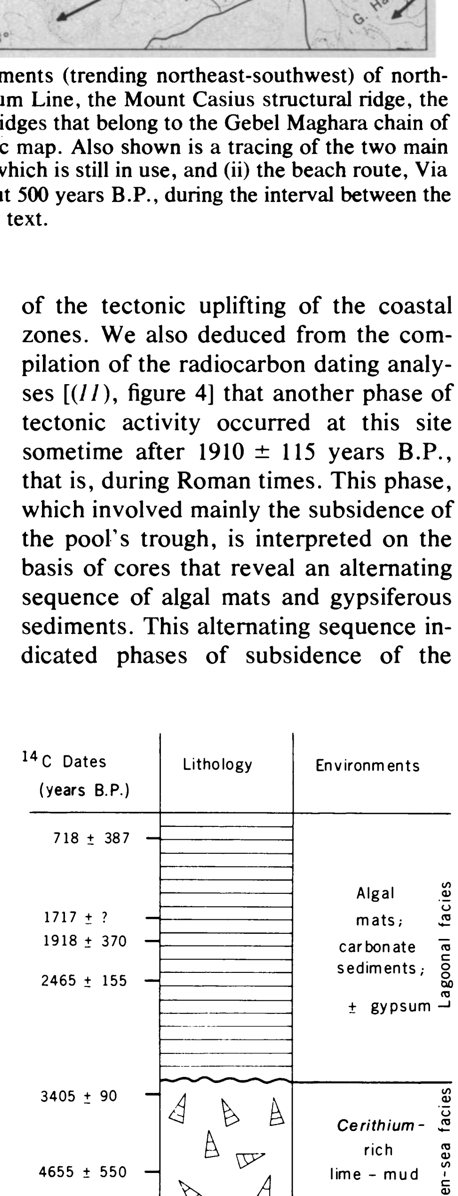

Fig. 3. Schematic profile of the uppermost sedimentary sequence in Solar Pond (southwest of Elat), showing the contact between a lower open-sea and an upper lagoonal facies. Approximately 3000 years B.P. the former bay was closed entirely as a result of tectonic activity (*10, 11*).

The data presented above from the western and eastern margins of the Sinai subplate indicate two phases of tectonic activity that probably occurred at roughly the same time: the first phase sometime between 2700 and 3500 years B.P. and the second in Roman times (after the end of the first century A.D.). On the other hand, no indications have yet been found for tectonic activity on the eastern margin during the youngest (Mamluk) phase. These various activities appear to be related to the regional tectonic evolution, as indicated by the following considerations.

In the model for the tectonic evolution of the Middle East since the upper Paleozoic (*5, 12*), an uneven rate of northward movement for the "Central plate" (the Sinai and Arabian subplates) and the adjacent Northwest African and Iranian plates was postulated. The faster rate of movement of the Central plate caused it to be wedged in between the two adjacent plates. Three en echelon sinistral transcurrent faults—the Qattara-El Alamain-Eratosthenes shear, the Pelusium Line, and the Gulf of Elat-Dead Sea-Jordan shear—are recognized at the western periphery of the Central plate (Fig. 1). The oblique collision energies generated mostly along the Pelusium Line by the northward wedging-in of the Central plate is believed to be split into shearing vectors along this transcurrent fault and compressional vectors perpendicular to it. This situation would cause vertical subsidence along the Pelusium Line and horizontal asymmetric folding adjacent to and away from it.

New data (*13*) indicate that, since the Miocene, no appreciable shear movements have taken place along the Pelusium Line, although the associated downward and lateral compressional movements have been maintained until the present (*4*). On the other hand, the first phase of movement along the Jordan-Dead Sea-Gulf of Elat shear occurred in the upper Oligocene or lower Miocene, in association with the opening of the Red Sea. A second phase of shear movement, which involves the rifting of the Dead Sea graben, probably as a result of the increasing counterclockwise rotation of the Arabian subplates, has been taking place since the late Pliocene. It appears, therefore, that since Miocene times there has been a shift in the active shear faulting from the Pelusium Line to the Jordan-Dead Sea fault.

The cause of the shift in shear faulting is most probably associated with the continent-continent stage of collision of the Central and Eurasian plates in East Anatolia. This stage coincided with the final separation of the Tethys ocean into two segments (the Mesopotamian and Mediterranean basins) which occurred during Miocene times (*14*). The combined effects of the geometry of the plates, the wedging-in mechanism, and the collision of the plates could supply a mechanism which caused the reshuffling of the active shear faulting within the crust.

At the same time, the driving forces that are manipulating the plate movements should not have changed. Therefore, exertion of lateral and vertical compressions, due to oblique collision along the Pelusium Line, are maintained. Hence, evidence for uplift and folding processes along both margins of the Sinai subplate described in this report, is not only explainable but is to be expected.

An eruption at the Volcano Santorini in the eastern Mediterranean, north of Crete, occurred at about 3400 years B.P., a date that coincides with the abrupt demise of the Minoan civilization on Crete (*15*). This event may perhaps have coincided with an earlier Holocene tectonic activity along the margins of the Sinai subplate; however, so far such an earlier event cannot be precisely determined.

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Copper in Aerosol Particles Produced by the Ocean

Abstract. *Measurements of particulate copper in the atmosphere near the island of Tasmania indicate that the ocean is a source of atmospheric copper. A biogenic agent may be responsible for the approximately 20,000-fold enrichment of copper during aerosol production from the ocean.*

Copper frequently is detected in atmospheric particles, even in those collected at locations far removed from anthropogenic sources. For instance, Duce *et al.* (*1, 2*) measured copper concentrations between 0.12 and 10 ng m^{-3} over the Atlantic Ocean north of 30°N and between 0.025 and 0.064 ng m^{-3} at the South Pole. These concentrations are much larger than those predicted for unenriched crustal weathering or oceanic production.

Because of the similar enrichments found over the North Atlantic and the South Pole, together with the short residence time of tropospheric particles compared with the mixing times between the Northern Hemisphere and the Southern Hemisphere, Duce *et al.* (*2*) argued that the enrichment may result from natural processes. Possible natural continental sources of anomalously enriched elements in aerosol particles include volcanism (*3*), low-temperature volatilization processes such as biological methylation (*4*), direct sublimation from the earth's crust (*5*), and emissions from plants (*6*). Fractionation at the air-sea interface can enrich elements in particles produced from the oceans (*7*). We present here evidence that the major source of copper in maritime particulate matter, collected at altitudes below 2000 m, is the ocean and that considerable enrichment must occur at the air-sea interface.

Atmospheric particles were sampled from a Cessna 402 aircraft flying near the island of Tasmania by direct impaction collection (*8*) on Whatman 542 filter papers. These samples were analyzed later by the ring oven technique for copper, sulfate, magnesium, calcium, aluminum, and other trace constituents. This technique allows better temporal and spatial resolution than is usually possible.

Aerosols collected near the surface (below 2000 m) have characteristics different from those collected above this altitude (*8*). Copper concentrations in aerosols collected at low altitudes in upwind conditions (so that local urban and industrial pollution was negligible) ranged from 0.3 to 190 ng m^{-3}. Most of the concentrations are comparable with those reported elsewhere, although the range is wider with some concentrations a little higher than usually observed. A wider range of values is expected because of the shorter sampling times and smaller sampling volumes (typically 10 to 20 m^3) in this work.

Magnesium in atmospheric particles is expected to arise from an oceanic source without enrichment at the air-sea interface (*7*). Aluminum, on the other hand, is derived from a crustal source. As expected, there is virtually no correlation between magnesium and aluminum concentrations in the samples. The correlation coefficient between log[Mg] and log[Al] is only 0.03 (*9*).

Evidence concerning the sources of the elements can be obtained from their correlations with magnesium and aluminum. The correlation coefficient between log[SO_4] and log[Al] was 0.02, indicative of negligible correlation, whereas that between log[Mg] and log[SO_4], based on 19 data points, was 0.71. The correlation between sulfate and magnesium is significant at above the 99 percent confidence level. The geometric mean of the ratio of the magnesium concentration to the sulfate concentration is 0.46 ± 0.09 (*10*). This ratio is essentially the same as the value for sea salt (0.48). The inferences are that the sea is the source of both magnesium and sulfate in these atmospheric aerosols, and that sulfate is not significantly enriched at the air-sea interface.

Because the precision of the measurements of the sulfate concentrations is greater than that for the magnesium concentrations and because sulfate is deduced to have an oceanic source, the correlation of copper concentrations with both magnesium and sulfate was estimated. A least-squares analysis of log[Cu] versus log[SO_4], based on 25 points, produces a gradient of 1.18 ± 0.29 and a correlation coefficient of 0.65. For log[Cu] versus log[Mg], based on 19 points, the gradient is 1.08 ± 0.35 and the correlation coefficient is 0.60. Both correlations are significant at above the 99 percent confidence level. The better correlation for copper with sulfate may result from the more precise sulfate measurements.

If two sources of copper, one independent of magnesium (and sulfate) and one linearly dependent on the magnesium concentration, contributed significantly to the overall copper concentration, a highly significant correlation coefficient could still result. However, in this case the gradient from the least-squares

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