Abnormal concentrations of boron, gold and heavy metals in the Pleistocene and Recent terraces at Wadi Al Hamd, northwestern KSA

A.M.B. Moufti and T.M. Qadi

Department of Mineral Resources and Rocks, Faculty of Earth Sciences,
King Abdulaziz University, B.O.Box 80206, Jeddah 21589, Saudi Arabia

ABSTRACT

The contents of boron, gold and some other heavy metals in the Quaternary terraces at Wadi Al Hamd area are abnormally high. The boron content can be used as paleo-indicator of salinity and pH conditions during deposition. These B-rich terraces lack detrital tourmaline which is the commonest source of the element.

The Quaternary terraces of Wadi Al Hamd comprise a lower consolidated very coarse part of Pleistocene age followed by a much finer Recent upper unconsolidated alluvial terraces. The Pleistocene terraces contain abnormal B content (161-345 ppm) in their coarse carbonate cement of conglomerate which is a strong indication of up to 12 during cementation. A relatively lower paleo-pH value of 8-9 is assigned to the topmost part of the Pleistocene terraces as B content in its quartz-arenite is lower (161-185 ppm). The upper Recent alluvial terraces are composed of silt and mud with kaolinite/illite (K/I) ratio in the range of 2.5 to 3 and have lower B content (16-40 ppm) owing to the dominance of kaolinite. The given boron content in the latter suggests low pH (amounting 5-6.5).

It is believed that B is incorporated into the crystal structure of calcite cement possibly in the form of B $(OH)^{-4}$ which is dependant on the pH value, being more enhanced by the incorporation of H^+ into the calcite structure. It is also believed that the organic matter plays a significant role in B fixation on plant remains of the clayey parts of the upper terraces.

The Ba and Sr contents show lowest values in the quartz-arenite at the top of the Pleistocene terraces suggesting elemental fractionation in more reducing conditions. This also suggests sea transgression after the depsoition of very coarse conglomerate in a lacustrine and hence the quartz-arenite was deposited under reducing conditions. There is also distinct variation in the contents of two analyzed REE (namely Ce&La) and geochemically-related Y.

The silt-sized fractions of the mud cracks and the upper unconsolidated terraces are characterized by the presence of free native gold. Considerable amount of economic gold amounting up to 1.4 and 6.1 g/t are assigned to both lithologies, respectively. On the other hand, the exposed older Pleistocene terraces lack gold that might be accumulated at unexposed depths due to gravity settling.

AIM OF STUDY AND METHODOLOGY

The Quaternary terraces of Wadi Al Hamd area were formed by vigorous channels drained into shallow lacustrines near the Red Sea after the Oligo-Miocene rifting (Basyoni and Surour, 2006). The present work deals with tracing the abundance of boron in both lower consolidated very coarse part of Pleistocene age and the much finer Recent upper unconsolidated alluvial terraces, in addition to the mudcracks capping the wadi alluvium as well. The study of B contents in such sediments alongside with gold and some other heavy minerals in such terraces aims to elucidate the possible physico-chemical conditions that prevailed during deposition and carbonate cementation in particular. The study of these mixed alluvial-lacustrine basins as palaeoenvironmental and palaeoclimate records is the interest of many workers worldwide during the last and current decades (e.g. Valero-Garcés et al., 2000). In the present work, the authors contribute to the use of boron abundance in Wadi Al Hamd terraces as an indicator for both paleo-pH and paleo-salinity.

The present work also sheds light on the anomalous contents of gold that could be of economic interest at Wadi Al Hamd terraces. Some earlier workers, e.g. Basyoni and Surour (2006) & Qadi et al. (2007) encountered exploitable economic gold contents at Wadi Al Hamd but in the stream sediments located at the main wadi course without handling the gold abundance in the wadi terraces. These authors (op. cit.) mentioned that placer gold in the stream sediments of Wadi Al Hamd may reach a grade in the range of 23-30 g/t if the silt sized-fraction (63-125 µm and finer) was subjected to heavy mineral separation.

For accurate determination of clay mineral species, each untreated (air-dried) sample was analyzed by a Philips diffractometer (housd at the Faculty of earth Sciences at King Abdulaziz University, Jeddah) followed by runs after glycolation (using ethylene glycol) and heating to 550 ºC. Glycolation aims to reveal expandable clay minerals expressed as lattice expansion, whereas heating aims to destruct kaolinite and dehydration of smectite that potentially hide the peaks of chlorite on the yielded XRD charts.

An ICP Optima 4300 DV machine was used for the measurements of trace elements, namely the incompatible elements, transitional and other heavy metals. A couple of rare-earth elements (REE), namely Ce & La were also measured by the same ICP machine that is housed at the Saudi Geological Survey (SGS) in Jeddah.

Gold content was determined by the fire-assay technique at the Central Laboratories of the General Authority of Mineral Resources of Egypt as well as by atomic absorption at the same laboratories. The obtained gold was in the form of tiny pea-like aggregates in a porcelain crucible. Analysis of gold using this technique was based on a 50 g or 100 g powdered-sample in the size ranges of 63-125 µm and <40-63 µm as starting specimens.

FIELD OBSERVATIONS

In the northwestern part of Saudi Arabia, vast areas of Al Wajh and Al Muwaylih quadrangles are covered by Neoproterozoic basement crystalline rocks. A portion of the general geology of northwestern Saudi Arabia is given in Fig. 1.

Detailed geological maps of Al Wajh and Al Muwaylih quadrangles were constructed by Davies (1985) and Davies and Grainger (1985) respectively, but they concentrated their works on the Precambrian Shield rocks only. These rocks show high and rugged topography and the width of coastal plain becomes narrower between Al Wajh and Duba. The Phanerozoic sedimentary rocks are situated at both Azlam basin and the coastal plain and they range in age from Cretaceous to Recent. Much older sedimentary successions are found at Al Wajh quadrangle in its northeastern extremity, being represented by Paleozoic sandstones. In the following, a brief description for the sedimentary rocks of Al Wajh quadrangle is given with special emphasis on the wadi terraces and alluvium which are the most favourable hosts for placer minerals. Several attempts had been done for mineral assessment in the Precambrian shield rocks and Phanerozoic sedimentary cover of Al Wajh quadrangle (e.g. Albouvette and Pelllaton, 1979)

The Quaternary terraces

a) The Lower consolidated conglomeratic Pleistocene terraces

At the downstream area of Wadi Al Hamd (Fig. 2), the lower member of the Quaternary sediments is represented by consolidated conglomeratic Pleistocene terraces. These Pleistocene terraces are confined to the downstream area only in dispatched occurrences indicating formation in channels characterized by the incursion of seawater tongues eastwards to the inland. On the other hand, the Recent sediments at the coastal plain can be arranged from oldest to youngest as follows: alluvial terrace deposits (characterizing its entrance from the north), eolian & alluvial beach sand, reworked alluvium, wadi alluvium and mudcracks.

The Pleistocene terraces across the west side of the quadrangle consist mostly of cobbles, pebbles and sand capped by a veneer of lag gravel that has a well-developed desert varnish. Where not disturbed by swamps, these older terraces are flat and support only sparse vegetation. They are thought by Müller (1977) to be of Pleistocene age, especially on the southern coastal plain of Saudi Arabia.

Generally, the topmost parts of the Pleistocene terraces at Wadi Al Hamd are exposed but in most cases they are partly covered by wind-blown sand (Fig. 3a). At many exposures, the lower and upper Quaternary terraces are encountered together where the latter occupies lower topographic levels (Fig. 3b). In most cases, the upper Quaternary terraces (the Pleistoocene ones) are represented by polymictic conglomerate ended at the top by quartz-arenite (Figs. 4a). In some instances, the Pleistocene terraces are unconformaly capping the Tertiary unit (Fig. 4b). The garvel-size clasts are composed of different basement compositions, mainly mafic metavolcanics, metadiorite and granitoids (Fig. 5a). Occasionally, the Pleistocene terraces contains cobbles and boulders up to 45 cm in diameter (Fig. 5b).

In the field, the Pleistocene terraces were surveyed and sampled. It appears that they are typical polymictic conglomerate with the dominance of pebbles over both cobbles and boulders. Two varieties of conglomerate can be distinguished based on the aspect of rock consolidation. The first variety is well cemented and the other is matrix-supported gravels. In most cases, the matrix-supported gravel terraces cap the well cemented terraces. The latter is much finer in size, more mature and sometimes contains secondary streaks of gypsum, mostly in the from of veinlets. The cementing material looks silicic in the handspecimens but the petrographic investigation documents its carbonate composition.

Holocene-Recent terraces

b) The upper unconsolidated silty to sandy terraces

As to the younger terraces, the water of floods exposes well-stratified sections of such terraces. They are composed of 10-15 cm thick buff mudstone (bottom), loose sand and gravel and thinly laminated siltstone at the top. Even in the horizon of loose sand and gravel, stratification and few laminations can be traced. Also, the Recent terraces are represented, as noticed in the field, by both reworked conglomeratic terraces and thinly laminated siltstone-dominated terraces (Fig. 6a).

Reworked alluvium extends over large areas in the western side of the quadrangle. It contains sand, silt and cobbles derived from the alluvial terraces and from over-bank deposits of the present drainage. Reworked alluvium flanks all major wadis, resulting from intermittent heavy discharge.

The siltstone-dominated upper terraces are exposed at the centre of main wadi courses and are in most vegetated as indicated by the presence of some plant roots (Fig. 6a). The upper terraces are covered by eolian and alluvial sands which are also distributed along the coast and the inland areas. Sometimes, change in the current direction during silt deposition of the upper terraces, they display typical cross-lamination (Fig. 6b). In some few cases, the upper terraces attain high topographic levels (Fig. 7a). Seasonal flooding still contribute to now-days formation of micro-terraces (Fig. 7b) formed by incision of the recent flood water into the stream sediments. Within the upper terraces, it can be observed that there is alternation of ill-sorted coarse pebbly sand and well-sorted sandstone band (middle) in a profile of the upper terraces (Fig. 8).

Wadi alluvium (stream sediments)

Stream sediments or wadi alluvium occupies the beds of all major wadis. It consists of silt, sand, gravel and boulders, being unconsolidated, poorly sorted and more or less stratified. These sediments are of great interest because they contain high opaque percentage as noticed by the naked-eyes in the field. Thus, some stream sediments from tributaries north of Al Wajh in order to represent one of our targets. The majority of grains belong to the sand size with variable amounts of silt and pebbles. The pebbles are discarded and its worthmentioning that the chemical analyses were only focused on sand and siltfractions.

The mud cracks are common at the main course of Wadi Al Hamd. They display different dimensions of the polygons (Figs. 9a&b). They are developed on the clayey fine sand of stream sediments which show exceptional concentration of heavy minerals.

Recent sabkha

Recent sabkhas at Wadi Al Hamd area (Fig. 9c) occur either on the main wadi course (inland) or at its downstream at the coast (coastal). In the first case, the inland sabkhas occupy the uppermost part of the wadi floor where they are associated with mud and algae. Generally, they are in the form of thin veneer and hence the thickness ranges from few millimeters to a maximum of 0.5 cm and contains coarse salt crystals (Fig. 9d). In some specific cases, salts of the sabkha represent thick crust over the basement boulder (Fig. 9e) where the thickness of such crust attains about 0.5-0.7 cm. Close to these encrusted boulders, sabkha's salts in the form of aggregated granules are also recorded. The coastal sabkhas are confined to the beach and sometimes they form isolated patches away from it due to invasion of the tidal water. In this case, the precipitated salts are dense and of distinct thickness. Presence of algae in the inland sabkha is responsible for upward doming and formation of tee-pee structure in the mud-salt crust of the sabkha (Fig. 9f&g).

PETROGRAPHY

Petrography of conglomerate

The following petrographic remarks were only possible for the granule to fine pebble conglomerates.

The studied thin-sections of the fine conglomerate from the consolidated Pleistocene terraces collected at Wadi Al Hamd show great variations in the rock compositions that include exotic clasts from the Precambrian basement rocks and finer matrix. They also contain coarse quartz clasts of different morphologies and grain size (Fig. 10a). Either the angular quartz or the sub-rounded ones are cemented by carbonate material that displays distinct optical growth zoning (Fig. 10b). Source of basement clasts is multiple; they are derived from pinkish-banded metatuffs (Fig. 10c), non-porphyritic metabasalts (Fig. 10d), porphyritic metabasalt (Fig. 10e) and metamorphic quartzite (Fig. 10f).

Petrography of quartz-arenite and pebbles in granule conglomerate

This section presents concise account on the petrographic characteristics of quartz-arenite and the pebbles encountered in the coarse conglomerates of the Pleistocene terraces at Wadi Al Hamd. The petrographic investigation of pebbles in conglomerate and arenite of Wadi Al Hamd shows that there is altered feldspar crystal with epidote-rich core in a metadacite variety (Fig. 11a). Spherulitic texture is very common in a massive metarhyolite variety (Fig. 11b). On the other hand, euhedral quartz porphyroclast is common in metarhyolite tuff (Fig. 11c). There are also altered biotite flakes and dispersed sulphides in the metarhyolite tuff (Fig. 11d). The recorded amphibolite pebbles have highly altered olivine (Fig. 11e) whereas the highly weathered serpentinite pebbles contain serpentine minerals and green garnierite (hydrated Ni-silicate) as shown in Fig. 11f. Concerning the bedded arenite that host the pebbles, it is rich in microcline and quartz clasts in a coarse carbonate cement (Fig. 11g). There are also angular quartz clasts and coarse zircon grains in the quartz-arenite bed (Fig. 11h).

CLAY MINERALOGY

Preparation of oriented clay fractions

Aiming to have XRD data of maximum credibility, -2 µm fractions from the mud cracks at Wadi Al Hamd were separated and oriented carefully glass slides. For such a job, the samples were were first treated with HCl in order to get rid of carbonate minerals, followed by the use of H_2O_2 for the removal of organic substances. In order to reduce the high electrolyte content of the examined mud and getting the clay particles in suspension, each samples was washed several times using distilled water containing few drops of ammonia. Then, the clay particles were then separated by sedimentation following Stock's law. Few drops of the resulted clay suspension were allowed to dry on glass slides. Triplicates of slides for each sample were prepared to have reserve of oriented mounts for more additional runs aiming certainty if needed.

Measurements and interpretation

XRD chart of sample No. 34 (4 km from the coast) shows that the clay minerals are a mixture of kaolinite and chlorite with remarkable dominancy of the former over the latter (Fig. 12a). The behaviour of the 14 Å peaks on the chart suggests that the chlorite is possibly of a swelling type, i.e. chlorite+montmorillonite. In sample No. 35 (1.5 km eastwards from the previous sample), it is obvious that the major clay mineral is kaolinite, again with swelling chlorite, some traces of smectite and illite (Fig. 12b). A mixture of kaolinite and lesser amounts of chlorite+smectite is characteristic for sample No. 41 (Fig. 12c). Only a single sample shows no distinct peaks (for all its triplicates) suggesting that it is made up mostly of colloidal substance (Fig. 12d). The latter two samples are separated by about 4 km distance from sample No. 35.

GEOCHEMISTRY

Boron geochemistry

Despite of very little detrital tourmaline as a heavy mineral in the studied terraces and mud cracks at Wadi Al Hamd, these sediments show abnormal contents of boron. The analyses of trace elements in the studied samples show distinct grouping of boron content among the studied Quaternary sediments. In both types of terraces, the B content reaches up to 3.5 times than the value in the average shale of the earth's crust (Woods, 1994). It is here emphasized that when the lower terraces of Wadi Al Hamd contain abnormal B content (161-345 ppm), this represent a strong indication that the pH of the cementing solution was extremely high. According to the parameters fitted experimentally by Hobbs and Reardon (1999), the pH of the cementing solution of Wadi Al Hamd terraces was as high as 12. Within the Quaternary terraces of Wadi Al Hamd themselves, there is also a variation in the B content among the different lithologies encountered in the terrace profile. The B content in the quartz-arenite at the top is relatively lower ranging from 161 to 185 ppm which indicates a paleo-pH equals to 8-9 which can be also attributed to the lack of carbonate cement in such case. Several recent studies during the last decade suggested that B is incorporated into the crystal structure of rhombhedral calcite which would be the case of the carbonate cement (authogenic calcite) for the Pleistocene polymictic conglomerate of Wadi al Hamd. It is believed that B gets into the calcite structure in the form of $B(OH)^{-4}$ in the acidic radical being dependant on the pH value (Sanyal et al., 1999). Recently, Sano et al. (2004) correlated the increase of B content in the carbonates with the incorporation of H^+ into the calcite structure. These workers also proved that boron in carbonates increases with the increase of dissolved authoginic silica. Also, Ishikawa and Nakamura (1993) documented the occurrence of boron in the tetrahedral silicon sites of the siliceous carbonate in similar Quaternary basins. During the Quaternary, invasion of seawater protrusions resulted in the authigenic carbonate cement as documented during the last decade elsewhere in the world, either in the presence or absence of organic matter (e.g. Vengosch et al., 1991; Deyhle et al., 2001; Sano et al., 2004).

Concerning the upper terraces, they are mostly composed of silt and mud with kaolinite/illite (K/I) ratio in the range of 2.5 to 3. For such reason, the B content is low and lies in the range of 16-40 ppm depending on the K/I ratio. It is known that illite is the most common clay mineral having the highest boron concentration where the average shale of the earth's crust has B content never exceeding 100 ppm (Vengosh et al., 1991; Woods, 1994). The given boron content in the upper terraces at Wadi Al Hamd suggests low pH value (amounting 5-6.5) owing to cement lacking and common presence of very fine silt-sized quartz.

It is worthmentioning here that the role of organic matter in the Recent terraces should not be ignored as small plant roots which is the case of Wadi Al Hamd, fix more boron which was analytically documented elsewhere in the world, for example in Egypt, Spain and U.S.A. (Dominik and Stanely, 1993; López-Buendia et al., 1999; Barrett, 2004; respectively). They all, in addition to Cody (1970) & Boon and MacIntyre (2007), document that boron in stream sediments, deltas and near shore channels increases because of salinity of protruded saline seawater. In accordance, the boron content can be here considered as useful paleo-pH and paleo-salinity indicators. Earlier parameters that are also account for abnormal concentrations of boron in sediments include size fractionation where boron is more concentrated in fine carbonates and shale (Walker, 1963).

The B content in a single sample of mud cracks is very low and lies below the limit of instrumental detection (< 5 ppm) supporting that the obtained X-ray diffraction results that indicate poorness in illite but richness in kaolinite instead (Fig. 12) and this is accepted for both continental and marine kaolinites (Walker, 1963; Cody, 1970). As a fact, mud cracks are always developed in the sediments rich in fine fraction (silt & clay) in the presence of organic matter and as a result these sediments contain more boron than the other sandy sediments.

Geochemistry of heavy metals and other trace elements

As revealed from Table 1, both the contents of Ba (up to 339 ppm) and Sr (up to 300 ppm) in the upper Recent terraces are 2-3 times than in the lower terraces of the Pleistocene age which is here attributed to the common occurrence of gypsum streaks. There is also distinct variation in the contents of two analyzed REE (Ce & La) and geochemically-related Y. The contents of these elements show lowest values in the quartz-arenite at the topmost part of the Pleistocene terraces suggesting elemental fractionation in more reducing conditions (Jones et al., 1995; Owen et al., 1999). This in turn suggests sea transgression after the development of Quaternary conglomerate in the near shore channels and hence the quartz-arenite was developed in a considerable water depth that favoured reducing conditions. This is attributed to the fact that the upper recent terraces are more mature (both texturally and compositionally) than that of the Pleistocene terraces. The upper Recent terraces are fine-grained and lack coarse components which are the basement clasts. They heavy metals are still hosted in the basement clasts in the Pleistocene terraces. Source of sediments in both types of terraces is the same which is the Eastern Arabian Shield rocks, i.e. both fluviatile. Variation in the geochemical signatures of both terraces is hence due to variation of the degree of maturity and not due to the change of the source rocks. This is clear where the upper loose terraces contain higher amounts of some heavy metals e.g. Co, Cu, Nb, Ni, V and Zr up to 36, 57, 10, 106, 111 and 123 ppm, respectively.

Owing to the difficiency of clay minerals in the lower Plaeistocene terraces, Li is very low and lies beyond the limit of detection (< 5 ppm). On the other hand, mud crack and upper terraces possess considerable Li contents (31 and 12 ppm, respectively) because of the presence of gypsum and organic matter in both similar (Smith, 1976).

Anomalous gold content

Table 1 shows that the sediments of the Pleistocene terraces are almost barren in detrital alluvial gold despite the fact that the noble metals are expected to be encountered in the conglomerate derived from the Precambrian shield rocks as a placer mineral. All analyzed Pleistocene samples show gold content below the limit of detection (< 0.2 g/t). Nevertheless, it can be stated here that gold may be confined to extremely lower horizons in the conglomerate due to gravity settling of heavy gold (sp. gr. of 19.3 g/cm^3); the six samples are collected from the exposed terraces that attain a maximum thickness of 25 m above the mean wadi level.

Due to the presence of free native gold in the mud cracks and Recent terraces in the silt fraction, both lithologies contain considerable economic gold contents amounting up to 1.4 and 6.1 g/t, respectively in fraction 63-125 µm and finer. The obtained results are for sieved raw samples that did not experienced any heavy minerals separation. Qadi et al. (2007) pointed out that the silt fraction of Wadi Al Hamd stream sediments contain anomalous gold contents reaching up to 6.64 g/t.

CONCLUSIONS

1. Tracing B contents in both Pleistocene, Recent wadi terraces and stream sediments at Wadi Al Hamd area indicates abnormal concentration of the element which can be safely used as a paleo-indicator of paleo-salinity and paleo-pH conditions of the cementing solutions.

2. The Pleistocene sediments or the lower terraces of Wadi Al Hamd contain abnormal B content (161-345 ppm) which is a strong indication of extremely high pH as high as 12 in the depositional basin. A relatively lower paleo-pH value of 8-9

is assigned to the upper part of the Quaternary profile as B content in its quartz-arenite is lower (161-185 ppm).

3. The Recent terraces or the upper terraces are composed of siltstone and mudstone with kaolinite/illite (K/I) ratio in the range of 2.5 to 3 and have lower B content (16-40 ppm) owing to the dominance of kaolinite over illite. The given boron content in these sediments suggests low pH (5-6.5) and deficiency of carbonate cements.

4. In the Pleistocene terraces, it is believed that B is incorporated into the crystal structure of calcite cement possibly in the form of $B(OH)^{-4}$ which is dependant on the pH value (Sanyal et al., 1999). The boron enrichment in the carbonate cement is enhanced by the incorporation of H^{+} into the calcite structure (Sano et al., 2004). It is concluded also here that the presence of organic matter enhances the fixation of boron (Barrett, 2004).

5. Concentrations of heavy metals in both Recent terraces and the mud cracks are much higher than in the Pleistocene terraces pointing out to sediment maturity.

6. The Ba and Sr contents show lowest values in the quartz-arenite at the topmost part of the Quaternary terraces suggesting elemental fractionation in more reducing conditions. There is also distinct variation in the contents of two analyzed REE (Ce & La) and geochemically-related Y.

7. the exposed Pleistocene terraces above the mean wadi level at Wadi Al Hamd show very poor gold content where the metal could be more enriched at the unexposed horizons because of its very high specific gravity.

8. The silt-sized fractions of the mud cracks and friable lower Recent terraces are characterized by the presence of free native gold. Considerable amount of possibly economic gold contents amounting up to 1.4 and 6.1 g/t are assigned to both lithologies, respectively.

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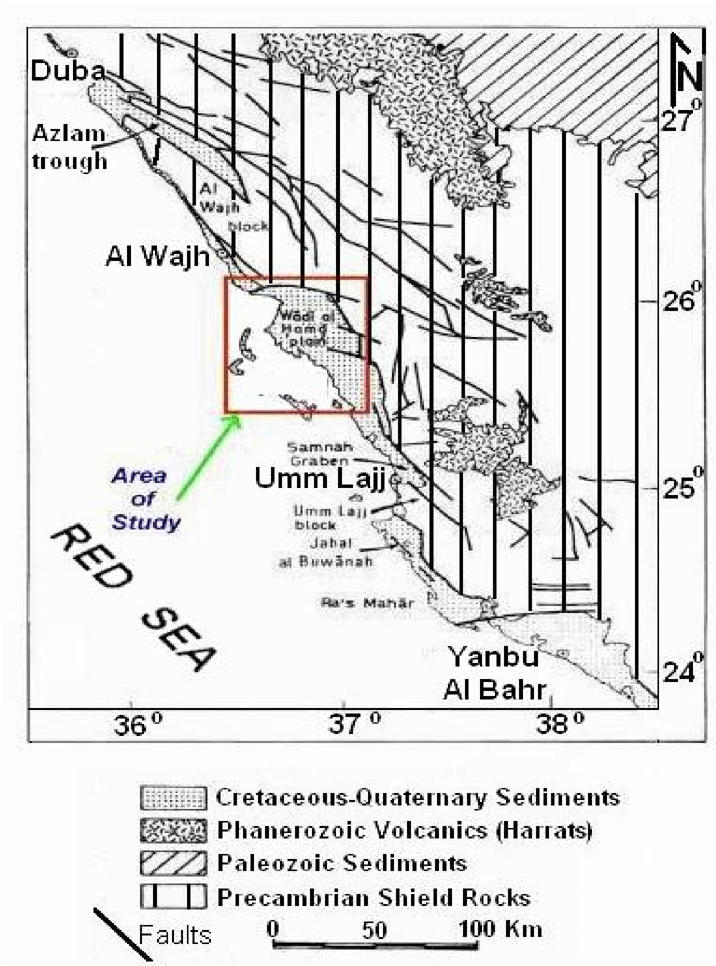

Fig. 1: Geology of northwestern Saudi Arabia (from Vazquez-Lopez and Motti, 1981)

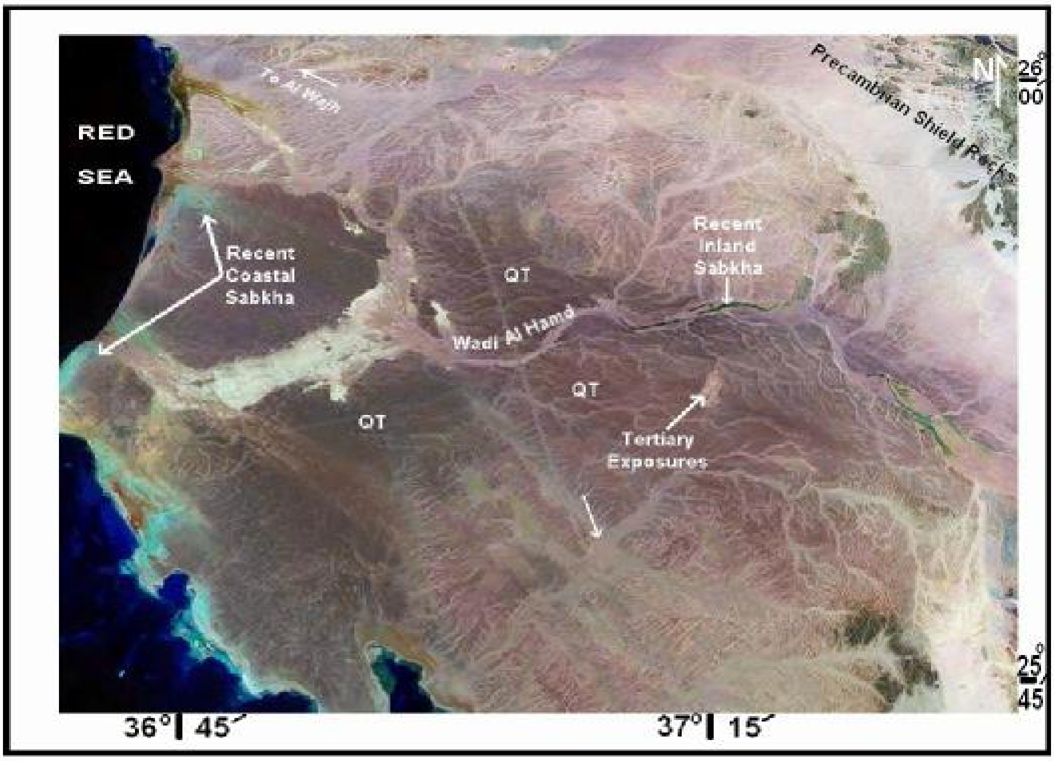

Fig. 2: Satellite image showing the main course of Wadi Al Hamd and the locations of the studied terraces. QT denotes Quaternary terraces. The image was acquired in July 2004.

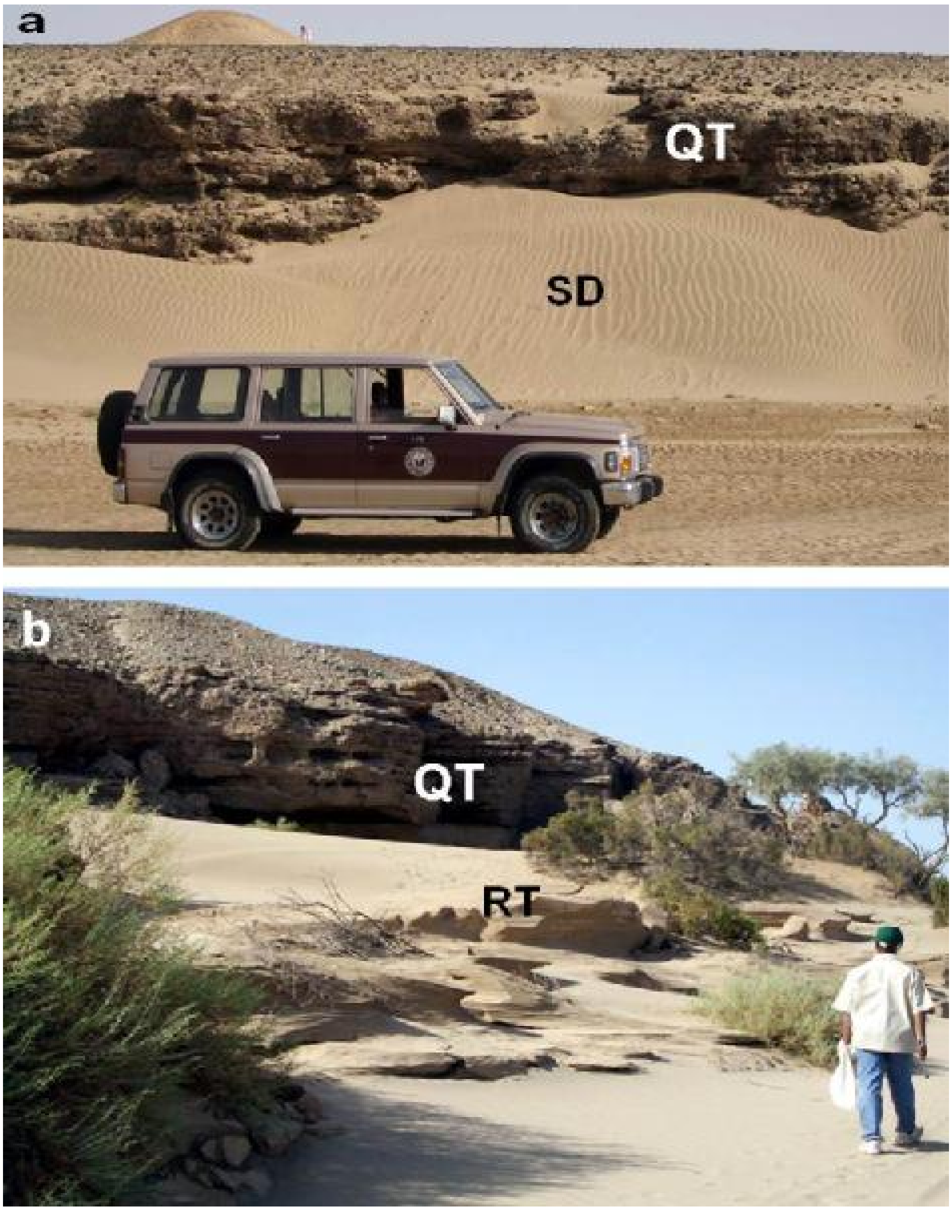

Fig. 3: a) General view for the Pleistocene terraces (QT) partly covered by wind-blown sand (SD).
b) Outcrop having two types of terraces, namely Pleistocene (QT) and Recent (RT).

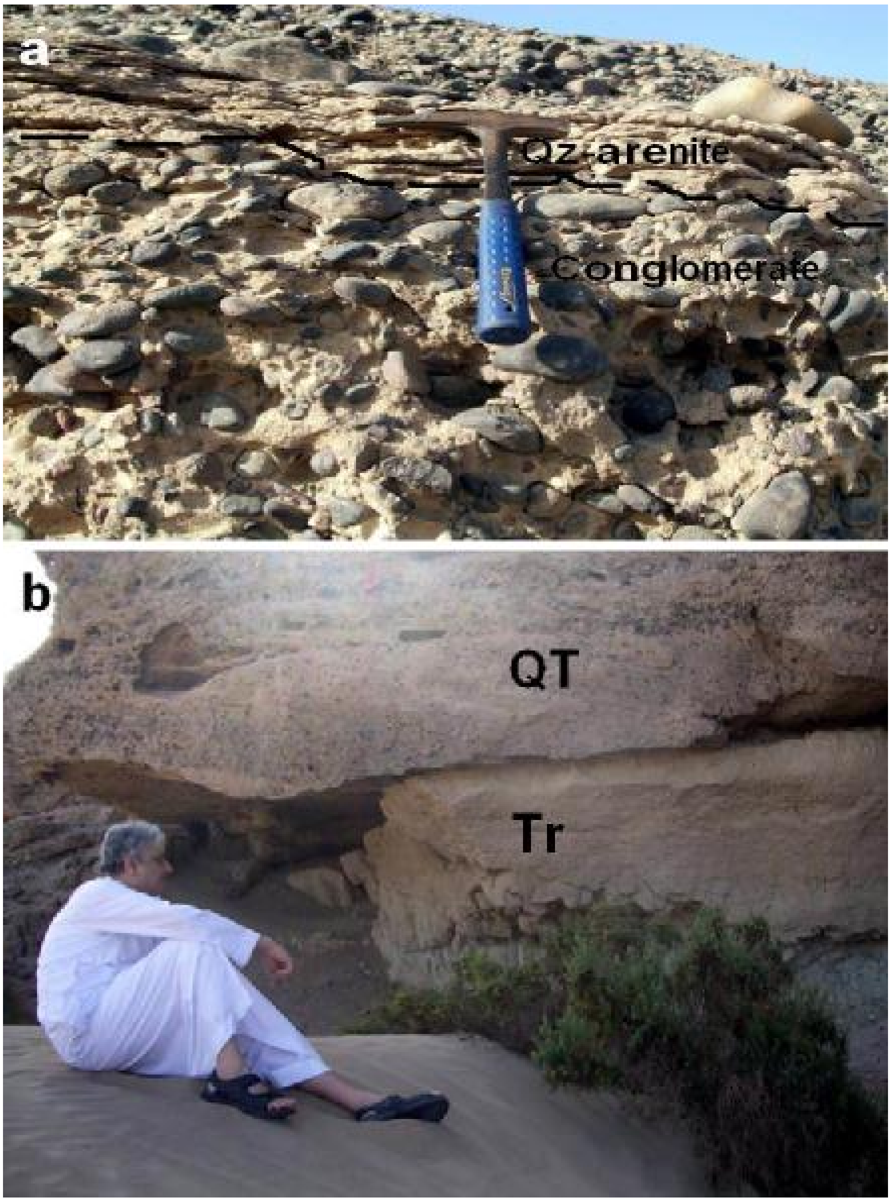

Fig. 4: a) Quaternary terraces composed of conglomerate grading upward to quartz-arenite.
b) Quaternary terraces (QT) unconformably overlaying Tertiary calcereous mudstone (Tr).

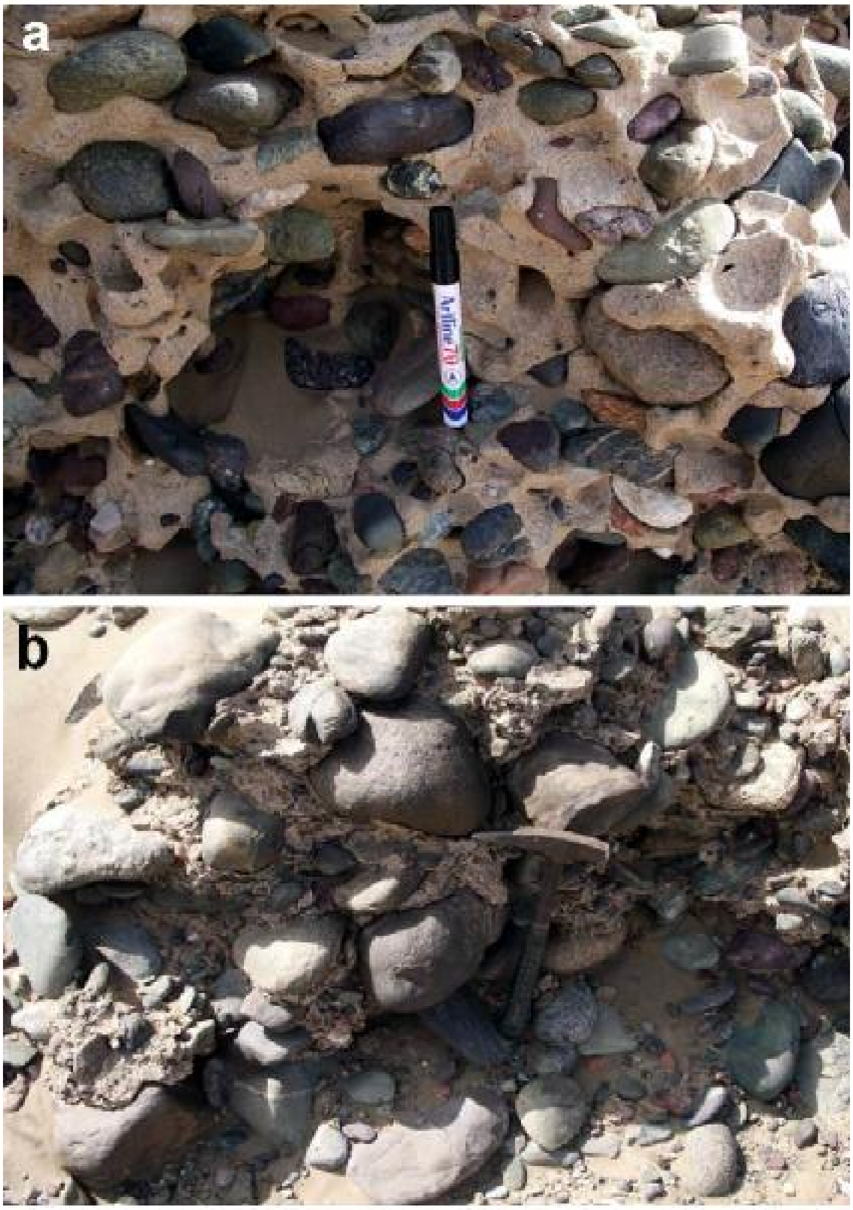

Fig. 5: a) Highly carbonate cement conglomerate of the lower Pleistocene terraces
b) Matrix-supported conglomerates of the Pleistocene terraces.

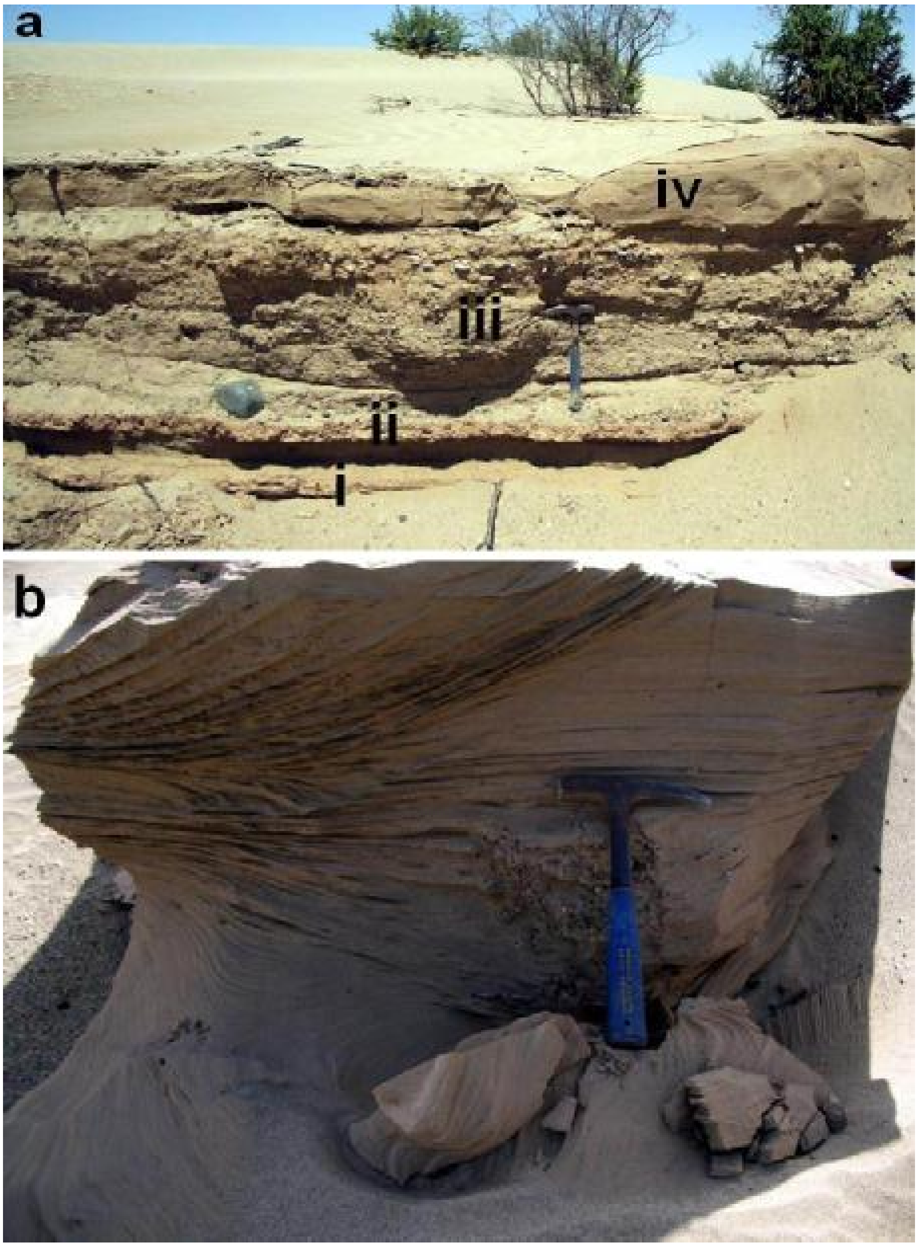

Fig. 6: a) Recent upper terraces showing a succession of i: siltstone, ii: mudstone, iii: sand-gravel layer and iv: siltstone with plant roots.
b) Siltstone of the Recent terraces displaying cross-lamination.

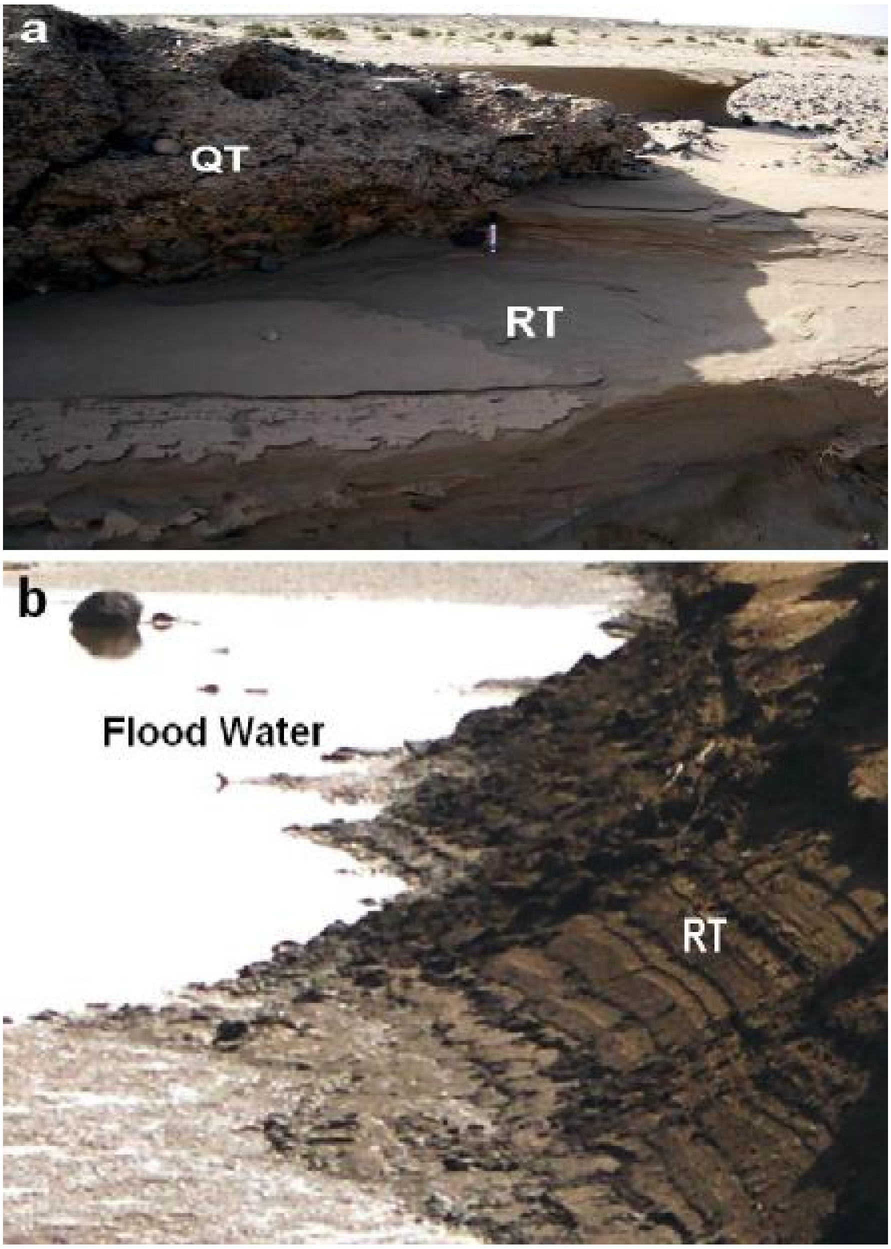

Fig. 7: a) Partial capping of Quaternary terraces (QT) by Recent terraces (RT).
b) Micro- Recent terraces (RT) developed on Wadi flanks incised by flooding water.

Fig. 8: Alternation of ill-sorted coarse pebble sand (above & below) and well-sorted sandstone band (middle) in a profile of the upper terraces

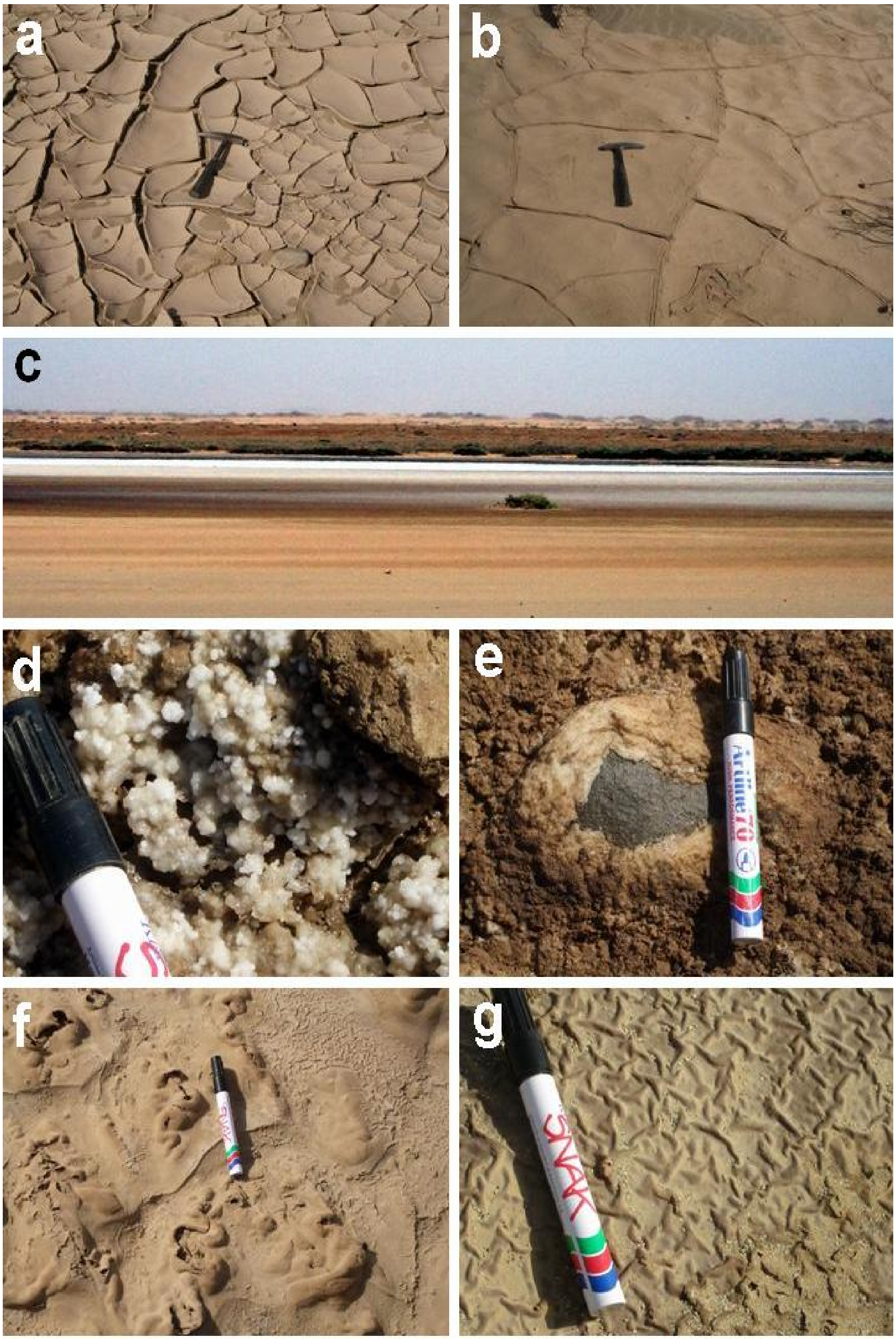

Fig. 9:

a) Small-dimensioned polygons in the mud cracks.
b) large-dimensioned polygons in the mud cracks.
c) General view of near shore sabkha.
d) Coarse salt crystals in inland sabkha far from the shore.
e) Coarse salt of inland sabkha encrusting a basement cobble.
f) Local doming in inland sabkha due to algal activities.
g) Common tee-pee structure in the inland sabkha

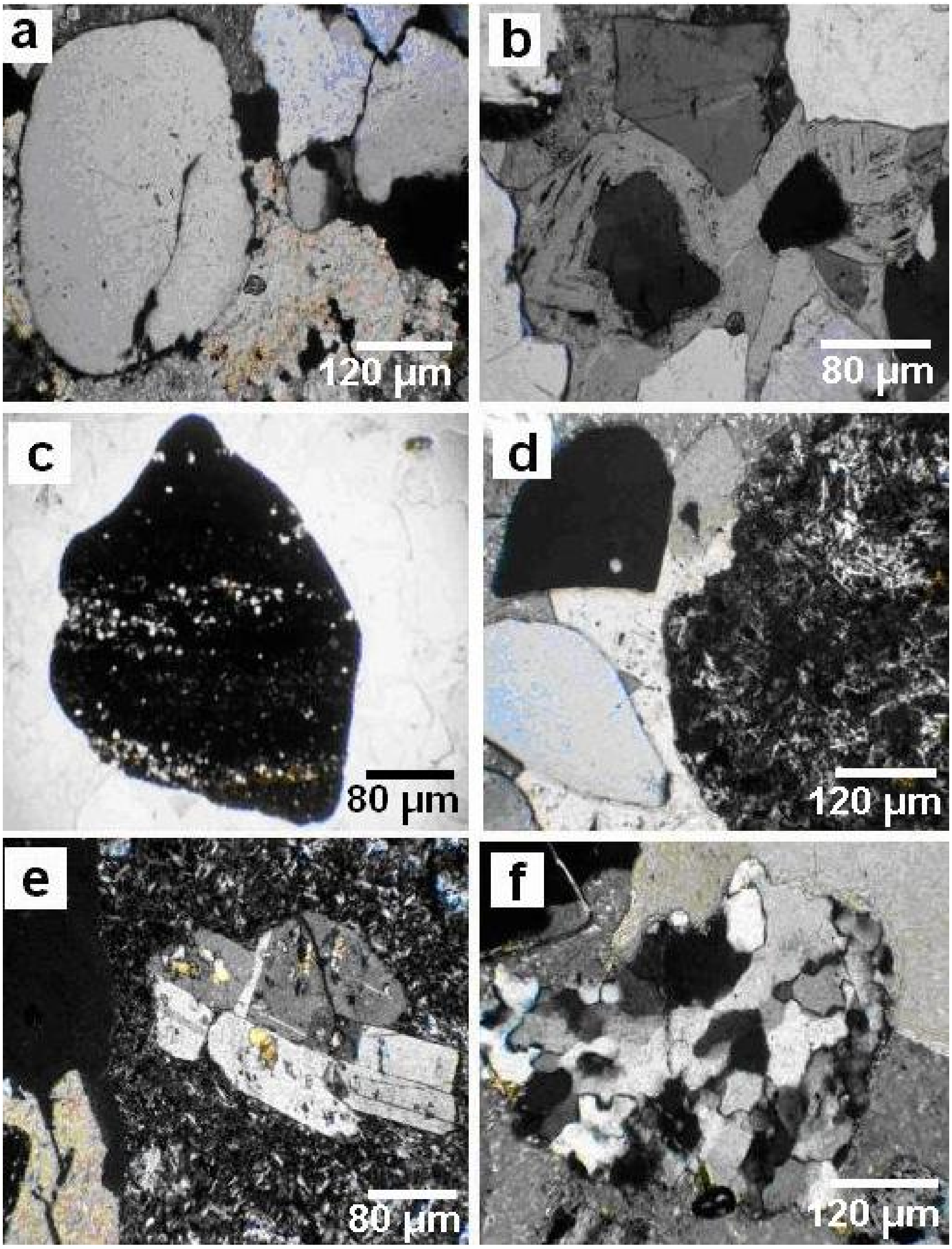

Fig. 10: Petrography of micro-conglomerate (consolidated Quaternary terraces):

a) Difference in quartz size and angularity, C. N.
b) Zoning displayed by carbonate cement, C.N.
c) Fragment of dark metatuff, P.P.L.
d) Non-porphyritic metabasalt fragment, C.N.
e) Porphyritic metabasalt fragment, C.N.
f) Metamorphic quartzite fragment, C.N.

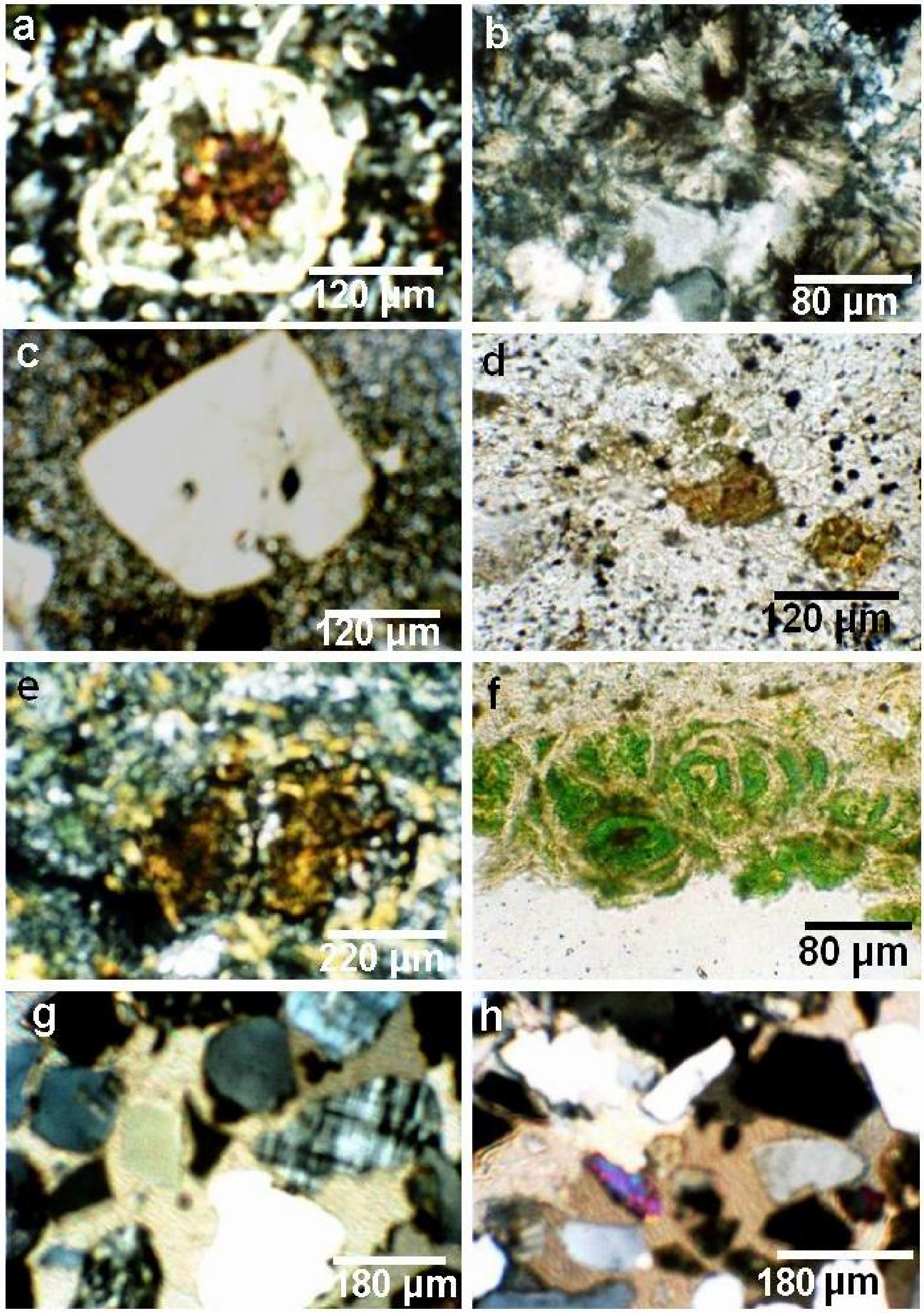

Fig. 11: Petrography of pebbles in conglomerate and arenite of Wadi Al Hamd

a) Altered feldspar crystal with epidote-rich core in metadacite, C.N.
b) Details of spherulitic texture in massive metarhyolite, C.N.
c) Euhedral quartz porphyroclast in metarhyolite tuff, C.N.
d) Altered biotite flakes and dispersed sulphides in metarhyolite tuff, P.P.L.
e) Highly altered olivine in amphibolite, C.N.
f) Green garnierite (hydrated Ni-silicate) in weathered serpentinites, P.P.L.
g) Microcline and quartz clasts in quartz-litharenite bed, C.N.
h) Angular quartz clasts and coarse zircon in quartz-arenite bed, C.N

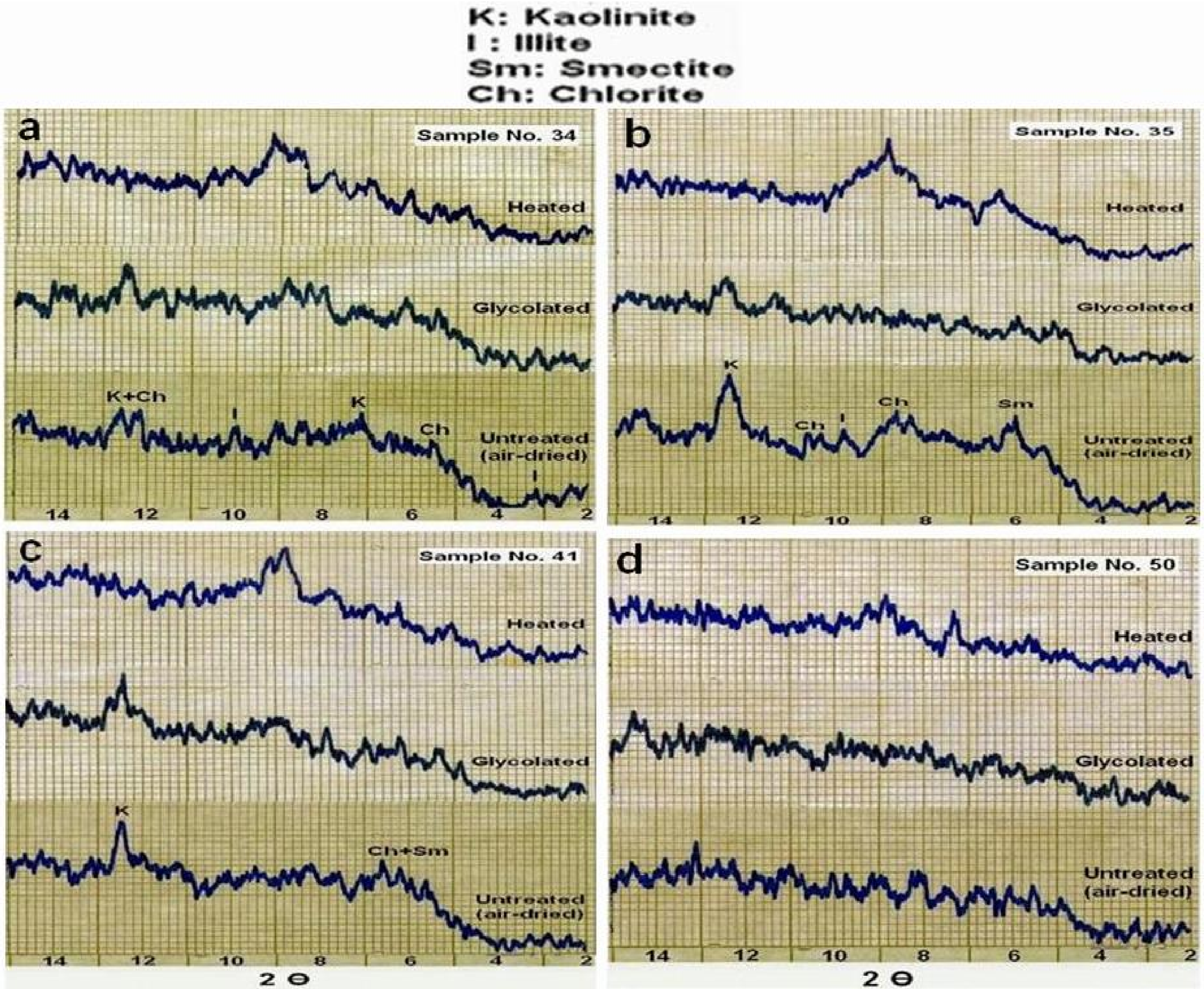

Fig. 12: XRD chart of some separated and oriented clay fractions from the mud cracks at Wadi Al Hamd. Sample No. 50 is possibly colloidal(?) as no distinct peaks can be identified.

Table 1: Chemical analyses of trace elements and gold in Wadi Al Hamd sediments *

Element & limit of detection / Sample type & number		B	Ba	Ce	Co	Cr	Cu	La	Li	Nb	Ni	Pb	Sr	V	Y	Zn	Zr	Au
		5 ppm	1 ppm	10 ppm	1 ppm	1 ppm	1 ppm	1 ppm	5 ppm	1 ppm	1 ppm	7.5 ppm	1 ppm	1 ppm	5 ppm	1 ppm	1 ppm	0.2 g/t
Carbonate cement of the lower Pleistocene terraces	H 1	345	142	10	3	24	8	5	< 5	2	9	<7.5	106	21	11	71	41	< 0.2
	H 2	295	143	10	3	22	8	5	< 5	2	9	8	120	18	11	80	53	< 0.2
	H 3	171	171	13	3	23	9	7	< 5	2	7	<7.5	102	17	13	81	52	< 0.2
	H 4	210	160	13	2	20	7	7	< 5	< 1	6	<7.5	103	16	13	78	53	< 0.2
Pleistocene Qz-arenite	H 5	185	190	< 10	3	22	7	3	< 5	< 1	8	<7.5	104	17	7	110	37	< 0.2
	H 6	161	241	< 10	2	19	6	4	< 5	1	8	<7.5	102	16	8	126	39	< 0.2
Mud crack	H 7	< 5	280	48	36	128	57	27	31	9	106	14	259	111	25	111	123	1.4
Upper Recent Terraces	H 8	40	328	24	17	104	23	13	12	8	58	<7.5	300	74	22	63	77	5.7
	H 9	16	339	24	16	97	24	13	12	10	59	<7.5	297	71	22	64	73	6.1

* Gold was measured by the fire assay technique in the silt-sized raw fraction and the rest of elements by ICP-MS based on unsieved raw samples.

التركيزات الغير اعتيادية لعنصري البورون والذهب والفلزات الثقيلة في شرفات العصر البلايستوسين والشرفات الحديثة بوادي الحمض، شمال غرب المملكة العربية السعودية

أسعد محمد بكر مفتي وطلال مصطفي قاضي

قسم الثروة المعدنية والصخور، كلية علوم الأرض، جامعة الملك عبد العزيز، ص. ب. ٨٠٢٠٦، جدة ٢١٥٨٩، المملكة العربية السعودية

الملخص العربي

محتويات عنصري البورون والذهب بالاضافة للفلزات الثقيلة تمثل قيم غير اعتيادية، وهنا يهدف البحث الي استخدام عنصر البورون كدليل قديم لظروف درجة الملوحة وقيمة الأس الايدروجيني أثناء الترسيب.

وشرفات العصر الرباعي بوادي الحمض تحتوي علي قيم غير اعتيادية عالية (١٦١-٣٤٥ جزء من المليون) وذلك ضمن المادة الكربوناتية اللاحمة لصخور المتدملكات وهذا دليل علي قيمة أس أيدروجيني عالية تصل الي ١٢ بحوض الترسيب. وتتميز الظروف القديمة بانخفاض نسبي لقيمة الأس الايدروجيني بالجزء الأعلي لشرفات العصر الرباعي والممثلة بالكوارتز- أرينيت حيث تقع القيمة في المدي الضيق ٨-٩ ويكون تركيز البورون أقل (١٦١-١٨٥ جزء من المليون). أما شرفات العصر الحديث فتتكون من صخور غرينية وصخور طينية مميزة بنسبة معدني الكاولينيت/ الأيليت في المدي 3-2.5 ومحتوي قليل من البورون (١٦-٤٠ جزء من المليون) ويعزي هذا الي سيادة معدن الكاولينيت علي معدن الأيليت. ومحتوي البورون في الشرفات الحديثة يدل علي بيئة ترسيب مميزة بقيمة أس أيدروجيني منخفضة (٥-٦,٥).

ويعتقد أن البورون يدخل الشبكة البلورية للكالسيت في المادة اللاحمة للمتدملكات علي هيئة $B(OH)^{-4}$ وهذا مرتبط بقيمة الأس الأيدروجيني والذي يساعد علي حدوث ذلك هو دخول أيونات الأيدروجين للمعدن أيضا. كما يعتقد أيضا أن المواد العضوية تلعب دوراً مهم في تثبيت عنصر البورون خصوصا في العينات الغنية بمعادن الطين مع الأخذ في الاعتبار تواجد بعض جذور النباتات في الشرفات الحديثة بوادي الحمض.

وتوضح محتويات عنصري الباريوم والأسترنشيوم بصخر الكوارتز- أرينيت في الجزء العلوي لشرفات العصر الرباعي أن هناك تجزئ للعناصر في ظروف أكثر اختزالية ويقترح هنا حدوث ذلك مع تقدم نسبي للبحر بعد تكوين المتدملكات في مستويات أقل ضحالة. وهناك أيضا تباين واضح بين نوعي الشرفات المدروسة في محتويات عنصرين تم قياسهم ضمن العناصر الأرضية النادرة (السيريوم واللانثانوم) اضافة الي عنصر الأيتريوم والمرتبط بهم جيوكيميائيا.

والقطفات الغرينية للشرفات الحديثة وكذا بعض الطين المتشقق مميزة بوجود حبيبات دقيقة من الذهب الطليق. وتعتبر قيم الذهب المسجلة معقولة وتبدو اقتصادية حيث يبلغ الذهب بالطين المتشقق ١,٤ جرام/طن وتصل القيمة الي ٦,١ جرام/طن في الشرفات الحديثة. وعلي النقيض، فان الاجزاء المكشوفة من متدملكات العصر الرباعي لا تحتوي علي الذهب والذي قد يكون مستقر في أعماق غير مكشوفة ويعزي هذا الي التراكم بفعل الجاذبية.