4 Volcanic Geoheritage of Other Harrats of Kingdom of Saudi Arabia

4.1 Geoheritage Value of Other Volcanic Fields in Western Saudi Arabia: Overview

Other than the intensive volcanological and geoheritage studies on Harrat Rahat (Moufti and Németh 2013; Moufti et al. 2013b; Murcia et al. 2014, 2015), only preliminary research has been done to document the volcanic geoheritage value of harrats in western Saudi Arabia. Several research paper and conference presentations published between 2012 and 2015 raised awareness of the opportunity to develop the geoheritage, geotourism and geoconservation works in many volcanic regions in the Arabian Peninsula (Moufti et al. 2013a, 2015; Moufti and Nemeth 2014). Preparing the initial volcanic geoheritage catalogue yielded some additional sites to be recognized and recommended for future investigations. The following descriptions result from lengthy and intensive field observations in the various harrats.

Harrat Kishb is a volcanic field in the south of Harrat Rahat (Fig. 4.1) which provides new insight into the evolution of a volcanic field that shows more similarity to normal intracontinental volcanism with bimodal (basalt and phonolite) alkaline volcanism (Camp et al. 1992; Coleman and Gregory 1983; Connor and Conway 2000). The first visits to Harrat Kishb were not only to understand the geological context of the region but also document and catalogue the volcanic geoheritage values of the region. Harrat Kishb is the home of two particular volcanic sites regularly visited by tourists in the past and initial concern about the preservation of sites with high geological heritage values (Moufti et al. 2013a) was raised by the Saudi Authority for Tourism and Antiquity. These two sites are considered to be the two most prominent eruption sites of the field; (1) the Al Wahbah maar crater (Fig. 4.2) and the (2) Aslaj volcanic complex (Fig. 4.3).

The SE edge of Harrat Kishb also has potential for geoheritage development (Moufti et al. 2013a); in that area phonolitic volcanoes (lava domes, dome coulees, phonolitic explosion craters) and large complex volcanic explosion craters are surrounded by tuff rings and nested by lava spatter and scoria cones and associated intra-crater to breached lava flows (Fig. 4.4). These regions are covered by extensive ash plains, which provides dramatic volcanic landscapes and graphic views to help to understand the consequences of major explosive volcanic eruptions. In this regard this region is considered an ideal place to develop volcanic hazard educational sites.

Some preliminary field observations were also taken from Harrat Hutaymah in the northern side of the Arabian Peninsula (Fig. 4.1), which is a prominent and less known volcanic field north of Harrat Rahat (Moufti et al. 2015). Harrat Hutaymah is located near to the city of Hail in Northern Saudi Arabia and has appropriate infrastructure for accessing excellent volcanic sites. In Harrat Hutaymah visitors can see some of the best sites in western Saudi Arabia for illustrating the eruption mechanism of explosion craters dominated by phreatomagmatic explosive eruptions (Moufti et al. 2015). Harrat Hutaymah is also an excellent site to contribute to our understanding of how maar craters form and how and to what extent we can relate maar volcanism and pre-maar scoria and lava spatter-forming eruptions which are commonly fissure aligned (Fig. 4.5).

The volcanic field is ideally located in the proximity of Hail city, allowing for day tours from the city. In addition to the volcanic past, rich archaeological remains document the development of irrigation in the region over the past several thousands of years history. Thus this location is a unique place to combine geological and cultural heritage studies and to develop geotouristic and geoeducational sites (Moufti et al. 2015).

Harrat Khaybar, just north of the city of Al Madinah (Fig. 4.1), has been very remote, but new road construction in the region in combination with the proximity to other cultural heritage sites, including the Mada'in Saleh UNESCO World heritage site, provide the opportunity for this field to

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Fig. 4.1 Harrats other than Harrat Rahat with volcanic geoheritage values on google earth image. Individual harrats described in this chapter are marked on satellite image such as Harrat Kishb, Harrat Khaybar, Harrat Hutaymah and Harrat al Birk

Fig. 4.2 Al Wahbah maar crater overview from the western scoria cone half sectioned by the maar-forming eruption [22° 54′ 37.69″N; 41° 8′ 2.98″E]

be one of the flagship regions to form a volcanic geopark in a unique volcanic landscape. The advance of a new road from the township of Khaybar to the east allows access to the deep interiors of the field across a relatively large area (Fig. 4.6). The purpose of the preliminary field campaign here was to locate volcanic geoheritage sites, and identify major geological features that make this harrat unique. Harrat Khaybar is one of the largest harrats in western Saudi Arabia and hosts nearly as many eruptive centers as Harrat Rahat, with a substantially larger number of silicic centers that are well-preserved (Camp et al. 1991).

The Harrat Khaybar is inferred to have had volcanic activity during historic time (Camp et al. 1991). The largest volcano preserved in Harrat Khaybar (Jabal Qidr) is one of the youngest (Fig. 4.7) and produced an extensive ash plain (Camp et al. 1991) suspected to have resulted from a

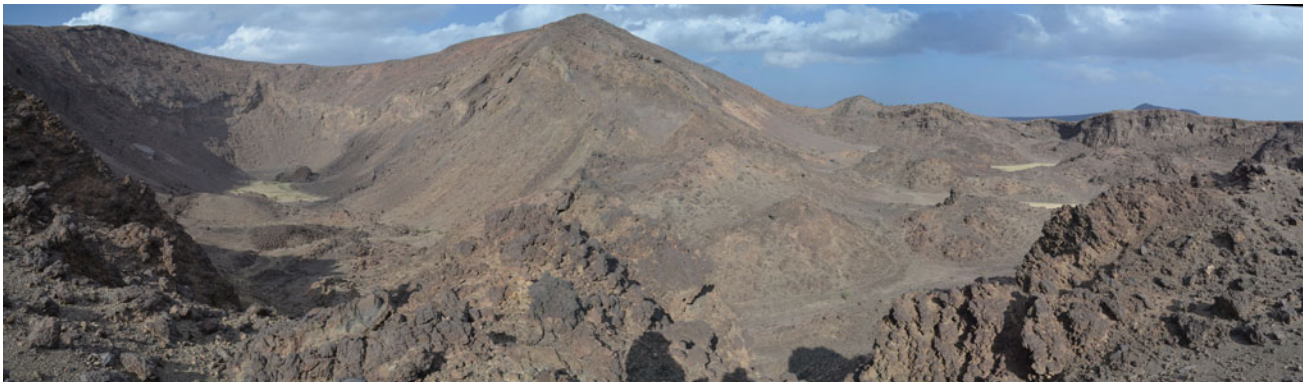

Fig. 4.3 Aslaj is a complex volcano surrounded by a volcanic ash plain in the norhtern margin of the Harrat Kishb [23° 14′ 17.19″N; 41° 16′ 6.64″E]

Fig. 4.4 Phonolithic volcanoes of Harrat Kishb looking toward the west/north-west from the southern margin of the volcanic field [22° 48′ 28.14″ N; 41° 20′ 53.92″E]

Fig. 4.5 Harrat Hutaymah overview and landscape [26° 58′ 57.50″N; 42°14′ 45.61″E]

Fig. 4.6 Typical dirt road in the interior of Harrat Khaybar with having Jebel Bayda in the background [25° 39′ 51.45″N; 39° 57′ 26.51″E]

Fig. 4.7 Jebel Quidr viewed from the east [25° 43′ 12.19″N; 39° 56′ 37.64″E]

Fig. 4.8 Harrat al Birk landscape looking toward south along the Red sea in the outskirt of Al Birk township [18° 12′ 48.73″N; 41° 32′ 17.94″E]

sustained eruption (active longer than few months) that likely reached sub-Plinian scales and accompanied the growth of a stratovolcano (Martin and Németh 2006; Valentine and Gregg 2008). Due to the young suspected age of Jabal Quidr the need to collect information to evaluate the volcanic hazard in the near future in the vicinity of the city of Al Madinah is justified. The presence of the intact volcanic landforms in the harrat can be used as geoeducation sites to demonstrate the causes and consequences of such eruptions in the future.

Harrat Al Birk is located in the southwest of Saudi Arabia, along the Tihamat Asir region near the Red Sea coast (Fig. 4.1). The Harrat Al Birk contains some spectacular volcanic landscapes that are particularly beautiful due to the proximity of the volcanoes to the Red Sea (Fig. 4.8). The volcanic geoheritage value of Harrat Al Birk is high and it is also justified by the fact that some historic eruptions are known from this region and the current dramatic economic development in the region accompanied with fast population growth would make perfect sense to continue a volcanic hazard study and associated geoheritage and geoeducational work to be conducted in the region in the near future.

4.2 Harrat Kishb

4.2.1 Al Wahbah Maar Crater Geotope [22° 54′ 2.11″N; 41° 8′ 23.36″E]

Al Wahbah Crater is part of the Harrat Kishb (Fig. 4.9), a bimodal (alkaline olivine basalt–phonolite) monogenetic volcanic field with extensive lava fields (harrat) formed in the last 2 millions of years (Abdel Wahab et al. 2014; Camp et al. 1992; Coleman and Gregory 1983; Grainger 1996; Grainger and Hanif 1989). Al Wahbah Crater is one of the largest and deepest Quaternary maar craters in the Arabian Peninsula (Fig. 4.9). It is NW-SE-elongated, ∼2.3 km wide, ∼250 m deep and surrounded by an irregular near-perpendicular crater wall cut deeply into the Proterozoic diorite basement (Fig. 4.10). The main feature of the Al Wahbah crater beside its impressive deep crater is the half section of a scoria cone dissected by the crater floor subsidence of the maar, exposing the entire inner part of the scoria cone (Fig. 4.10). The age of Al Wahbah is poorly constrained, however a recent Ar/Ar study on a dolerite plug filling the half sectioned scoria cone confirmed a minimum age of Al Wahbah to be 1.147 ± 0.004 Ma, younger than the uppermost pre-maar lava flow emplacement period (1.261 ± 0.021 Ma–1.178 ± 0.007 Ma) (Abdel Wahab et al. 2014). While the age difference between the pre-maar lava fields and the maar appears to be too long (at least 20 ka) to view the maar and its underlying volcanic succession as a result of the same volcanic episodes, there is geological evidence indicating that at least the uppermost pre-scoria cone/pre-maar lava flow is in close genetic relationship with the scoria cone sitting on it.

Maar craters are relatively rare (or rarely preserved due to quick eolian crater fill formation) features of the arid Arabian landscape, and with their “hole-in-the-ground” morphology (Heiken 1971) they differ strikingly from other volcanic landforms in the region; this adds significant and unique landscape value to the volcanic fields of Arabia (Camp et al. 1991, 1992). Al Wahbah is not only unique by its landscape, but also its volcanic geology is special. Pre-maar scoria cone-building rock units and phreatomagmatic successions associated directly with the formation and growth of the maar crater are perfectly preserved. Similar examples are rare globally, particularly ones that are perfectly exposed and/or accessible (Keating et al. 2008; Valentine and Cortes 2013; Valentine and Gregg 2008).

The Proterozoic diorite basement is covered by at least two basaltic lava sheets exposed everywhere in the crater wall (Fig. 4.11). They are dark, aphanitic basanitic rocks with olivine and pyroxene phenocrysts. The lower lava flow is hard to access, and it can be examined only from distant photographs or an access path from the northern edge of the crater rim which leads to the crater floor and an old and abandoned terraced garden in the NE crater wall. The lowermost lava flow unit is columnar jointed thick (10–15 m) lava that thins toward the south. Its base cannot be seen due to cover from debris while its upper boundary to the upper lava flow is separated by lava top, lava foot breccias, and some mixed dusty sedimentary layers that indicate a potential time break between the emplacement of the two flow units. In the upper flow unit (about 5–10 m thick) the lava foot breccias occasionally developed over fairly thick intermediate volcaniclastic bedded sediments in which some pillowed lava lobes can be recognized indicating that the topmost lava flow may have been emplaced in a terrain contained some pond with accumulating volcaniclastic dust from various distal sources. The topmost part of the upper lava flow unit (Fig. 4.12) appears to be multiple lava flow units, including an upper lava flow unit that is clearly thinning from the pre-crater scoria cone and which is the basal part of the scoria cone cut subsequently by the maar crater.

This topmost basal lava flow seems to evolve gradually to a succession that is dominated by lava spatter horizons, clastogenic lava flows and agglutinated scoria beds as the base of the pre-maar scoria cone. The scoria cone edifice up section shows more evidence of a loose scoria ash and lapilli hosted occasional spindle bomb-bearing pyroclastic sequence that is gradually transformed in distal areas to a grain flow-dominated reworked talus that results from a growing scoria cone as a response to the enlarged edifice when the freshly erupted pyroclasts roll down to the foothill of the cone for their resting point. The scoria cone succession is capped by a fine lapilli tuff and tuff succession that is rich in accidental lithic fragments from country rocks and chilled blocky juvenile pyroclasts indicating that they formed due to phreatomagmatic fragmentation and underground explosion triggered country rock fragment excavation (Fig. 4.13a, b). The uppermost tuff ring-forming pyroclastic succession is up to 30 m thick in the NNE and NNW side of the crater located just in the side of the half-sectioned pre-maar scoria cone.

The tuff ring succession consists of a coarse grained basal succession that is rich in accidental lithic fragments and large juvenile pyroclasts with impact sags and it is stratified (Fig. 4.13b). In the middle of the section in the NNE crater wall a thick massive topography filling lapilli tuff forms a prominent unit that is interpreted to be a result of a high particle concentration “moist” pyroclastic density current, e.g. similar to pyroclastic flows (Fig. 4.14). The uppermost pyroclastic succession has more prominent dunes and cross stratification (Fig. 4.15) and abundant evidence of plastering, ballistic bomb emplacement, accretionary lapilli beds and a typical coarse—fine—coarse repetition of tuff lapilli

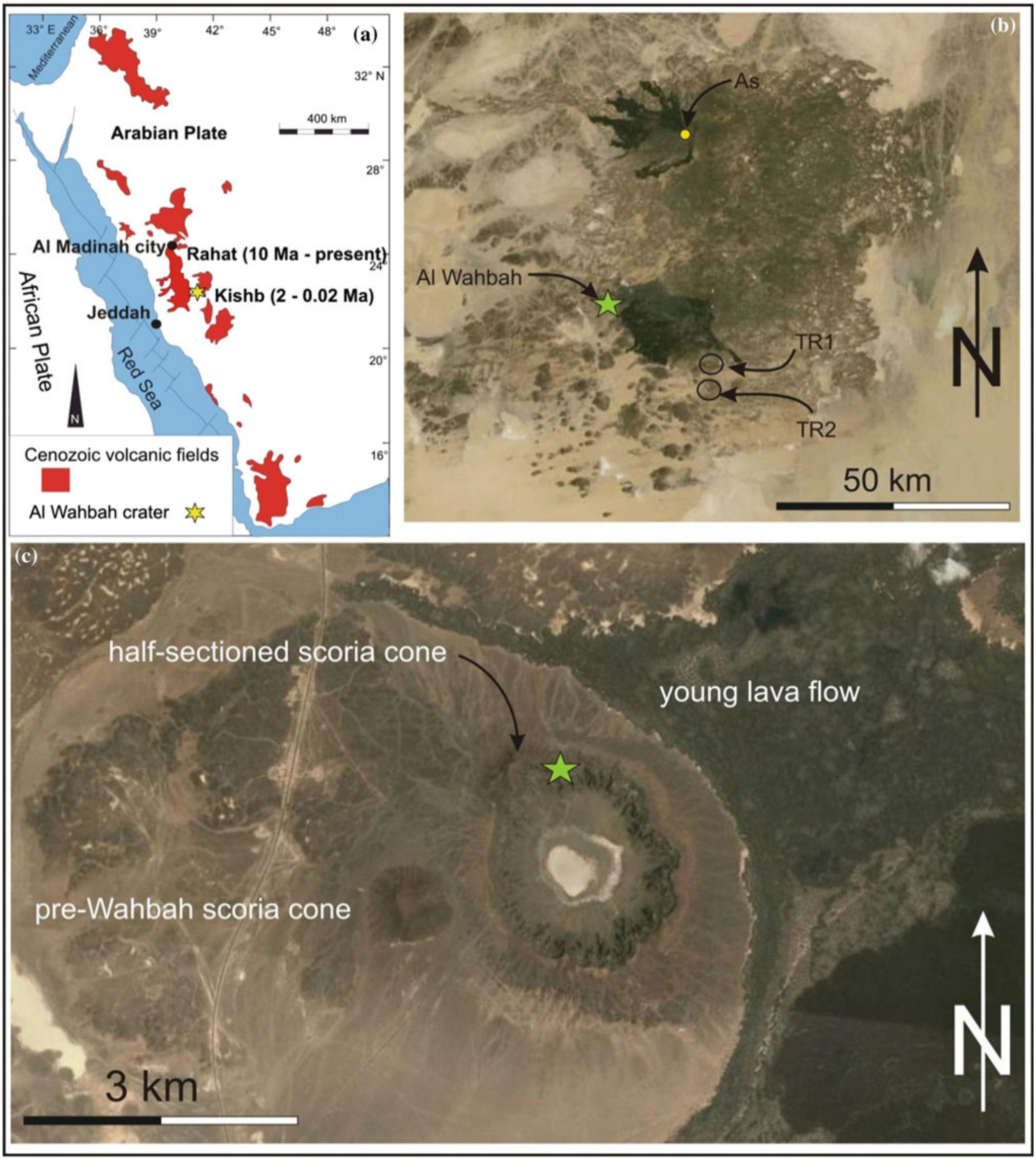

Fig. 4.9 Overview map of the Harrat Kishb from google earth image **b** marking Al Wahbah Crater, Aslaj volcano (*As*) and two other large tuff ring (TR1, TR2) in the southern margin of the volcanic field. On **c** Al Wahbah crater is seen with a *green star* marks the main section of the tuff ring succession

tuff units indicating a stage in the eruption when the erupting conduit was fairly stable and open (e.g. the vent clearing was completed and the maar crater was probably already formed). Interestingly the tuff ring succession is different in the NNW side where the upper succession of dune bedded tuff is more prominent and thicker, and fine ash dunes can be traced over a km from the crater rim. The tuff ring succession thins toward the south, however in the most southernmost

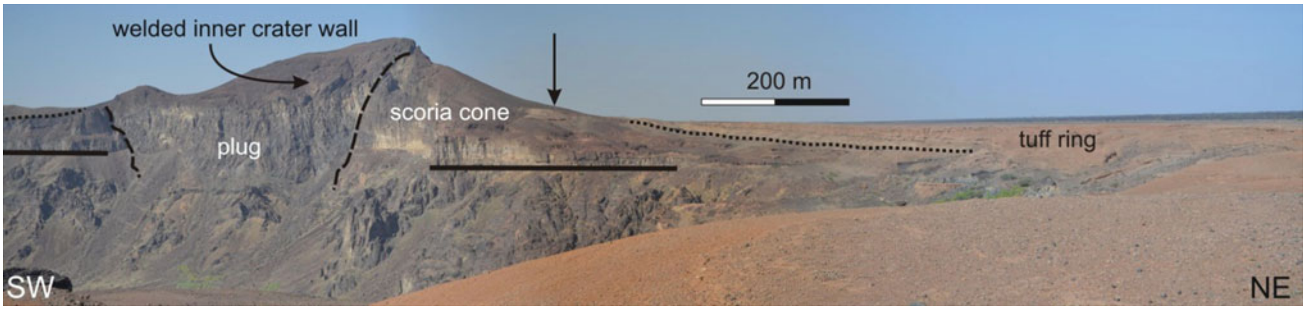

Fig. 4.10 Half-section of a pre-maar scoria cone [22° 54′ 31.84″N; 41° 7′ 59.93″E] in the NW crater wall of Al Wahbah. The pre-maar scoria cone sits on at least two major lava flow units

Fig. 4.11 Topmost pre-maar lava flow unit with multiple individual flow units and undulating upper surface [22° 54′ 12.93″N; 41° 9′ 2.35″E]. Note the *reddish colour* of the capping tuff ring deposits that form about a 30 m thick pile in the eastern edge of the maar crater

Fig. 4.12 Occasionally the *uppermost* pre-maar lava flow shows apparent intrusive contact with the tuff ring deposits [22° 54′ 39.44″N; 41° 8′ 36.90″E] suggesting that the flow might have been still moving in the time the tuff ring-forming deposits accumulated (*bottom image*)

part of the maar crater rim it is again became slightly thicker providing an impression that the tuff ring around the gradually forming maar crater must have been irregular in thickness and potentially indicates that the source of the tuff ring might have been along a fissure allowing to form complex tuff ring around the finally formed maar basin.

There is no clear evidence to support significant time break between the pre-maar cone-building eruptions and the tuff ring-forming base surge-dominated successions, suggesting that pre-maar cone (and lava flow(s), at least their upper part) and the tuff ring formation might be in a time-continuum and part of the same eruptive episode. In this respect Al Wahbah's eruption can be seen as unique and differs from other maar formation implying initial magma-water interaction-driven shallow sub-surface explosions followed by gradual explosion locus down-migration as a result of gradual exhaustion of ground-water sources (Lorenz 1974, 1986). Al Wahbah seems to have followed an opposite eruption evolution starting with an initial lava shield and cone-building phase that have been intervened by

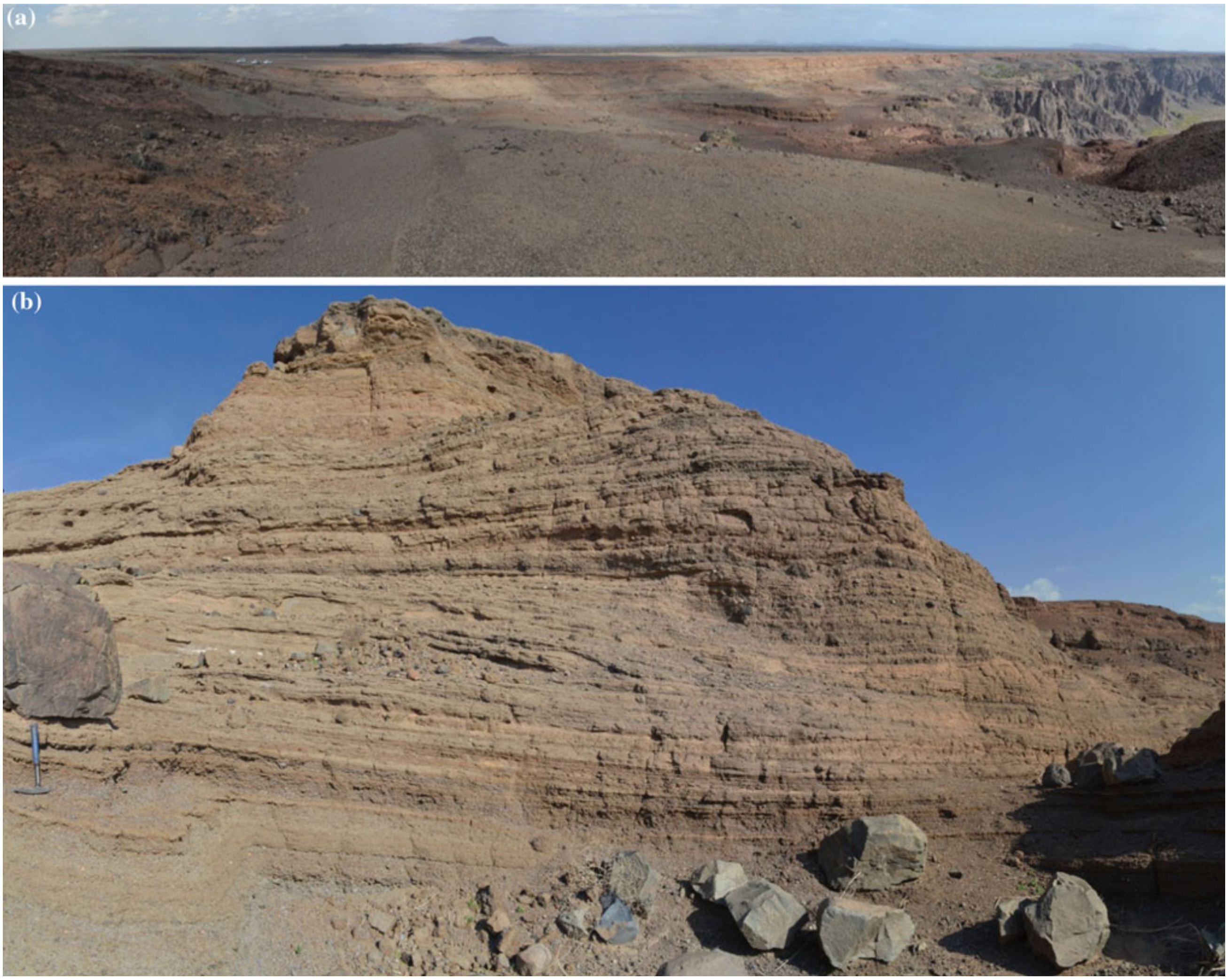

Fig. 4.13 Images from the tuff ring deposits exposed in the N–NE side of the Al Wahbah maar [22° 54′ 41.88″N 41° 8′ 17.33″E]. **a** The tuff ring deposits developed over the pre-maar scoria cone succession covering it partially. **b** Well-bedded, cross-bedded successions of pyroclastic density current deposit dominated succession forms the majority of the tuff ring succession. Large cross-stratification and dune-bedded nature with large accidental lithic clasts derived from the underlying Proterozoic basement are prominent characteristic features of the tuff ring succession

phreatomagmatic explosive eruptions subsequently that have culminated in a maar collapse and tuff ring formation. This eruption scenario can be best explained in similar way how it was proposed for another spectacular maar, the Crater Elegante in Sonora, Mexico (Gutmann 1976, 2002). The drop of the magma discharge rate is inferred to cause magma withdrawal below the regional ground-water table allowing direct entry of groundwater to the hot interior of the shallow plumbing system of the volcanic complex and triggering phreatomagmatic explosions that formed numerous base surges built the tephra ring (Németh et al. 2013). Country rock excavation and the mechanical destabilisation of the basement and pre-maar volcanic edifices eventually led to subsequent crater floor subsidence.

The flat-floored crater hosts an ephermal lake today that is filled with shallow saline water after occasional heavy rain fall (Fig. 4.16) that can diminish quickly leaving behind saltpans and aeolian silt bars. The large crater also acts as "humidity trap" providing refuge for living creatures from the heat, making Al Wahbah a host of a unique ecosystem (Fig. 4.17).

The crater rim has some advanced erosional features, where ~200 metres retreat of the original tephra ring is apparent due to the erosional strip off the tephra beds from the underlying pre-maar lava flows. To constrain the above proposed model some independent data would be essential to constrain the age relationship between pre-maar lava flow units, the half sectioned scoria cones and the maar-related tuff ring. The recently published Ar–Ar age survey has

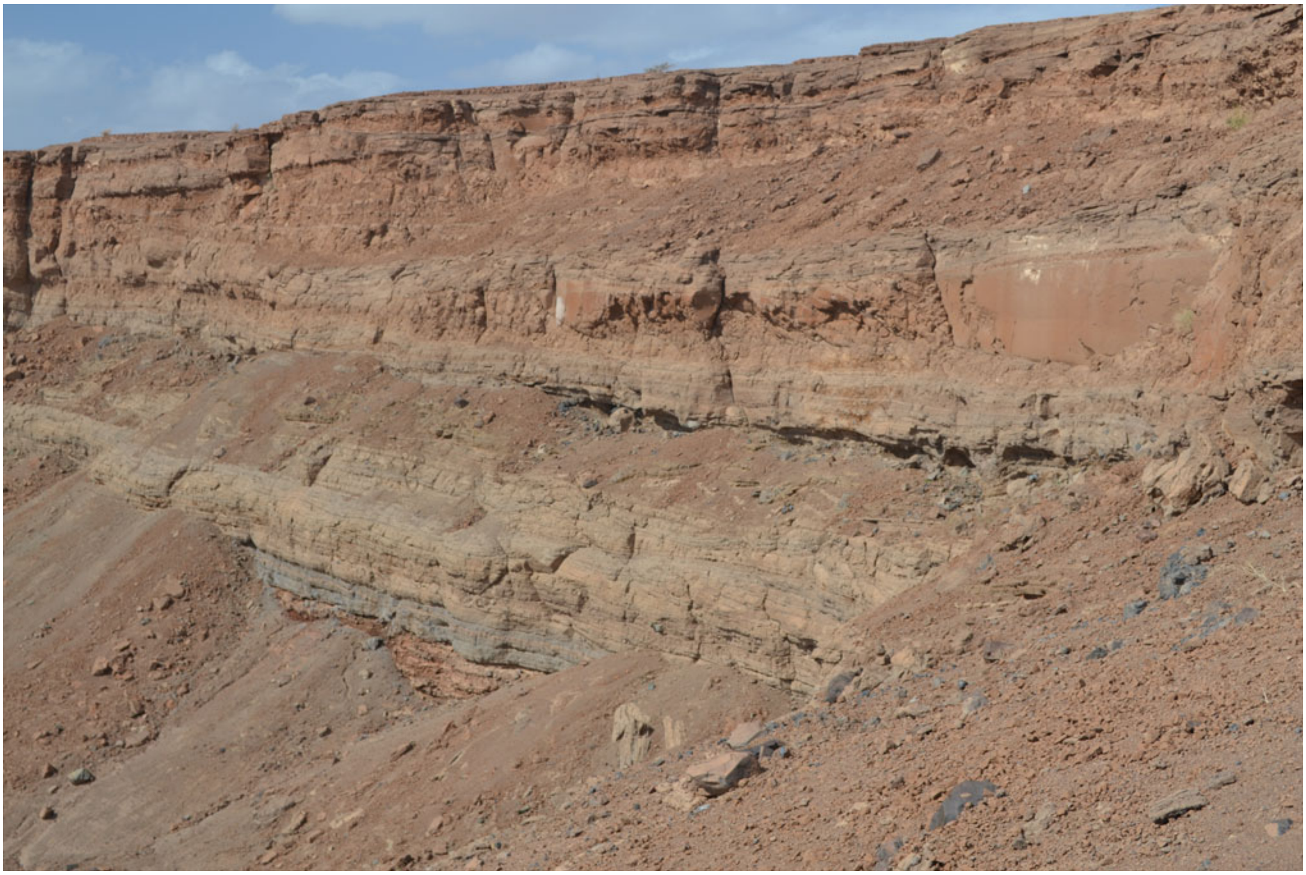

Fig. 4.14 Prominent pyroclastic flow bed in the middle of the Al Wahbah tuff ring [22° 54′ 45.51″N; 41° 8′ 25.79″E]

suggested that the time difference between the onset of maar-forming eruption (based on the dolerite plug intruded into the half sectioned scoria cone) and the age of the pre-maar lavas could be in the range of 20 Ka, and thus the two events are separate and there is no link between the maar-forming eruption and the pre-maar scoria cone activity and lava flow effusion (Abdel Wahab et al. 2014). If this is the case the eruption that created the Al Wahbah maar occurred in a place where pre-existing scoria and spatter cones formed just few thousands to tens of thousands of years ago. The violent explosive eruption cut into the pre-existing scoria and spatter cone field exposing in its crater wall those half-sectioned older volcanoes. Interestingly similar situations have recently been documented from the Harrat Hutaymah, and therefore this eruption history can equally be valid (Moufti et al. 2015).

In conclusion Al Wahbah is a maar with a peculiar geological history and a complex volcanic stratigraphy. Its volcanic rock units' stratigraphic position is under intensive research to determine whether the pre-maar scoria cone and topmost pre-maar lava flows erupted immediately prior the maar formation, or if they represent completely different volcanism pre-dating the maar forming eruption. Al Wahbah maar can be seen as a complex geotope. It demonstrates a complex volcanic geology history through well-preserved geosites along its crater wall and crater rim many of them providing spectacular views. The fact that this location merits active research in cutting edge research fields warrants general scientific interest in the site by the volcanology community.

4.2.2 Other Silicic Explosion Craters in Harrat Kishb

As an initial exploration to see the geoheritage diversity of volcanic products of Harrat Kishb, field visits were arranged to other volcanic sites Just SE of Al Wahbah are volcanoes here referred to as TR1 (the northern volcano) and TR2 (the southern volcano) (Fig. 4.9). TR1 is a complex volcano in which a double small scoria cone was visible in its main crater (Fig. 4.18a). TR2 is a broad flat-floored crater sitting on a broad relatively gentle sloped volcanic edifice (Fig. 4.18b). These two sites are about 5 km apart.

TR1 is a positive volcanic landform standing about 70 m above the basement, which is a typical alluvial plain with

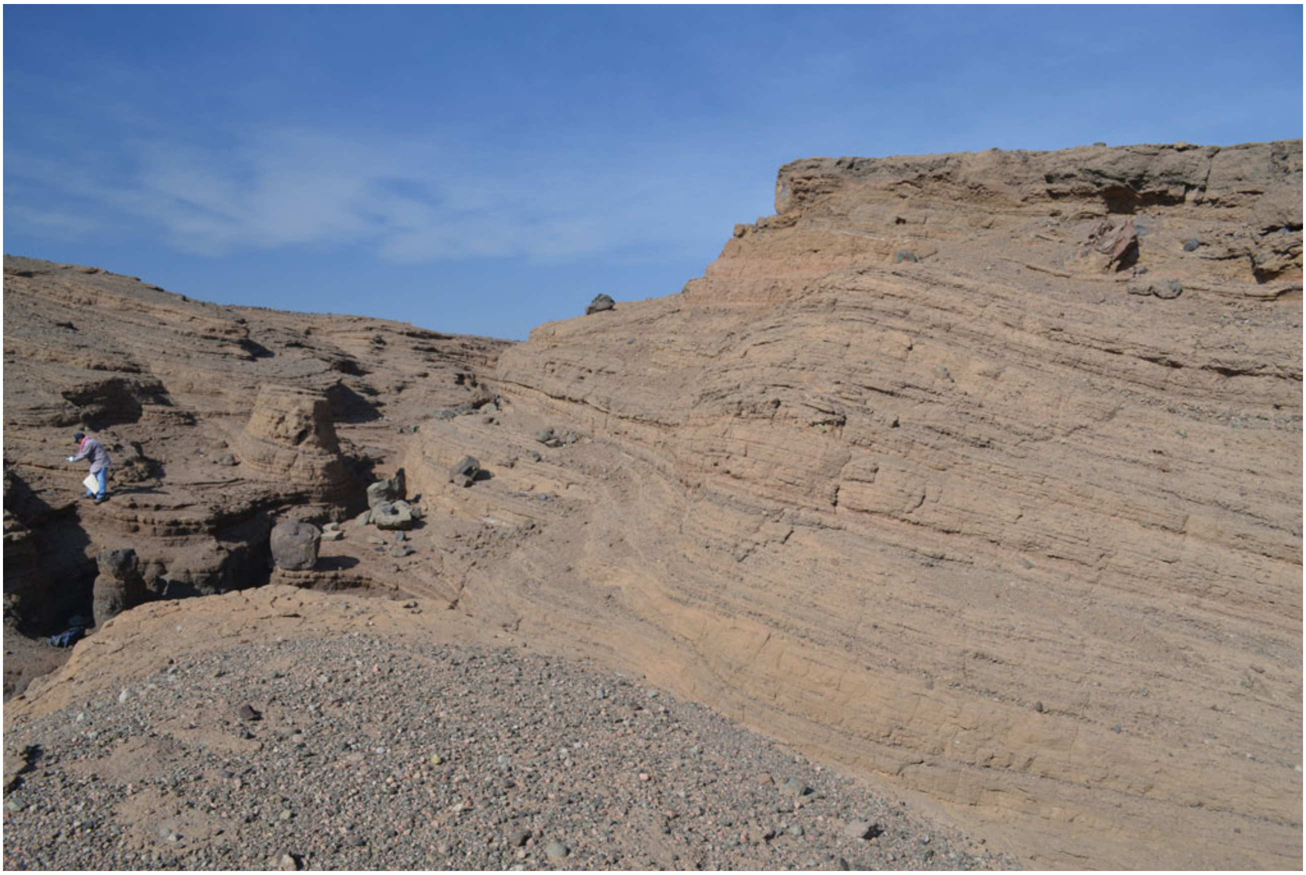

Fig. 4.15 *Upper* dune-bedded surge beds [22° 54′ 46.49″N; 41° 8′ 15.04″E]

shallow dry valleys and windblown dust. Its volcanic entity and the associated volcanic geosites made this location a stand-alone volcanic geotope that can offer numerous geosites to understand the formation of a broad flat floored crater and eruption of post-crater formation volcanic products. The volcano is slightly asymmetric and has a peak on its western edge, while in the east its crater rim is open and initiated an extensive lava flow that can be traced over several kilometres toward the east. The lava outflow point is above the basement suggesting that the entire TR1 edifice is sitting on a lava shield and that the eruption and formation of this volcano might have started with effusive activity.

The main edifice building succession of TR1 is exposed in several dry gullies in the southern flank of the volcano and exposes chaotic tuff breccias and lapilli tuff that are rich in silicic pyroclast fragments in an ash matrix. It is inferred to be a result of eruption-fed pyroclastic density currents interbedded with some syn-eruptive reworked volcaniclastic deposits. The upper section of the TR1 edifice is more prominent and consists of finer grained, dune-bedded, cross-bedded tuff and lapilli tuff with occasional accretionary lapilli. The crater of the TR1 is flat-floored filled with aeolian dust and is an oval shape with distinct geometry suggesting that it might have been evolved in multiple events and potentially aligned along a fissure along a feeder dyke length. The central to eastern sector of the crater is filled with intra-crater cones (Fig. 4.19). Some lava spatter bench can be traced in the northern central inner wall of the inner crater wall. This lava spatter is clearly connected to a large intra-crater spatter rampart forming an edge in the southern inner crater wall from the base of the crater to its top. This suggests that some larger lava spatter cone must have been existed in the double crater that was either destructed by some explosions and/or were originally largely asymmetric and only provided some lava spatter to plaster against crater walls indicating changes of lava spatter activity during the eruption. In the centre part of the crater closer to the southern crater wall two circular and well-preserved lava spatter/scoria cones stand in the flat crater floor. They are dominated by agglutinated lava spatter, fusiform bombs and minor scoriaceous ash and lapilli. Their intact morphology suggests that they represent the final eruption episode of the volcano growth.

Logistically the TR1 can be accessed through dry valleys (Fig. 4.20) from Al Wahbah; this takes about an hour as a 4WD trip. Potential hazards are the sand dunes and dust

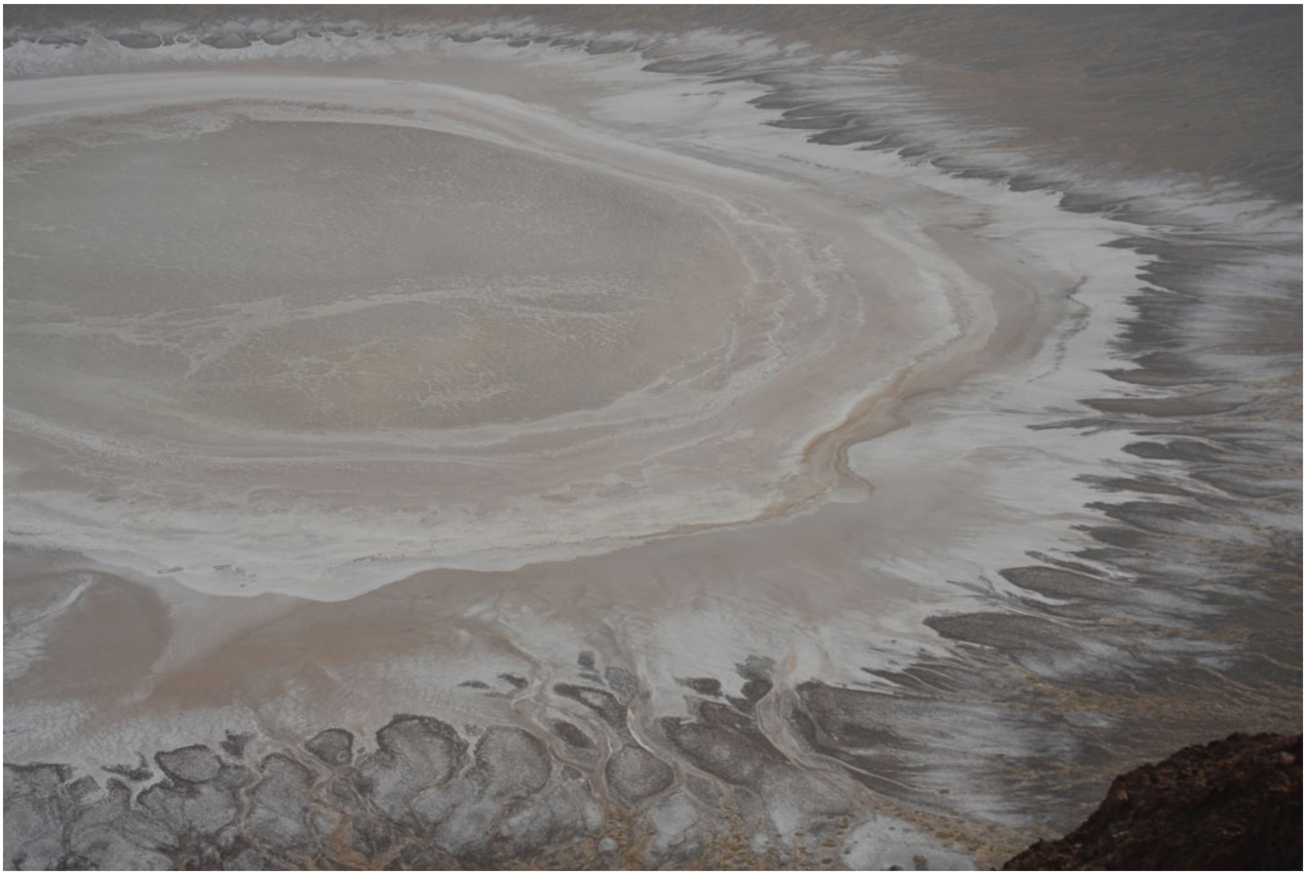

Fig. 4.16 Ephermal lake in Al Wahbah maar crater [22°54′ 2.12″N; 41° 8′ 20.96″E]

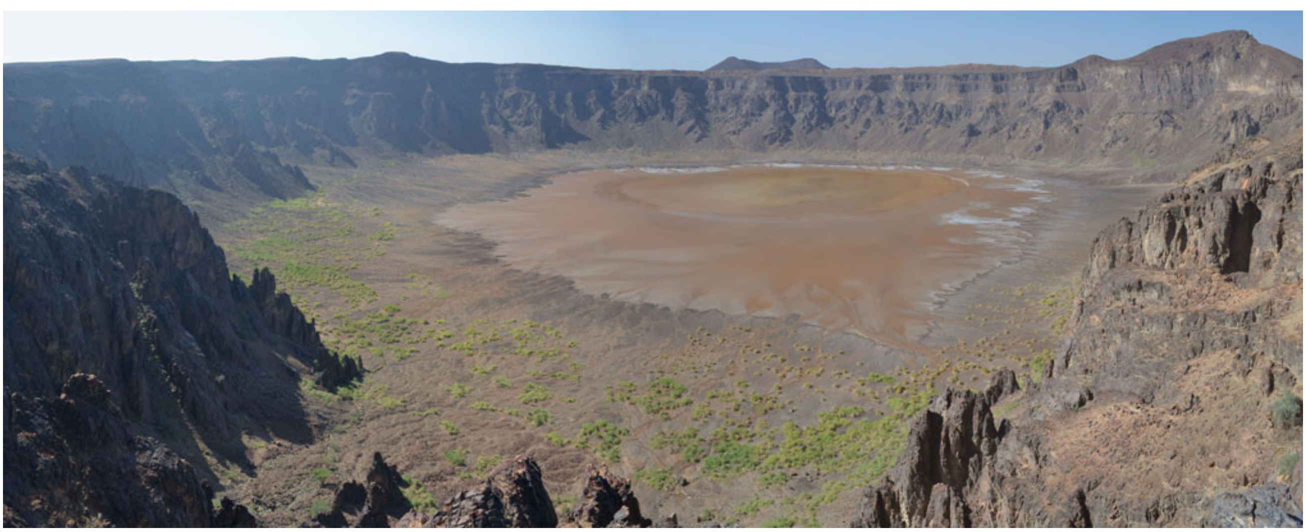

Fig. 4.17 Vegetation in Al Wahbah crater after a rainy day [22° 54′ 9.86″N; 41° 9′ 3.10″E]

storms. The majority of the main sections can be accessed from the southern foothills. From the east through the lava outflow there is a rough 4WD track which allows driving into the crater.

TR2 is a broad gentle sloping volcanic edifice which stands about 100 metres above the basement of alluvial plains (Fig. 4.18b). The crater rim is not breached and therefore there is no access to the crater by 4WD. The volcanic edifice

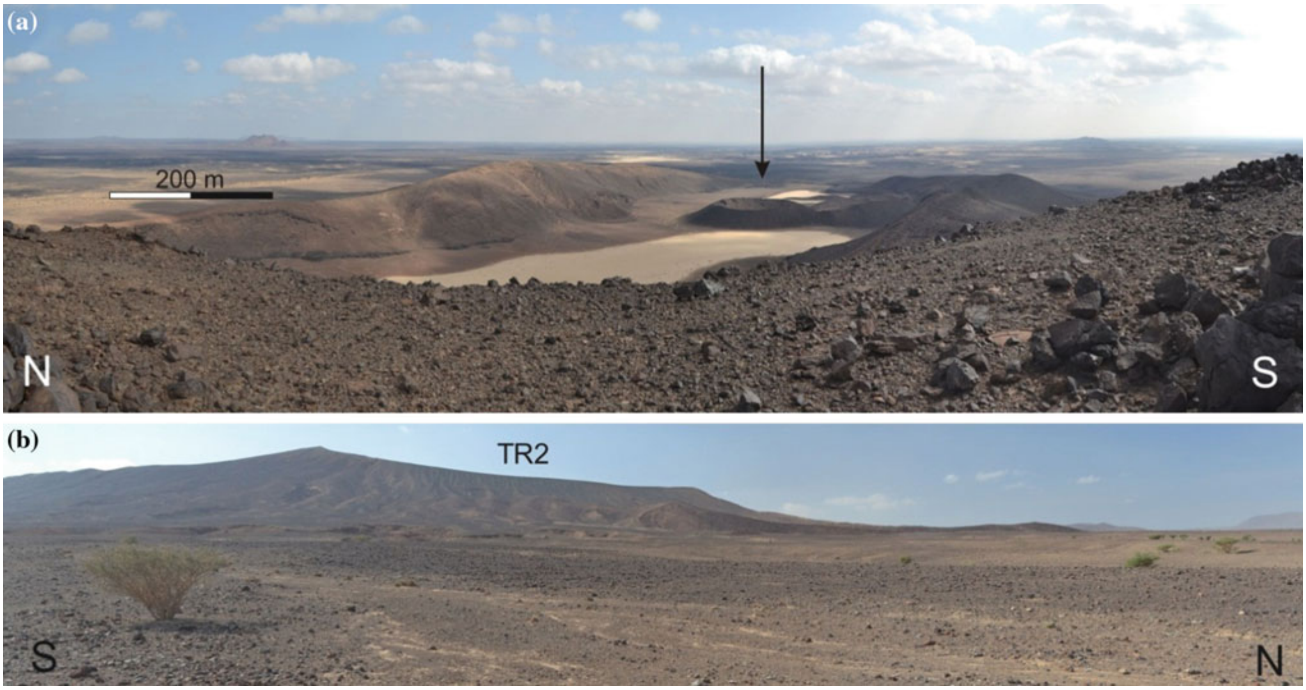

Fig. 4.18 TR1 tuff ring [22° 48′ 15.58″N; 41° 21′ 12.80″E] in the southeastern side of Harrat Kishb is a positive landform with an elongated crater that is filled with small lava spatter and scoria cones (**a**). TR2 [22° 45′ 45.86″N; 41° 21′ 24.08″E] is also a positive volcanic landform with intact crater rim with no intra-crater edifices (**b**)

of TR2 is surrounded by a broad ash plain that consists of light coloured pumiceous ash. In the northern side of the volcanic edifice shallow gullies have developed as a deep and steep walled gully network near the top of the tuff ring. In these valleys dune-bedded lapilli tuff and tuff are exposed that are interpreted to be deposits of pyroclastic density currents initiated radially from the TR2 volcano.

In the northern flank of TR2 an access road approaches the crater rim, allowing the crater rim to be accessed on foot. The crater is filled with aeolian deposits and a few humps in the crater floor indicate buried intra-crater lava spatter cones or lava buds. The majority of the pyroclastic succession along the volcanic edifice seems fairly uniform and suggests that the formation of this volcano might have been a relatively simple and not to long process that is different from the TR1.

The TR1 and TR2 volcanoes are fairly different from Al Wahbah, as they are more like tuff rings without a characteristic deep crater and form a positive volcanic landform with broad but relatively shallow craters (in comparison with Al Wahbah). Each location can be defined as an individual volcanic geotope that can offer useful comparisons with other tuff rings (Kereszturi and Németh 2012). The unusual aspect of these sites is that they are more silicic in composition (phonolitic) than the majority of the eruptive products known from the field and their eruption history may reflect long lived eruptions fed by silicic magma (Camp et al. 1992). There is some evidence for phreatomagmatism in both volcanoes, but their formations were more dominated by some magmatic explosive processes; e.g. their explosive eruptions were probably triggered by phreatomagmatism but sustained by magmatic volatiles due to their more silicic composition. This question needs to be resolved in the future and it could give a substantial research direction for future work.

4.2.3 Aslaj Volcanic Complex Geotope [23° 14′ 26.06″N; 41° 16′ 1.22″E]

Aslaj is located in the northern part of the Harrat Kishb (Fig. 4.9), slightly off from the main volcanic chain that consists of 7 large cones (Fig. 4.21). Aslaj is associated with an extensive lava field that fed pahoehoe to transitional pahoehoe lava flows toward the west (Guilbaud et al. 2007; Peterson and Tilling 1980; Rossi 1997; Rowland and Walker 1990; Sato 1995; Self et al. 1998). The lava field is partially covered by an ash plain that is wind erosion modified. The Aslaj cone is a complex volcanic cone with a network of pit craters, and a large central crater. The main cone of Aslaj is a large steep sided relatively well-preserved volcanic edifice that stands about 100 m above the base (Fig. 4.22a, b). It sits on a gently sloping "shield-like" edifice that consists of mantle nodule bearing multiple lava lobes and sheets. The main cone has a fairly deep crater that is unusually deep in comparison to its base diameter (Fig. 4.23a, b).

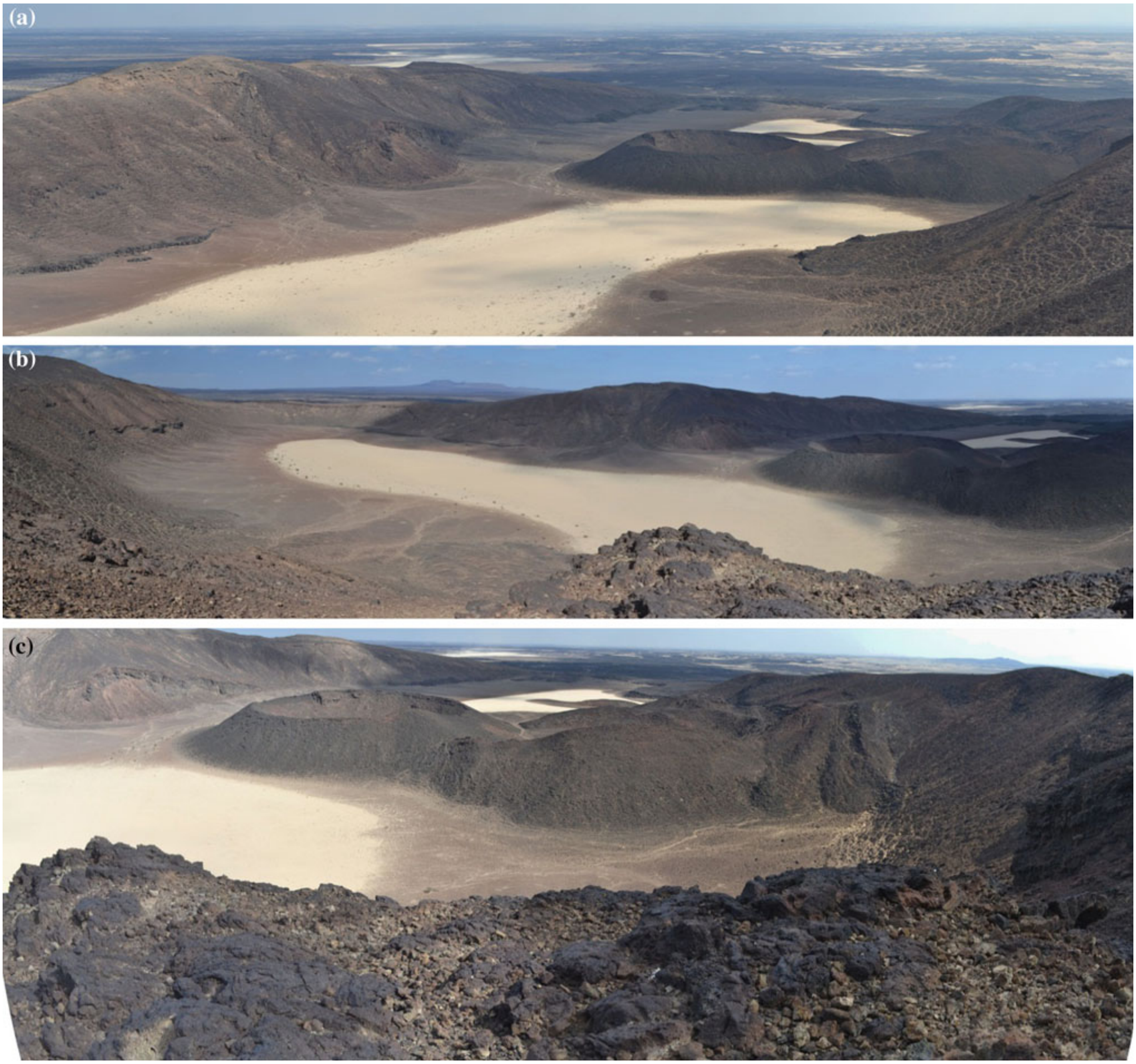

Fig. 4.19 Crater interior of TR1: In *upper* image, note the open crater with a lava initiation point. In the NW side of the crater is flat and rimmed by relatively low tuff ring (*middle*). The intra-crater cone complex stands in the middle of the elongated crater floor (*bottom*) [22° 48′ 13.91″N; 41° 21′ 14.58″E]

The steep sloped pyroclastic beds forming the volcanic edifice are dominated by juvenile pyroclasts of scoria of mostly ash to fine lapilli grain size. The individual beds are a few dm thickness and form fairly uniform facies architecture from base to top. The main cone building succession is covered by a relatively thin but accidental lithic rich pyroclastic unit that is dune-bedded, cross-bedded and rich in impact sags commonly cause by large (dm-scale) mantle nodules (Fig. 4.24). These beds are particularly rich in mantle nodules; however, the main cone building pyroclastic beds also contain mantle-derived xenoliths. In addition, these capping pyroclastic beds are also rich in various deep-crustal fragments and accidental lithics. Fine-grained beds exhibit some accretionary lapilli and prominent plastering effect against obstacles.

The best example of this process is the steeply inclined thin dune bedded pyroclastic unit plastered against the main cone inner crater wall. The thickness of this succession varies greatly along the main cone and is seemingly thicker in the south where the main edifice consists of the lower crater rim that is obscured. The southern part of the volcanic complex is complicated by local pit craters, lava spatter

Fig. 4.20 TR2 tuff ring [22° 45v49.53″N; 41° 21′ 22.72″E] in the southeastrn margin of the Harrat Kishb is in the distance in the panoramic view taken from Tr1. Note the extensive ash plain in the inter-cone areas. In the *right hand side* of the *panoramic view*, phonolitic lava flows and domes form the landscape. *View* is toward the SW

vents and local initiation points of lava flows that erupted toward the south and reach several kilometres downhill from their source. This lava flows are thick and consist of lava tubes and pahoehoe surface textures that quickly transform to more aa-like lava flow surface textures. The base of the lava flows are commonly choked with large (dm-scale) mantle nodules. From the top of Aslaj it is evident that a broad (but wind modified) grey ash plain associated with the volcano is cantered in the slightly eastern edge of the visible ash plain.

Aslaj is potentially an interesting volcano to develop as a geotouristic destination with high volcanic geological value due to its complex volcanic evolution. On the available field data, we can infer that the initial cone growth was followed and/or been penecontemporaneous with the lava shield building phase that gradually caused some sort of cone modification over time. The cone growth must have been not only the result of relatively low energy Strombolian style periodic explosive eruptions, but some higher energy explosive events must have taken place also to generate an unusually deep crater in relative to the cone base. Accompanied with the cone growth lava flows were initiated mostly from the southern side of the cone complex that partially and gradually rafted the growing edifice. This process likely induced local pit crater formation (Okubo and Martel 1998; Rymer et al. 1998) that led to the formation of a complex crater area in the south. This rough terrain has been covered by a pyroclastic deposit with non-uniform thickness that is rich in large mantle nodules. The cross bedding and large dunes, plastering effect, and presence of accretionary lapilli together as characteristic features inferred from many places (Moore et al. 1966; Németh 2010; Vespermann et al. 2000) suggest that a paroxysmal phreatomagmatic explosive eruption must have occurred in the final stage of the formation of Aslaj that generated blast-like base surge-dominated eruptions that deposited a typical pyroclastic density current deposit over the rugged topography.

In addition, this eruption episode likely produced highly fragmented ash (phreatomagmatic) that is the likely deposit of the upper part of the extensive ash plain. While this working model needs to be refined and supported or modified in future field works it can be stated that Aslaj could serve as a very valuable geotouristic destination especially in a form of adventure tourism. In addition, the abundant

Fig. 4.21 Chain of scoria cones in the northern part of Harrat Kishb from about 10,000 m height. Aslaj is a tuff cone that is located in the top left side of the 7 cones chain. Note the phonolitic lava flows and dome in the *right bottom side* of the image [23° 11′ 16.16″N; 41° 22′ 48.28″E]

mantle nodules make this place also a perfect site to develop a complex geoeducational program on understanding alkaline basaltic magma generation, rise and the various style of explosive fragmentation. Aslaj is a very significant site where complex volcanological research could bring significant and fundamental results that could feed into a well-designed geoeducational and geotorustic program. Aslaj in this regard has a high volcanic geoheritage value as a complex volcanic geotope in spite its remoteness.

4.3 Harrat Hutaymah

4.3.1 Overview

Harrat Hutayma consists of small-volume volcanoes typical for an alkali basaltic volcanic field (Fig. 4.25). The field has been mapped in the 80 s to 90 s (Pallister 1985; Thornber 1990; Thornber and Anonymous 1988; Thornber and Pallister 1985) and has an abundance of mantle and crustal-derived nodules primarily recovered from various tuff ring and maar deposits (Duncan et al. 2016; Konrad et al. 2016; Thornber 1992, 1993, 1994; Thornber 1988, 1991; Thornber and Pallister 1985). Relatively little information is available in major international journals about the significance of these nodules (Blusztajn et al. 1995; Gondal et al. 2009; McGuire 1988). Volcanological study that characterizes the style of volcanism, its depositional environment and associated volcanic landscape evolution has not been published from this region other than basic information collected for the preparation of geological maps (Pallister 1985). This lack of information as well as the apparent difference of volcanic landforms visible from satellite imagery in comparison to the Rahat Volcanic Field provided a driving force to arrange pilot research to evaluate the Harrat Hutaymah as a potential future research area and initially catalogue its potential geoheritage value and sites (Moufti et al. 2015).

Harrat Hutaymah contains numerous tuff rings and maars that were reported in the first mapping of the region, which identified these volcanic landforms as the main volcanic features that makes Harrat Hutaymah different from other harrats. In this respect Harrat Hutaymah has shown some common volcanic features with Harrat Kishb which made this field also a good target area to explore the variety of

Fig. 4.22 Aslaj tuff cone complex from the SE (*top*) [23° 14′ 16.78″N; 41° 16′ 24.91″E] and S (*bottom*) exhibit a complex volcanic edifice architecture [23° 13′ 40.65″N; 41° 15′ 47.60″E] indicating long-lived eruptions of various eruption types

Fig. 4.23 Complex crater zone of Aslaj volcano with a deep crater of the main cone [23° 14′ 18.28″N; 41° 16′ 6.98″E]

volcanic landforms and associated volcanic processes that created them. These fields demonstrate the diversity of volcanic fields across the Arabian Peninsula.

Harrat Hutaymah covers an area of about 900 km^2 and is considered to be one of the at least 13 distinct flood lava fields (harrats) of the Arabian Peninsula (Pallister 1985). While lava flows are volumetrically important contributors to the total volume of the volcanic eruptive products of Harrat Hutaymah, the field is differ from Harrat Rahat in that areas covered by lava fields strongly influence access to the region. At Harrat Hutaymah, lava flows are more distinct, commonly follow longitudinal networks of valleys, and their apparent thickness is less than the thick multiple lava flow fields in Harrat Rahat. Eruptive centers are commonly aligned at Harrat Hutaymah and scoria cones form long (over tens of kilometres) N-S oriented chain of cones (Fig. 4.25). In this respect Harrat Hutaymah shows great similarity to Harrat Kishb, having a main aligned chain of cones in its central axis. Volcanic cones also commonly form multiple nested cones and ellipsoid (in map view)

Fig. 4.24 Large lower crustal xenolith from the Aslaj volcano [23° 14′ 13.20″N; 41° 16′ 3.47″E]

Fig. 4.25 Overview GoogleEarth map of the Hutaymah Volcanic Field. The black circles mark volcanic craters with high volcanic geoheritage values. *White circle marks* an additional crater that could be used as a site to demonstrate crater filling processes and its importance to understand volcanic landscape evolution

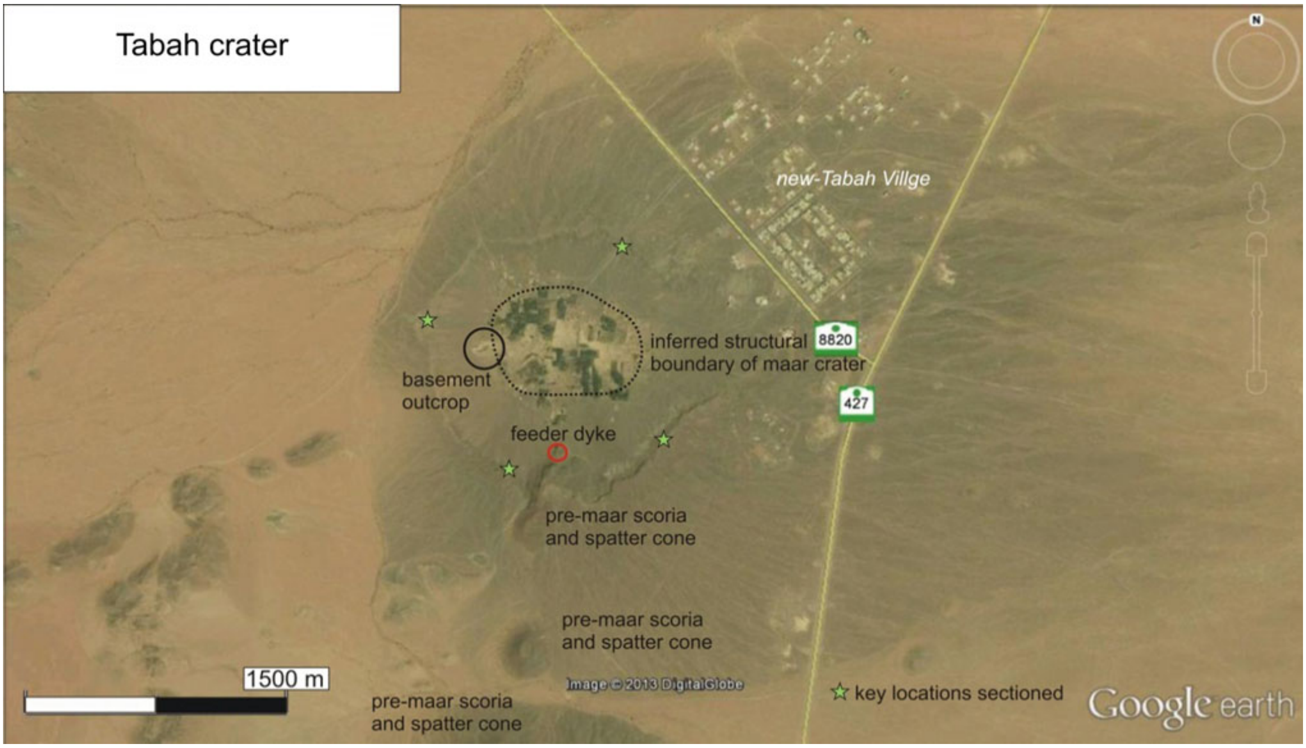

Fig. 4.26 Google earth map of the Tabah crater [27° 1′ 36.34″N; 42° 10′ 6.48″E]. Sections recorded are marked with *green stars*. Note the exposed basement rock in the western side of the present day volcanic depression

shape chain of craters indicating lava curtain-style eruptions along fissures (Pallister 1985). The lava flows are dominantly alkali basaltic flows (Pallister 1985). The age of the flows is poorly constrained having listed Quaternary and probably in the range of 2–1 millions of years age. K-Ar dating from a basal lava flow cut by the Harrat Hutaymah maar yielded an age of 1.8 ± 0.5 Ma (Pallister 1985). Recent age determinations on 14 lava flows by the Ar-40-Ar-39 laser step heating method provided ages between 260–850 Ka, all younger than the previously defined 0.1 to 2.7 Ma age range for the volcanic activity of Harrat Hutaymah (Duncan et al. 2016).

The field contains at least 57 relatively small scoria and lava spatter cones (Pallister 1985) which are smaller than those in Harrat Rahat. At least 22 tuff rings and maars were identified in this field (Pallister 1985; Thornber 1990); however, very little detail is given about their volcanic facies architecture and their inferred eruption mechanism. The field is covered by aeolian deposits that make it difficult to identify volcanic landforms especially in the southern margin of the fields where volcanic craters are entirely filled with such deposits and the crater rims are commonly completely eroded (Thornber 1990). In this field visit we report key volcanic features and provide some recommendations for future research that could contribute significantly of our understanding of formation of volcanic craters by explosive eruptions. Due to the preliminary nature of this field research here we provide a brief summary of the key geological features identified.

4.3.2 Volcanic Geotopes of Harrat Hutaymah

After an initial pilot project four volcanoes have been identified to have high volcanic geoheritage value and should be part of future geoeducation, geoconservation or geotouristic programs (Moufti et al. 2015). These are the Tabah crater, Harrat Hutaymah crater, Jubb crater (near Ni'ayy village) and the Humayyan/Haram crater (Fig. 4.25).

The **Tabah** crater geotope [27° 1′ 36.34″N; 42° 10′ 6.48″E] is a broad low-rimed volcanic crater about 1.3 km across (Fig. 4.26). It is fairly symmetric and the present day volcanic depression is surrounded by a low crater rim composed of about a few metres to up to 25–35 m thick volcanic succession of pyroclastic rocks (Fig. 4.27).

The crater floor of Tabah is flat and partially filled with reworked volcaniclastic material mixed with some aeolian deposits (Fig. 4.26). The crater wall is steep in the western side where it forms a well-exposed continuous outcrop that starts from the crater floor (Fig. 4.27). The pre-eruptive rocks are not exposed in the crater wall in this site, however in the northern segment of the crater interior granitoid rocks are exhumed that are sitting on a bench-like feature about

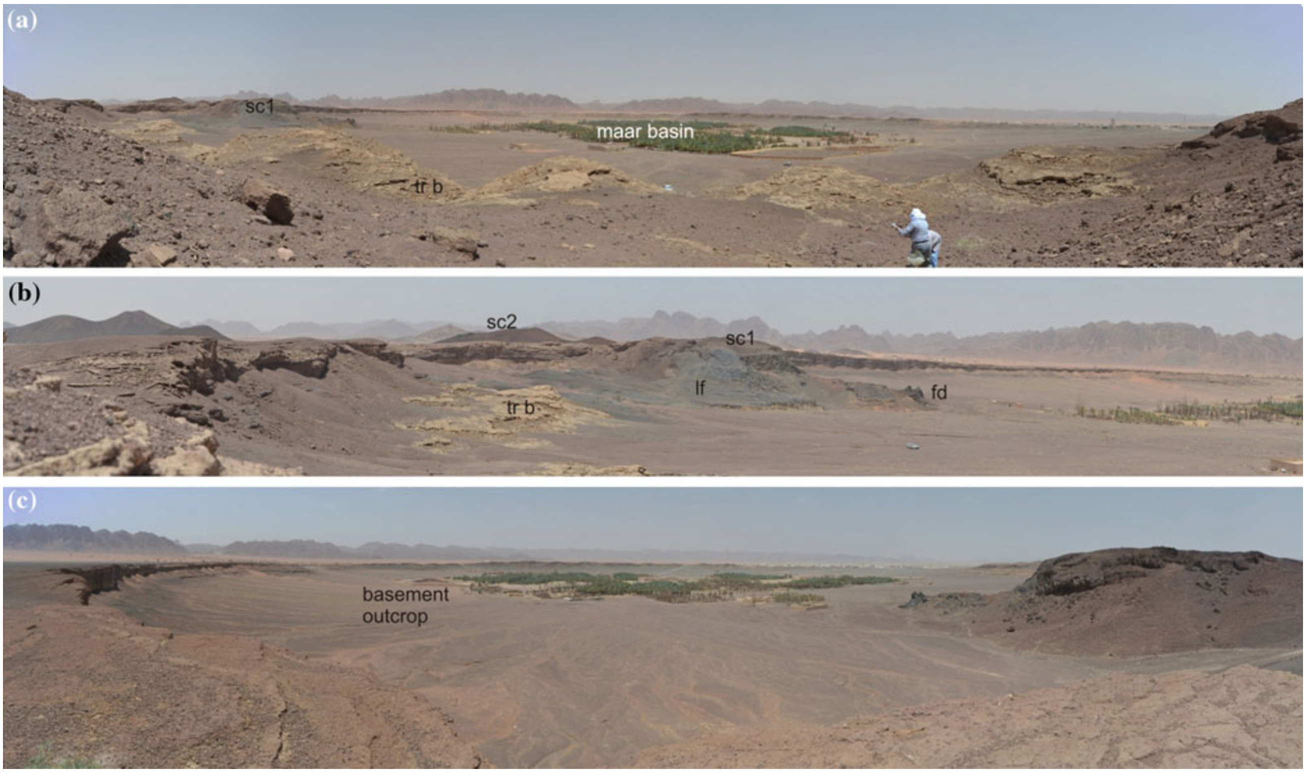

Fig. 4.27 Overviews of the Tabah crater [27° 1′ 36.34″N; 42° 10′ 6.48″ E] toward west (**a**), toward south-west (**b**) and toward north-west (**c**). Note the *green* plantation marking the inferred extent of the maar crater on (**a**) and (**c**). Pre-crater scoria and spatter cones (sc1) with lava flow (lf) and a feeder dyke (fd) form an aligned zone that can be connected to another scoria cone on the outer tuff ring flank (sc2). Note the exposed basement rocks on the surface of the erosionally enlarged present day crater floor on (**c**). Tuff ring beds (tr b) are exposed in the inner crater wall showing plastering effect against the steep wall of the crater

few tens of metres above the centre part of the depression (Fig. 4.27). These granitoid rocks are inferred to represent an exhumed syn-eruptive paleo-surface that marks the depositional surface on what the crater rim deposits accumulated. The location of the exposed, in situ granitoid rocks is about 200 metres from the present day crater wall suggesting significant retreat of the crater wall outward causing an apparent enlargement of the crater itself (Fig. 4.27). To constrain the syn-eruptive paleosurface and the crater inner morphology, a combination of geophysical methods, including MT, gravimetry, and geomagnetics need to be conducted in the near future. The centre part of the volcanic depression hosted a village that was well-served by drilled water sources which supported a palm plantation.

Due to water withdrawal the centre part of the depression has gradually subsided and resulted in a critical situation in the 1980s that forced the relocation of the village outside the crater. Today, numerous cracks on preserved buildings and structures are visible on the base of the crater floor where the early settlement was situated (Fig. 4.28). The cracks on the crater floor are restricted to the centre and deepest part of the present day crater, suggesting that the crater that is likely underlain by a diatreme (volcaniclastic sediment-filled volcanic conduit) is located in the centre part of the present day volcanic depression (Blaikie et al. 2014; Valentine and White 2012) and therefore the present day crater wall is an erosional feature and not the original crater wall. Similar crater area enlargement due to erosional processes has been proposed in other unusually large flat-floored maar craters such as those in the Auckland (New Zealand) (Cronin et al. 2009; Németh et al. 2012a) or in the Newer (Australia) Volcanic Fields (Jordan et al. 2013). In this respect the maar craters of Harrat Hutaymah are scientifically important and potentially can serve as excellent examples of an unusual volcanic landscape evolution process. In this respect these volcanoes could support volcanic geoeducational programs that would actively feed from scientific research.

In the southern margin of the volcanic crater a lava spatter cone with clastogenic lava flows and associated feeder dykes have been mapped (Fig. 4.27b). The clastogenic nature of the lava flows (Sumner 1998; Valentine and Gregg 2008) is constrained by the abundance of dark clast outlines preserved in the otherwise coherent solidified lava bodies exposed in the preserved volcanic edifice in the middle of the present day crater (Fig. 4.27). These volcanic rocks stratigraphically underlie the pyroclastic successions forming the tuff ring

Fig. 4.28 Ghost town with date plantation in the Tabah maar crater in Harrat Hutaymah [27° 1′ 49.30″N; 42° 10′ 7.32″E]

surrounding the volcanic depression and are inferred to represent a pre-existing volcanic feature prior to the current volcanic crater (Fig. 4.27). This scoria and lava spatter cone complex is part of a north-south trending chain of at least three volcanic cones that are partially eroded and form a line of about 4 km long in the southern part of the tuff ring.

The tuff ring is nearly intact and there is no characteristic breaching through it other than some narrow gaps that were the pathways for inhabitants lived in the crater (Fig. 4.29). The stratigraphy of the tuff ring-forming succession is fairly uniform across the entire tuff ring, and only some minor variations can be identified that are inferred to reflect variation of transportation axis of pyroclastic density currents, relative distance from the explosion locus and variations in the 3D geometrical position of the tuff ring rim in relationship to the position of the explosive eruption source (Fig. 4.29a). The base of the tuff ring (the base is not exposed) consists of a tuff breccia and lapilli tuff succession that is about 15 m thick in its thickest part (in the eastern and southern quadrant). This stratigraphy unit is rich in accidental lithic fragments and light coloured fine matrix. The base of this unit is more coarse- grained and upward a clear gradual change to a dune bedded coarse-fine-coarse alternation of pyroclastic beds is prominent. The middle section is a dark colour, juvenile ash and lapilli-rich bedded to dune-bedded and cross-bedded dark colour unit with variable thickness (Fig. 4.29a, b). Its thickest part is about 15 m thick in the eastern segment of the tuff ring.

This unit's base composed of a few metres thick succession that is very rich in cored bombs with mantle nodule and megacryst cores. In the upper section the bedding of this unit is well-developed with some spectacular antidune to dune structures, chute-and-pool features, impact sags and numerous evidence for micro-relief and interacting PDC deposit suggesting that this unit is dominated by PDC deposits and its fed from magma probably deeper sourced (e.g. mantle nodule abundance) (Fig. 4.29a, b) making this location a globally unique geotope with numerous excellent geosites. The pyroclastic density current successions are well-exposed and the textural features can be seen in them are in the same quality as those exposed around the Laacher Sea in the Vulkaneifel Global Geopark in Germany (Bogaard and Schmincke 1984; Fisher et al. 1983; Schmincke et al. 1973; Schumacher and Schmincke 1990). The uppermost stratigraphy unit is starts with a light coloured tuff breccia and lapilli tuff that are inferred to be deposited from PDCs (Fig. 4.29a). The section top part is

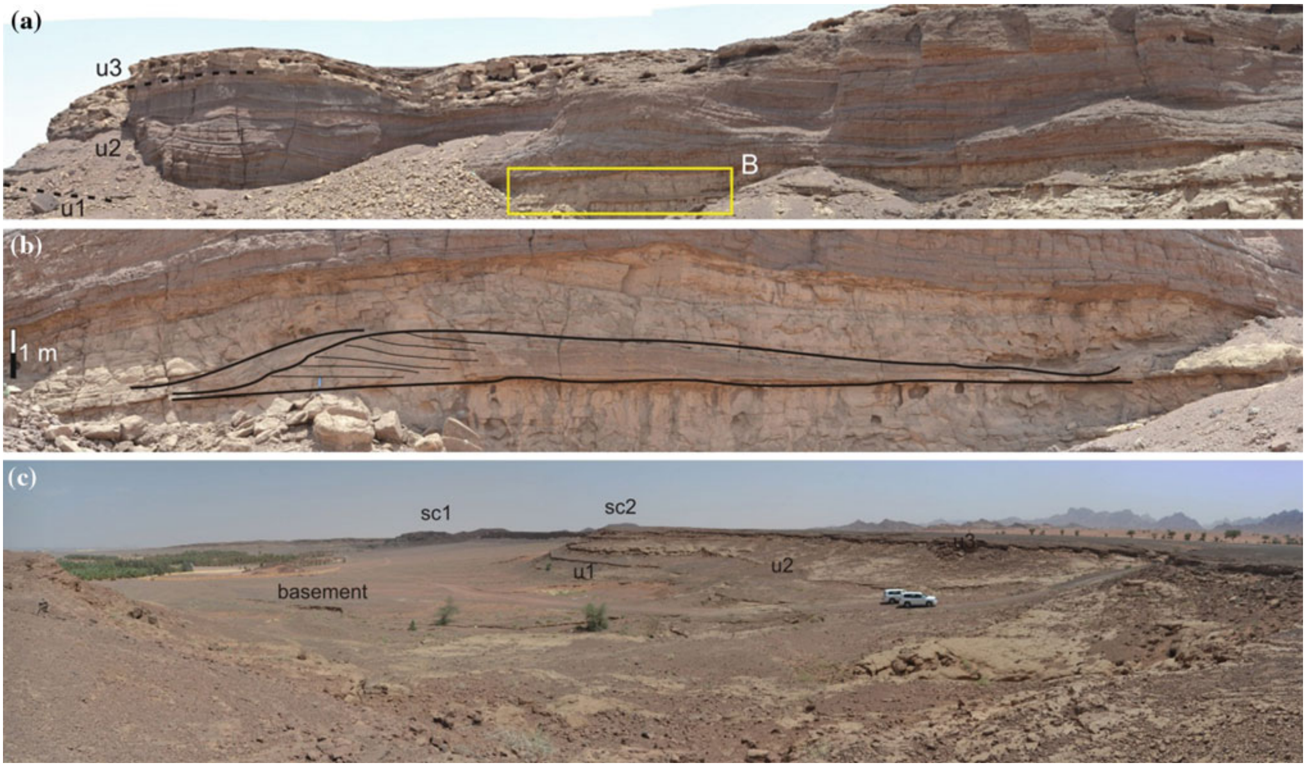

Fig. 4.29 The thickest tuff ring section is about 30 m thick in the eastern margin of the Tabah crater [27° 1′ 36.34″N; 42° 10′ 6.48″E] (**a**) and exposes at least three major stratigraphy units (u1–3). Around the inferred boundary of u1 and 2 long wavelength dunes and antidunes are exposed indicating a pyroclastic density current origin of the majority of the deposits (**b**, *yellow rectangle* on **a** marks the location shown on **b**). In the western edge of the Tabah crater typical compressed tuff ring succession is exposed that are inferred to represent more distal base surge-dominated pyroclastic succession, however the triplicate stratigraphy still can be recognized. Pre-crater scoria cones of s1 and s2 are also marked on the image. Note the exposed basement rocks in the present day crater basin as well as the reddish tan of the crater floor suggesting the proximity of the sun-eruptive granite surface to the present day crater floor

rich in juvenile ash and lapilli. This stratigraphy can be mapped along the entire volcanic depression however the total thickness of the tuff ring deposits is greater in the east and less in the west. In the western side the preserved tuff ring deposits mimic a medial to distal section (e.g. better bedding, abundance of relatively short wavelength dunes) of a tuff ring suggesting that the present day crater wall (cliff) is an erosional feature and the structural boundary of the original crater might be much closer to the center of the present day depression (Fig. 4.29c). Indeed about 300 m from the present day crater wall on the crater floor granitoid basement rocks crop out that are inferred to represent the syn-eruptive paleosurface (Fig. 4.29c).

Harrat Hutaymah geotope is a maar [26° 59′ 19.39″N; 42° 14′ 50.85″E] with a volcanic depression that is about 120 m deep from the top of its well-preserved tuff ring crest to the crater floor (Fig. 4.30). The crater floor is flat and it hosts a temporal lake that is located slightly in the eastern edge of the crater floor. In the present day crater wall about 50 m above the present day crater floor is a contact between pre-volcanic succession and country rocks of Proterozoic granitoid rocks (Fig. 4.31). The Proterozoic granitoid rocks are covered by about 3–5 m thick siliciclastic deposits (e.g. aeolian and fluvial sand and silt). This siliciclastic succession is covered by at least three distinct lava flow units with lava foot and top breccias each having an average thickness of about 2 metres (Fig. 4.31b–d). This lava flows seem to be tabular and laterally extensive with no systematic thickness variations (Fig. 4.32). This basal lava flows are covered by an about 1–2 m thick aeolian/fluvial deposits (e.g. part is weakly developed soil). In the southern side of the preserved crater a lava spatter-dominated cone form a marked volcanic edifice that is half sectioned in a similar way as it has been identified at Al Wahbah in Harrat Kishb (Fig. 4.31).

This volcano is a complex volcanic feature with at least three distinct half sectioned volcanic craters and a relatively small ponded lava below its main crater exposed in the crater wall. Small lava flows that are inferred to be dominated by clastogenic flows can be traced in the vicinity of this pre-maar scoria- and spatter cone (Fig. 4.32). In the flank of this pre-maar volcanic cone finer grained and bedded, light coloured tuff breccia and lapilli tuff beds mantling the cone edifice. The top of the cone is not covered by these deposits associated with the maar crater formation or there are just thin accidental lithic-rich veneer deposits can be recognized.

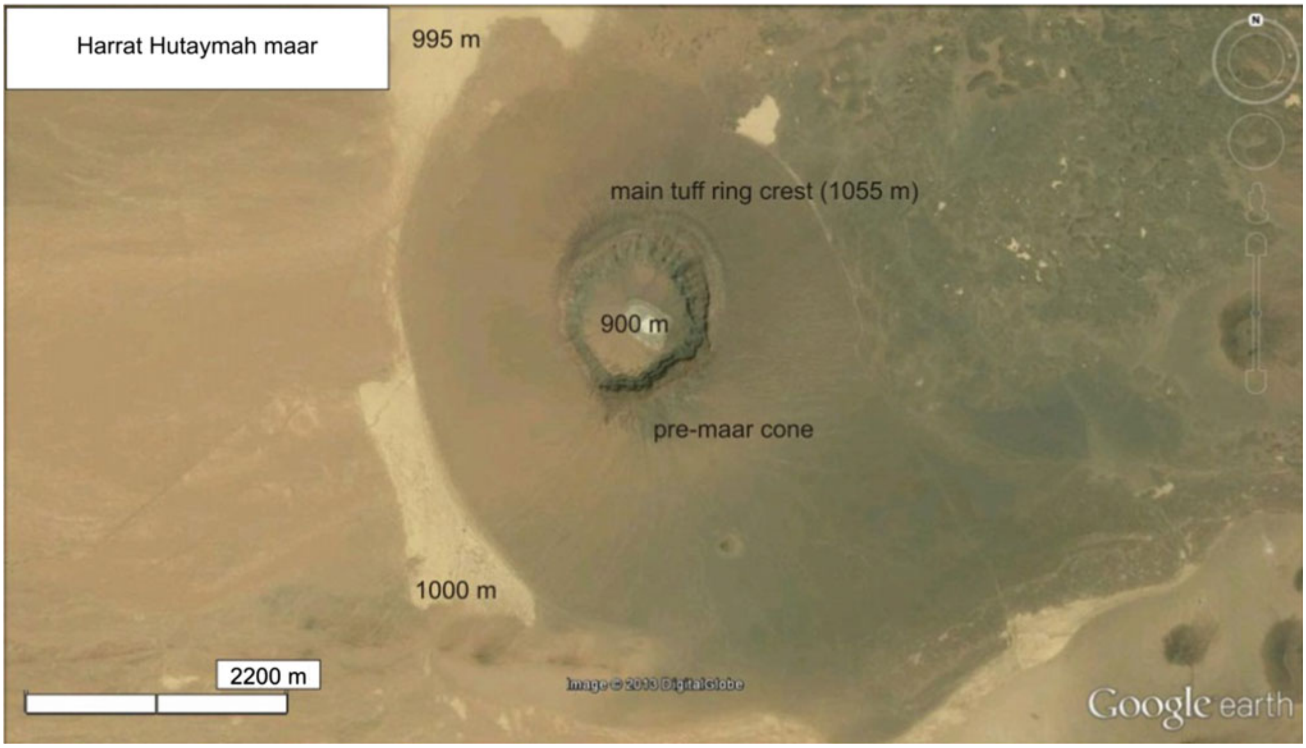

Fig. 4.30 Harrat Hutaymah maar [26° 59′ 15.11″N; 42° 14′ 43.48″E] on a GoogleEarth image. Elevation values refer to the elevation of the outet and the intra-crater surface elevations

The pyroclastic succession inferred to be part of the tuff ring that formed around the maar crater is thicker in the northern side of the crater suggesting a fairly asymmetric volcanic edifice. In the northern flank of the Harrat Hutaymah the tuff ring is steep in the proximity of the crater wall and gradually flattening out toward the north. The edifice can be traced about a kilometre from the present day crater wall. Further away from the crater wall, the bedding become well-developed and the entire succession is composed of dune-bedded lapilli tuff and tuff. The base of the tuff ring is a tuff breccia that is rich in accidental lithic fragments and generally thickly bedded. In the middle stratigraphy position the bedding is improved and fine grained lapilli tuff to tuff beds dominate with various ratio of accidental to juvenile pyroclasts. In this section there are some few-dm thick fall-dominated beds that are rich in cored bombs, and numerous mantle nodules. The uppermost succession of about 25 m thick lapilli tuff is dominated by well-bedded, inverse-to-normal graded juvenile lapilli and ash rich pyroclastic beds that contain cored lapilli and mantle nodules and deep crustal xenoliths (Fig. 4.33). The stratigraphy around the maar is fairly uniform (Fig. 4.33c, d).

Jubb geotope [27° 10′ 51.38″N; 42° 16′ 49.53″E] is a volcanic depression located in the northern part of the Hutaymah Volcanic Field next to Ni'ayy village (Fig. 4.34). It has an abandoned village in its crater similar to Tabah. The villagers were relocated due to an observed gradual crater floor subsidence noticed since the middle of the 80 s as a result of intensive ground water withdrawal (Al-Harthi 1998; Al-Rehaili and Shouman 1985; Bankher and Al-Harthi 1999; Roobol et al. 1985; Vincent 2008). The modern village is currently located in the eastern side of the tuff ring sitting on an alluvial fan (Fig. 4.34). Jubb is a volcanic depression and sits entirely on/between Proterozoic granite land (Fig. 4.34). In the present day volcanic depression's eastern side some granites crop out indicating that this area represents an exhumed syn-eruptive surface on what the tuff ring sits on (Fig. 4.35). This is inferred to be a similar situation to those identified at Tabah crater but in a much clearer 3D view. The tuff ring is thicker in the eastern side of the volcanic depression—up to 40 m—while in the west the crater rim is about 20 m thick in total (Fig. 4.35).

The tuff ring stratigraphy composed of three major units (Fig. 4.36a, b). The basal unit is dominated by accidental lithic fragments from various shallow and deep sourced country rocks, mantle nodules and angular juvenile fragments. Fluidal shape juvenile bombs are usually large and cored with various country rocks. The same light coloured basal unit exposed also in the western side of the crater but it is finer grained, rich in accretionary lapilli, vesicular tuffs and individual ballistic bombs commonly form impact sags on underlying beds (Fig. 4.36c). The middle section is more

Fig. 4.31 *Close up view* of Harrat Hutaymah maar on a google earth image (**a**). Three separate *panoramic images* show the key features of the Harrat Hutaymah [26° 59′ 15.11″N; 42° 14′ 43.48″E] crater (**b**–**d**). *Yellow arrow* on **b** points to a lava flow initiated from the pre-maar scoria cone

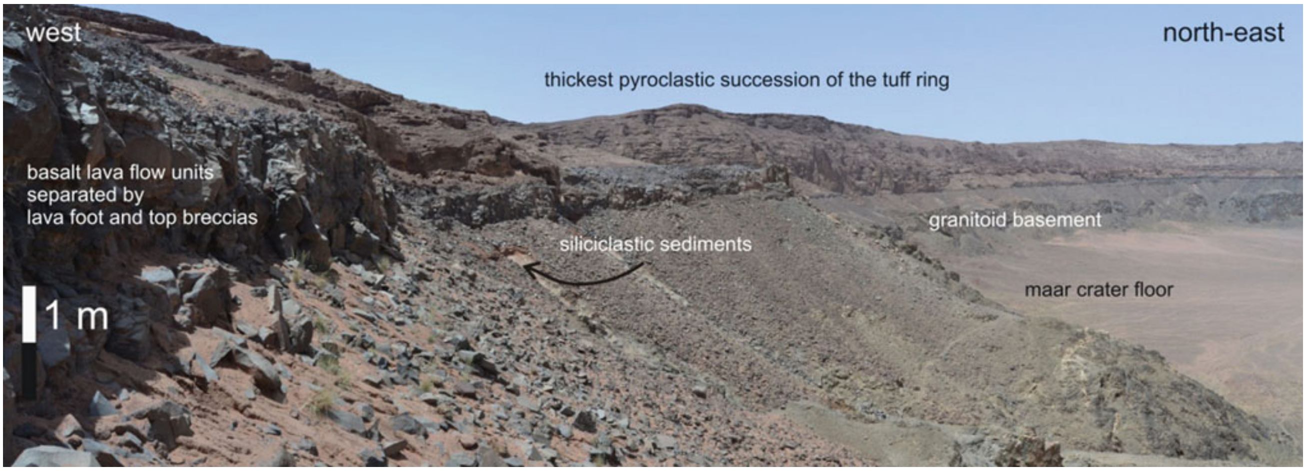

Fig. 4.32 Basal pre-crater lava flows exposed in the crater wall of Harrat Hutaymah volcano [26° 59′ 10.97″N; 42° 14′ 29.54″E]. The basal lava flows consist of at least 3 lava flow units and they are sitting over a siliciclastic sedimentary succession estimated to be at least 5 m thick over the granitoid basement rocks

Fig. 4.33 Cored bombs with mantle nodules in the upper pyroclastic units of Harrat Hutaymah [26° 59′ 15.11″N; 42° 14′ 43.48″E] maar (**a**). Intact cored bomb with contractional cracks (**b**) are signs of fast chilling of magma upon fragmentation (**b**). Antidunes (**c**) and matrix supported base surge beds (**d**) dominates the Harrat Hutaymah tuff ring succession

juvenile pyroclast dominated and exceptionally well bedded in its middle part with some spectacular moderate wavelength (0.5–3 m) antidunes (Fig. 4.37a, b). Antidunes are exceptionally well-exposed in the road cuts enter to the crater from outside (Fig. 4.37c, d).

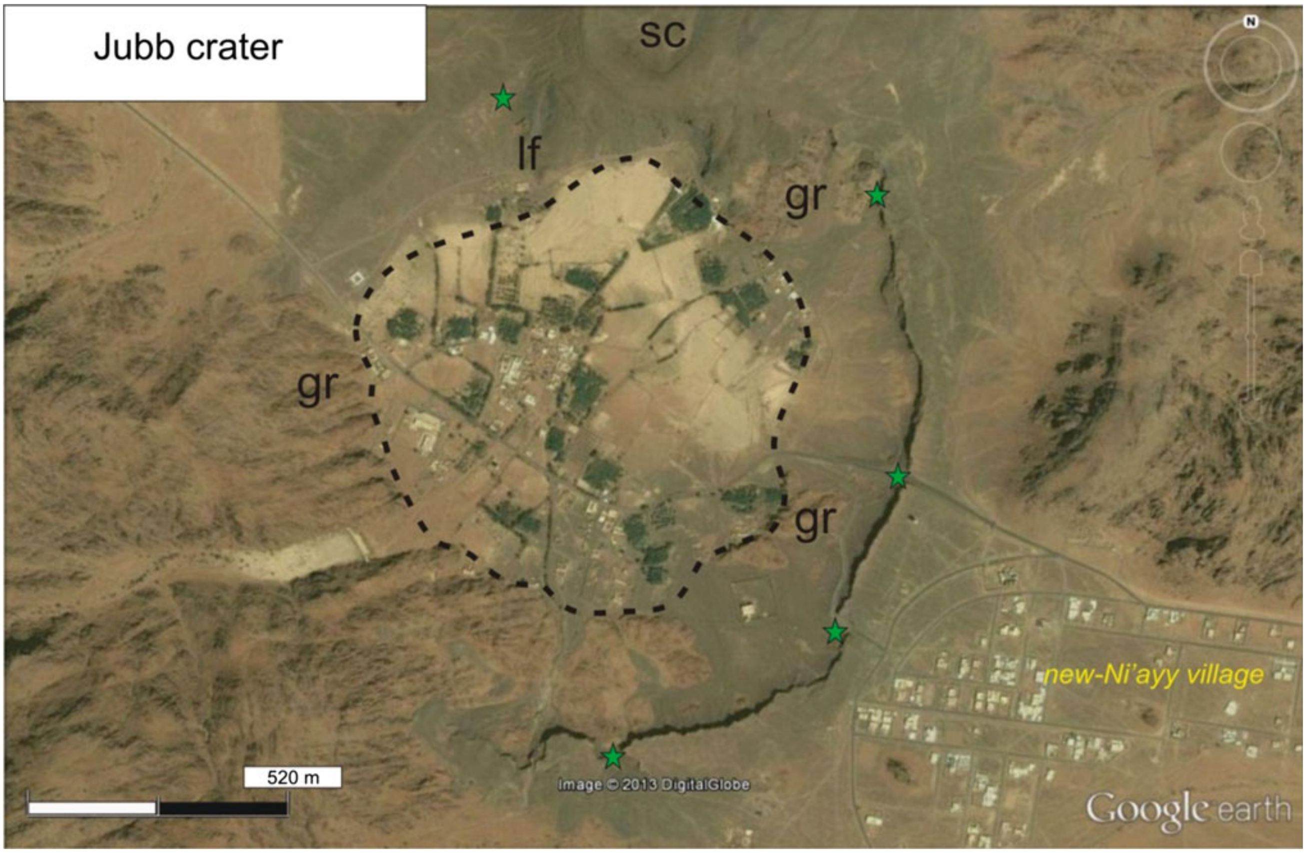

Fig. 4.34 Google earth image of the Jubb crater near new-Ni'ayy village [27° 10′ 25.28″N; 42° 17′ 33.45″E]. The present day volcanic depression is an erosionally enlarged volcanic landform. The structural boundary ot the original maar crater is inferred to be located in the area (*dashed line*) where the crater floor is relatively flat and filled with various sediments (loess, silt, sand etc.). Exhumed basement granitoid rocks are marked by *gr*. *Green stars* are measured sections. A pre-maar scoria cone is labelled by *sc* while a small lava flow marked by *lf*

The topmost succession is more abundant in juvenile fragments, and an increase of fusiform lapilli is prominent in the uppermost part of the succession that can be defined as a separate unit (Fig. 4.37e). In the northern side of the volcanic depression an aligned lava spatter/scoria cones represents a pre-eruptive morphology. This volcanic cone complex has some basal lava flows that are exposed in the present day crater. The crater-ward side of the cone truncated by landslides but it has not been half-sectioned as it the case in Harrat Huttaymah. This indicates that the structural boundary of the volcanic crater must be closer to the center of the present day depression and this crater has also been erosionally enlarged similarly as it has been inferred for the Tabah crater.

The Jubb is a truly complex volcanic geotope with high geoheritage value. The preserved pyroclastic successions show a complex explosive eruption story that were violent and energetic similar to well-known sites in Europe like the Laacher Sea in Germany. The advantage of exposures at Jubb however is that the arid climate has a unique effect on the preservation potential of the pyroclastic rocks providing fantastic exposed 3D volcanic facies architecture to see in a confined and relatively easy to access region. The fact that a small township and roads are crossing the maar crater made this location as a perfect site for geoeducational and geotouristic programs.

Humayyan/Hamrah volcano [27° 11′ 4.46″N; 42° 22′ 45.07″E] is a complex volcanic geotope that is located about 10 km to the east from Jubb. It consists of a large crater-like depression that is located in a centre of an extensive lava flow field. In the crater wall no pyroclastic rocks exposed, suggesting that this depression might be a pit crater formed on a top of a growing lava shield (Fig. 4.38).

In the southern part of the volcanic complex however exposes thick succession of pyroclastic rocks rich in accidental lithic fragments, mantle nodules, and abundant angular volcanic pyroclasts hosted in a fine ash matrix. This pyroclastic succession is clearly covered by the lava flows initiated from a lava shield host a large (double) pit crater (Fig. 4.38). This facies relationship suggests that a large tuff ring must have been formed prior the lava shield and subsequent pit crater formation. In a large single horst in the SE exposes about 100 m total thickness of tuff breccias and

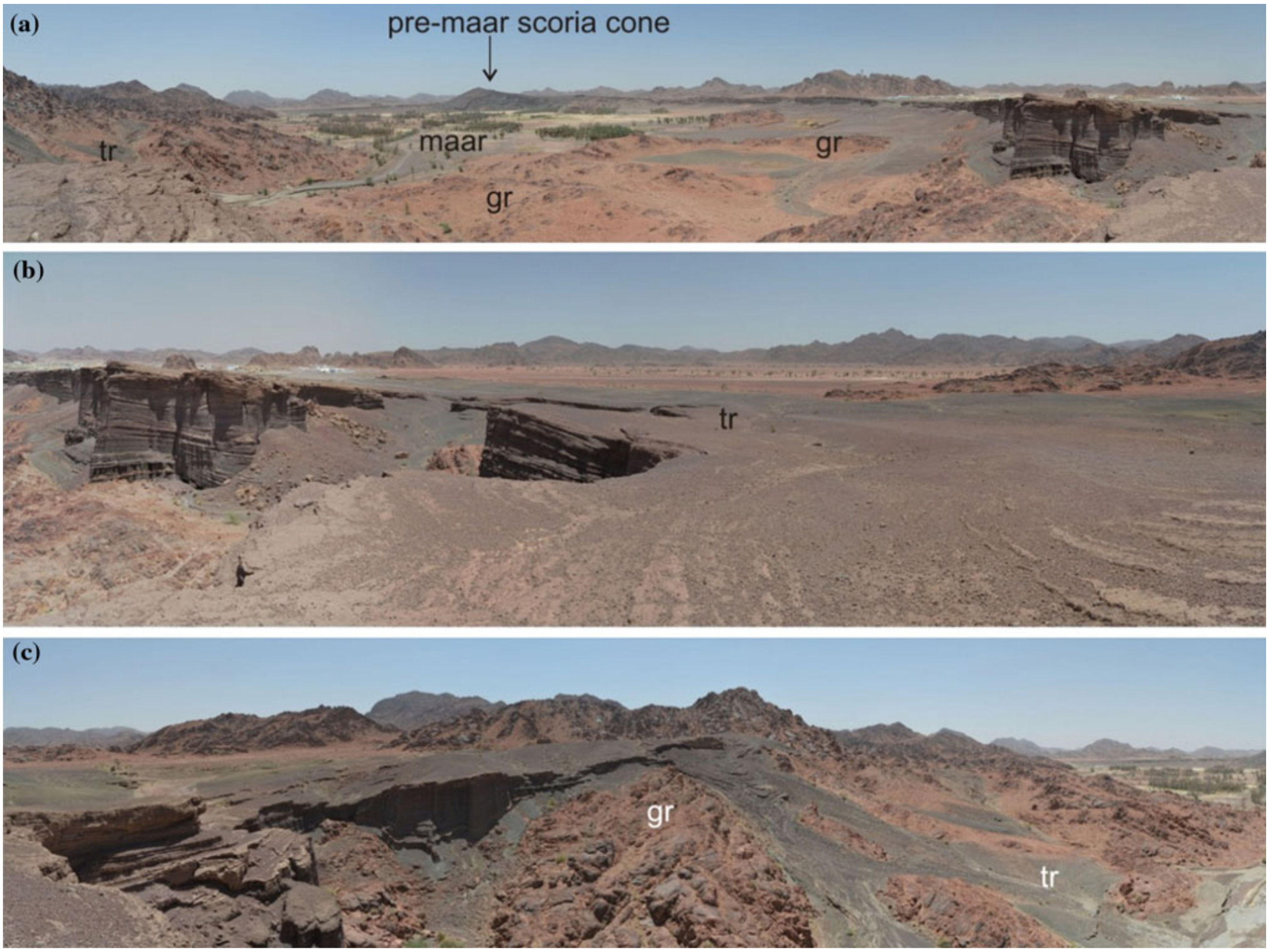

Fig. 4.35 Panoramic views to Jubb crater [27° 10′ 47.34″N; 42° 16′ 49.10″E] toward NW (**a**), to the E (**b**) and toward the SW (**c**). Note the exhumed granite surfaces (*gr*) in the interior of the present day volcanic depression draped by base surge deposit dominated section of a tuff ring (*tr*)

lapilli tuffs (Fig. 4.39). In this section a threefold stratigraphy can be identified (Fig. 4.40). The basal succession is a grey tuff breccia and lapilli tuff that is stratified, massive and contains abundant angular juvenile fragments as well as lithic pyroclasts. This about 60 m thick unit is covered by a yellow tuff breccia (∼20–25 m thick) that is in angular unconformity with the basal grey pyroclastic unit and forming a dish-filling nature toward the centre of the volcanic complex. This yellow pyrolcastic unit contains large accidental lithics that are over 4 m in diameter. The top of the succession composed of an about 5–10 m thick matrix-supported units that contains bed-flattened lava spatters and agglutinated pyroclast horizons. In the center part of the volcanic complex this basal pyroclasts clearly covered by lava flows that can be correlated around the depression. In the southern part of the entire volcanic complex along an entry path to the main pit crater the present day morphology is subdued by strong erosion and exposing individual buttes with a very similar stratigraphy but various bedding orientation and attitude suggesting that this zone might be the former crater of a tuff ring.

For reconnaissance purposes the expedition visited another tuff ring that is completely filled with aeolian deposits in its former crater. This volcano also exposes a nice section of typical tuff ring succession with accidental lithic rich lapilli tuffs and tuffs that hosts accretionary lapilli and numerous angular ash and fine lapilli consistent with an explosive phreatomagmatic origin. In addition scoria cones forming the central chain of the volcanic field suggest their NS aligned nature, fissure-like distribution is manifested in the individual volcanic edifice natures.

4.3.3 Main Findings and Geoheritage Value of Harrat Hutaymah

Four of the most prominent and best exposed volcanic explosion craters of the Harrat Hutaymah inferred to be

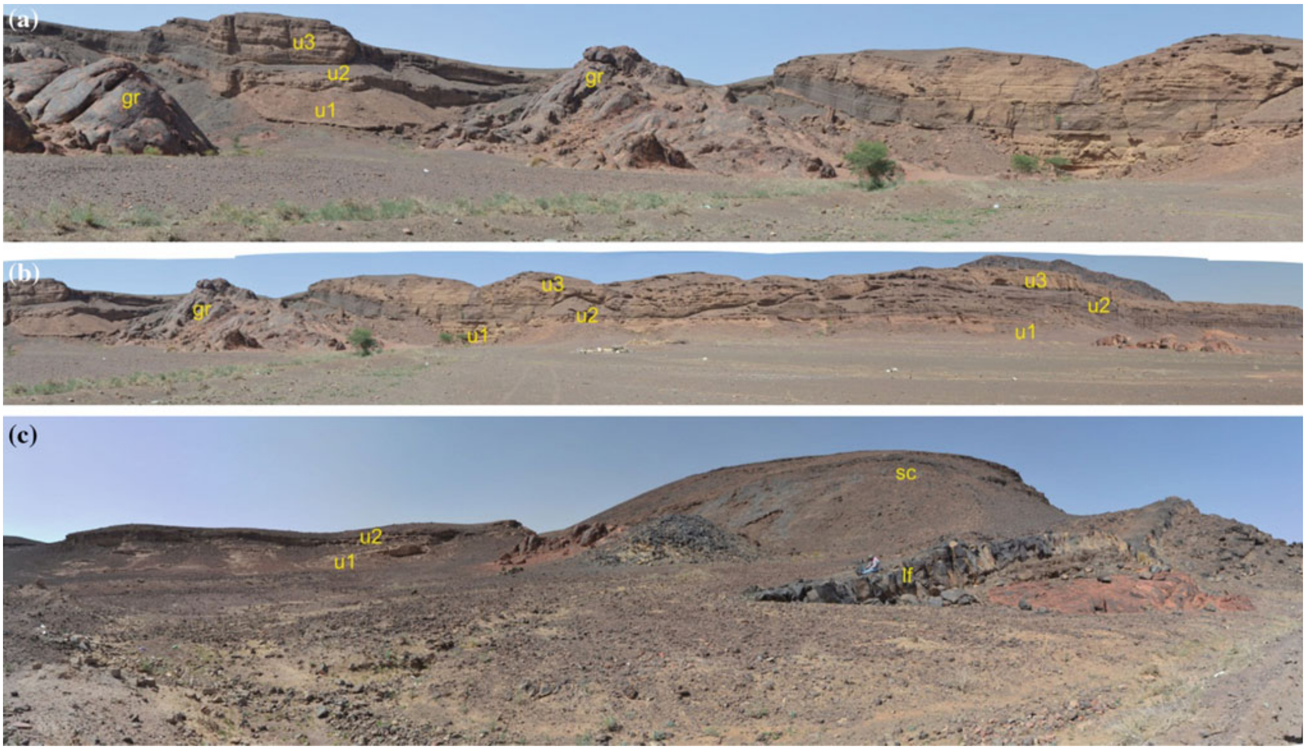

Fig. 4.36 Pyroclastic units (u1–3) of the Jubb crater [27° 11′ 1.83″N; 42° 17′ 17.68″E] form thick tuff ring pile in the eastern edge of the volcano (**a** and **b**), while in the western edge pyroclastic rocks show textures and bedding characteristics are more typical for distal PDC units. In the northern side of the crater the tuff ring pyroclastics sit on a pre-crater scoria cone (*sc*) and associated lava flow (*lf*). Granitoid basement rocks are exposed in the erosionally enlarged maar crater (*gr*)

formed due to phreatomagmatic explosive eruptions. In each of the detailed studied volcanoes it can be conclude that their formation was dominated by magma fragmentation that produced chilled pyroclasts as well as fine ash and excavated country rocks from various levels. Accretionary lapilli and vesicular tuffs were recognized in Tabah, Hutaymah and Jubb volcano, especially in sections typical for medial or distal part of a tuff ring. At Hamrah however, the exposed (and visited) sections are likely representing proximal tuff ring successions and therefore such features are not expected to be seen. However, at Hamrah the tuff ring forming successions are typical for explosive eruptions produce abundant country rocks, deep seated xenoliths and transported through relatively cold PDCs that are consistent for a proximal succession of tuff rings formed due to phreatomagmatic explosive eruptions.

From the four identified geotopes and their geosites Harrat Hutaymah is the best preserved and it is likely the most intact volcano. The fact that country rocks are exposed in the crater wall well above of the crater floor clearly classify Harrat Hutaymah to be a maar volcano (White and Ross 2011). In the case of Tabah and Jubb the volcanic edifices are more subdued and the erosion likely formed a significant retreat of the crater wall toward the distal part of the tuff ring resulting exhumation of syn-eruptive surfaces on the granitoid landscape. In addition these two craters are also filled nearly completely, and to identify the structural boundary of the craters is difficult and potentially a subject of excellent geophysical surveys planned in the future as it has recently been demonstrated from other low profile wide craters from the Newer Volcanics in Victoria, Australia (Blaikie et al. 2012). Recent researches also targeted flat, broad maars with an aim to determine the number of eruptive sites, and the role of vent migration across a broad crater area to form large amalgamated maar craters versus the fact how wave-cut erosion and lake infill processes can enlarge an original maar crater (Boyce 2013; Jordan et al. 2013; Németh et al. 2012a). The broad volcanic craters of Harrat Hutaymah are the perfect sites to contribute to this frontline research questions.

At this stage it can be said that these two volcanic depressions are also formed due to explosive phreatomagmatic eruptions and they are also maar volcanoes. In case of Humayyan/Hamrah, the present day large volcanic depression is inferred to be a pit crater complex on a large lava shield. However, the initial eruption of the Humayyan/Hamrah must have also been explosive phreatomagmatic and produced a fairly large and extensive phreatomagmatic volcano once occupied the southern part of the volcanic complex. In many respect the lower part of the exposed

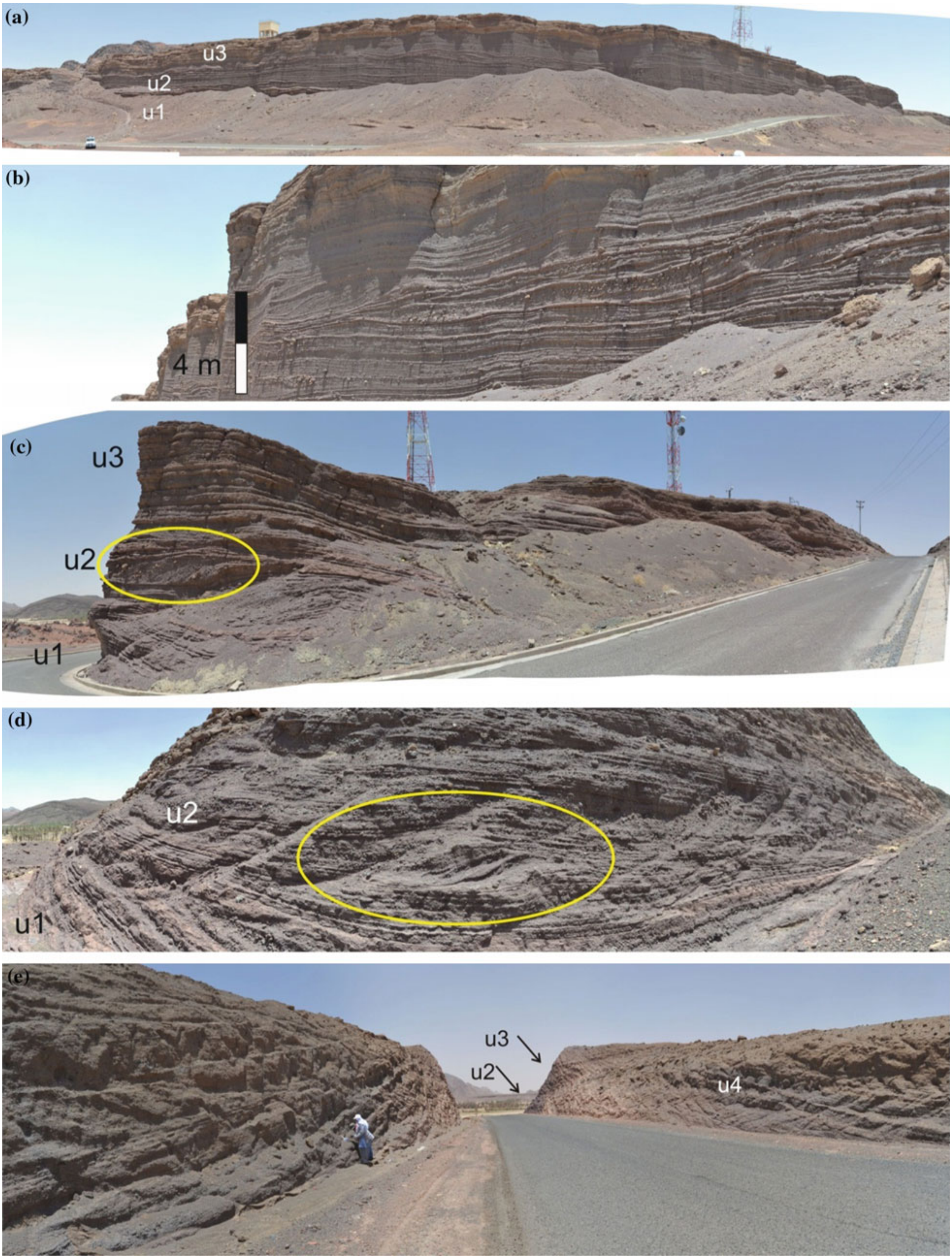

Fig. 4.37 *Panoramic views* of the tuff ring succession [27° 10′ 41.86″N; 42° 17′ 17.88″E] in the eastern sector of the tuff ring of Jubb with its pyroclastic units (u1, u2, u3 and u4) (**a**–**c**). On **c** and **d** *yellow circles* locate the well-developed dunes/anti-dunes of the PDC deposit

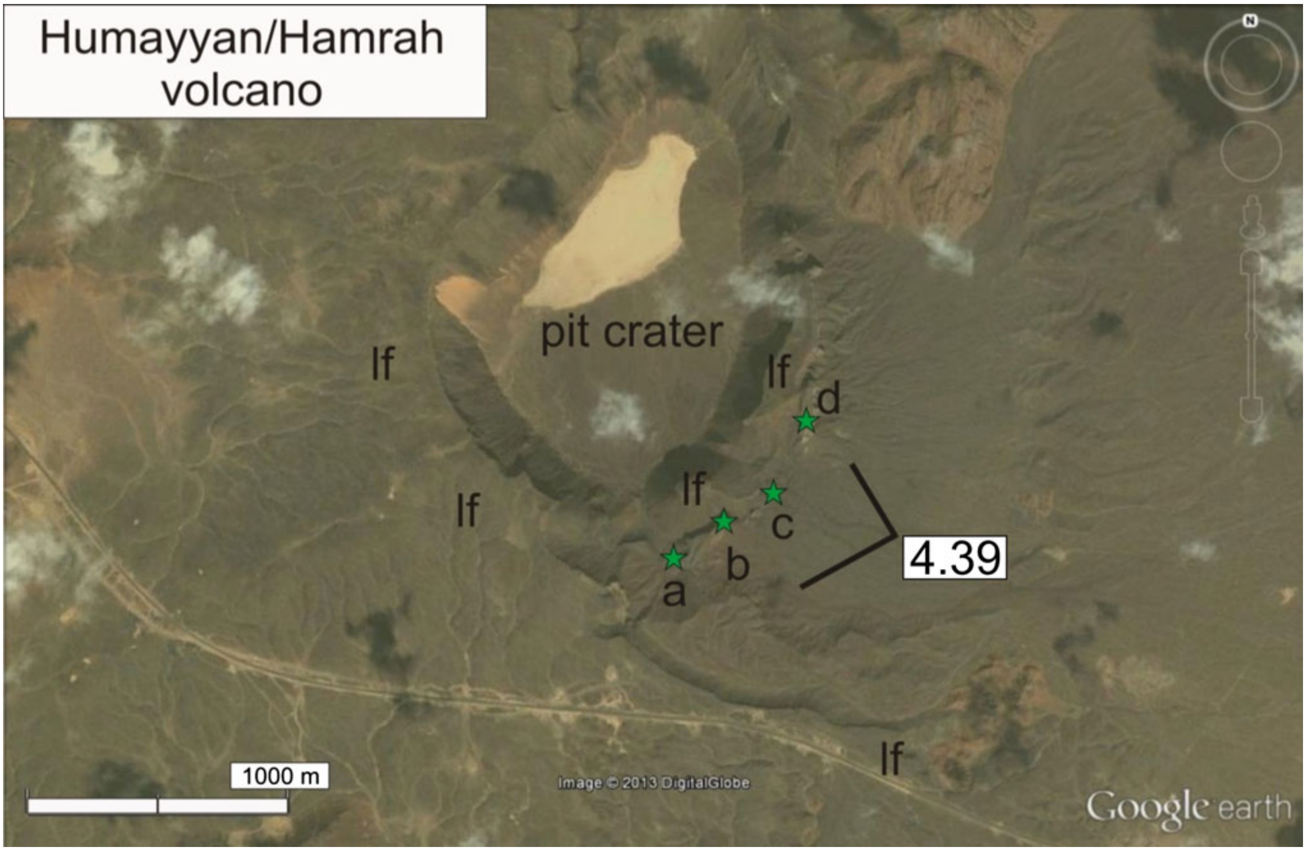

Fig. 4.38 Google earth image of the Humayyan/Hamrah volcano with its large pit crater [27° 11′ 6.57″N; 42° 22′ 33.59″E]. Pyroclastic rocks of part of a tuff ring exposed under lava flow (*lf*) units (part of a lava shield) in the SE sector of the volcanic complex. View-point from where the Fig. 4.39 was taken is marked on the map. Signs from **a** to **d** represents large cliffs composed of pyroclastic rocks, a dissected part of a former tuff ring

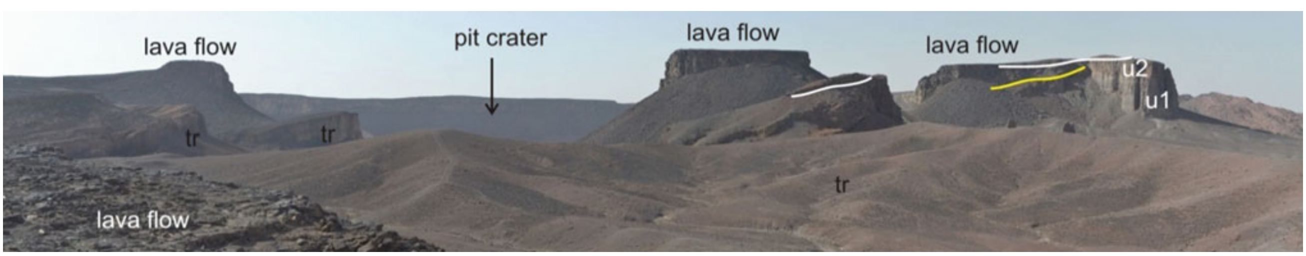

Fig. 4.39 View toward the NW to the main crater of Humayyan/Hamrah volcano [27° 10′ 39.54″N; 42° 22′ 56.00″E]. *Yellow line* marks contact between lava flow units and pyroclastic successions (tuff ring - *tr* and its units u1 and u2). *White line* marks the contact between phreatomagmatic successions and capping lava spatter-dominated tuff breccia

pyroclastic units resemble textural features typical to diatreme filling successions similar as it has been reported from Hopi Buttes, Arizona (Lefebvre et al. 2013; White 1991), Waipiata, New Zealand (Németh and White 2003), or the Pannonian Basin, mostly in Hungary (Németh et al. 2001). In this respect the exposed pyroclastic rocks could represent an exposure level of volcanoes near or even below the syn-eruptive surface. To map the specific units and correlate them it would help to clarify the 3D architecture of this interesting volcano. It is however, can be inferred, that the eruption mechanism to form this volcano was also phreatomagmatic and produced significant volume of pyroclasts that transported and deposited by various particle concentration PDCs. Overall, the visited sites confirmed that at Hutaymah Volcanic Field phreatomagmatism and in general explosive volcanism that produced primarily PDCs were a major eruption style, which is indeed makes this field outstanding from other harrats.

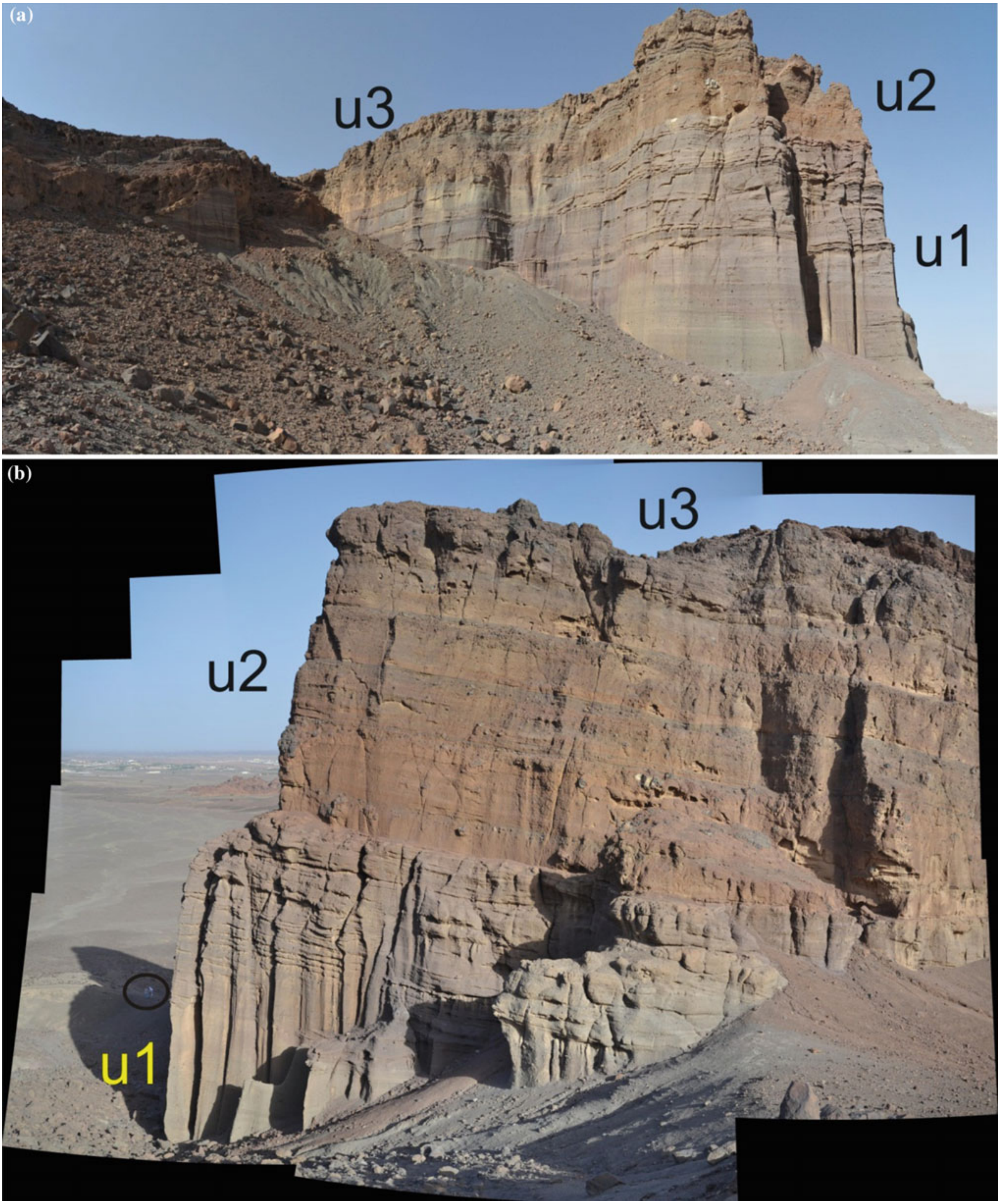

Fig. 4.40 Composite views of the main pyroclastic succession of the preserved tuff ring in the SE sector of the Humayyan/Hamrah volcano [27° 10′ 44.09″N; 42° 22′ 50.20″E]. Three major stratigraphic units (u1, u2 and u3) could be distinguished in locations about a kilometre apart from each other. On **b** people for scale marked in a *circle*

The volcanic explosion craters of Hutaymah Volcanic Field can provide an excellent playground for modern geophysical techniques to conduct including gravimetry, MT and geomagnetic survey to delineate the structural boundaries and the nature of the crater filling rocks. In combination with modern geochemical and geochronological work, these studies could yield to a state-of-art research that could significantly contribute to current cutting edge research on crater formation processes. With this high scientific potential these region can generate high scientific interest that can build a strong scientific foundation over years to describe, catalogue and rank volcanic geoheritage value in the region. The good exposures, the easy access and the high aesthetic value in addition made this region an ideal location to develop geoheritage projects that may culminate in the formulation of regional or global geopark in the near future.

4.4 Harrat Khaybar

4.4.1 Overview

A reconnaissance visit to Harrat Khaybar (Fig. 4.41) was performed recently (in 2013) with an aim to collect information on the general field conditions, the accessibility of the key geological sites and asses the geoheritage value of the region by identify key geological sites that could be used in the future for detailed geological projects. The southernmost part of the field was explored where potential historic eruptions sites are suspected as well as various silicic tuff rings are located. In the central part of the field geology work was concentrated on the Jabal Quidr region as this volcano being the youngest of the region as reported and generally accepted (Camp et al. 1991; Chagarlamudi et al. 1991; Coleman and Gregory 1983; Demange et al. 1983). In addition this volcano shows many very young volcanic features such as lava flow surface textures and lack of erosional features on its flanks. This volcano also associated with an extensive ash plain that can be traced at least 17 km from its source (Fig. 4.29), putting this volcano and the eruption produced this ash plain into the eruption range of being sub-Plinian or violent Strombolian (Valentine and Gregg 2008). Near Jabal Quidr, dual silicic volcanic systems were the main interest of the field visit. The so called "*White Mountains*", Jabal Bayda and Jabal Abyad are comenditic centers (Baker et al. 1973; Camp et al. 1991; Demange et al. 1983) produced a tuff ring and a lava dome complex with short run out distance block and ash flow deposits and associated obsidian lava domes and coulees. Just north of Jabal Quidr an extensive fissure zone with pit craters and a chain of lava spatter cones were visited to study lava flow surface textures and their implications to lava flow rheology and behavior. In addition the region exceptional geoheritage value was also documented.

The dominant rock types of the western Arabian Miocene to Recent intracontinental volcanic fields are hawaiite, but subordinate, more felsic rock types, such as benmoreite, mugearite and trachyte, are also known, especially in the largest volcanic fields with the most complex volcanic stratigraphy, such as the Harrat Khaybar (Camp et al. 1991). Harrat Khaybar basal volcanics formed the Jarad Basalt (5–3 Ma) that is overlain by the Murash Basalt (3–1 Ma) and it is capped by the Abyad Basalt (1 Ma—Recent) (Camp et al. 1991). Harrat Khaybar has the most prominent felsic volcanoes of the Arabian Peninsula erupted from a compositionally zoned near-surface magma chamber along a N-S fault zone in the central part of the field (Camp et al. 1991).

4.4.2 Jabal Quidr [25° 43′ 11.23″N; 39° 56′ 37.32″E]

Jabal Quidr is one of the most prominent volcanic landform of the Harrat Khaybar (Fig. 4.42). It dominates the center part of the volcanic field with its near perfect symmetric volcanic cone that is composed of a basal gentle sloping lava flow dominated part and crowned by a reddish volcanic cone (Fig. 4.42a). The slope angle changes coincide well with the boundary between a basal lava shield and a capping volcanic cone that has formed due to explosive volcanic eruption and accompanied crater subsidence triggered by lateral drainage of a central crater on top of it (Fig. 4.42b). The base of the volcanic edifice composed of complex pahoehoe lava flows that characterised by few m wide lava tubes that cross cut each other forming a complex network of tube-fed solidified lava fields. In major axial zones, uplifted lava crusts commonly twisted and rotated forming several tens of metres wide zones of inflated and deflated lava ponds commonly associated with lava tumuli (Anderson et al. 2012; Duraiswami et al. 2004) (Fig. 4.42a). Individual lava tubes are partially covered and connected with zones of outflows where cm to dm scale lava fingers form a complex surface texture (Fig. 4.42b).

Larger inflated lava flows are commonly forming blistery surfaces with shelly pahoehoe surface textures (Stevenson et al. 2012) (Fig. 4.43a). These lava blisters normally in a few metres across size and in many occasions their roof is collapsed and broken, exposing large voids beneath them (Fig. 4.43a). In other cases, especially along the base of the volcanic edifice lava flows are commonly ponded and thick lava crusts exposed along fractured and uplifted/downthrown margins of tumuli (Fig. 4.43b). Complex surface wrinkle textures (Fig. 4.43c, d) suggest some outpouring of fresh lava along cracks on the lava tubes and ponded surfaces that were then subsequently sheared away. These surface textures suggests that lava flows from Jabal Quidr were low viscosity and moved fast in the high slope angle regions preventing to form extensive and thick lava crusts commonly broke apart

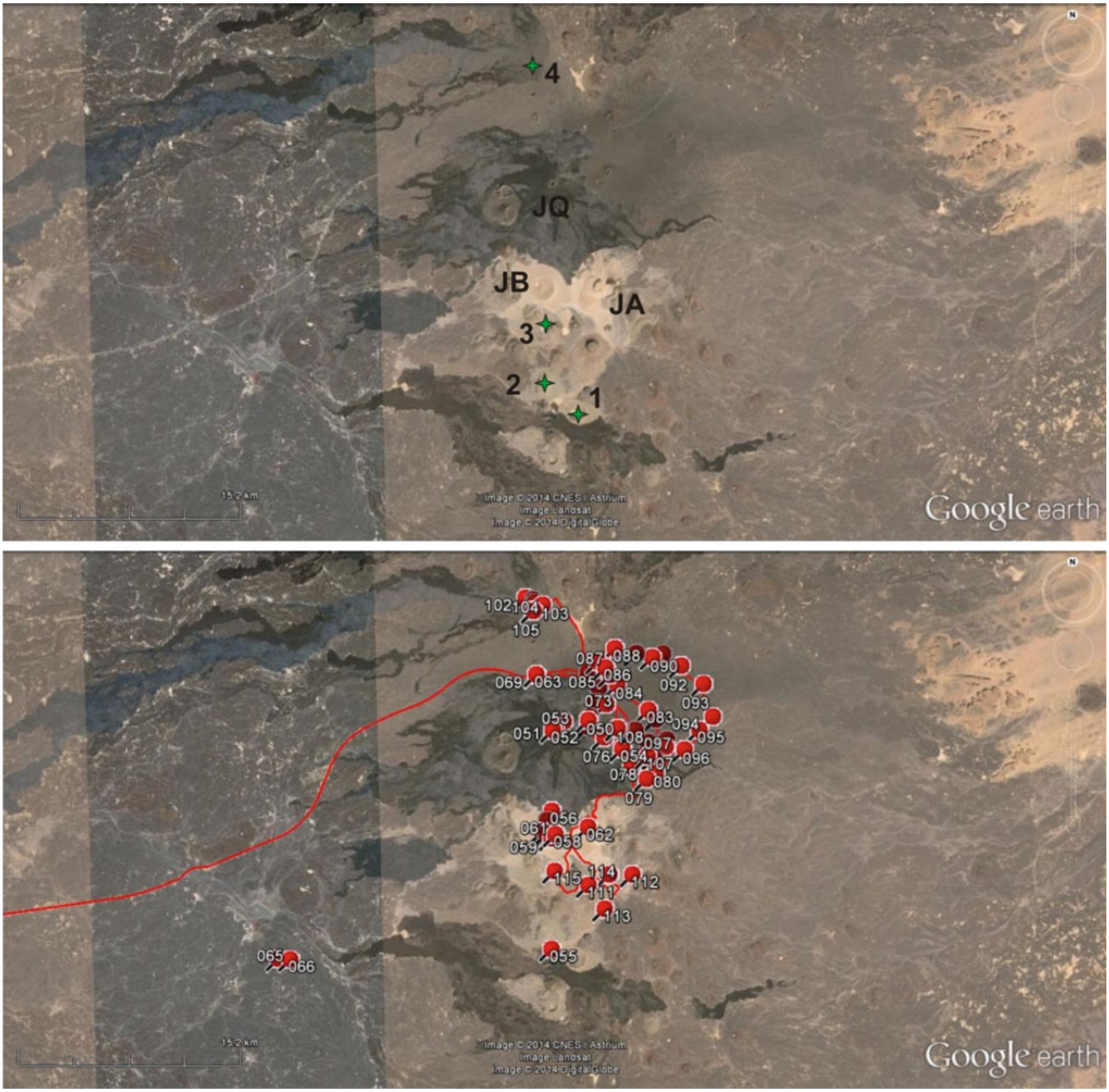

Fig. 4.41 Harrat Khayber in Google earth satellite images. The *upper image* shows the key locations visited during the field campaign: *JQ* Jebel Qidr, *JB* Jebel Bayda, *JA* Jebel Abyad, *1* young silicic tuff ring with broad crater, *2* inverted silicic tuff ring with eroded rims, *3* well-preserved complex silicic tuff ring with broad crater, *4* lava spatter complex with pit crater network and extensive lava outbreak points. The bottom immage shows the waypoints and tracks coverred during the field campaign. 065–066 are the locations of the entry points of a major lava tube network

the freshly ponded crusts while in the low slope angle regions where lava flow movement slowed down ponding and crust formation were more pronounced (Keszthelyi and Denlinger 1996). The common mechanical stress on large lava crusts indicates repeated inflation and deflation processes in the ponded lava zones (Calvari and Pinkerton 1999; Hoblitt et al. 2012; James et al. 2012) that is inferred to be controlled by the inflow and outflow of melt from the ponded zones. The lava flow surface texture variations and the common development of transitional lava fields has been documented as a widespread feature of the Harrat Rahat (Murcia et al. 2014) that is seemingly the case at the Harrat Khaybar as well.

In the feet of Jabal Quidr large ponded lava flows form thick crusted ponded lava zones where the crust is over 1 m

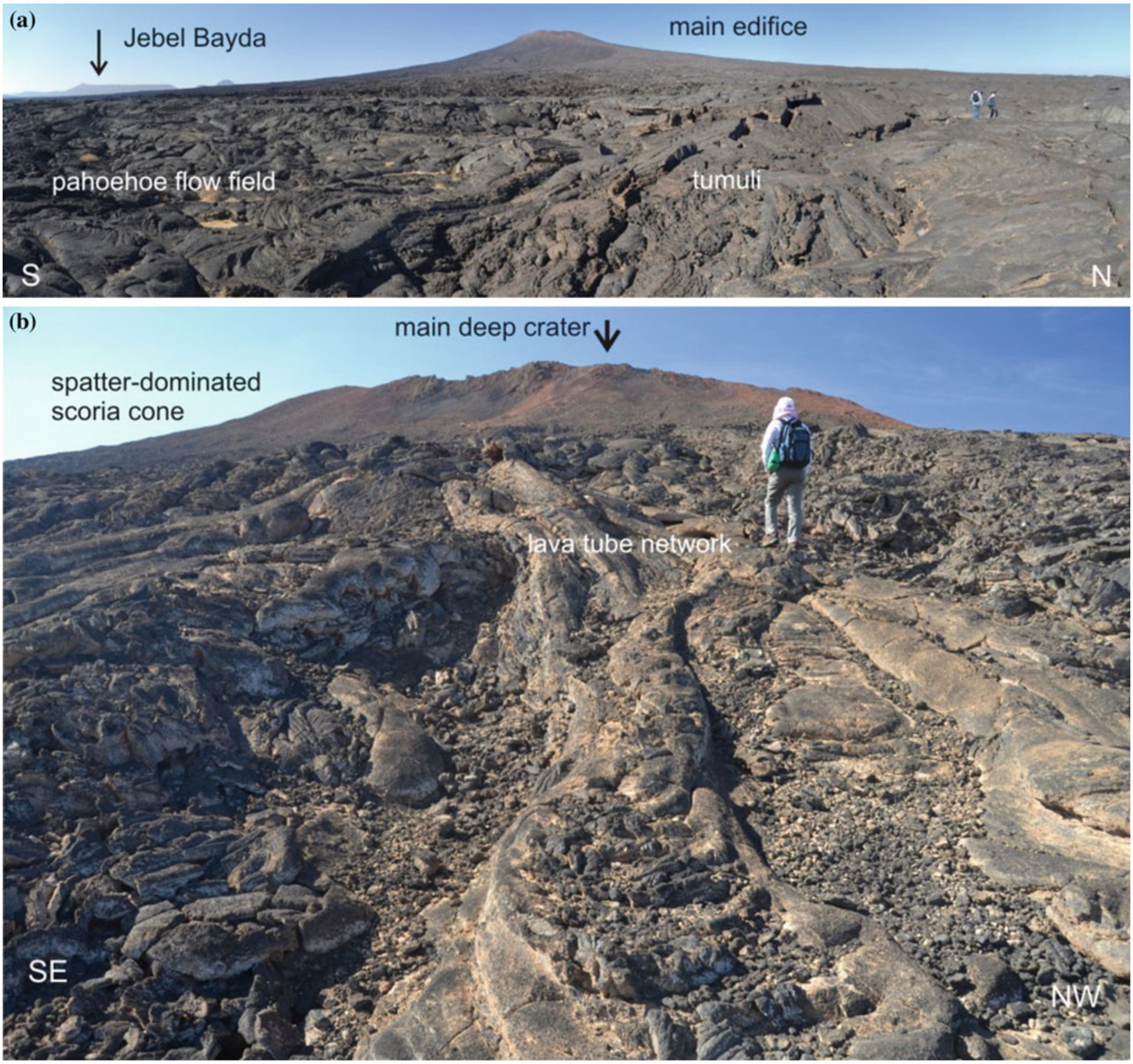

Fig. 4.42 **a** Overview of Jebel Qidr from the east [25° 43′ 36.74″N; 39° 57′ 4.39″E]. Note the shape of the cone having a well-distinguished scoria cone over a shield-like edifice. **b** The gentle dipping slope of the eastern flank of Jebel Qidr is dominated by pahoehoe lava flows and abundant tumuli and pressure ridges. The *upper section* of the lava flows near the initiation points (*boccas*) lava flows are rubble demonstrating fast removal of freshly developed lava crusts while in the *lower section* of the edifice flank flow movement might have been less vigorous allowing to develop proper lava clasts and fantastic pahoehoe surface textures

thick indicating relatively stable conditions of the lava ponds to develop thick crust (Fig. 4.44a). On the basis of the texture and the thickness of the lava crust it can be inferred that the time needed to form such crusts is in the range of days to weeks suggesting a relatively stable melt supply to keep this lava ponds stationary over long time. In places where new melt entered to a ponded lava zone an open roof channel might formed along the lava moved and commonly changed its level as it is evidenced from solidified open channel systems commonly associated with local tumuli (Harris et al. 2009; Patrick and Orr 2012; Stovall et al. 2009) (Fig. 4.44b).

The volcanic edifice of Jabal Quidr is primarily composed of lava spatter dominated breccias and agglomerates interbedded with welded spatter, clastogenic lava flows and relatively thin (m-scale) fluidal lava flows covering the outer edifice rim in a sheet-like fashion (Fig. 4.45). The agglomeratic pyroclastic breccia is mixed with vesicular pyroclasts of red, brown and balck lapilli and ash (Fig. 4.45a).

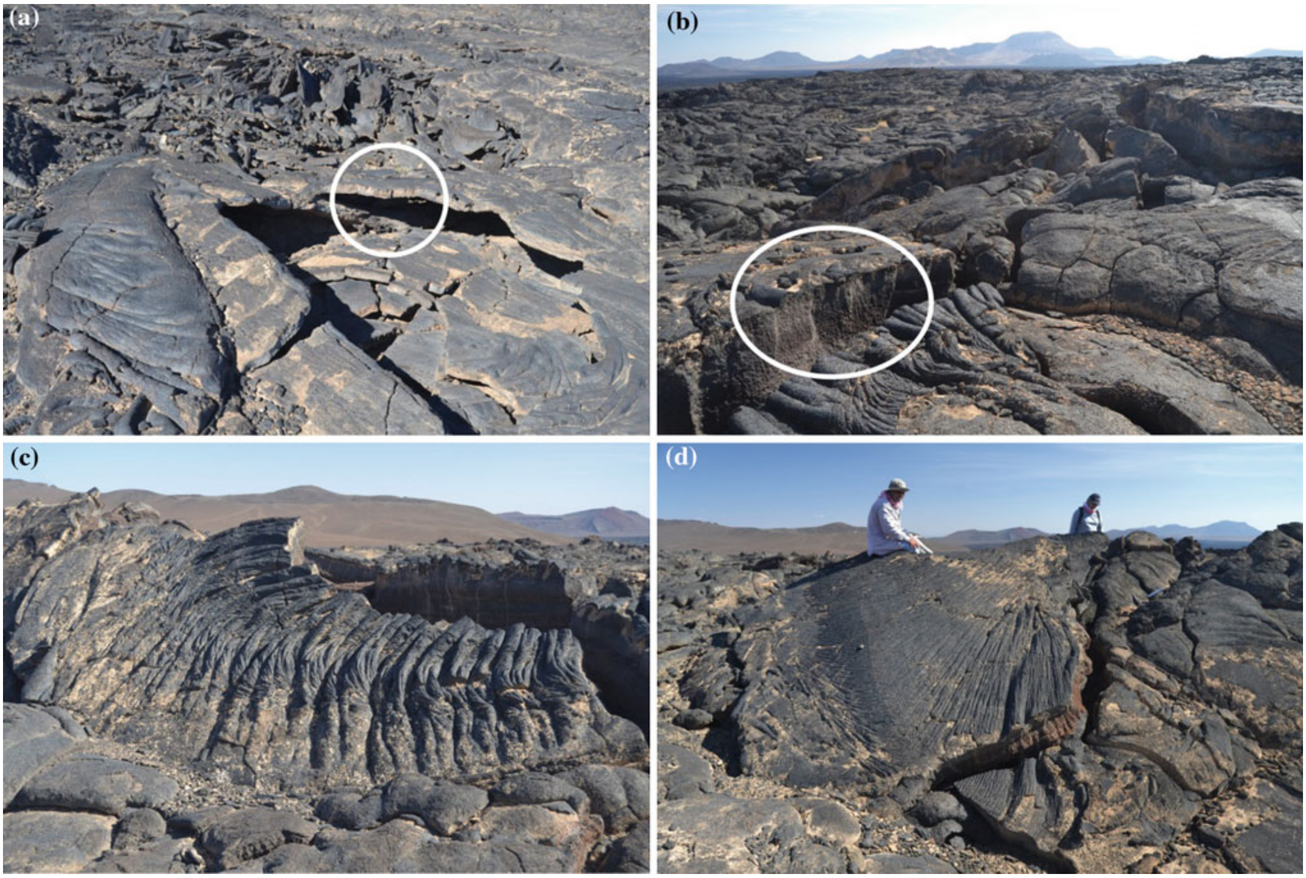

Fig. 4.43 Lava surface textures from the proximal lava flow regions of the Jebel Qidr volcano [25° 43′ 41.34″N; 39° 57′ 45.68″E]. Note the thin and thick lava crusts develop two different types of lava tube network (**a** and **b** with *white circle*). Common features are the ropy basalt textures and wrinkles on an uplifted lava tube roof commonly associated with break out tumuli in the ponded lower section of the lava flow fields (**c** and **d**)

Occasionally exhalation marks present as evidence of high temperature fumarola and/or solfatara activity after the formation of the edifice. Some cracks, fractures are common feature along the lip of the crater indicating some mechanical instability of the crater that is a common feature on such edifices (Németh et al. 2003; Thordarson and Self 1993).

The inner crater wall of Jabal Quidr is perpendicular (Fig. 4.45b) and exposes a succession of lava flows that are partially covered by drained back lava lounges as an evidence of some lava lake presence in various stages of the crater evolution (Fig. 4.45a). In the cross-section of the lava flow networks there are U-shaped lava ponds exposed indicating the presence of lava lakes in a smaller scale (tens of metres) and subsequent pit crater formation similar to those documented on large mafic volcanoes such as on those in Ambrym (Németh and Cronin 2008) or Piton de la Fournaise (Carter et al. 2007). The size of the crater is about 600 m across which is a large size capable to host significant volume of melt that then later on can be released through flank "boccas" as it has been documented in various outbreak fractures mostly in the western side of the upper outer flank of the cone (Fig. 4.45c). In the western side of the edifice there are in situ lava spatter sections that are steep (over 40 degrees slope angle), and agglutinated together to be erosion resistant remnants, but they also mark a situation if the magmatic pressure behind an edifice increasing, such edifice could become instable very quickly and initiate collapsing sections through lava lakes can be drained in a catastrophic way (Head and Wilson 1989). Similar steep spatter cones were documented from the Harrat Rahat and defined among the steepest on Earth (Moufti et al. 2013b).

Jabal Quidr has been surrounded by an extensive ash plain with a dispersal axis toward NE. The ash plain composed of scoriaceous ash and lapilli beds in several units indicating various episodes of violent explosive activity that were able to provide sustained eruption column and allow pyroclast to be transported beyond 15 km from the source making these eruptions in a range to be sub-Plinian or violent-Strombolian. The ash and lapilli are equi-dimensional to flat but highly vesicular suggesting full expansion of pyroclasts through fragmentation. The ash plain provided a base for the majority of the long lava flows initiated from Jebel Quidr, suggesting

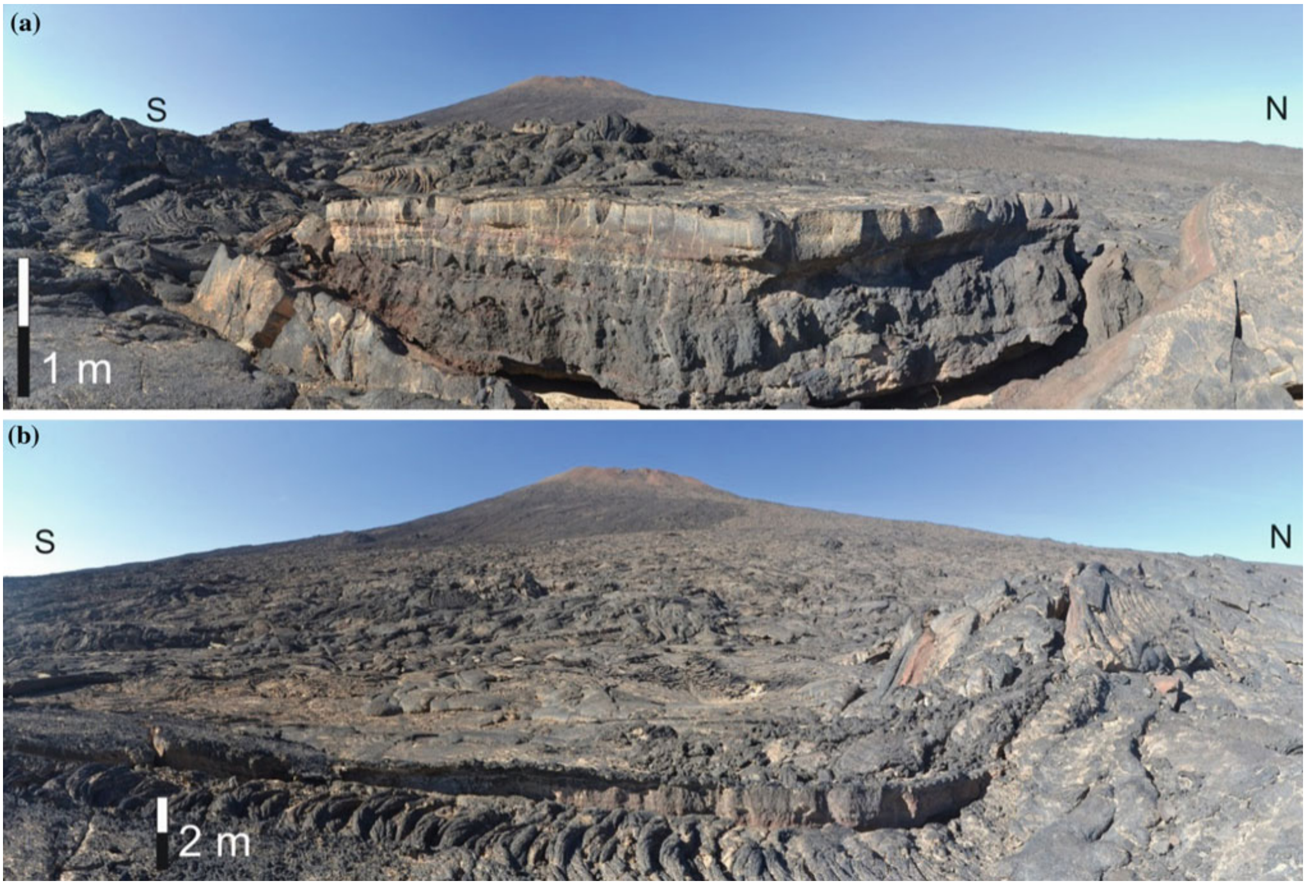

Fig. 4.44 Thick lava crust in the ponded pahoehoe lava flow field of Jebel Qidr's foothill [25° 43′ 41.34″N; 39° 57′ 45.68″E] where the slope angle of the volcanic edifice has changed leading to slow the lava flow down allowing some degree of ponding and thickening thus developing thick crust. The over a m thick crust can be interpreted several days of relatively stationary lava pond to exist in the foothil of the volcanic edifice

that the main violent explosive phase of the eruptions preceded the lava effusion stage. The lava flows reached over 10 km in length and followed morphological depressions, fluvial networks (Fig. 4.46a). In the medial section the lava flows are commonly transitional in type suggesting that they were derived from a tube fed lava that were mechanically abraded and pushed ahead to the medial distance. Where the terrain became relatively flat, the transitional lava flows were able to retain heat enough to maintain some tube to be active and feed further pahoehoe lava flow sheets that spread in a relatively thin skin-like manner over the ash plains (Fig. 4.46b, c). Lava flows were commonly flow into pre-existing craters filling them completely (Fig. 4.46a).

4.4.3 Jabal Abyad [25° 39′ 34.35″N; 39° 58′ 16.50″E]

The "White Mountains" of Harrat Khaybar are strikingly different in their appearance and their eruption history to the most landscape-dominant volcano of the field, the Jabal Quidr, which is a hawaiite stratovolcano and believed to have erupted in historic time and emitted dark lava fields (Camp et al. 1991) that are banked against the white comenditic ash and lapilli plain associated with the "White Mountains" (Fig. 4.47). The "White Mountains" refer to a pair of comenditic volcanoes (Baker et al. 1973; Camp et al. 1991): Jabal Abyad and Jabal Bayda (Fig. 4.47). Both Arabic names mean "White Mountain", with Abyad a masculine and Bayda a feminine form of white in Arabic reflecting that Jabal Bayda is a near perfect circular tuff ring with a shallow crater, while Jabal Abyad is a lava dome complex that forms a hill standing about 300 m above the surroundings (Fig. 4.47). Jabal Abyad is the highest volcano of Harrat Khaybar, reaching 2093 m above sea level, while Jabal Bayda is 1913 m high (Figs. 4.47 and 4.48). Their age is poorly constrained, but inferred to be between 0.86 and 0.22 My (Camp et al. 1991). While felsic lava domes and tuff rings exist elsewhere (Austin-Erickson et al. 2008, 2011; Cano-Cruz and Carrasco-Nunez 2008; Németh et al. 2012b; Riggs and Carrasco-Nunez 2004), the significance of the felsic intracontinental volcanism of the Arabian Peninsula is

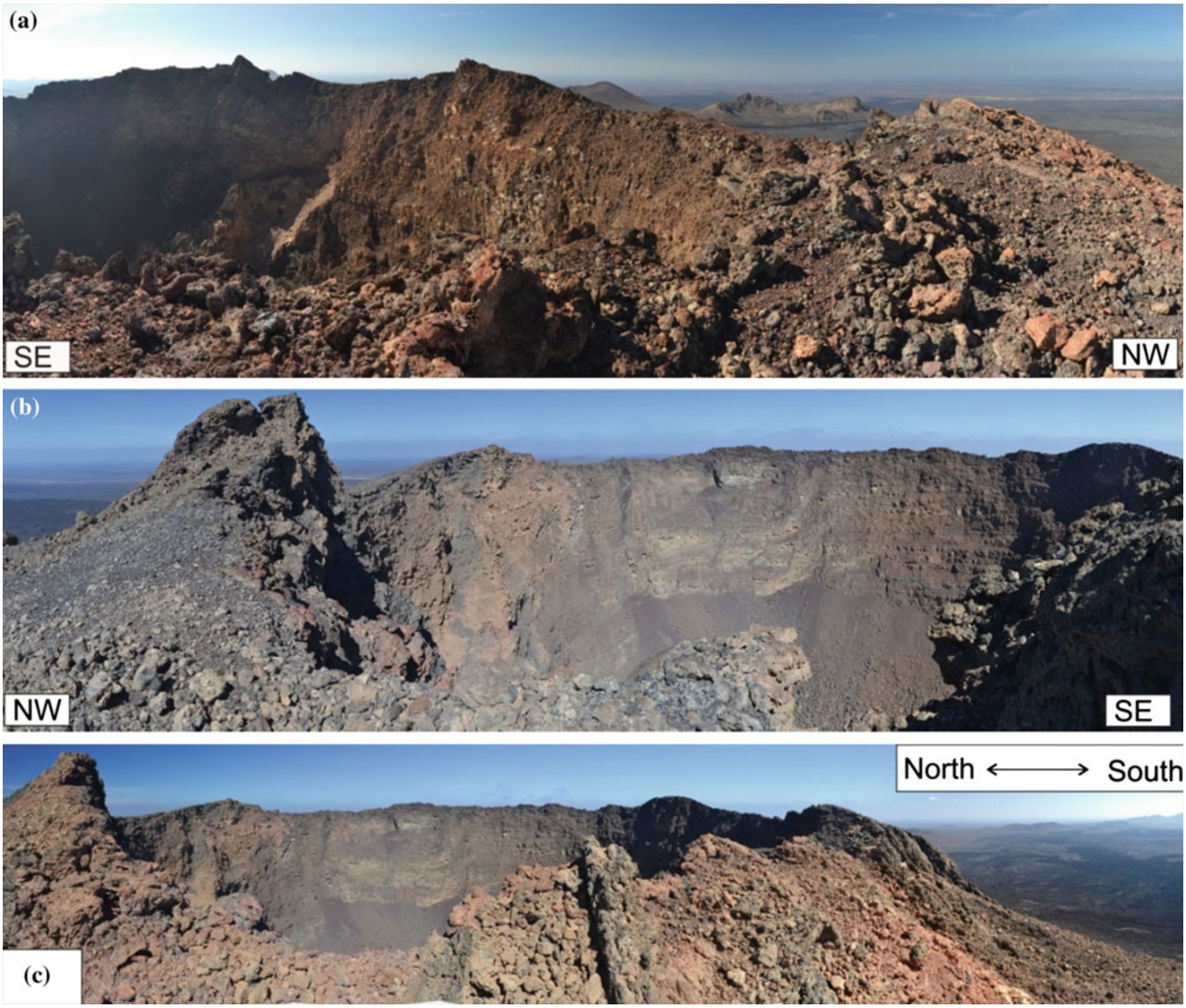

Fig. 4.45 *Panoramic views* of the deep crater of Jebel Qidr [25° 43′ 11.23″N; 39° 56′37.32″E]. Note the lava spatter-dominated pyroclastic succession forming a steep edifice on top of Jebel Qidr (**a**). In the crater wall a succession of lava flows of 1–3 m thick exposed with some evidences to infer the existence of lava lakes and pond that subsequently provided to form pit craters upon their release from the base of the edifice (**b**). The steep nature of the edifice is the result of a welded lava spatter-dominated capping units forming the *top* of Jebel Quidr (**c**). Note the slight depression and darker colour zone in the right hand side of the image that is a lava flow outbreak along spatter and lava flow pieces were cascading down on the steep edifice slope

great in terms of understanding the evolution of dispersed magma in near–surface compositionally zoned magma chambers (Camp et al. 1991).

The "White Mountains" are composed of comenditic pyroclastic successions of intercalated small-volume block-and-ash flow, pyroclastic density current and minor air fall units (Figs. 4.49 and 4.50), comenditic lavas including short, but thick obsidian lava flows (Fig. 4.51) and that form very distinct volcanic landforms with white and beige-to-orange colours, making them stand out from the otherwise dark hawaiite, mugearite and benmoreite lava flows, domes, and dome coulees. A recently initiated Arabia Geoparks Project has demonstrated the high geoeducational value of these volcanic landforms of western Arabia and how these could be utilized to understand volcanic hazards and geoconservation (Moufti and Németh 2013). The "White Mountains of Harrat Khaybar" will be flagship geotopes with numerous geosites in the provisional volcanic geopark of the region.

Jabal Abyad is a fantastic volcanic geotope. It has some excellent outcrop to study the short run-out distance block-and-ash flow deposits commonly related with lava dome growth and repeated explosive eruption producing typical pyroclastic density current dominated successions

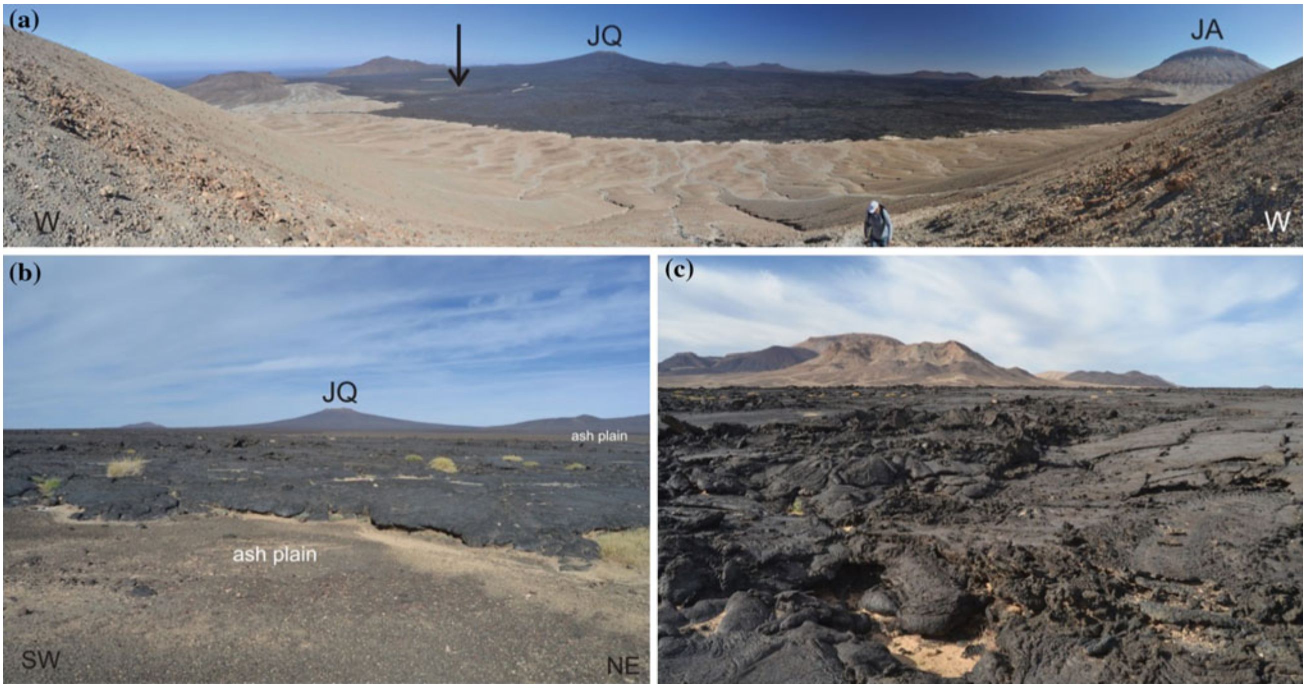

Fig. 4.46 Distal lava flows of Jebel Qidr [25° 43′ 11.23″N; 39° 56′ 37.32″E] are thin pahoehoe flows along main streamline of lava flows slabby to rubble pahoehoe textures are common. Lava flow fields are extensive and commonly filling gaps between volcanic edifices or completely infil preexisting tuff rings sucha s shown on **a** with *arrow* (*JQ* Jebel Qidr, *JA* Jebel Abyad). Lava flows are commonly less than a meter thick about 7 km from their sources **b** where the lava flows are accumulated over thin ash plain deposits. Truncated surface textures **c** are commonly present in areas where the thin lava flows are blocked against obstacles, or banked agains gently upward sloping landscape

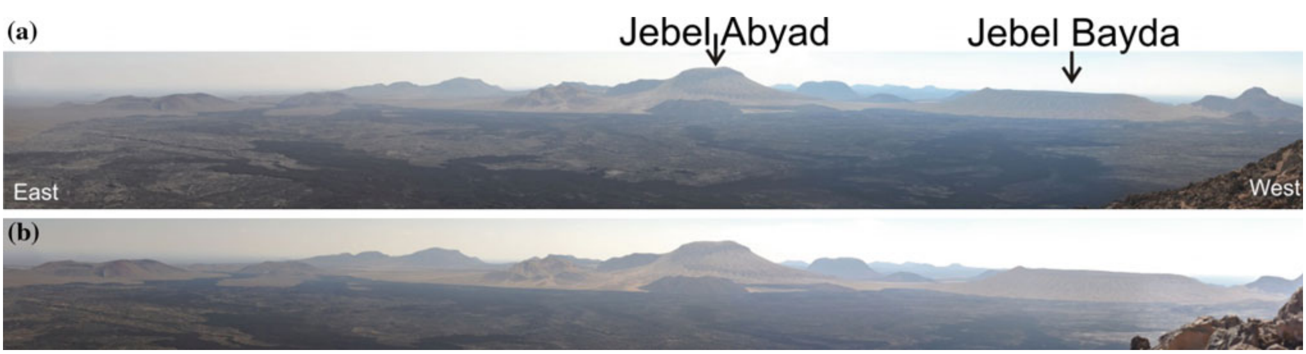

Fig. 4.47 *Panoramic views* show the White Mountains (Jebel Abyad and Jebel Bayda) from the *top* of the Jebel Qidr [25° 43′ 11.23″N; 39° 56′ 37.32″E]. Note the extensive lava fields sourced from Jebel Quidr in the foreground

rich in flow banded lava dome-derived clasts (Fig. 4.50). The numerous individual block-and-ash flow deposits identified in the flank of the Jabal Abyad cone indicate repeated lava dome growth and collapse event through the evolution of the volcano. Some flow banded obsidian unit is still preserved in the middle section of the volcanic edifice (Fig. 4.51). The facies architectue, the relatively small size of the edifice and the small volume of the individual pyroclastic successions made Jabal Abyad comparable in size to those rhyolitic domes commonly form fields in intracontinental settings (Riggs and Carrasco-Nunez 2004).

4.4.4 Jabal Bayda [25° 39′ 38.15″N; 39° 56′ 0.27″E]

Jabal Bayda is a perfectly preserved silicic tuff ring near the Jabal Abyad. It composed of white pumiceous ash and lapilli beds that have some degree of gully network formed on its outer edifice flank (Fig. 4.52a). The tuff ring crater rim is in an even elevation, and forming a relatively broad crater lip. The crater is partially filled with reworked (fluvial and Aeolian reworking) ash and dust, that cut by a gully network sometimes reaching 5 m in depth in their deepest points

Fig. 4.48 Jebel Abyad [25° 39′ 34.35″N; 39° 58′ 16.50″E] from the top of Jebel Bayda [25° 39′ 29.66″N; 39° 56′ 9.22″E]. *View* on **b** is slightly more focused from a slightly different angle than it is on **a**. Note the extensive white debris fan and fluvial network around the lava dome of Jebel Abyad. The hard rocks crop out halfway on the lava dome are interbedded obsidian lava flows and block and ash flow deposits. White pyroclastic density current deposits from Jebel Bayda overlain short run out block and ash flow deposits from jebel Abyad. Note on **a** other steep lava domes in the region dominated by comenditic voclanism both explosive and effusive, lava dome-forming styles

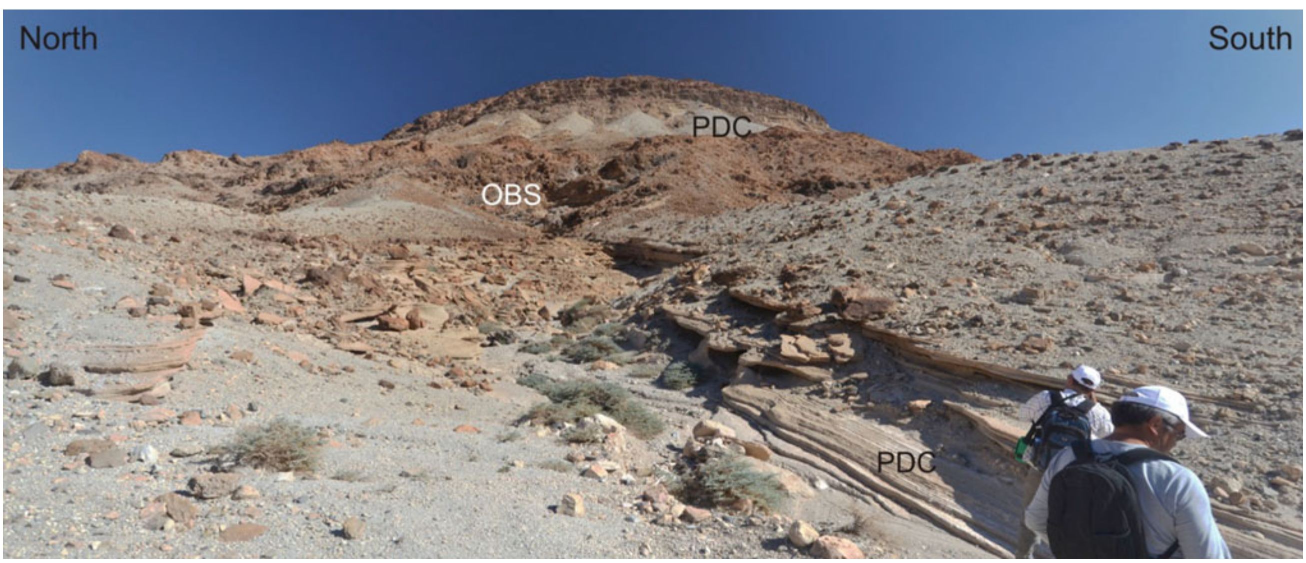

Fig. 4.49 Pyroclastic density current (PDC) deposits in the feet of the Jebel Abyad [25° 39′ 49.60″N; 39° 57′ 36.74″E] showing low angle cross bedding, grading, and relatively unsorted nature. In the middle section obsidial lava flow crops out (OBS)

(Fig. 4.52b). The crater hosts a double lava dome that occupies its northern inner sector. In the SE side of the tuff ring, the highest point of the tuff ring rim is defined by another lava dome that is partially exposed in the inner crater wall and directly connected to proximal block-and-ash flow deposits flanking into the crater basin. In the NW outer edifice flank about half way to the top deep gullies exposes a pyroclastic density current dominated succession in the main pyroclastic facies of the Jabal Bayda tuff ring. The pyroclasts are normally angular, microvesicular, and coated by white siliceous dust. The matrix of the pyroclastic beds is fine silicic ash. Obsidian coarse ash and lapilli as well as silicic volcanic lithic fragments are common. In fine beds ash aggregates can be inferred to be result of pyroclast accretion and they can be defined as accretionary lapilli. Cross bedding, dune bedding and some cross lamination is prominent

Fig. 4.50 Oucrop features of the pyroclastic successions of the Jebel Abyad volcano [25° 39′ 48.84″N 39° 57′ 43.65″E]. Large banded obsidian clasts hosted in fine matric (**a**) forming massive facies commonly underlain by bedded basal layer (**b**). The block and ash flow deposits are matrix supported and unsorted with abundant obsidian clasts (**c**) forming about one meter thick units (**d**)

Fig. 4.51 Flow banded obsidian lava flow in the Jebel Abyad [25° 39′ 40.75″N; 39° 58′ 4.09″E]

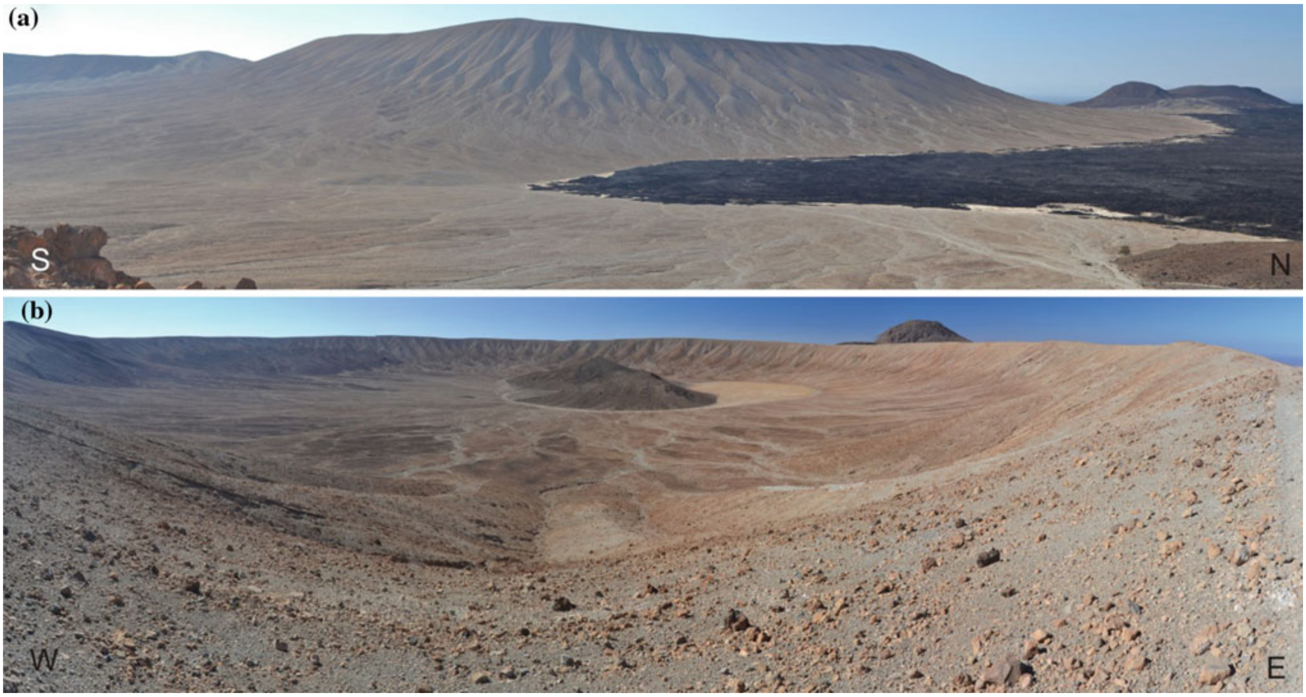

Fig. 4.52 Jebel Bayda [25° 39′ 38.15″N; 39° 56′ 0.27″E] is a comenditic tuff ring with a tuff ring of over 50 m high (**a**) that surrpounds a flat floored, broad crater (**b**). Well developed gully network is visible in the outer flank of the tuff ring (**a**), while in the crater a small lava dome is preserved (**b**)

between coarser grained massive, unsorted matrix supported dm-thick beds that are best to interpret as pyroclastic surge beds intercalated and/or associated with small-volume block-and-ash flow deposits. Such pyroclastic architecture is similar as described from other silicic tuff rings elsewhere (Austin-Erickson 2007; Campos Venuti and Rossi 1996; Druitt et al. 1995; Tait et al. 2009).

4.4.5 Other Silicic Volcanoes

Harrat Khaybar hosts several other unique silicic volcanoes that were visited for an initial field work during 2013 November. In the southern edge of the volcanic field several intact tuff rings are preserved such as those numbered as Tr1 (Fig. 4.53a). This tuff rings are similar in size and morphological appearance to the Jabal Bayda, being either perfectly preserved ring structures with various level of gully network developed on their outer edifice flank (Fig. 4.53a) or being partially eroded by rock fall and undercut erosion where their crater is partially preserved, but their proximal edifice eroded and cut back significantly (Fig. 4.53b). From the southern edge of the field toward Jabal Bayda at least 3 major tuff ring complexes are preserved (Fig. 4.53b).

In addition to the silicic tuff rings in the southernmost part of Harrat Khaybar an apparently young, and potentially historic eruption site is evident (Fig. 4.54a, b). A black, steep scoria cone form a prominent landform here that emitted dark, fresh-looking pahoehoe to transitional lava flow fields that moved toward the west, but a small arm break into a region where silicic tuff rings dominate a landscape (Fig. 4.54). The scoria cone is composed of fine scoria ash and lapilli that primarily restricted in the volcanic edifice, and just a thin ash plain associated with the volcanic cone. From the scoria cone a perfect view can show the volcanic morphology of an enclosed tuff ring (Tr1), that is a perfect similarity to Jabal Bayda (Fig. 4.54c).

The pyroclastic succession of Tr1 is similar to those recorded in Jabal Bayda, with a potentially more evidence to support involvement of magma and water explosive interaction in the formation of the volcano in the form of abundance of angular, equidimensional low vesicularity (and darker colour) pyroclasts of ash and lapilli, some abundance of crustal-derived accidental lithics and/or xenoliths point toward a potential deeper excavation through the eruptions.

Next to Tr1, another tuff ring provide probably a better access to its proximal to medial pyroclastic succession through a collapsed near vent edifice, exposing about 20 m of pyroclasitc units along the top of the edifice (Fig. 4.55a, b). The pyroclastic succession of Tr2 composed of angular lapilli and block rich fine ash hosted closely packed pyroclastic succession best interpreted to be as a block-and-ash flow deposit. The main pyroclastic units are over 2 m thick and separated by typical cross- and dune-bedded finer grained

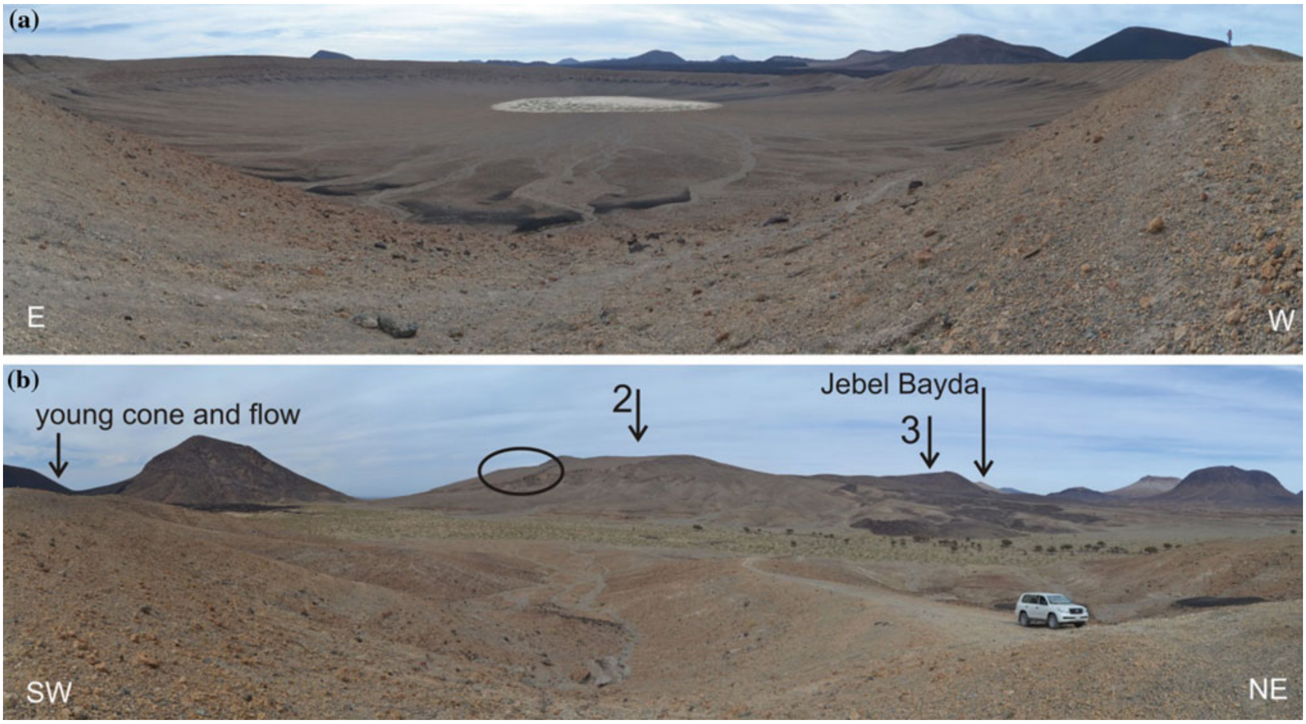

Fig. 4.53 Flat floored broad crater of one of the southernmost silicic tuff ring in Harrat Khayber [25° 35′ 14.58″N; 39° 57′ 13.09″E]. The deposits of this tuff ring is simialr to those exposed at Jebel Bayda and dominated with pyzorlcastic density current deposits abundant in fglow banded silicic fragments (**a**). A slightly more eroded tuff ring with rock fall bordered upper rim exposes the tuff ring succession well (circle) allowing to investigate the sediment characterisitcs to infer the volcanic eruption styles dominated the growth of this volcano (**b**). Numbers of "2" and "3" refer to tuff ring 2 and 3

cm-to-dm thick beds (Fig. 4.55b) commonly associated with the formation of block-and-ash flows (Freundt et al. 2000; Ui et al. 1999). The upper part of the succession is more indurated, probably by slight welding and/or some hydrothermal activity that cemented the clasts together to form an erosion resistant capping unit (Fig. 4.55c). From a view point SE of the Tr2 a chain of tuff rings aligned toward Jabal Bayda can be seen that represents a potentially age-defined morphological nature of the tuff rings (Fig. 4.55d).

Just north of Tr2 another slightly better preserved tuff ring is located that has a pyroclastic density current dominated upper succession and a slightly coarser grained lapilli tuff dominated unit in its base. This pyroclastic architecture differs from those recorded from Tr2 and is similar to those identified at Tr1 suggesting a larger variation in eruption style and mechanism in the formation of these volcanoes as we could guess from their general edifice preservation and appearance (Fig. 4.56a).

Interestingly in the eastern side of these chain of tuff rings that form a morphologically characteristic ridge-like massif, a flat floored, low rimmed tuff ring can be seen (Fig. 4.56b). Its crater is filled with aeolian dust suggesting that its original crater floor might have been fairly deep, and the landform might have been a prominent volcanic depression. The great elevation difference between the floor of this and the neighbouring tuff ring crater floors suggest either presence of significant syn-eruptive morphological relief and/or significant age difference between these landform to allow time to cut deeply into the inter-cone relief by fluvial processes and/or different eruption mechanism in the formation of these landforms (e.g. tuff ring versus maar formation). These site by its easy access, relatively small size (500 m across), would make this location a perfect site to apply shallow subsurface geophysical methods to constrain the subsurface architecture of these volcanic edifices. Such future work would also help to constraint the volcanic eruptions scenarios such eruption would pose to the surrounding areas.

In addition to visit the specific silicic tuff rings an effort was taken to locate inter-cone/ring sites where multiple pyroclastic deposits are exposed with an aim to establish the general stratigraphy and the general relationship between variously sourced eruptive products that accumulated in the inter-cone areas. Especially in the middle of the field there were several suitable sites to nominate as key locations to establish the regional volcanic stratigraphy which is a future research goal.

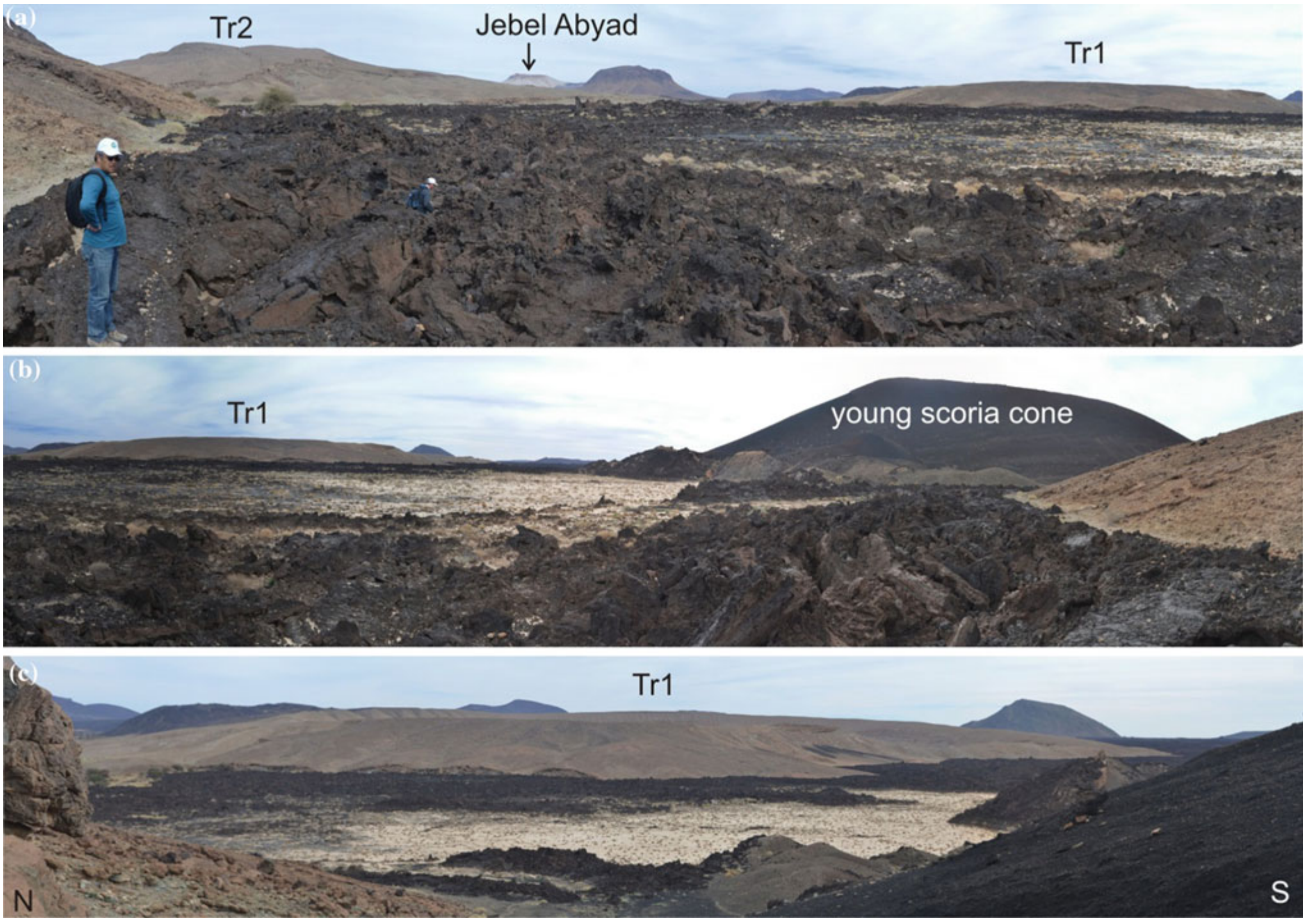

Fig. 4.54 Young scoria cone in the southern region of the Harrat Khayber [25° 35′ 5.55″N; 39° 56′ 16.67″E] emitted transitional type lava flows that enterred in the gap between silicic tuff rings such as Tr1 and Tr2 (**a** and **b**). The Tr1 tuff ring [25° 35′ 14.58″N; 39° 57′ 13.09″E] is nearly perfectly circular with only few gully network and rock-fall dominated erosion scarse

4.4.6 Other Fissure Vents, Lava Shields and Pit Craters

Just north of Jabal Quidr, an extensive lava field and associated spatter and scoria cone dominated volcanic region represent the northern side of Harrat Khaybar. The primary aim to visit this region was to delineate the ash plain associated with Jabal Quidr lateral boundaries. During this exploration work a visit was arranged to one of the main source region of the extensive tube-fed lava field dominate the northern sector of the Harrat Khaybar. One of the most prominent locations is marked as location 4 and it is best described a scoria cone—spatter cone complex with a massive lava tube network (Fig. 4.57).

The main scoria cone has a deep pit crater that is partially mantled by lava drain back features (Fig. 4.57a) recording the fluctuation of lava lake level in the crater. In the inner crater wall abundant, relatively thin lava units suggest a long lived activity persistently released relatively thin lava sheets (Fig. 4.57a). The main crater is connected with a massive lava drain point over 50 m across (Fig. 4.57a) that fed some lava spatter along its margin (Fig. 4.57b) releasing fluidal small-scale (dm to several metres) lava tubes of shelly pahoehoe flows (Fig. 4.57c). In the proximity of this cone other cones form a similar volcanic architecture, commonly feed large tube-fed flows. In steep slopes such tubes commonly disrupted, broken apart, and the lava flow preserved as a rubble pahoehoe mass in a drain channel (Fig. 4.57d).

In the northern side of these vent systems it is evident that the emitted lava flows were dominantly tube-fed, but thin shelly pahoehoe outflows clearly define a lava shield-like architecture (Fig. 4.58a). Main lava tubes are inferred to have accumulated large ponded lava zones where the slope angle has changed (Fig. 4.58b). These ponded lava zones formed fan-like zones that are slightly sink in their middle upon gradual drainage of the flows. In extreme, the roof of these ponded zones collapsed and accumulated a slab-dominated, rubble flow interior confined in circular lava ponds (Fig. 4.58c).

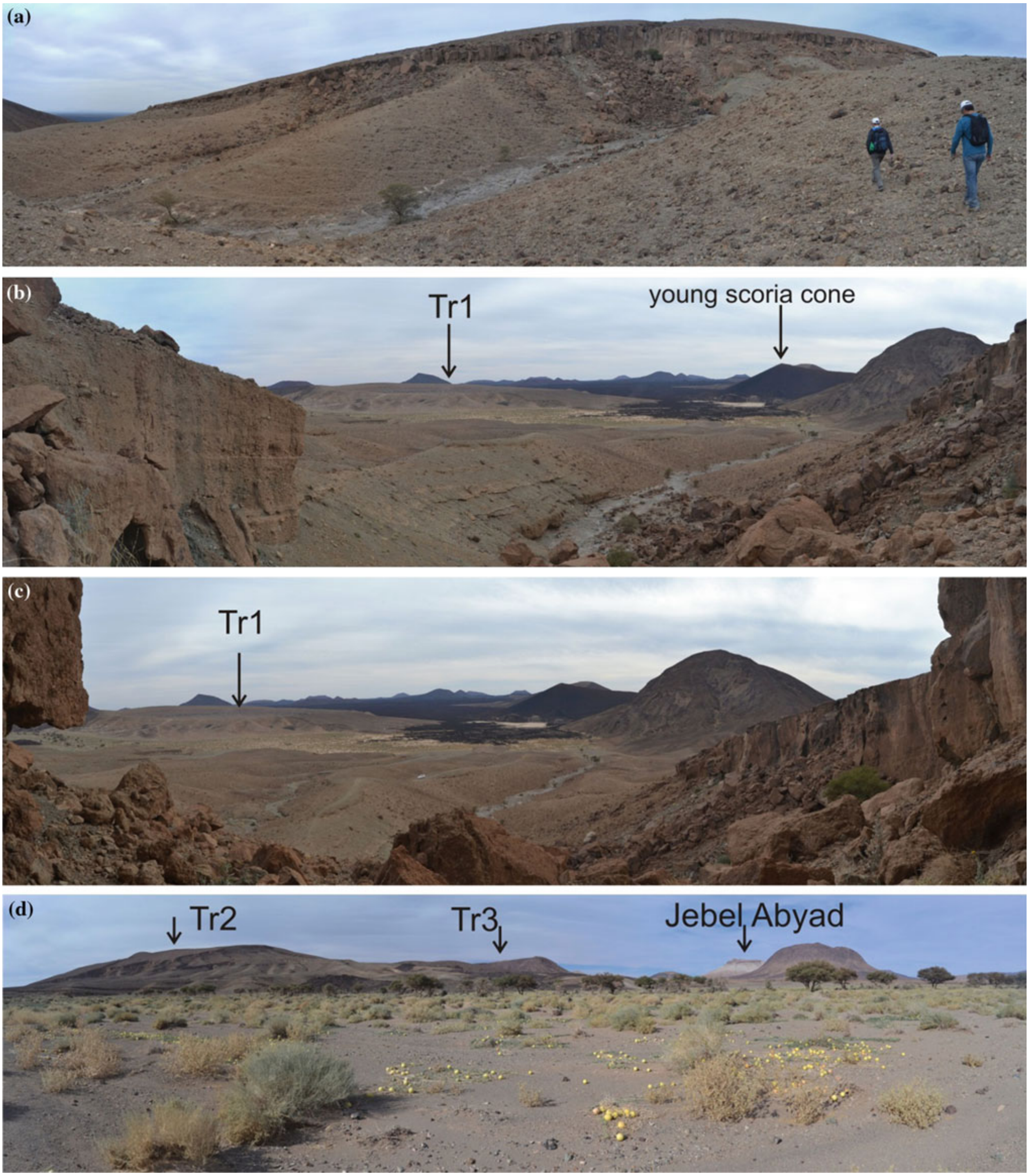

Fig. 4.55 Tr2 tuff ring [25° 36′ 21.69″N; 39° 56′ 5.52″E] pyroclastic succession is exposed in a rock fall cliff face (**a**). The majority of the pyroclastic rocks are angular silicic clast-dominated deposits hosted in variable amount of ash matrix (**b**). The top of the Tr2 pyroclastic succession is moderately welded forming an erosion resistant cap (**c**). From the top of Tr2 a perfect view can be seen toward Tr1 tuff ring [25° 35′ 14.58″N; 39° 57′ 13.09″E] a young scoria cone in the south. Tr2 is a broad tuff ring that is likely to be one of the oldest tuff rings in the region judging from its preservation and the edifice geometry in relationship with the background's topography (**d**)

Fig. 4.56 Panoramic view of the Tr3 tuff ring [25° 38′ 18.99″N; 39° 56′ 10.93″E] crater (**a**). Note the flat floored crater with an initial drainage network and the exposed pyroclastic density current deposits in the inner crater wall. Next to Tr3 a large tuff ring is visible with thick aeolian infill (**b**). In the background other silicic lava domes and the Tr2 tuff ring is visible

4.4.7 Main Findings

The preliminary field survey in Harrat Khaybar confirmed that the field is far easier to access as it was in the past. The field conditions are reasonable good in comparison to Harrat Rahat's conditions, and making this field as an ideal target area for future field work. Geologically the field host numerous silicic tuff rings which are the keys to understand the geochemical evolution of magma from the source conditions through the magma ascent. The explosive nature of the eruptions are evident in many of the silicic tuff rings offering a unique opportunity to understand the nature of dispersed small volume silicic volcanic fields eruption behaviour and develop a realistic eruption scenario-based volcanic hazard study that could be used not only locally but also could serve as a model for understanding similar volcanic fields elsewhere. The young eruptions that formed probably the most complex volcanic edifice in Harrat Khaybar (Jabal Quidr) point to the fact that this volcano likely erupted much longer time than expected from a so called "monogenetic" volcano in intraplate settings and show common features to stratovolcanoes. Its eruption style is likely fall into a sub-Plinian or violent-Strombolian style and therefore its volcanic hazard value for evaluating volcanic eruptions scenarios in western Saudi Arabia, is significant.

4.5 Harrat Al Birk and Tihamat Asir

4.5.1 Overview

In 2014 a field campaign has been arranged to the southern regions of the western Saudi Arabian Cainozoic volcanic fields (Fig. 4.59). The aim of this visit was to assess the field conditions, the general volcanic framework, the accessibility, and the possible geoheritage value of these volcanic fields. In addition the field survey intended to identify key volcanic sites that could be studied in detail to develop a volcanic eruption scenario-based volcanic hazard study on this volcanic region inferred to be active in the past 1 Ma and has some poorly documented historic eruption sites as well (Brown et al. 1989; Coleman and Gregory 1983; Coleman 1993). Thus it can be considered a potentially active volcanic region. The visit was also justified by the fact of several earthquake swarms in the recent past that raised some concern about potential volcanic eruptions in the future. Since the region developing very fast and large cities (Jizan, Sabya, Abu Arish) appear along the coastal area as well as near to the coastal range, the population raise and the infrastructure growth justify well, that such young volcanic field have to be studied in volcanic hazard perspective.

The initial field campaigns were focused on the Al Birk region (Fig. 4.59), mostly along the coast commonly

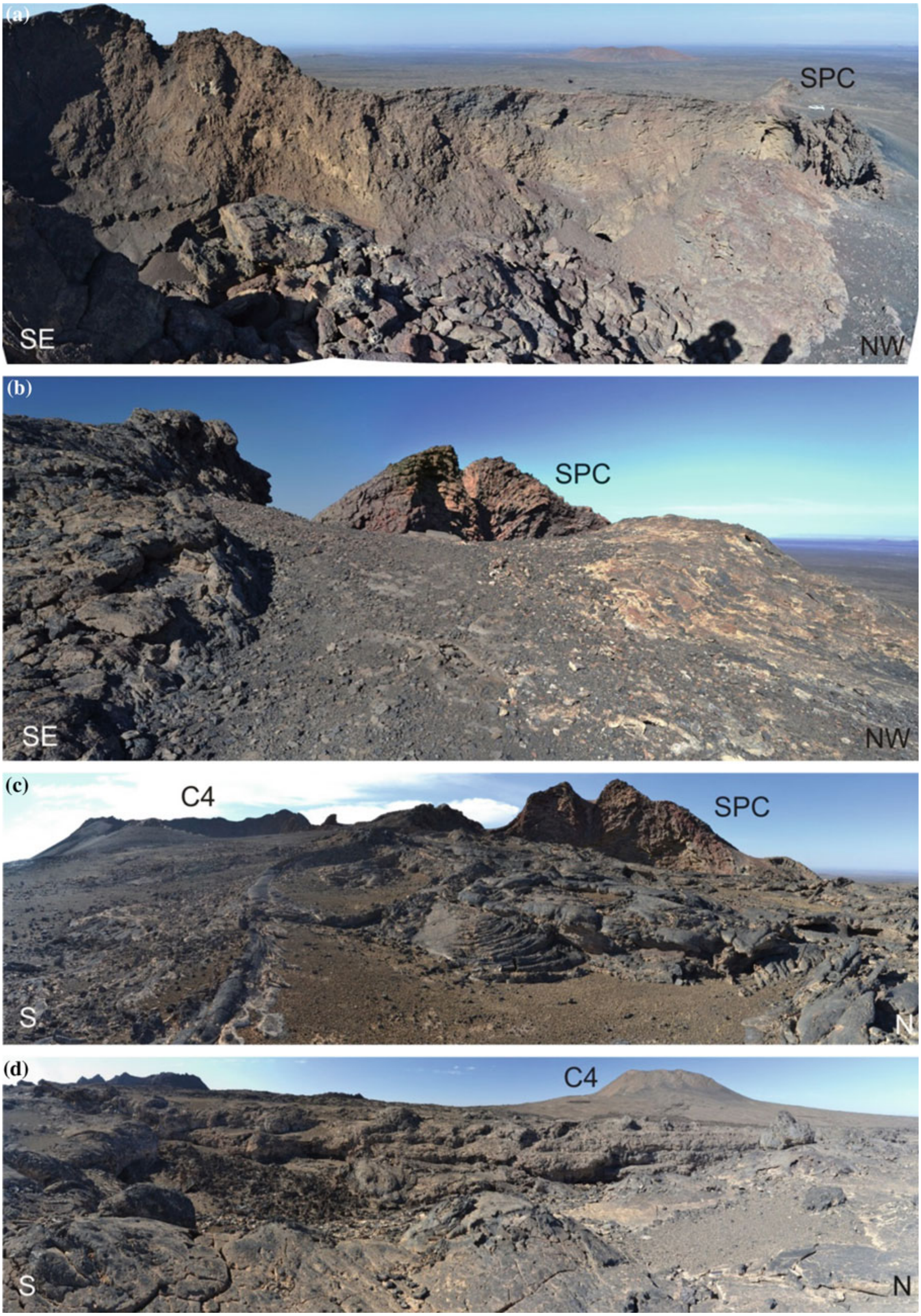

Fig. 4.57 Scoria cone (C4) and spatter cone (SPC) along a fissure fed an extensive lava flow in the northern part of the Harrat Khayber [25° 47′ 37.23″N; 39° 55′ 57.42″E]. The scoria cone inner crater wall exposes alternating lava flow and scoria beds (**a**). In the norhtern edge of the fissure aligned vent a lava spatter half section exposes the core of a spatter cone (SPC) (**b**) that also emitted low viscosity pahoehoe lava flow fingers forming a cascading lava tube network (**c**). Collapsed lava tubes and confined channelized lava flows are common features in these part of the lava field at Harrat Khaybar (**d**). Fromt eh distance the scoria cone appears to be a prominent volcanic landform (**d**)

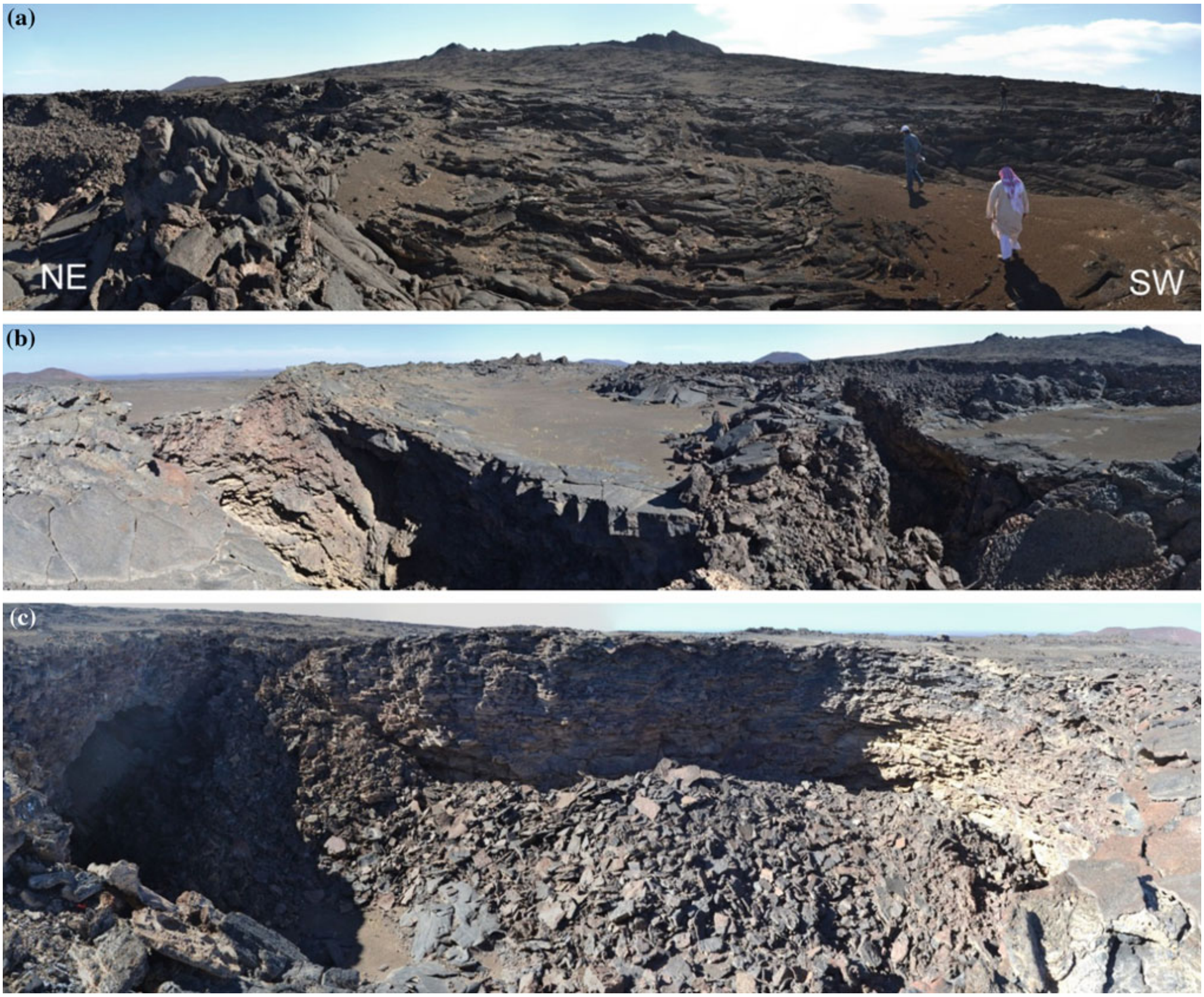

Fig. 4.58 Lava shield-like volcanic edifice in the northern sector of the scoria cone [25° 48′ 9.66″N; 39° 55′ 39.89″E]. Note the relatively thin and narrow convolute lava flows that are commonly forming tube network (**a**). In the area where slope angle change and the flow were able to pond, thick crust formed over the lava and large collapsed roofed channels are exposed (**b**). In the wall of such collapsed lava tubes in the wall a series of relatively thin lava layers can be seen (**c**)

referred as Tihamat Asir (*The Coastal Plain of Asir*), a visit to a well-distinguished volcanic area that consists of two individual volcanic complexes (*Jabal Akwa*) relatively far from any other young volcanoes nearby, and a short visit to one of the sites near the coastal range (*Jabal Jirratan*), where some documents record an eruption in the beginning of the last century, however such information have not been confirmed yet.

The Al Birk volcanic field in SW Saudi Arabia is a young intracontinental volcanic field that formed alkaline basaltic volcanoes that are dominated by scoria and spatter cones, extensive lava fields and lava domes/dome coulees (Arno et al. 1980; Brown et al. 1989). The main part [the northern part by Coleman and Gregory (1983)] of the Al Birk volcanic field (Fig. 4.59) spreads over an area 100 km in length and 50 km in width along the Red Sea coast in SW Saudi Arabia (from lat 18° 45′ to lat 17° 45′N) and comprises over 200 individual eruptive centres (Brown et al. 1989; Coleman and Gregory 1983). The main part of the volcanic field is located about 100 km north from the city of Jizan (Fig. 4.59), where a dorsal ridge of older basal lava flows form the base of younger scoria and spatter cones with younger lava flows. Scattered small volcanic regions in the south are separated by the Ad Darb transform fault from the main volcanic region of Harrat Al Birk (Fig. 4.59) are commonly referred to as the harrat of the coastal plain of Asir region, the harrat of Tihamat Asir (Coleman and Gregory 1983). Some work group these volcanic regions as part

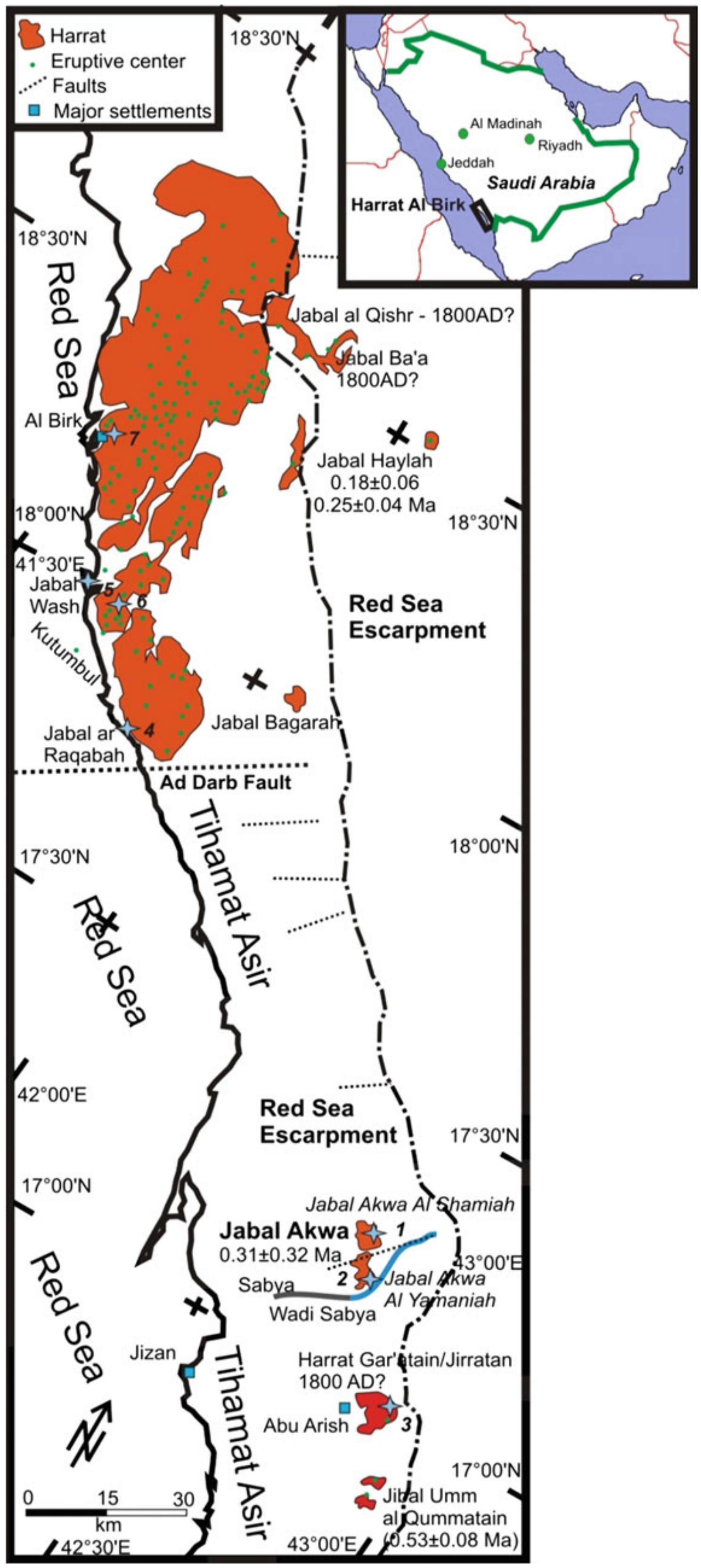

Fig. 4.59 Overview of the Harrat Al Birk. Visited sites are numbered: *1* Jabal Akwa Al Shamiah, *2* Jabal Akwa Al Yamaniah, *3* Harrat Jirratan, *4* Jabal Al Raqabah, *5* Jabal Wash, *6* Khurma, *7* lava fields around Al Birk

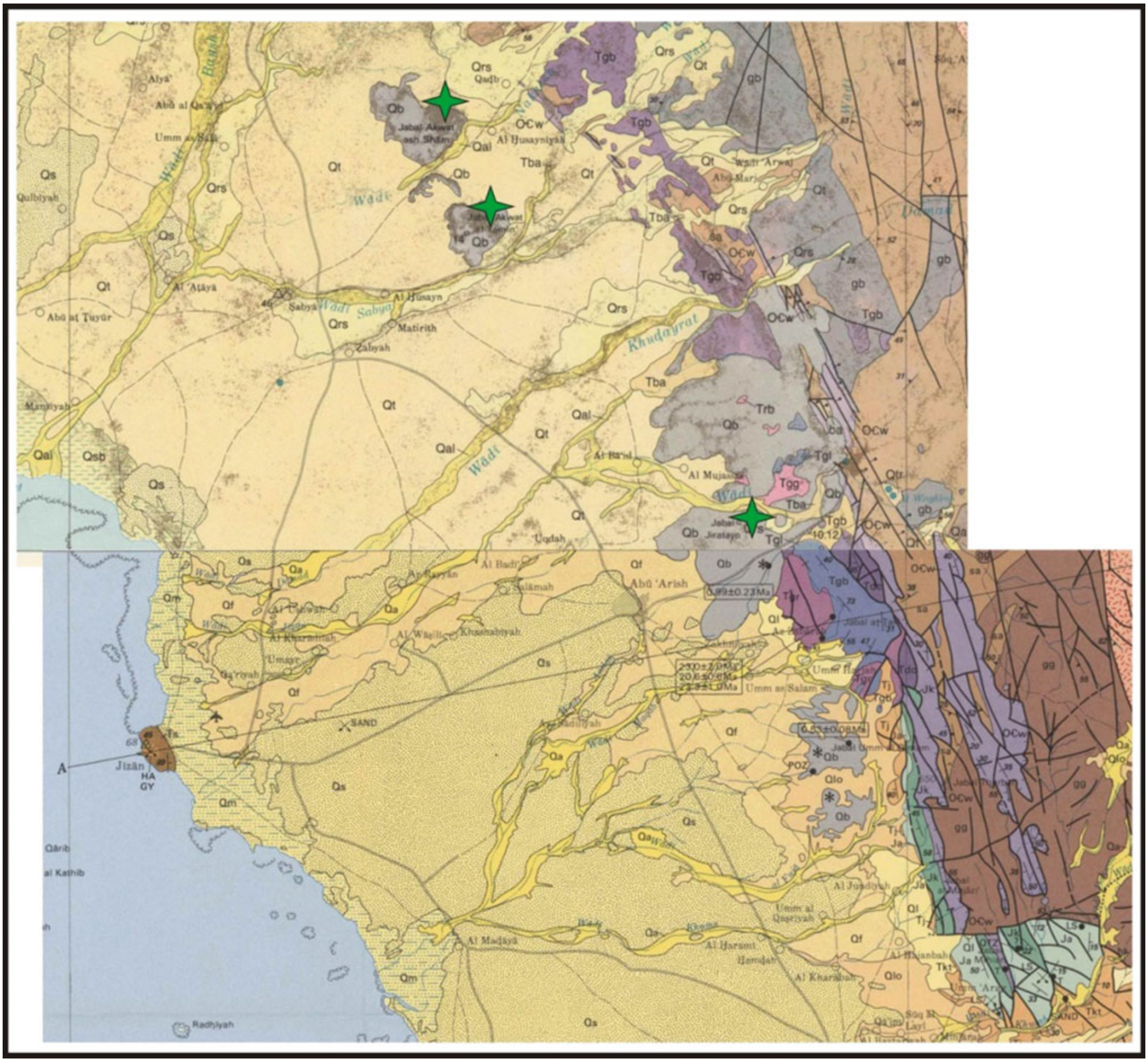

Fig. 4.60 Visited three locations in the southern part of the Tihamat Asir (marked by *green stars*). Geology data is from the geologic map of the Wadi Bays Quadrangle, Sheet 17F, Kingdom of Saudi Arabia (1:250,000 scale) by Fairer (1986) and geologic map of the Jizan Quadrangle, Sheet 16F, Kingdom of Saudi Arabia (1:250,000 scale) by Blank et al. (1984)

of the broader Harrat Al Birk, however they are clearly distinct individual scattered volcanic fields (Arno et al. 1980; Brown et al. 1989; Coleman and Gregory 1983).

While older ages have been reported for the basal lava flows (e.g. as old as 12.4 Ma), some renewed dates have put the age of the volcanic field at less than 2 Ma, with the majority of the eruptions being younger than 1 Ma (Brown et al. 1989; Coleman and Gregory 1983). Some reports have described historic eruptions taking place in the eastern margin of the field, such as Jabal Ba'a and Jabal al Qishr (Fig. 4.59), where isolated patches of black scoriaceous ash on the steep mountain slopes near the volcanic vent appear very fresh and may represent eruptions during the last century (Brown et al. 1989; Coleman and Gregory 1983). Similarly, in the southern part of Harrat Al Birk (after Coleman et al. 1983), commonly referred to as the harrat of Tihamat Asir—the coastal plain of Asir (Vincent 2008), an eruption in the last century was reported in an area called the Harrat Gar'atain (Jiratan) (Fig. 4.59) (Neumann Van Padang 1963). These reported (but only loosely confirmed) young volcanic eruptions of the Harrat Al Birk and the Harrat of Tihamat Asir are associated with volcanic cones that appear

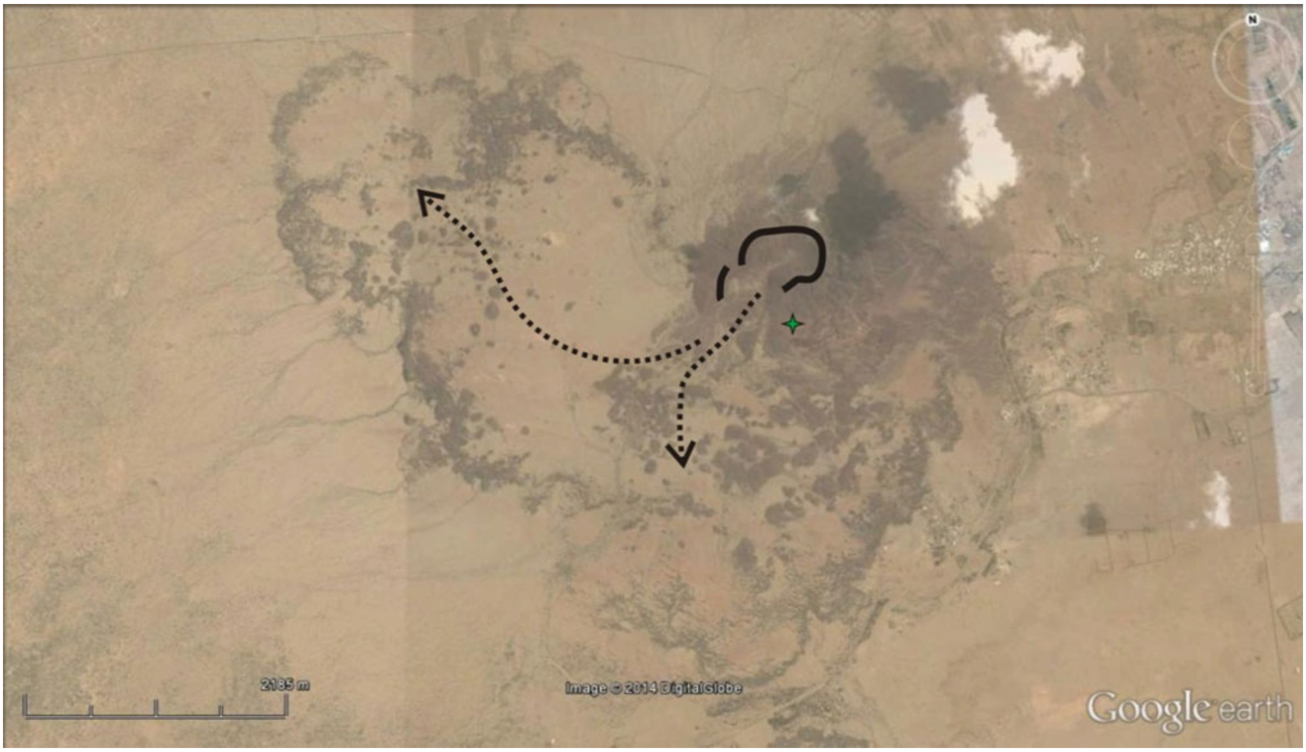

Fig. 4.61 Google earth image of Jabal Akwa Al Shamia [17° 15′ 13.99″N; 42° 42′ 59.66″E]. Continuous line represents the crest of the preserved crater rims. *Dashed arrows* show lava outflows feeding large lava fans in the western side of the cones. *Green star* mark the top of the quarry where the pyroclastic succession of the scoria cones can be observed

to be very youthful in their morphology, vegetation cover, and erosion level, indicating that this region in SW Saudi Arabia is a potentially active volcanic area, and therefore detailed study of these young volcanoes is essential to shed light on potential future volcanic eruption scenarios with which the region may be faced. The general view of the volcanoes formed in the past 1 Ma in Harrat Al Birk and the Harrat of Tihamat Asir is that the harrat is largely dominated by scoria and spatter cones associated with extensive lava flows. Identification of any evidence of phreatomagmatic explosive eruptions in the recent history of this volcanic field is critical in terms of defining volcanic hazards that are considered to be fast, destructive and highly unpredictable.

4.5.2 Jabal Akwa Al Shamiah as a Complex Volcanic Geotope [17° 15′ 13.99″N; 42° 42′ 59.66″E]

South of the main body of Harrat Al Birk, just NE from Jizan city, near the city of Sabya (Fig. 4.59), two well-distinguished large scoria cones and associated lava fields dominate the landscape: Jabal Akwa Al Shamiah in the north and Jabal Akwa Al Yamaniah in the south (Fig. 4.60). Both volcanoes (called Akwa cones in English, or Jibal Akwa in Arabic) are composed of a large (about 100 m high) scoria cones with a breached crater toward the west, an extensive lava field and some mounds that are inferred to be rafted cone pieces or distal lava flow fronts, which stalled and formed piles of lava about 3 km from their sources (Fig. 4.61). Both cones are covered by aeolian deposits that make the identification of their volcanic facies difficult (Fig. 4.61).

The northern cone complex, Jabal Akwa Al Shamiah has a complex morphology with at least two well-distinguished craters (Fig. 4.61), each breached toward the west and composed of steeply dipping lava spatter and spindle-bomb rich proximal edifice-building pyroclastic units (Fig. 4.62a, b). The inner crater wall has been preserved in a few places and is defined by agglutinated spatter that forms an erosion-resistant collar on the lip of the crater, indicating that, at least in the final stage of the volcanic activity, this cone had lava fountain dominated eruptions (Fig. 4.62a). In contrast, the main edifice is composed of black and red scoria lapilli and ash, which forms a well-developed cone edifice that is gradually transforming into an inter-cone ash plain traceable over 3 km from the cone (Fig. 4.62c). The scoriaceous ash and lapilli is angular, moderately to highly vesicular and the clasts are primarily isometric, but more flattened clasts are also known, indicating fluctuation between normal Strombolian style

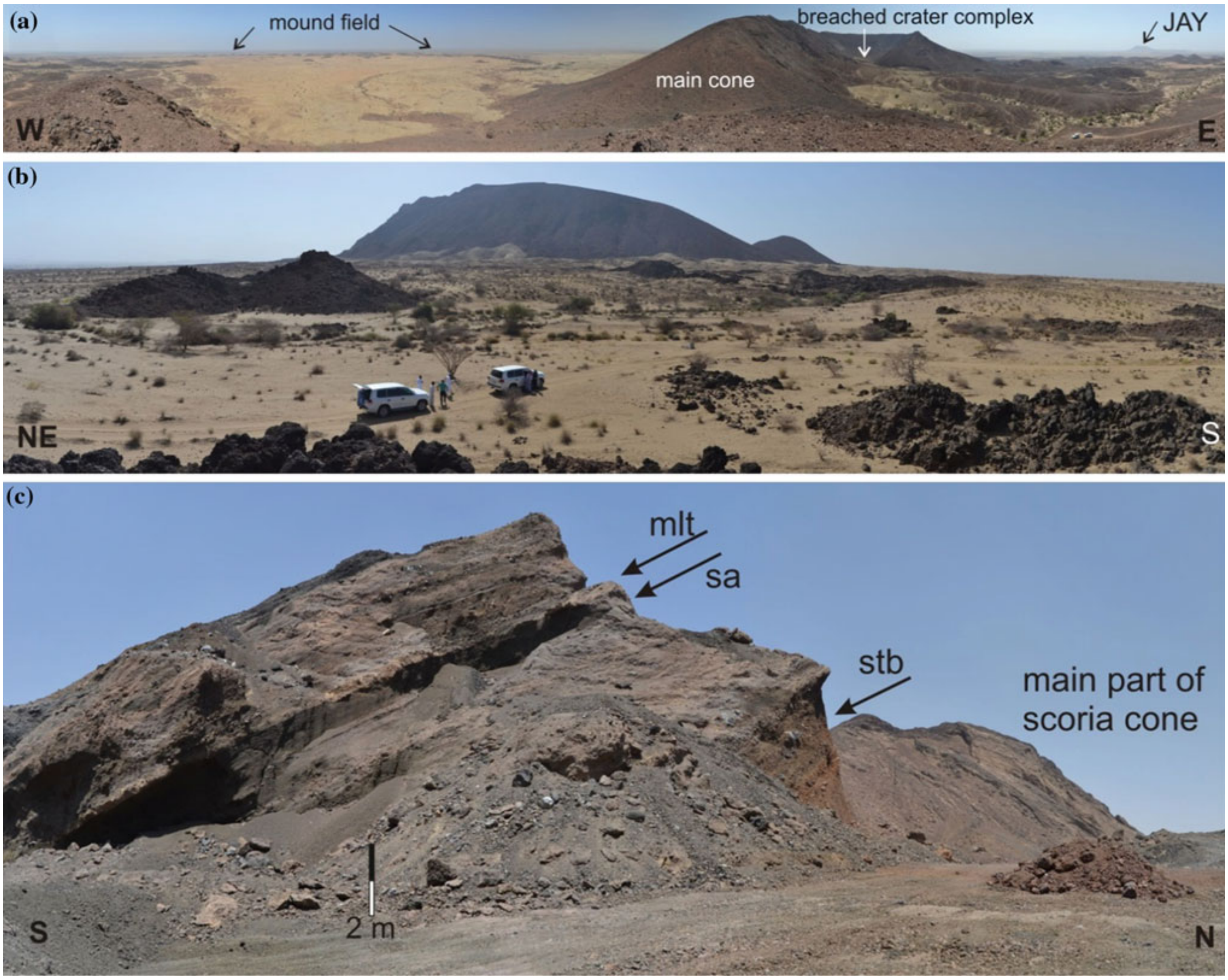

Fig. 4.62 *Panoramic views* to Jabal Akwa Al Shamia [17° 15′ 13.99″ N; 42° 42′ 59.66″E]. The main cone is complex scoria cone (**a**) that is breached toward the SW from where a lava field fed (JAY = Jabal Akwa Al Yamaniah). In the medial to a distal part of the lava flow some spatter-rich mound field can be observed (**a** and **b**). The pyroclastic succession of the main cone (**c**) composed of black to grey vesicular equidimensional scoria ash and lapilli. Scoriaceous tuff breccias (*stb*) are commonly host large lava spatters and fusiform bombs. The *upper* part of the section is dominated by a scoria-rich black ash (*sa*) and grey matrix rich lapilli tuff (*mlt*)

eruptions and lava fountaining (Fig. 4.62c). Large chunks of former cone flanks form a mound zone on a lava field spread isometrically toward the western side of the cone, suggesting that the cone erupted in a gentle westward dipping coastal plain. In the south, another cone complex is known (Fig. 4.62a, b).

4.5.3 Jabal Akwa Al Yamaniah as a Complex Volcanic Geotope [17° 11′ 26.18″N; 42° 44′ 6.48″E]

Jabal Akwa Al Yamaniah is a similar size to Jabal Akwa Al Shamiah (Fig. 4.60); however, this cone is more eroded in its northern flank, forming a steep and evenly spaced gully network (Fig. 4.63a). The cone is surrounded by two circular lava flows. An upper lava field, which has a flow front in the west, reaches about 3 km from the cone, while the other lava field spread about 6 km from the cone and formed a lava surface about 50 m below the other lava field. The cone has a large breach toward the west, and the upper lava flow front and the cone area is covered by a thick aeolian Quaternary succession. In addition, the gently westward-dipping, Quaternary sedimentary cover hosts numerous archaeological sites with pottery remains and grinding stones, suggesting that this volcano has hosted a village in the past (Fig. 4.63a).

Undescribed tuff deposits have been noted below the Pleistocene lava flows intercalated with fluvial terrace and aeolian deposits in the south of Jabal Akwa Al Yamaniah, along the Wadi Sabya; however, their origin was not known

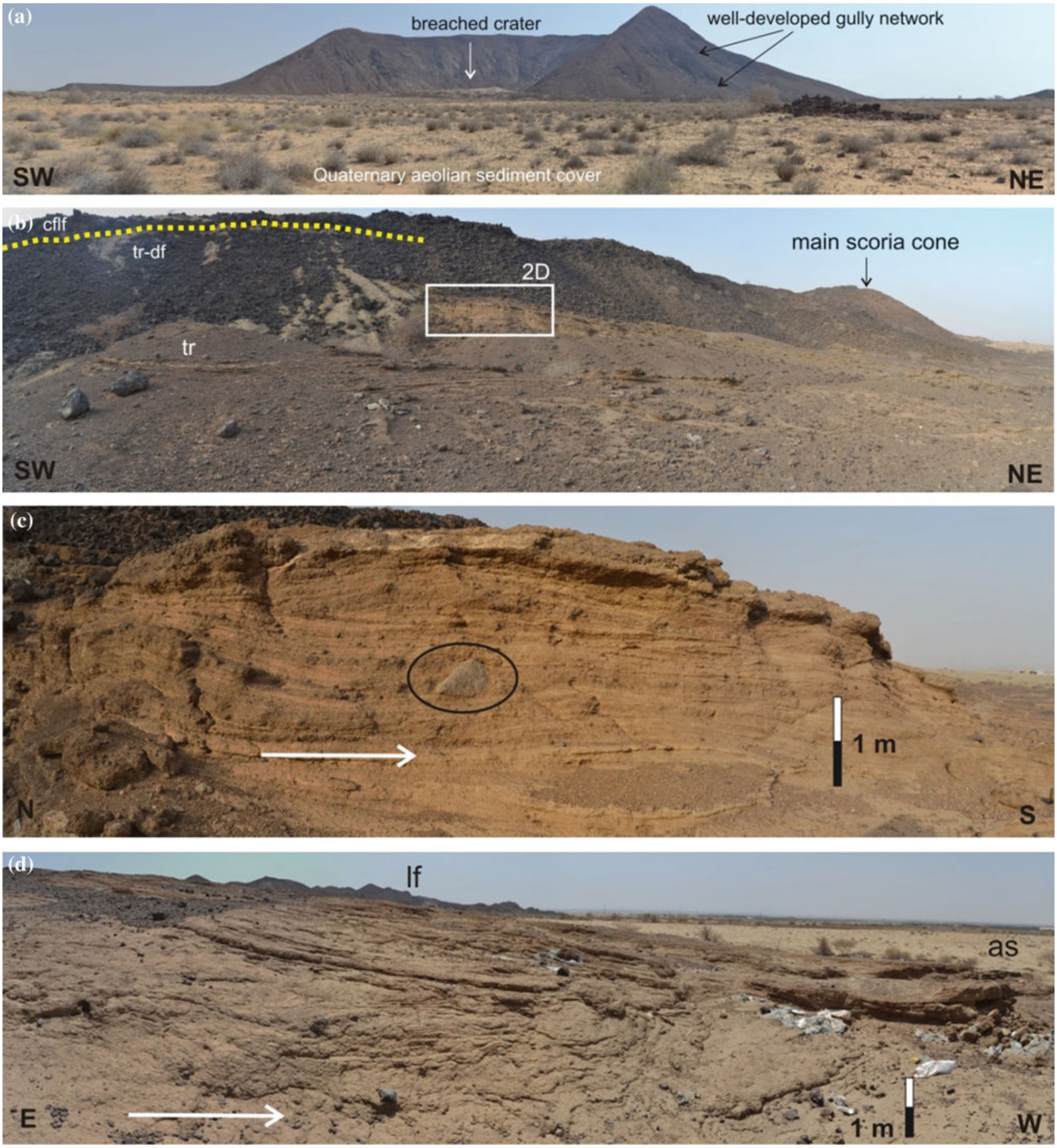

Fig. 4.63 The main scoria cone of Jabal Akwa Al Yamaniah [17° 11′ 26.18″N; 42° 44′ 6.48″E] (**a**) is breached toward the west and it has a well-developed gully network on its outer flank. The top of the volcanic massif is covered by aeolian deposits on what archaeological sites reveal a presence of a large human settlement that were active during wet climatic periods. The southern and western side of the volcanic massif (**b**) exposes a tuff ring (*tr*) rim, that is partially overrun by a lava flow that were inferred to infill a large volcanic crater a maar. The debris fan (tr-df) that covers the tuff ring made it difficult to identify the tuff ring itself. The boundary between the crater-filling lava—overspill lava flow (*cflf*) is marked by *yellow dashed line* on (**b**). The tuff ring is dominated by accidental lithic rich lapilli tuff and tuff deposited from base surge dominated currents (**c** and **d**). In the southern edge of the volcanic massif the tuff ring is partially covered by aeolian dust (*as*) and backed the lava flow (*lf*) confining it in the crater. Transportation indicators (*white arrow* on **c** and **d**) show base surge transportation from the volcanic massif

(Dabbagh et al. 1984). An accidental lithic rich tuff and lapilli tuff succession has been identified in the southern and eastern margin of the thick upper lava flow fronts of Jabal Akwa Al Yamaniah (Fig. 4.63b). The tuff and lapilli tuff deposits dip about 15–20° away from the cone, forming the well-defined remains of a former gently sloping volcanic edifice in these sectors of the volcano (Fig. 4.63c, d). The pyroclastic succession is composed of angular glassy pyroclasts (lapilli and ash sized), with a majority being partially or completely altered, red to brown palagonite, abundant various sizes of accidental lithics of known crustal rock types, and mantle-derived nodules (Fig. 4.63c, d). The pyroclastic succession shows a general trend of fining upward, having a lapilli tuff succession that is more lithic-dominated at its base, which gradually transforms to a better sorted, finer grained and more juvenile pyroclast-rich, coarse-fine succession at the top of the section (Fig. 4.63c, d). The accidental lithic fragments are commonly well-rounded gravels, while silts and mud-stones are common among the large angular lithics. The upper part of the succession is more dune and cross-bedded with abundant features recording the deposition from horizontal moving pyroclastic density currents and the microtopography of the depositional surface (Fig. 4.63c, d). The total thickness of this pyroclastic succession is about 40 m in the SE.

The abundant glassy to palagonitized, low vesicularity juvenile pyroclasts indicate fast chilling of the fragmented magma, which is consistent with magma-water interaction triggered explosive fragmentation (White and Ross 2011). The abundance of a great variety of country rocks as accidental lithics in the pyroclastic units indicates that the explosions excavated a significant proportion of the bed rocks, suggesting that the magma and water interaction took place below the syn-eruptive surface, such as in the case of a maar-forming volcanic eruption (White and Ross 2011). The dune-bedded and unsorted nature of the majority of the pyroclastic succession is consistent with an origin from a base surge dominated eruption (White and Ross 2011).

The at least 40 m thick pyroclastic succession is inferred to be part of a former tuff ring that is today partially engulfed by post-eruptive, Quaternary aeolian and fluvial terrace deposits. The tuff ring formed a barrier to the intra-crater lava flows emitted from the spatter cones that were formed in the crater of the initial phreatomagmatic volcano. The accidental lithic-dominated pyroclastic deposits suggest that the explosive eruptions must have excavated a significant portion of country rocks and formed a maar volcano that is surrounded by its tuff ring in the ancestral Wadi Sabya. A crater was carved in the wadi deposit and subsequently functioned as a depocentre, collecting lava flows emitted from the scoria and spatter cones in the maar crater. By the complete exhaustion of the available ground-water supply, the initial phreatomagmatic explosive eruptions led to the formation of a scoria cone similar to common trends associated with monogenetic volcanoes elsewhere (Kereszturi and Németh 2012), probably on the syn-eruptive surface outside of the maar, on its northern side. The large size and complex stratigraphy of the scoria cone indicates that it was erupted over a prolonged period of time.

Jabal Akwa Al Yamaniah is the first volcano where a phreatomagmatic pyroclastic succession has been identified in SW Saudi Arabia in the Tihamat Asir. It records a complex volcanic eruptive history that started with a violent explosive eruptive phase, when rising magma interacted with ground-water and formed a deeply excavated crater: a maar surrounded by a tuff ring. Mapping indicates that the tuff ring was probably thicker in the SE and absent in the northern sector of the volcano. The circular distribution of the lava flows and spatter mounds of Jabal Akwa Al Yamaniah is the direct result of the lava flows being controlled by the crater rim of the initial phreatomagmatic volcano, capturing and collecting post-maar eruptive products in a broad maar crater. The identification of the basal maar volcano in this location reveals for the first time that the explosive interaction between magma and water needs to be evaluated seriously in this region as a potential high consequence volcanic hazard similarly to other coastal regions elsewhere (Agustin-Flores et al. 2014; Brand et al. 2014; Németh et al. 2012a). Alluvial fans, wadi deposits or deep faults, especially along the coastal escarpment, can host significant volumes of water (particularly in the rainy season) and this is capable of dramatically changing the volcanic eruption style of the rising magma, making it more destructive and hazardous.

A complex of phreatomagmatic volcanoes has been identified for the first time in the southernmost portion of the Al Birk volcanic field in SW Saudi Arabia. The newly identified accidental lithic clast-rich tuff and lapilli tuff succession is partially covered by aeolian sand and wadi deposits, with abundant mantle- and deep crustal-derived xenoliths in the southern margin. This pyroclastic succession of the Jabal Akwa Al Yamaniah volcanic cone complex is typical of a volcano that had phreatomagmatic explosive eruptions in its initial eruptive stage. The large volume of accidental lithics in this basal pyroclastic succession indicates that this volcano is a maar-diatreme and its eruption was triggered by the explosive interaction of rising magma and ground water in a thick gravelly alluvial plain cross-cut by wadi networks. The young age (<1 Ma) of the Al Birk volcanic field in general puts this discovery in the spotlight, as it provides firm evidence that phreatomagmatism cannot be neglected, at least in the initial stage of any future eruptions—especially those that occur over thick alluvial fans in the coastal regions of Jizan—and should be viewed as a potentially destructive and highly unpredictable, high impact volcanic hazard.

Fig. 4.64 Youthful appearance of the Jirratan scoria cone [17° 0′ 44.01″N; 42° 54′ 12.45″E] that was reported to be active in the beginning of the last century. *Arrow points* to another scoria cone that could also be the mystery young scoria cone in Harrat Jirratan

4.5.4 Harrat Jirratan [17° 0′ 44.01″N; 42° 54′ 12.45″E]

A short field visit explored the vicinity of Harrat Jirratan, a region mentioned as hosting a volcano that erupted about 100 years ago (Neumann Van Padang 1963). This initial visit aimed to assess the site and to provide some recommendation for research strategy to understand the geological context of the region. Harrat Jirratan is located near to the town of Abu Arish, along the main highway from Jizan to Yemen (Fig. 4.64). The location is the border zone between KSA and Yemen and therefore it is difficult to access sites. One of the suspected sites for instance is a military base where access was not permitted (Fig. 4.64). From the distance however the cone look fresh and indeed could be as young as a century. In the other hand another cone (Fig. 4.64) that were more likely the mentioned historic site can be accessed but the cone itself is surrounded by fence, and direct access to the main part of the cone is not allowed without appropriate administrative preparations. The area however consists of a lava field of blocky lava forming a characteristic plateau (Fig. 4.64) above the town of Abu Arish. The lava field surface morphology is difficult to assess due to the exposed gently westward dipping slopes that are brushed by strong winds and therefore aeolian dust pressed into the gaps of any lava surface (Fig. 4.64). The lava flows however seem to be thin micropahoehoe styles and indeed they share some evidence that they cannot be too old. The cones are also steep, their crater rim is well-preserved and the flank of the cones has no gully network visible. These morphological features point to a relatively young age of the cones however not providing enough evidence to support their very young age. The difficulty is in this area that the elevation of the cones, and the occasional rainfall able to sustain some scrub and grass vegetation that makes the landscape fairly similar to those known from Chyulu Volcanic Field in eastern Kenya (Shaitani and Chainu eruptions in 1856) [http://www.volcano.si.edu/volcano.cfm?vn=222130], where recent scoria cones look also older than they are (Haug and Strecker 1995).

The scoria cones are composed of red vesicular scoria that is isometric in shape. Fine black ash is occasionally visible in the upper section of the edifice. The cones have an enclosed crater that is not filled with aeolian dust indicating its relatively young age.

4.5.5 Jabal Al Raquabah [17° 48′ 40.12″N; 41° 50′ 35.49″E]

Jabal Al Raquabah is an eroded volcanic edifice located directly on the Red Sea coast in the southern part of the main body of the Harrat Al Birk. The erosional remnant can be accessed all around and there are some tracks that cross cut the edifice allowing a fairly complex view for the visitor. The edifice is not covered by any vegetation however its north facing site has a significant aeolian sand dune cover about one third up on its flank. The southern side of the edifice however perfectly exposed and allow a complete

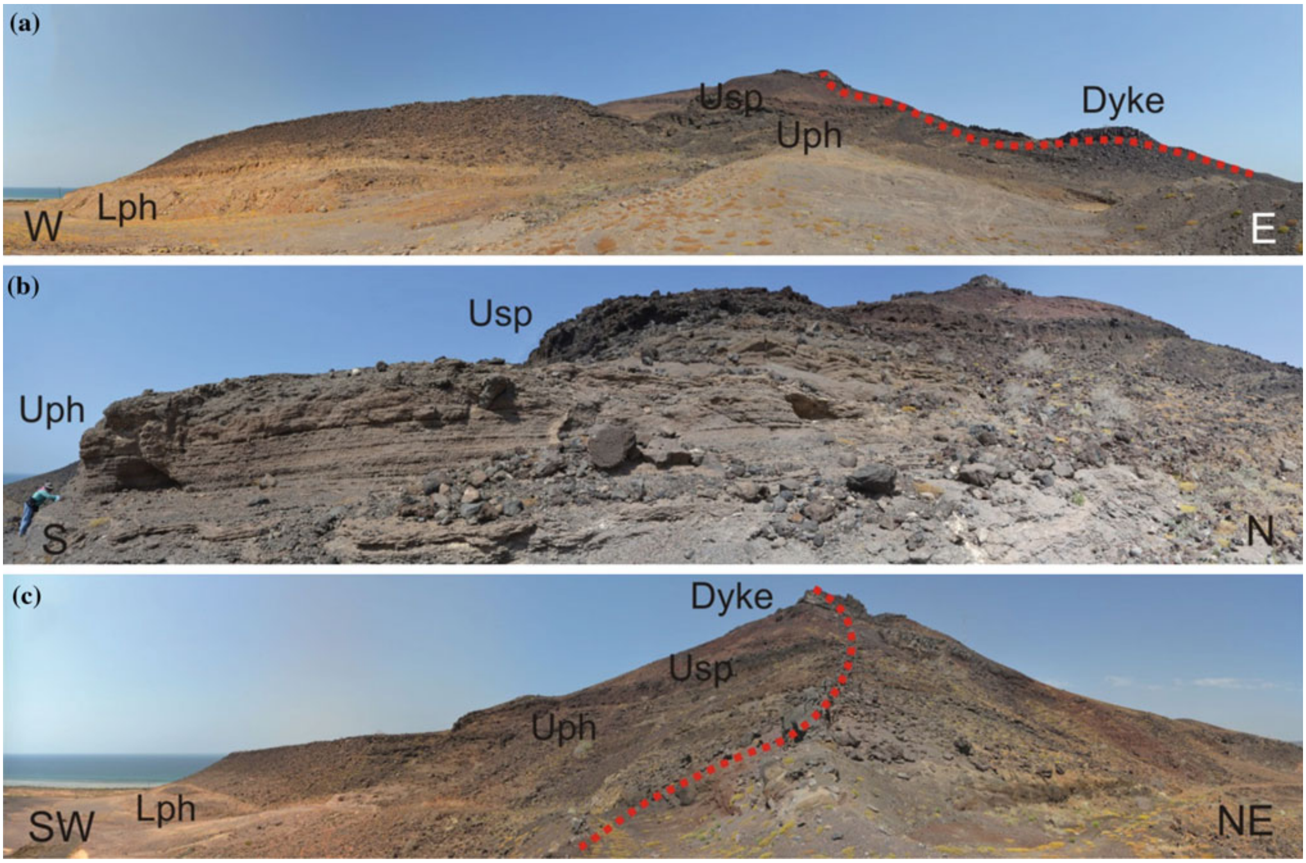

Fig. 4.65 Overview images of Jebel Raquabah volcano [17° 48′ 40.12″N; 41° 50′ 35.49″E] that is inferred to be an erosional remnant of a Surtseyan emergent volcano. Its base composed of phreatomagmatic deposits (*Lph*) deposited from pyroclastic density currents that is gradually transforming into a more fall-dominated well-bedded, glassy pyroclast-rich succession (*Uph*) (**b**). The entire succession is capped by a spatter dominated partially agglutinated unit (*Usp*) that is framed with some dykes (**c**)

section to be measured from the sea level up to the top of the cone. The volcanic edifice is a conical shape broad volcanic massif about 3 km across with a small crater on top of the entire basal succession (Fig. 4.65a). The base of the pyroclastic succession forms an about 15 m thick succession of glassy pyroclast rich bedded lapilli tuff and tuff that is rich in ballistic bombs of angular chilled juvenile lapilli and bomb (Fig. 4.65a). The abundance of glassy pyroclasts, the dune to cross bedded nature of the deposits and presence of accidental lithic clasts as accidental lithics suggest that these beds formed through phreatomagmatic explosive eruption. The relative low proportion of deep seated accidental lithics, the abundance of glassy pyroclasts and presence of coral and other shallow marine sediment-derived clasts suggest that the eruptions were triggered by interaction of rising magma and shallow seawater behind a reef and the eruption were likely initiated in a shallow subaqueous setting forming an emergent, Surtseyan style volcano (White and Houghton 2000). The water depth could have been very low and at this stage it is difficult to say that the volcano evolved as a typical Surtseyan volcano (Agustin-Flores et al. 2015; Brand and Clarke 2009; Mattsson 2010; Sohn et al. 2008), or it was just strongly influenced by the availability of surface water and otherwise evolved as a tuff ring on a marshy coastal plain (Agustin-Flores et al. 2014) or phreatomagmatic rift-edge volcanoes commonly develop on volcanic islands coastal regions (Németh and Cronin 2009, 2011).

The stratigraphy of Jabal Raquabah is simple by having a basal phreatomagmatic succession dominated by pyroclastic density current deposited beds (Lph) that gradually transform to an upper phreatomagmatic succession (Uph) that is more clast-supported and more consistent with fall deposition in sub aerial conditions during the fully emergent stage of the volcano, and an upper spatter dominated part (Usp) that is a capping unit and clearly demonstrate the complete emergent and/or water cut of stage of the eruption (Fig. 4.65).

Texturally the basal successions are rich in horizontal transport indicators (Fig. 4.66a, b). About 15 m above the base of this initital succession the pyroclastic beds have a zone of about 2 m where multiple flow indicators

Fig. 4.66 **a** Basal pyroclastic succession of Jabal Al Raquabah [17° 48′ 40.12″N; 41° 50′ 35.49″E], **b** matrix supported part of the basal phreatomagmatic succession of Jabal Al Raquabah, **c** transitional multiple transport indicator-dominated section of Jabal Al Raquabah, **d** coral fragments in the phreatomagmatic successions, **e** clast supported lapilli bed in the upper phreatomagmatic unit with great variety of palagonitization (various brown coloured clasts) and some coral fragments (*white clasts*), **f** upper lava spatter dominated capping unit

demonstrate a multioriented transportation regime best explained by a wave action dominated transportation region in shallow coastal regions (Fig. 4.66c). The basal section and the upper phreatomagmatic units contain large number of coral fragments (Fig. 4.66d) as accidental clasts indicating that these clasts were excavated by an explosive eruption. The upper phreatomagmatic succession clast supported beds show variable palagonitization of individual pyroclasts suggesting an intensive recycling in a water, steam and acid-rich environment (Fig. 4.66e). The capping succession is typical lava spatter dominated unit that can be more matrix supported in what large spatter float or more

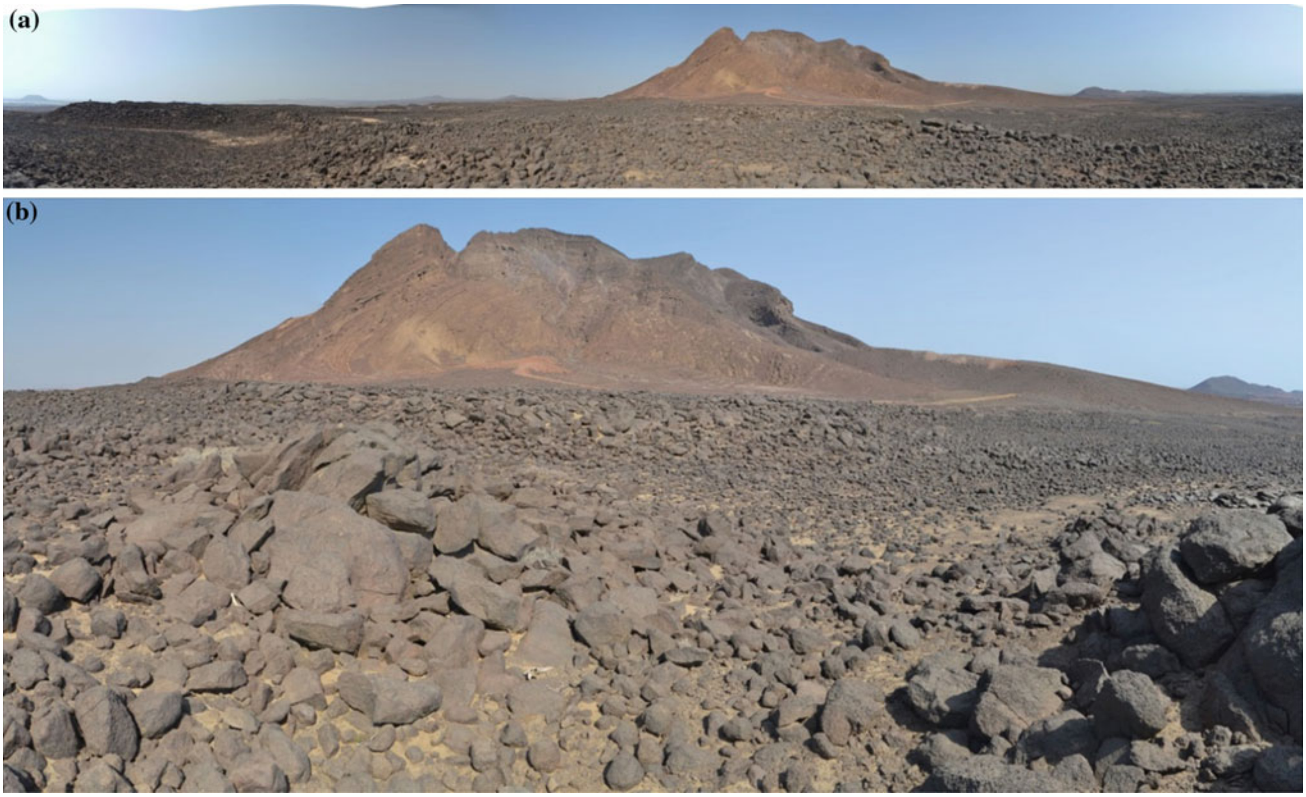

Fig. 4.67 Khurma scoria cone [18° 13′ 32.99″N; 41° 36′ 29.77″E] sits on an elevated plateau (**a**). The cone itself is dissected, partially collapsed, and its edifice interior is exposed (**b**)

Fig. 4.68 Al Birk town [18° 12′ 47.56″N; 41° 32′ 17.70″E] from the lava plug forming a hill in the centre of the town (**a**). The centre of the town form an elevated coherent lava body that is surrounded by a "wall" of circular lava flows (*arrows* on **b**). The origin of these features is not clear, and could be a subject of future research

homogeneous up-section an form agglutinated and welded beds that acted as an erosion resistant cap on the volcanic edifice (Fig. 4.66f).

4.5.6 Khurma [18° 13′ 32.99″N; 41° 36′ 29.77″E]

Khurma is a large scoria cone dominates the central part of the Harrat Al Birk (Fig. 4.67). It sits over a blocky lava flow field that considered to be an older paleosurface. The cone is complex and shows multiple collapse and rebuild events in their exposed sections (Fig. 4.67b). It has no associated ash plain around the cone, however it could have been eroded since the volcano sits over a wind exposed plateau (Fig. 4.67a). The location is accessible and could be an important easy to access and nice geosites for a future geopark in the region.

4.5.7 Al Birk [18° 12′ 47.56″N; 41° 32′ 17.70″E]

The town of Al Birk is the location after the Harrat Al Birk got its name. The city center seems to sit on an elevated platform that stands out from a depression that is surrounded by a circular feature. This geometrical set was the reason the field visit was arranged. Such setting is commonly linked with a maar-diatreme feature. However, the circular feature turned to be a lava flow front that is by some reason stopped in a semi-circular fashion. In the center of this circulate feature a large cliff with alkaline basaltic rocks form a prominent landmark (Fig. 4.68). Toward the Red Sea similar older looking alkaline basaltic lava flows commonly form a paleo-surface against old reef banked suggesting some sea level rise and fall since these lava fields formed. The age and chemical composition of these lavas could provide interesting information on the general landscape forming lava flow fields in the core of the Harrat Al Birk.

4.5.8 Main Findings

Harrat Al Birk is an interesting volcanic field in term of the variety of volcanic landforms identified in this field campaign. First time a partially buried maar volcano have been located at Jabal Akwa, that highlight the need for further detailed studies in the region and evaluate the volcanic hazard aspects of this finding in regard of linking the location for these vents and the location of major wadi networks. Also, along the Red Sea coast the first time phreatomagmatism were noticed. The described features point to infer a shallow submarine, emergent tuff cone growth that fits very well for the expected eruption scenarios during higher sea level one can envision. The centre part of the Harrat Al Birk is also promising in regard of the large partially eroded scoria cones that allow looking inside their edifice and characterises their volcanic eruptions. Interestingly, there are several cones that are fairly steep, and suggest that some sort of lava dome activity may have played a role in the evolution of these cones.

Harrat Al Birk is located in a fast growing region where population growth and investment increase is huge. The Harrat Al Birk is a potentially active volcanic field, and therefore it is important to fully develop eruption scenario hazard models and communicate those scientific results with local communities and authorities. The newly identified volcanic eruption styles in the Harrat Al Birk made it important that such eruption scenario studies conducted in the near future.

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