Chapter 3
Volcanological Studies of Barren Island

In the volcanological studies, we study the formation of volcanoes, and their historic and current eruptions on the basis of eruptive products including tephra (such as ash or pumice), lava and rock samples. In this work, I report the results of our detailed geological and volcanological observations and interpretations of volcanic sequences on Barren Island, based on three field trips to the volcano in January 2007, April 2008 and March 2009. During the field investigations we have identified different flows and structures on the island, mapped the island, and made an attempt to understand the origin and evolution of the volcano. These results have already been published (Sheth et al., 2009, 2010 and 2011).

3.1 Introduction

The Barren Island active volcano lies in the Andaman Sea, northeastern Indian Ocean. It is situated ~70 km east of India's Andaman and Nicobar Islands chain, where sequences of oceanic volcanic and metavolcanic rocks (pillow basalts, ultramafics, serpentinites, greenstones) as well as flysch sediments are exposed (e.g., Allen et al., 2007). The Andaman Trench, along which the NE-moving Indian Plate currently subducts beneath the Burmese Plate, is ~ 250 km west of the volcano (Fig. 1.10). The tectonic scenario is complicated by the presence of active back-arc spreading in the Andaman Sea ESE of Barren Island (Curray et al., 1979; Kamesh Raju et al., 2004; Khan and Chakraborty 2005, Subba Rao, 2008).

Barren Island is the only active volcano in Indian territory, and the northernmost active volcano of the great Indonesian arc. To the north of Barren Island is one more important dormant volcano in Indian subcontinent named as Narcondam (Fig. 1.10), which is situated ~140 km NNE of Barren Island, may have erupted in the Holocene (Simkin and Siebert 1994, Siebert and Simkin, 2002).

Barren Island is only ~3 km across. It is not all barren and has a lush jungle on its southern and eastern sides, with some freshwater springs (Chandrasekharam et al., 2003). But it is uninhabited by man, which may explain its name. Wildlife on the island includes feral goats, fruit bats, rats, and parrots.

Barren Island has restricted public access and can be reached by Indian Navy or Indian Coast Guard vessels from Port Blair (135 km), the capital of the Andaman and Nicobar Islands. A few scientists from the Geological Survey of India (GSI) have been studying the volcano for nearly two decades; however, with rare exceptions their studies have been published as the GSI's internal reports and as conference abstracts, not easily accessible (e.g., Haldar, 1989; Haldar et al., 1992a, 1994, and several others). The volcano has therefore had quite low visibility internationally. There is also no continuous monitoring of the volcano. A GSI photographic atlas dedicated to the volcano (Shanker et al., 2001) gives some valuable first-hand information on the recent eruptive activity in the form of eyewitness accounts; however, the atlas is targeted in part at the layman, and our identifications and interpretations of several volcanic features on the volcano differ significantly from those offered in the atlas. When we started working on the Island in 2007 only a few studies existed in peer-reviewed Indian and international literature (Haldar et al., 1992b; Haldar and Luhr, 2003; Alam et al., 2004; Luhr and Haldar, 2006; Pal et al., 2007) which addressed aspects of magma evolution at the volcano and provided accounts of its recent post 1991 eruptions. Since 2007 several publications including ours, have come into public domain (e.g., Sheth et al., 2009, 2010 and 2011; Chandrasekharam et al., 2009; Banerjee, 2010; Pal et al., 2010; Streck et al., 2010; Awasthi et al., 2010, Ray et al., 2011). In following paragraphs I discuss our finding of the volcanological studies on the Island.

3.2 Geology

Barren Island (Figs. 3.1, 3.2) is roughly circular with a diameter of ~3 km and represents the topmost part of a submarine volcano rising more than 2 km above the sea floor. In the absence of proper geophysical survey, drilling or dredging no information is available about the rocks that make up its submarine mass. Luhr and Haldar (2006) estimate its submarine volume to be ~390 km^3 based on the bathymetry and the subaerial volume to be only 1.3 km^3. The volcano has a nearly circular caldera of ~2 km diameter, with a breach in the caldera wall on the northwestern side, which has existed since at least 1787 as the earliest sketches of the volcano (by Colebrooke and Captain Blair, reproduced in Shanker et al., 2001) show.

A cinder or scoria cone rising to about 500 m above sea level exists roughly at the caldera centre. The caldera wall exposes prehistoric volcaniclastic deposits and lava flows, which are interbedded with radial outward dips (Fig. 3.1a, b and 3.2b). By “prehistoric” is meant that these deposits formed at some (unknown) time before the first “historic” eruptions which began in 1787 and continued till 1832 (Shanker et al., 2001; Luhr and Haldar, 2006). Alam et al. 2004 reported for a 5-m-wide, NNE-SSW-trending basaltic dyke cutting the prehistoric lava flows on the southeastern inner caldera wall, no intrusions are known on the volcano.

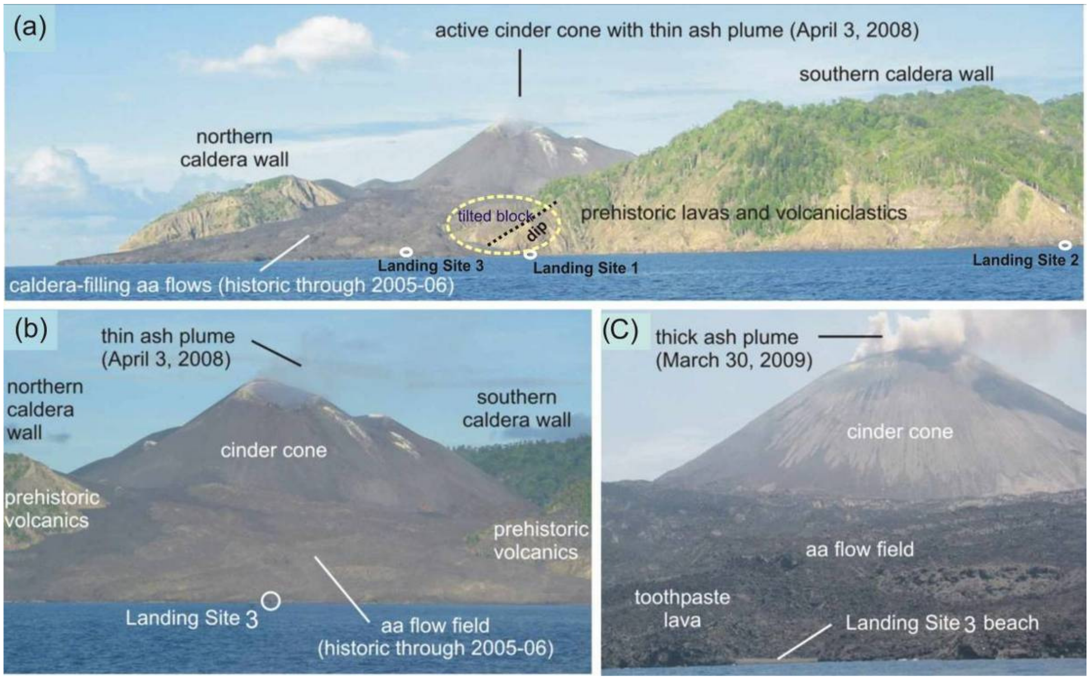

Fig. 3.1 ***a-c*** *Panoramic views (in April 2008 and March 2009) of Barren island taken abroad Indian coast guard vessels, showing general morphological and geological features. The cinder cone is ~ 500 m high above the sea and the south caldera wall 334m.Yellowish white patches on the cinder cone in (a) and (b) are fumarolic deposits. In (c) ~20m wide beach at landing site 3 and the lava flows and first time reported tooth paste lava flows also marked.*

Barren Island has had four recent eruptions in 1991, 1994–95, 2005–06 and 2008-09 (Fig 3.2) during which it has erupted aa lava flows of basalt and basaltic andesite and pyroclastic materials. Previous workers have used variable terminology for the various eruptions. Shanker et al. (2001) call the 1991 and 1994–95 eruptions, which they describe, as “recent”, or the “third cycle”, their second and first cycles referring to the historic (1787–1832) and the prehistoric eruptions respectively. Luhr and Haldar (2006) include the 1991 and 1994– 95 eruptions among “historic” volcanism. Here we use the terms (recent, historic, prehistoric) following Shanker et al. (2001), and also introduce two new useful terms. Because the prehistoric deposits exposed on the caldera wall must predate the formation of the caldera itself, we call them the “pre-caldera” volcanic deposits. The historic (1787–1832) as well as the recent eruptions have occurred from the central cinder cone, well within the caldera. We therefore address both the historic and recent eruptive products as "caldera-filling" volcanic deposits.

Regarding caldera forming event, Shanker et al. (2001) speculated that the caldera may have formed in late Pleistocene time, by an original, 1,100-m-high cone blowing its roof off in a giant eruption. However, our observations suggest that the formation of caldera on the Barren Island volcano is not associated with eruptions because we didn't get evidence for a high proto-Barren Island volcano blowing its roof off in a Krakatau-1883-like eruption. Shanker et al. (2001) didn't identify the deposits left on the volcano itself by this proposed event, and some that we describe below might correspond to such an event, or to older (pre-caldera) volcanism itself. We believe that the caldera of Barren Island is bounded by a ring fault, and note that there is a small tilted block on the western end, rising to about 100 m above sea level but without a clear relationship to the caldera wall, which shows the otherwise south-dipping prehistoric pile forming the southern half of the volcano to dip northwards, towards the caldera-filling lava flows (Fig. 3.1a, b). Cole et al. (2005) provide a recent review of calderas, and the Barren Island caldera can be considered a "simple, single-event, symmetric collapse, circular basaltic caldera" following their terminology. This, as the modelling of Roche et al. (2000) suggests, may indicate a shallow-level magma chamber. This would be consistent with the observations of Luhr and Haldar (2006) that several Barren Island lavas contain disaggregated troctolitic (olivine + plagioclase) cumulates from a shallow magma chamber under the volcano. Although the timing of this caldera forming event is not known, the suggestions made by Awasthi et al. (2010) is worth mentioning the point. Correlating Nd isotopic composition of pre-caldera formations with ash layers in a

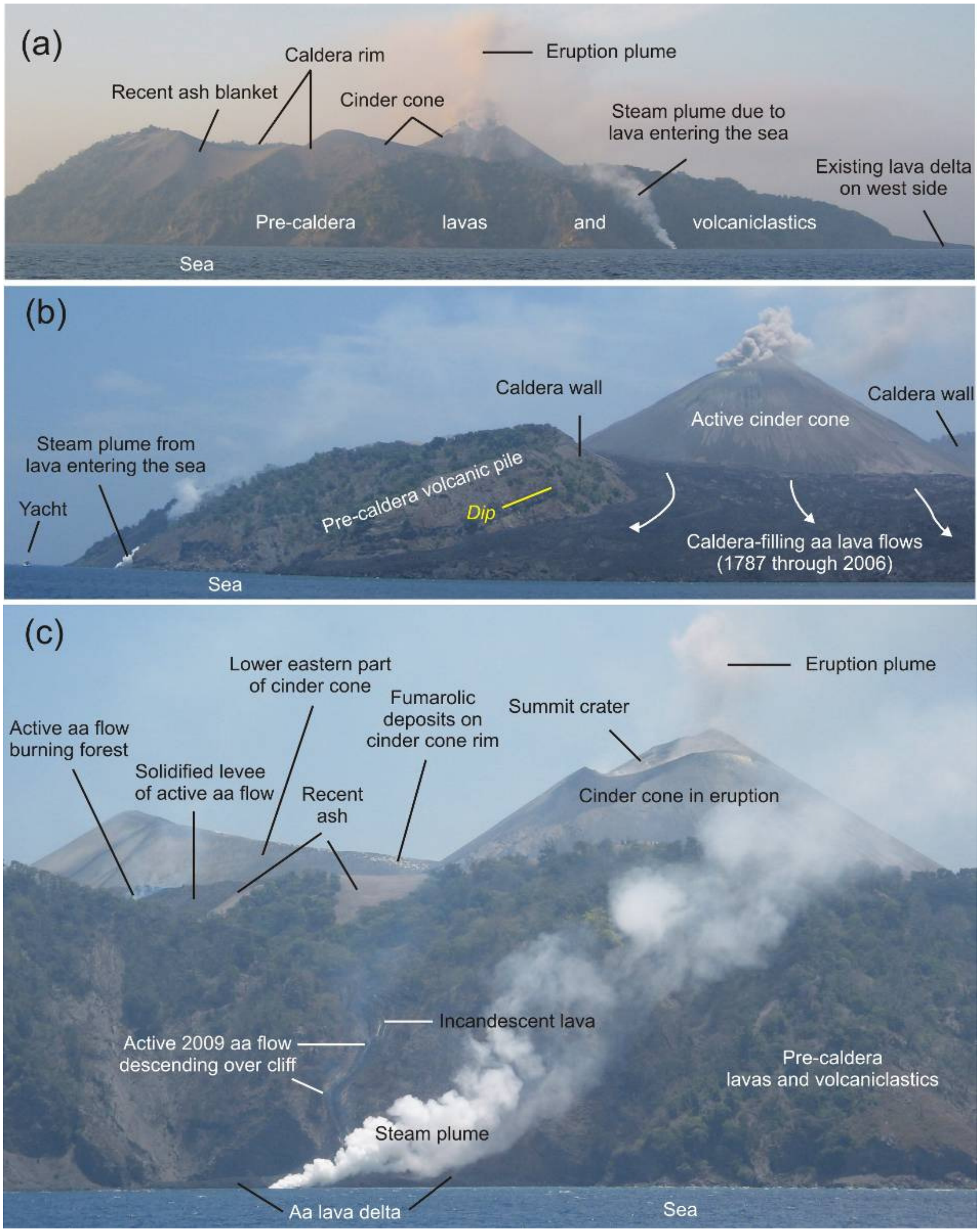

*Fig. 3.2 **a-c** Most recent lava flows (of 2008-09) on Barren Island volcano have taken a route through the northern section of the caldera wall (Sheth et al 2010)*

well dated sediments core near the volcano Awasthi et al., (2010) speculated that the caldera on Barren Island could have formed prior to 10 kyrs before present.

We have developed a new geological map of the Barren Island (Fig. 3.3) based on earlier information, satellite photographs and our field observations. Our map is more accurate compared all other existing ones and a major difference in this map and the previous ones is the considerably enlarged area of recently erupted lava flows at the western coast of the volcano that is represented here. In addition we have also mapped most recent (2009) lava flows that have taken a complete different route to these compared to the earlier ones (Fig. 3.3).

3.3 Prehistoric eruptions

3.3.1 Pre-caldera tuff breccias: deposits left by lahars and debris flows

The lowermost exposed prehistoric deposits on the inner caldera wall of Barren Island are polymodal deposits with sharply angular blocks of basalt as big as a metre, dispersed in a matrix of fine, ash-size, clay-like material (Fig. 3.4). These can be called as tuff breccias. The best exposures are on the western shore of the volcano just south of the 1994–95 aa flows, where several of these deposits underlie a prehistoric aa flow (Fig. 3.4a). Two distinct tuff breccia deposits are visible in Fig. 3.4, and only a few metres southwards, four distinct tuff breccia deposits are exposed, with an unconsolidated, well-sorted ash bed in the middle (Fig. 3.4c), interpreted here as a pyroclastic fall deposit. The prehistoric lava flow and the tuff breccias below have steeply dipping fractures filled by still younger coarse fragmental material almost to the base of the exposed section (Fig. 3.4a). The aa flow may correspond with the lowest of the three aa flows exposed on the northern caldera wall, below which ash and lapilli beds are seen, followed by a tuff breccia deposit (presumably corresponding to the youngest on the southern side) (Fig. 3.4d; the interpretative logs and correlations in Fig. 3.5).

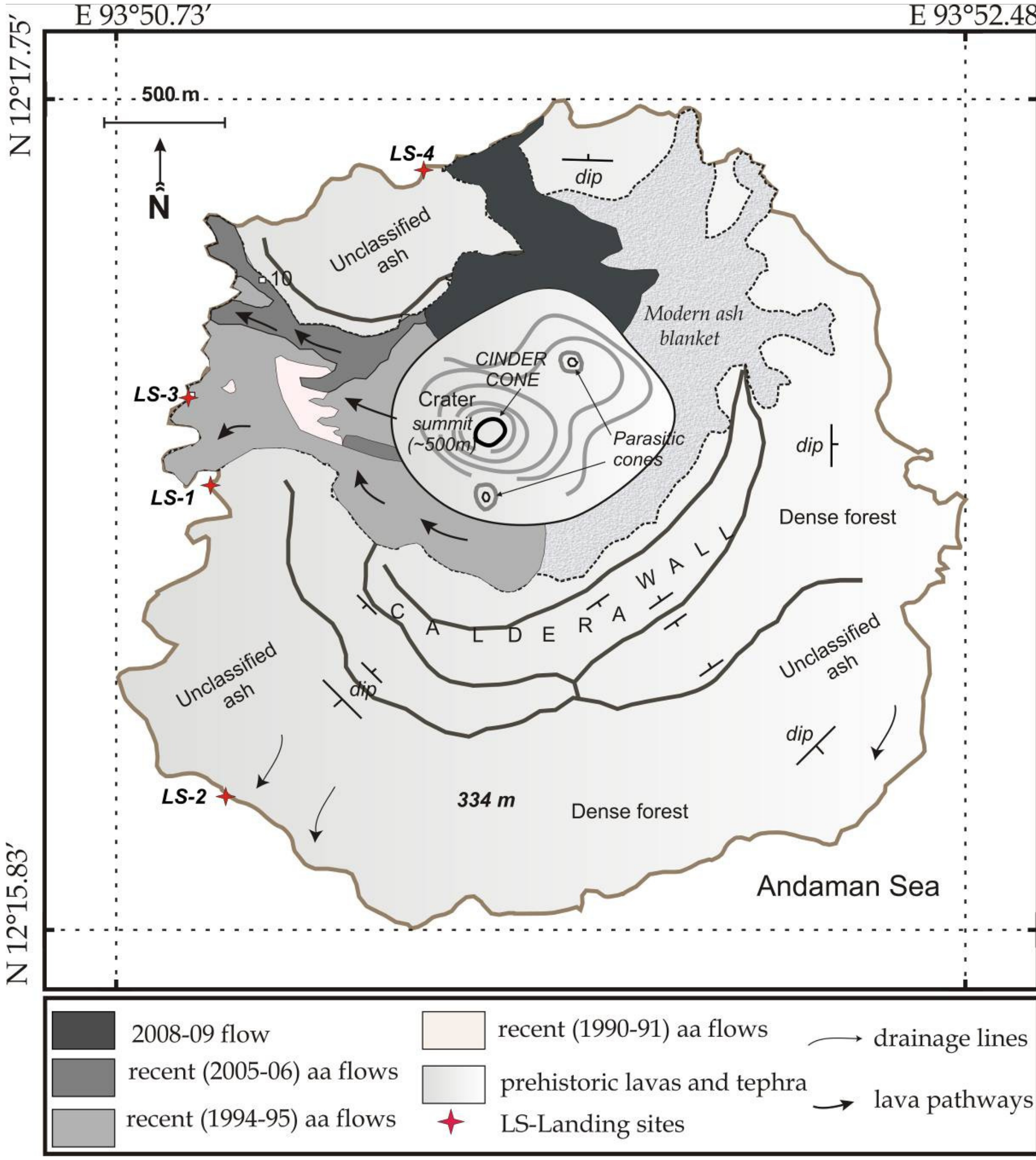

Fig. 3.3 Geological map of Barren Island Volcano based on field observations in 2008 and 2009, showing various lavas flows and structure

Shanker et al. (2001) have described these tuff breccia deposits as agglomeratic flows (e.g., their Fig. 1.9), but the total absence of bombs in them suggests that no molten rock was involved in the flows. Such tuff breccias may represent deposits of pyroclastic flows, particularly the subtype of pyroclastic flows known as block and ash flows. Alternately

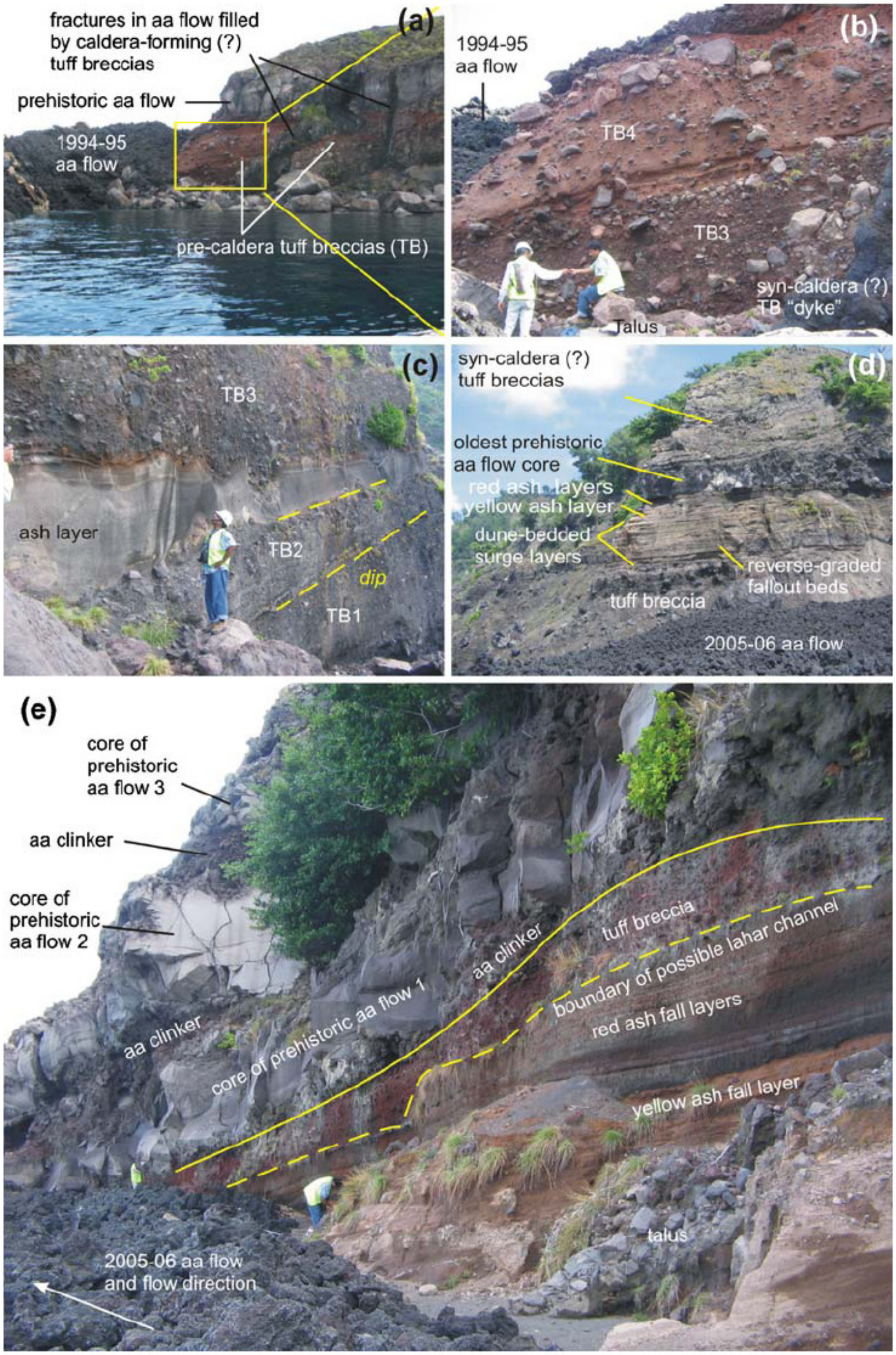

Fig. 3.4 ***a–e*** *Prehistoric, pre-caldera tuff breccias (TB, interpreted as lahar and debris flow deposits and numbered TB1 through TB4 from oldest to youngest) and lava flows exposed on the inner caldera wall.*

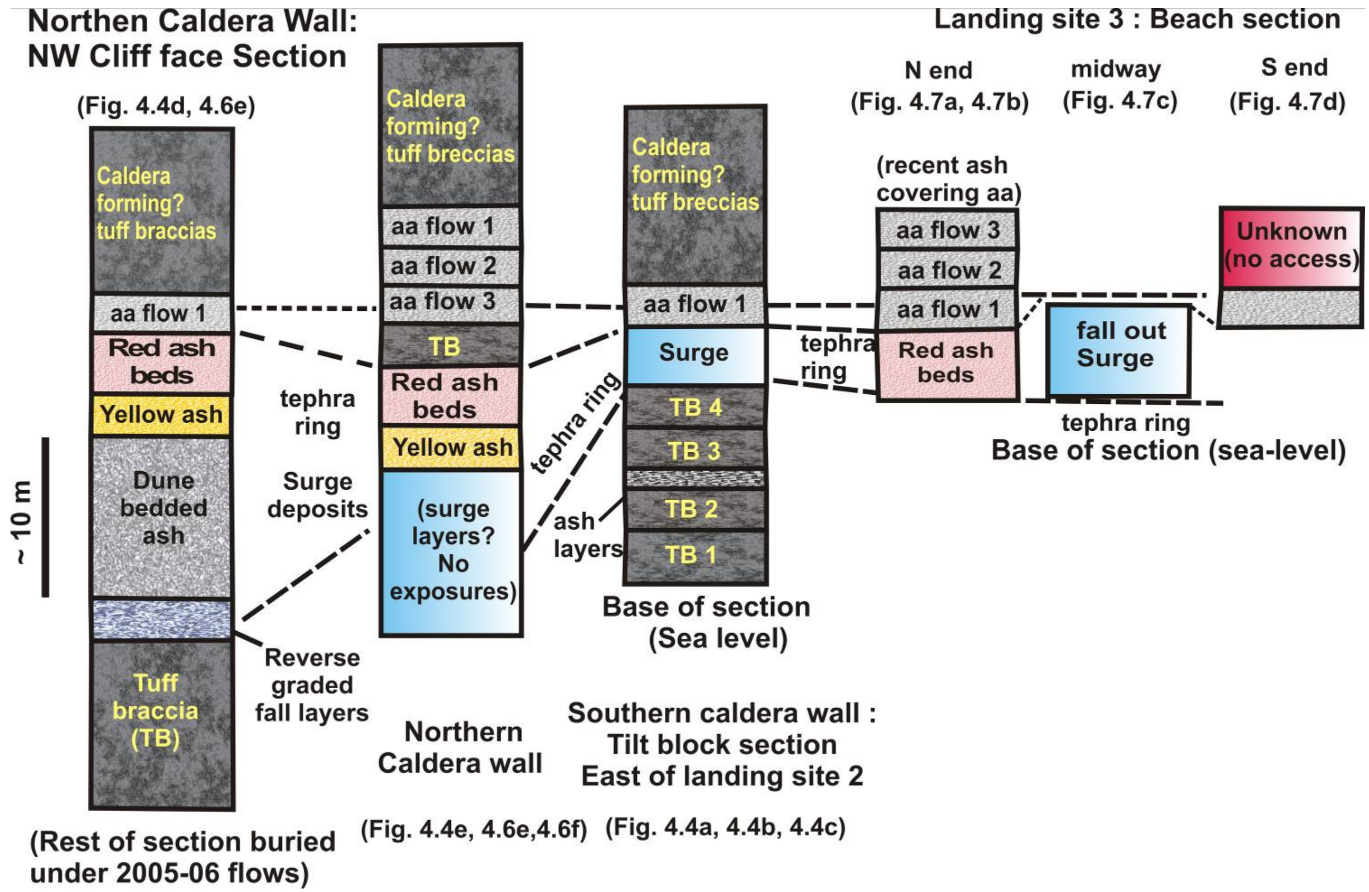

Fig 3.5 Litho logs for the six locations examined on Barren Island in the present study, with their correlations. TB 1 to TB 2 is precaldera tuff breccia deposits (Sheth et al., 2009).

tuff breccias may be the deposits left by debris avalanches or lahars, simply representing mass movements. Both are common and abundant on the large oceanic volcanoes. Whereas debris avalanche deposits are typically hummocky, lahars deposits are channelized. The prehistoric tuff breccias on Barren Island appear to be channelized (Fig. 3.4e). We did not encountered carbonized plant remains that can help distinguish the deposits of the (high-temperature) pyroclastic flows from those of lahars. On the other hand, lahars, especially highly fluid hyperconcentrated flow varieties, contain substantial water. Considering the above, the tuff breccia deposit immediately underlying the prehistoric aa flow (Fig. 3.4b) is interpreted here as a lahar deposit with rainwater as the mobilizing agent. The two similar, but block-rich, matrix-poor deposits that underlie it are interpreted here as deposits left by debris flows. Accumulations of loose, coarse (~1 m), angular rubble that can be seen on the present slopes of theVolcano, only some hundred metres to the south of these outcrops, supports the interpretation that the prehistoric tuff breccias were formed essentially by mass movements.

3.3.2 Ash beds: pyroclastic surge and fall deposits

In the southern inner caldera wall section, in the tilted block described in the “Geology” section above, the lowest prehistoric aa flow and the lahar deposit beneath it are separated by ash and lapilli ash layers (Fig. 3.6a). They show mantle bedding (Fig. 3.6b) as well as dune bedding, sometimes with sags produced by angular basalt blocks (Fig. 3.6c, d). On the northern caldera wall, between the oldest prehistoric lava flow and the tuff breccia deposit are layers with reverse grading, followed upwards by ash and lapilli ash layers with dune bedding (Fig. 3.6e). They are overlain by well-bedded, well-sorted yellow and red ash layers (Fig. 3.6f). Shanker et al. (2001) report rare normal grading in these tephra at other locations. We interpret the ash and lapilli ash beds with reverse or normal grading, or which are well sorted (e.g., Fig. 3.4c), to represent pyroclastic fall deposits, and the ash beds with dune bedding to have been deposited by the pyroclastic surges.

Surge-deposited beds overlain by fall deposits are also seen on the outermost southwestern side of the island, below the prehistoric aa flows (Fig. 3.7a–d). Therefore we believe that these prehistoric, pre-caldera pyroclastic surge and fall deposits, exposed on both the northern and the southern caldera wall sections (sandwiched between the aa flows above and the tuff breccias below), as well as on the western shore of the island, represent a complete tephra ring that existed before the eruption of the prehistoric lavas. Tephra cones, rings, and maars are characteristic products of phreatomagmatism, the explosive interaction between magma and shallow surface water or groundwater (Hamilton and Myers, 1963; Sheridan and Wohletz, 1983; Sohn and Chough, 1989; Zimanowki, 1998; Thouret, 1999; White and Houghton, 2000).

Based on Shanker et al.'s (2001) observation, that "coral beds around the western shore (of Barren Island) were badly affected (by the 1991 eruption)", it is possible that coral reefs were in existence at the time the prehistoric pyroclastic surge and fall deposits formed on Barren Island. But the fact that these deposits contain no coral reef fragments and few other accidental lithics (basalt blocks) suggests the absence, or at least non-involvement, of reefs, and certainly the dominance of juvenile magma and minimal vent quarrying. In fact there is nothing to suggest that sea water was involved in magma fragmentation. The absence of accretionary lapilli

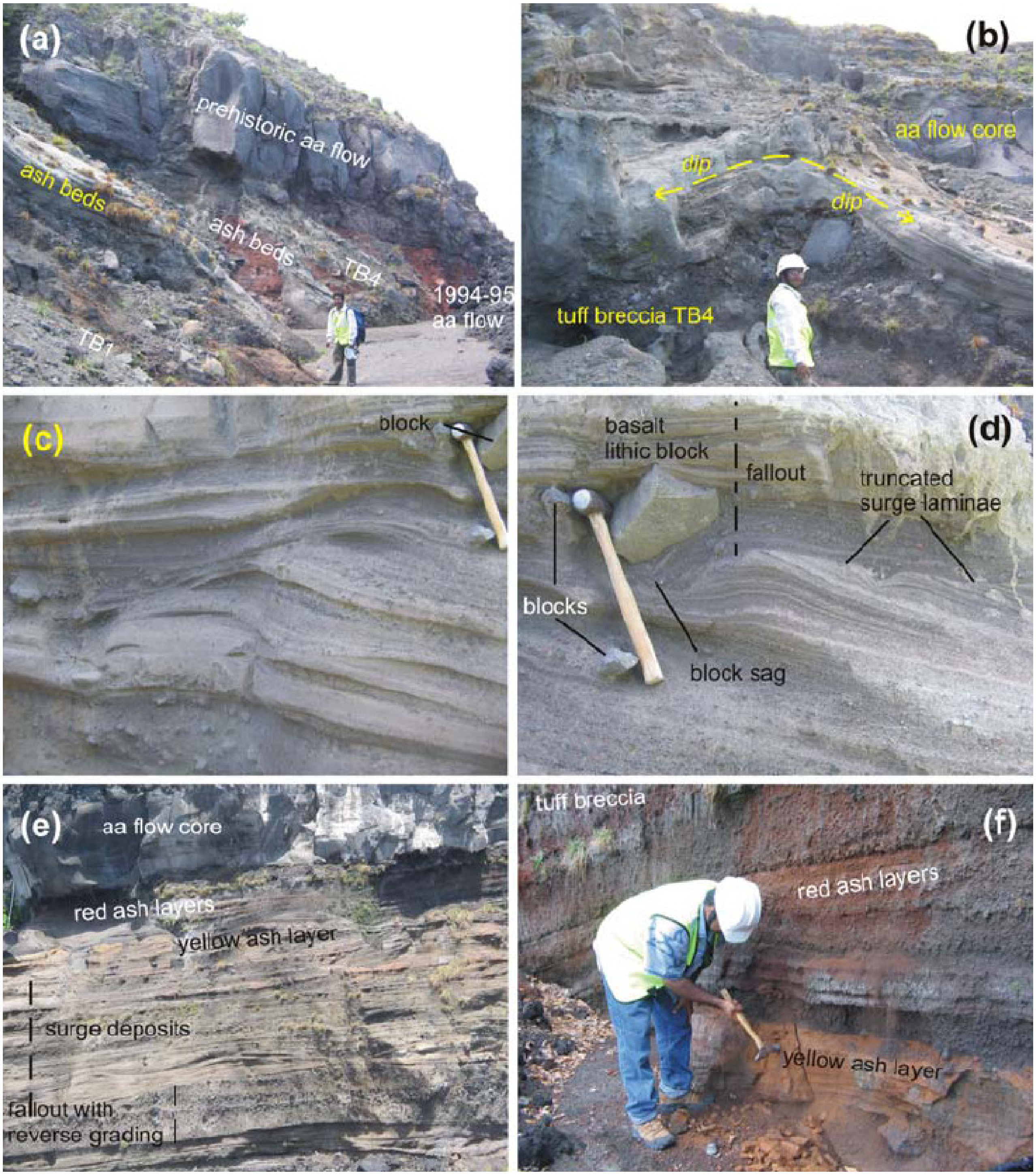

*Fig. 3.6 **a–f** Pyroclastic surge and fall deposits preserved beneath the prehistoric aa flows and above the pre-caldera tuff breccias.*

throughout the outcrops examined suggests that the pyroclastic surges were more or less dry, with little external water involved (e.g., Wohletz and Sheridan 1983).

Shanker et al. (2001) have interpreted the cross-bed characteristics of the surge deposits on Barren Island as aeolian in origin. Whereas syn- or post-eruptive erosion by slumping, debris flows or wind does operate on tephra rings (Leys, 1983; Sohn and Chough, 1989; Chough and Sohn, 1990), there are no palaeosols or erosional contacts within these deposits, suggesting the rapid eruptions without breaks, and no horizons of coarse, angular rubble that might suggest reworking.

3.3.3 The prehistoric aa flows

Each of the three aa flows on the northern caldera wall exhibits a distinct clinkery base and top, and a thick, massive, unjointed or poorly jointed core between the upper and lower clinker (Fig. 3.4e). Each clinkery horizon is about a metre thick, and the cores are about 4 m thick. The upper two lava flows appear to merge into one towards the northwestern end of the cliff face.

3.3.4 Possible syn-caldera deposits

On Barren Island, it is unclear if there are deposits associated with the caldera-forming event. Shanker et al. (2001), who speculated about a giant caldera-forming prehistoric eruption, did not identify the associated deposits. Luhr and Haldar (2006) write that "Outcrop photographs in Shanker et al. (2001) show sequences of unconsolidated pyroclastic-surge deposits more than 15 m thick with prominent cross beds and bomb sags, likely from the caldera-forming eruption." We believe that these photographs are of the outcrops we have described as pyroclastic fall and surge deposits underlying the prehistoric lava flows, which means that they were emplaced long before the caldera-forming event. Also bombs are not observed in these deposits (only blocks, and very few of them).

The youngest deposits exposed in the caldera wall are ~50 m thick pyroclastic deposits above the prehistoric aa flows. These include mainly

Fig. 3.7 The beach section at Landing Site 2 on the western side of the island, showing (a) two prehistoric aa flows underlain by tephra deposits, (b) close-up of the lowermost aa flow and underlying red ash beds, (c) fine, dune-bedded ash representing surge deposits overlain by airfall-deposited ash with a few lithic blocks of basalt, and (d) surge deposits underlying fallout ash beds.

well-stratified ash beds with some tuff breccias (Fig. 3.8a). Following many workers (e.g., Nakamura 1964; Decker and Christiansen 1984; Robin et al., 1993) we interpret these uppermost deposits as possibly representing the caldera-forming eruption. Some of the tuff breccias have entered the fractures in the prehistoric lava flows and underlying tuff breccias (Figs. 3.4a, 3.8b, c), and these fracture filling materials sometimes have a strong superficial resemblance to dykes (Fig. 3.8c). In places the ash layers and the tuff breccias dip inward towards the centre of the caldera (Fig. 3.8d) and show mantle bedding, suggesting that they were deposited on whatever topography existed at that time (Fig. 3.8e).

3.4 Historic eruptions

Based on the accounts of Hobday and Mallet (1885), Ball (1888, 1893), Mallet (1895), Washington (1924), Raina (1987), Haldar et al. (1992a, b, 1999), Shanker et al. (2001), Haldar and Luhr (2003), Luhr and Haldar (2006), and reports from the Bulletin of the Global Volcanism Network (Smithsonian Institution, Venzke et al., 2002), Barren Island volcano had its first historically recorded eruptions in 1787, observed by passenger ships crossing the Andaman Sea. The earliest sketches of the island (sketches by Colebrooke and Captain Blair reproduced in Shanker et al., 2001) show the volcano in much its modern shape, including the breach in the caldera wall. However, the height of the central cinder cone has been shown to be a little less than that of the caldera wall and, rather unrealistically, the cinder cone has been shown to have extremely steep (50°) slopes.

The activity in 1787 is said to have started with the formation of a new cinder cone near the centre of the caldera during a Strombolian-style eruption.

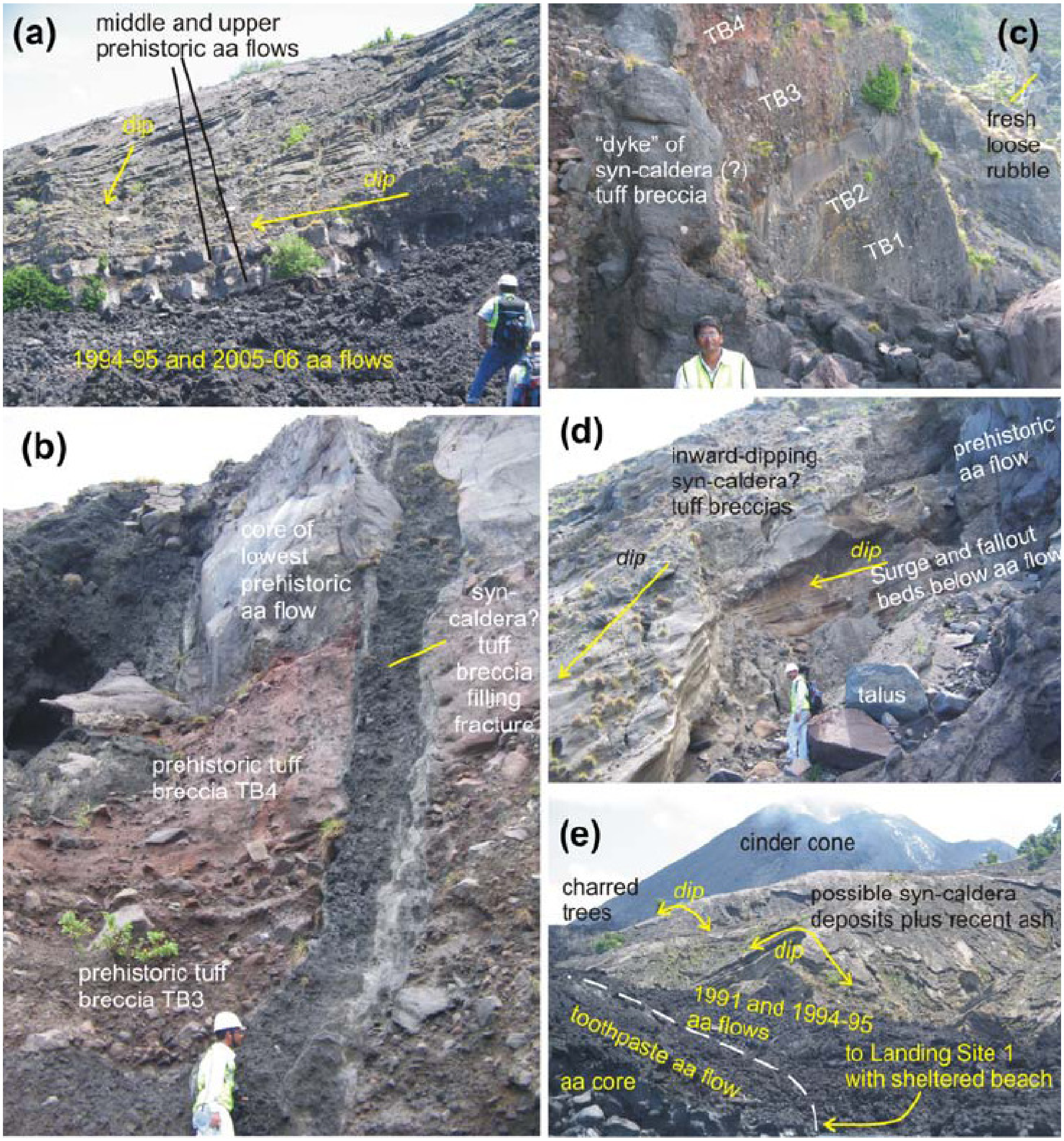

Fig. 3.8 **a–e** *Uppermost prehistoric deposits that may represent the caldera-forming eruption, overlying the prehistoric lava flows and tephra layers. Frame (a) is from the northern caldera wall, and (b) through (e) are from the tilted block just south of the recent aa flow field (Landing Site 1)*

Activity continued until 1832 with breaks of 2–29 years between individual eruptions. The Smithsonian Institution lists the following eruptions during this interval: 1787, 1789, 1795, 1803–1804, and 1832 (Siebert and Simkin 2002). The cinder cone grew to 305 m height and developed a summit crater ~60 m across. The eruptions occurred from three subsidiary vents about 80 m below the crater rim on the northeast, west, and south flanks of the cinder cone (Raina 1987, and references therein). Basaltic aa lavas emerged from the three subsidiary vents, flooded the annular moat between the new cinder cone and the caldera wall, and ultimately flowed westward to cascade into the sea (e.g.,
see Fig. 3b of Luhr and Haldar 2006). Luhr and Haldar (2006) estimate a volume of ~25 million m^3 for them.

3.5 Recent eruptions

The recent (1991, 1994–95 and 2005–06, 2008-09) basalt and basaltic andesite flows have largely, apparently completely, covered and hidden the older historic (1787–1832) lava flows. Shanker et al. (2001), Haldar and Luhr (2003), and Luhr and Haldar (2006), as well as the Smithsonian Institution's Global Volcanism Program website (http:// www.volcano.si.edu) offer valuable first-hand information on the recent eruptions. The 1991 flows erupted from the central cinder cone and flowed to the sea (Fig. 3.2), and the 1994–95 flows flowed along the southern margin of the 1991 lava field (Figs. 3.2, 3.9a) according to eyewitness accounts (Shanker et al., 2001), though they also appear to make up much of the lava front along the island's west coast. The 2005–06 flows travelled along the northern part of the lava field, close to the caldera wall, and reached the sea. The three eruptions have by now created a sizeable lava delta (term used by Luhr and Haldar, 2006) at the western shore of the Island (Figs. 3.1a, b, 3.2, 3.9a). We describe these eruptions only briefly, as detailed descriptions can be found in the references cited above.

3.5.1 The 1991 eruption

This eruption began in late March 1991 from the existing cinder cone, producing thick jets of gas and red-hot lava fragments. The eruption began at the NE subsidiary vent from the 1787–1832 eruption; about 80 m below the rim of the crater of the cinder cone, and formed a new spatter cone. Lava flowed from that vent and also from the other two subsidiary vents of the historic eruption, and filled the annular moat between the central cone and the caldera by 6 April. Two new small, ~10-m-high lava driblet cones formed ~100 m and ~130 m west of the cinder cone atop these basaltic andesite lava flows, which were mostly blocky aa. These lava flows travelled westward to the sea where they buried a 12-m-high gas lighthouse on the shore and caused profuse boiling of the sea water and generation of thick steam clouds. The lava flows were individually 5–6 m thick, but by the late stages of the eruption they became ~25 m thick near the base of the cone and at the ocean entry.

Based on the mapped distribution of the 1991 lava flows, Luhr and Haldar (2006) estimate that they covered an area of ~0.26 km^2. Multiplying by an average lava thickness of 10 m over this area gives a total lava volume of 2.6 million m^3 (not 26 million m^3 as reported by them). If the ratio of tephra to lava was roughly 2:1, as estimated by eye (Haldar and Luhr, 2003), then the associated 1991 tephra volume is 5.2 million m^3 (not 52 million m^3 as stated by them). Therefore, while we cannot account for the lava or tephra volumes that are under the sea, we consider that a good estimate of the total 1991

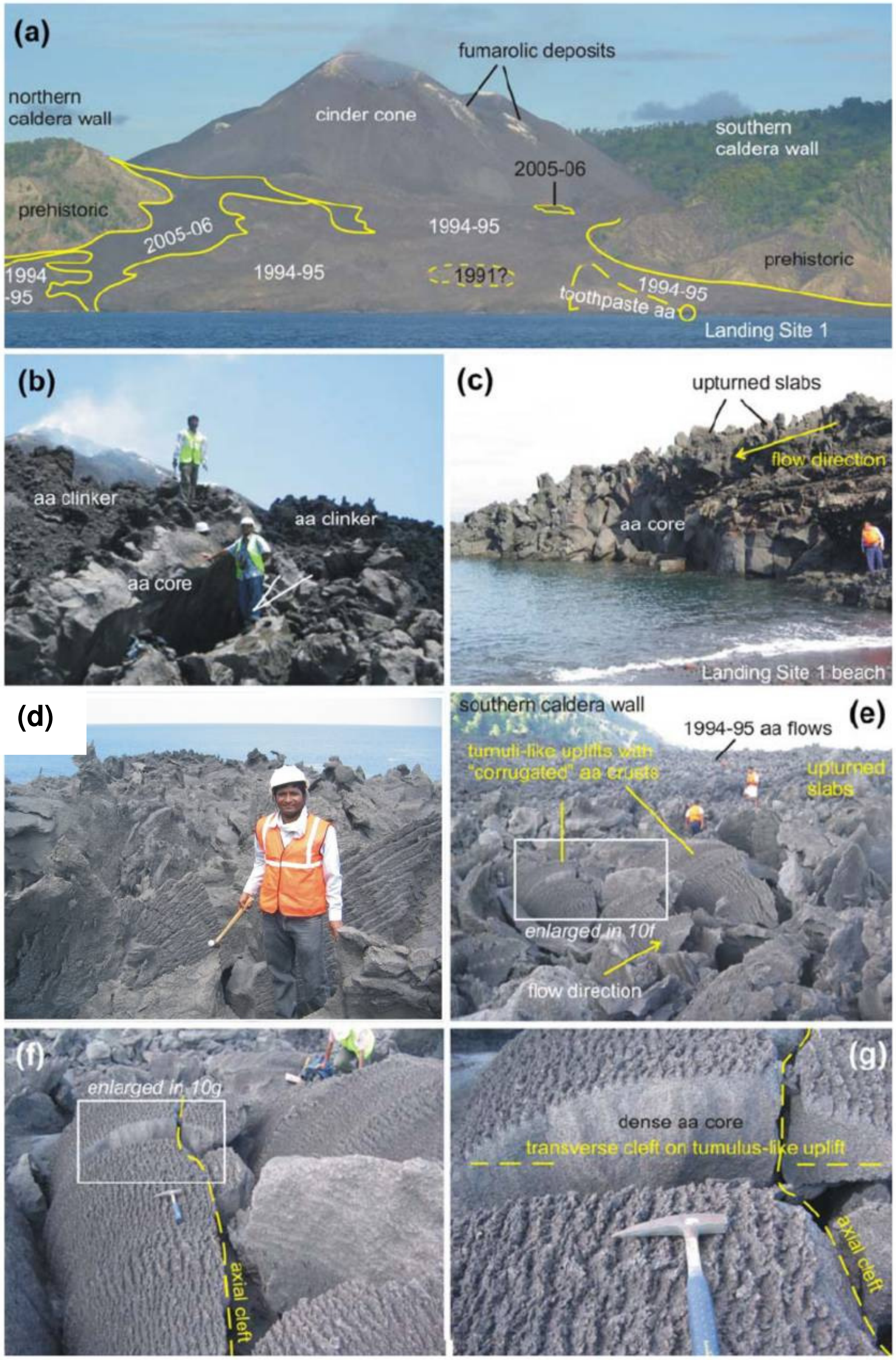

*Fig. 3.9 **a-g** Recent aa flows. (a) is a panoramic view (looking east) of the recent lava flow field. Dotted boundaries are conjectural. (b) is between the L.S.3 and the northern caldera wall. (c–g) show the toothpaste aa flow at the L.S.3*

magma volume (lava plus tephra) that remains on the island is ~8 million m^3. Luhr and Haldar's (2006) figure of ~78 million m^3 is about an order of magnitude too large.

By early May 1991 the NE flank vent was ejecting incandescent fragments in pulsing pyroclastic columns (fire fountains), and this has been described as Strombolian activity. A pulsing fountain without pauses would probably be considered Hawaiian rather than Strombolian (e.g., Valentine and Gregg 2008). By August–September this activity advanced into sub-Plinian behaviour as incandescent columns reached heights of about 1 km. Scoria and ash rained down upon the island, and a 3 m thickness of these is said to have covered the active lava flows. By late September all the three subsidiary vents on the cinder cone had broadened and merged with the central crater. The uppermost 80 m of the pre-1991 cone was removed and the summit crater, greatly broadened, was now 400 m wide, with the cone standing only 225 m high above sea level. Shanker et al., (2001) reported that the crater viewed from its rim resembled a giant funnel narrowing down to a conduit only about 25 m wide at a depth of 200 m, i.e., just 25 m above sea level. The eruption was continuing on 17 October, when the NOAA-11 satellite captured an image of a plume extending ~150 km WNW from Barren Island, but the eruption waned soon thereafter and was over by 31 October.

3.5.2 The 1994–95 eruption

This eruption started in mid-December 1994 and persisted into mid-June 1995. The event sequence for the first weeks of the 1994–1995 eruption is not known because the first GSI expedition did not arrive at Barren Island until 24 January 1995. Like the 1991 eruption, the 1994–1995 eruption has been termed mainly Strombolian in character and gained momentum over time to each its paroxysmal stage during March 1995. It began with thick, dark smoke like jets of ash and coarser clasts from a newly created flank vent on the cinder cone, 50 m below the 225-m-high crater rim. Three flank vents subsequently developed, which along with the central vent form a N-S-trending alignment. This alignment presumably reflects the orientation of the feeder dyke underneath. The only reported dyke on the island, the dyke cutting prehistoric lavas on the southeastern caldera wall (Alam et al., 2004), has a closely similar trend (NNE-SSW), perhaps suggesting that the regional tectonic stresses have remained much the same over the exposed history of the volcano.

The 1994–1995 lavas were basalt, and the eruptive activity did not change into sub-Plinian as it did for the 1991 eruption involving basaltic andesite. By late January, a spatter cone ~100 m high formed on one of the flank vents, and stood ~50 m higher than the summit crater rim of the central cinder cone. Block-lava flows fed from this vent travelled 1.5 km to reach the sea following a route between prehistoric lavas to the south and the 1991 lavas to the north, and caused profuse steaming at the ocean entry. The lava stream from a flank vent was about 50 m wide and 6 m high. Incandescent columns ~100 m high were produced from the vents, accompanied by vigorously pulsing plumes of gas, ash, and steam at every 30 s or so and rising to 800 m before being drawn by winds into a horizontal plume. A Space Shuttle image, taken on 14 March 1995 (Luhr and Haldar, 2006; their Fig. 3d), shows the eruption plume drifting west towards the Andaman Islands. The eruption probably continued until the second week of June 1995, after which the volcano entered a strong but waning fumarolic stage.

Luhr and Haldar, (2006) mapped the 1994–95 lava flows over an area of ~0.23 km^2. Assuming an average lava thickness of 10 m over this area gives a total lava volume of 2.3 million m^3, not 23 million as quoted. Based on the tephra to lava ratio of roughly 1:1, as estimated by eye (Haldar and Luhr, 2003), the associated 1994–1995 tephra volume must also have a volume on the order of 2.3 million m^3. Therefore, the total erupted magma volume during the 1994–95 eruption (excluding the lava and tephra volume that entered the sea) is ~4.5 million m^3, an order of magnitude less than the ~46 million m^3 reported by Luhr and Haldar, (2006).

3.5.3 The 2005–06 eruption

This is an extremely brief summary written based on the Smithsonian Institution's Global Volcanism Program website, where eight individual contributors are identified (http://www.volcano.si.edu). This eruption began in late May 2005 with an ash plume and fresh black basalt lava flows which did not reach the sea but produced a lot of steam from heavy rainfall. In June the eruption is stated to have become Strombolian, with periodic fire fountains ~100 m high and a dark plume rising 1 km (again, fire fountains, especially sustained ones, are typical of "Hawaiian" eruptions, e.g., Valentine and Gregg, 2008, but there is no report of clastogenic lava flows fed by fire fountains). More lava erupted from the vent and flowed down the cinder cone. By September the lava flows reached the sea. Fire fountains from the cinder cone reached 300 m height. The eruption column's top formed a spectacular mushroom of gas and smoke, blowing to the north. Subsequent reports received from the Indian Coast Guard indicated that the eruption was continuous until at least 25 September. All active vents observed during the 2005 eruption lie in a zone trending almost N-S, an alignment also noted for active vents during the 1991 and 1994–95 eruptions. This activity continued through January 2006. Several earthquakes of moderate magnitudes (4–5) occurred in the region around Barren Island between November 2005 and January 2006. In January 2006 geologists observed dense clusters of incandescent pyroclasts of various sizes ejected forcefully from the crater with ballistic trajectories, presumably in discrete "Strombolian" bursts. By September 2006 the activity had slowed and become sporadic. Several ash plumes and red night glows over the crater have been observed since, well into July 2007.

3.5.4 The 2008 -09 eruption

The central cinder cone was sending periodic plumes of dark ash during our first field trip in January 2007, but on our second trip in April 2008 it was in a rather quiet, fumarolic stage (Figs. 3.1a, 3.2b). Red glows over the cone at night, as well as ash plumes rising up to 2.5 km height, are reported between May and November 2008 (http://www. volcano.si.edu). A team of GSI's geologists visited the Island on 7th January 2008, and landed apparently at the same site as our Landing Site 3. It reports the formation of a new cinder cone south of the existing cone, and both cones sending "Strombolian" tephra columns upward in pulsating fashion every 10–60 s. The photographs in their report (http://www.gsi.gov.in/news.htm) suggest instead the development of a parasitic vent southwest of the crater of the existing cinder cone.

On 30 March 2009, we landed on the lava delta on the western shore with a Gemini (inflatable rubber boat) as on previous occasions, and observed the cinder cone, one kilometre to our east, to be in vigorous eruption (Fig. 3.2c). Every few seconds a dark cloud of ash and hot gases would rise from its summit crater, expand, and rise higher and get deflected towards the south by prevailing winds. This was reminiscent of the activity we observed in 2007. The dark clouds that were repeatedly emerging from the summit crater were accompanied by a loud, thunderous sound closely resembling the noise made by a jumbo jet flying low over one's head.

A spectacular new feature of the volcano however is a large steam plume that is rising from the sea, on the northern side of the volcano, away from the lava delta on the west (Fig. 3.2a, c). Initially, while observing this steam plume (as well as the periodic eruption plumes emerging from the cinder cone's summit crater) several kilometres from the island, on board the ship, we could not be sure whether the steam plume was rising from the sea was caused by a submarine, flank eruption (Fig. 3.2c). Getting closer to the volcano revealed that the steam plume was being caused by an active lava flow descending over the cliffs forming the outer caldera wall, on the north side (Fig. 3.2a, c). Thus we are able to confirm a fairly long (estimated to be at least half a kilometre), channelized, active lava flow on Barren Island. What is significant is that this lava flow has taken a completely different direction and route than all the historic through recent flows, which flowed westward to the sea through the caldera wall breach after erupting from the cinder cone.

What caused this major shift in the lava route (north instead of west)? It is apparent that the active lava flow is not ensuing from the summit crater of the cinder cone, as most of the historical and recent lava flows have done. The active lava flow is issuing apparently from an intermediate elevation on the cinder cone, by eroding through its loose tephra, though details were hard to distinguish given the distance of the ship from the island. The path of the active lava flow can be approximately guessed by burning vegetation as it moves through the forest on the caldera wall. It appears that the pre-existing valley between the cinder cone and the northern caldera wall, which existed till our second visit in April 2008, has been completely filled up by deposition of voluminous new ash since then. This has therefore enabled the new, active lava flow to completely abandon the westerly route and to take a “short cut” to the sea over the northern caldera wall.

The new flow is channelized, like all Barren Island aa flows, and aa flows in general, and is currently descending at a steep angle over the outer caldera wall’s cliffs on the north side of the volcano, and into the sea. It has built a structure resembling an alluvial fan along the shore, which can be called an embryonic lava delta. Incandescent lava is seen at a few places along the steep active flow channel, particularly in the dark, and the morphology of the lava flow channel as well as the “lava fan” leaves no doubt that it is an aa flow. We were able to reach this “lava fan” by using a Gemini from the ship, carefully circumventing the steam plume and sharp rocks underneath and through seawater which was very hot (an estimated ~60–70°C). We could collect lava samples from the southern edge of this lava fan”, which are typical clinkery aa basalt in hand specimen, black in colour.

3.5.5 The 2010 - 11 eruption

Our group revisited Barren Island volcano in December 2010. They have observed the shape of the Island which is changing with time and also the nature of eruption on the volcano is changing compared with our last trips. They have observed central cinder cone was sending periodic plumes of dark ash like our first field trip in January 2007, but the intensity is more powerful then 2007. The activity of plume eruption is typical mushroom type of plumes of dark ash which pulsating in every 5 - 10 minutes (Fig. 3.10a, b), that indicate typical strombolian nature of eruption. They have also observed that all the lava flows are covered by recent ashes which suggest that the volcano erupted huge amount of ash in between 2009-10 (3.10c, d).

3.6 The nature of the caldera-filling aa flows

Aa and pahoehoe are the two fundamental types of basaltic lava flows (e.g., Macdonald, 1953; Peterson and Tilling, 1980; Rowland and Walker, 1990). All Barren Island lava flows, prehistoric through recent, are aa, including blocky aa. There is no pahoehoe on Barren Island, arguably due to (i) somewhat lower eruption temperatures of the lavas, consistent with melt inclusion studies and water-present melting in arcs (Luhr and Haldar, 2006), and (ii) high strain rates experienced by the flowing lavas due to the steep ground slopes.

It is difficult in the field to distinguish between the aa flows issued in 1991, 1994–95 and 2005–06. The flows are distinctly channelized, as is typical of aa flows worldwide, and the whole aa flow field is made up of ridges of the aa flows sloping towards the sea but with overall surface amplitude of as much as 25 m. From a distance the aa lava streams can be distinguished by subtle colour differences (shades of grey through black, with darker shades for younger lavas), and the younger lava streams can be seen to have left some "islands" of the older lavas between them (Fig. 3.9a). All these aa flows have jagged, very sharp and highly vesicular clinker at the top (Fig. 3.9b), based on which they can be characterized as proximal aa (terminology of Rowland and Walker, 1987). They also show massive cores at several places (Fig. 3.9b, c), as do all Barren prehistoric aa flows (Fig. 3.4e), and aa flows do in general. Rowland and Walker, (1990) describe how massive cores of aa flows can climb up from below the surface clinker along ramp structures,

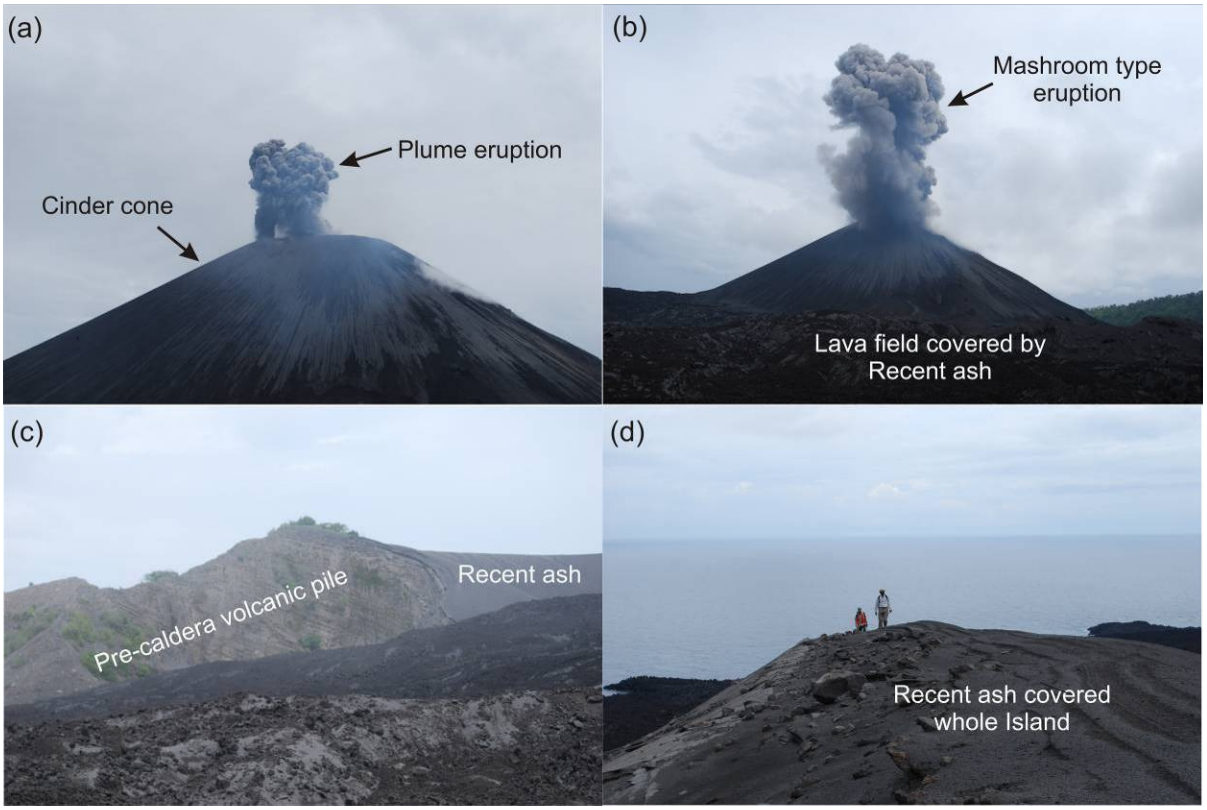

Fig. 3.10 ***a-d*** *Most recent ash blankets (2010-2011) on Barren Island volcano covered all the lava flows of the Island*

once the aa flow front has come to a halt and aa behind the front continues to flow forward. This is particularly seen in what Rowland and Walker (1990) term distal aa. One such ramp structure is shown in Fig. 3.9b.

An intriguing morphological type of aa makes up a small part of the aa flow field near Landing Site 3 on Barren Island (Figs. 3.2, 3.9c–g). Its surface crust has been extensively broken into plates or slabs throughout, whereas it shows well developed aa cores underneath (Figs. 3.8e, 3.9c). Evidently, the broken slabs of the surface crust— any of them razor sharp— were carried along atop largely molten, mobile aa lava (which later solidified as the cores) and in the process experienced rotations, overturning, and even collisions.

An intriguing feature of this aa flow is that, locally, its surface crust is distinctly bent into convex upward shapes, resembling the tumuli common in pahoehoe flows which form by localized inflation (e.g., Anderson et al., 1999; Fig. 3.9e–g). Tumuli are most common in tube-fed pahoehoe flows (e.g., Walker, 1991; Rossi and Gudmundsson, 1996; Mattsson and Höskuldsson, 2005; Sheth, 2006), though they are also known from aa flows (e.g., Duncan et al., 2004; Lodato et al., 2007). These tumuli-like uplifts, elliptical in plan, and with long axes of 5–10 m, are approximately transverse to the overall flow direction. They also exhibit well developed, smooth, axial and axis-perpendicular clefts (Fig. 3.9e–g) usually associated with true tumuli. By analogy, these clefts should indicate periodic crack propagation from the surface downward into viscous lava, consistent with tensional cracking of bulging, uplifting crust (e.g., Anderson et al., 1999).

An interesting aspect of the convex tumuli-like features is the long, linear, closely-spaced wrinkles or "corrugations" that run across the surface, parallel to their long axes and axial clefts (Fig. 3.9f, g). Shanker et al. (2001), without giving location information, have illustrated very similar, possibly the same, outcrops, judging from their photographic figures 1.23 (showing upturned slabs) and 1.24 (showing slabs with "corrugated" surfaces). They described the latter as "pahoehoe with ropy structure", but these lavas are neither ropy nor pahoehoe. Note that the strong visual impression of continuous grooves and ridges imparted from a distance (Fig. 3.9f) is illusory; when traced these terminate and splay laterally, and are actually arranged en echelon (Fig. 3.9g).

Guest and Stofan (2005) have described comparable examples from the 1983 eruption of Mount Etna. These Etna flows have continuous, level slabs of pahoehoe crust normally 1–2 m wide and tens of metres long, and they typically erupt from ephemeral boccas which develop at a late stage of development of an aa flow field. They call these flows "slab-crusted" flows, and note their similarities with the "toothpaste aa" flows described from Hawaii by Rowland and Walker, (1987). Toothpaste aa (also called spiny pahoehoe) typically issues from boccas within aa flows. The linear grooves and ridges of spiny pahoehoe are parallel to the local flow direction, and are believed to reflect the roughness of the boccas' cross-sections. Tumuli are not unexpected in toothpaste aa; in fact, Walker (1991) writes that some of the best examples of tumuli are found in toothpaste aa. Rowland and Walker (1987) also illustrate imbricate stacking of surface plates or slabs on a toothpaste aa flow tongue (their Fig. 3.7), within a broader aa flow field, much as in the Barren Island flow.

We therefore consider this flow to represent a form of toothpaste lava, with which it shares many characteristics (Rowland and Walker, 1987; Guest and Stofan, 2005). This flow forms a part of the present-day western coastline as well as the edge of the lava delta. Its location is significant, as it provides indirect information about its likely age, a matter of some confusion in the literature. Shanker et al. (2001, Fig. 1.24) ascribed this toothpaste aa flow (whose corrugated surfaces they described as "ropy pahoehoe") to the historic (1787–1832) eruptions. But if this is indeed historic, how does it form the edge of the lava delta which is overwhelmingly made up of the recent (1991, 1994–95 and 2005–06) flows? Note that this toothpaste aa flow cannot represent a long and isolated promontory of an historic aa flow, jutting out into the sea much more west than other historic flows and which the recent lava flows might have failed to cover. No such promontory is visible in the photograph of March 1990 (Fig. 3b in Luhr and Haldar, 2006) which shows the extent of the historic flows. In fact we find no grounds for allocating this flow to the historic eruptions (~150–250 years old), and also note its freshness and lack of alteration despite the moist, tropical climate, and, most important, the absolutely total absence of vegetation on it. In comparable settings, such as Hawaii, new vegetation begins growing on lava flows only a few years after their emplacement (Macdonald et al., 1983).

The confusion is further accentuated by a January 2009 report by a GSI geologists' team, referred to earlier. This report (http://www.gsi.gov.in/news.htm) contains a photograph (their Fig. 4) of the lava flow on the northern side of their landing site (our Landing Site 3). This is exactly the toothpaste aa flow we have illustrated in our Fig. 3.9c, and the said report considers this flow as having erupted between July 2005 and March 2006. But this toothpaste aa flow cannot be a 2005–06 flow, because photographs of it appear in Shanker et al. (2001), and eyewitness accounts have described the 2005–06 flows as having flowed mainly along the far northern edge of the recent flow field. Therefore the most likely date for this toothpaste aa flow is either 1991 or 1994–95. Noting that the 1994–95 aa flows cover a major portion of the recent aa flow field (Fig. 3.2, 3.9a), the latter is the more probable of the two.

Recently Pal et al. (2010) attempted to explain magmatic evolution of all the eruptions on the Barren Island except 2009. They have reported that due to inaccessibility of the Island they could not able to collect 2009 eruption samples which we have collected and reported in Sheth et al., 2009. For magmatic correlation of the different eruptions of the Barren Island lavas their approach was field and experimental based. They did petrography, major, trace and mineral chemistry of Barren lavas. Based on the petrological studies they have reported the nature of the lavas of Barren Island has changed due to magmatic differentiation during its residence in the diapers/ magma chamber. Based on mineralogical compositions they suggest that due to changing of eruption styles from Strombolian to Plinian its lava compositions have changed and argued that the recent magma chamber is shallower then older eruptions.

On the basis of major and trace element contents Pal et al. (2010) explained that the 2005 and 2006 lavas are not from same parental melt because the 2005 lava has restricted and clustering nature compared to 2006 lava and this nature imply that the earlier lava experienced more accumulation process with later one. They have also argued that the enrichment of large ion lithophile compared to high field strength elements in Barren magma is because the source mantle peridotite is already enriched with subduction zone component and mentioned low degree of partial melting on the basis of high Zr content of 2005-06 lava and other eruptions.

Further Pal et al. (2010) reported very low water content in Barren magma and produced a magma genesis model for Barren lavas. They have suggested that Barren basalt is nearly anhydrous so the malting is controlled by upwelling and pressure release process. They have used mantle diaper model which was reported by Tamura, 1994. On that model they have argued that 2005 eruption are due to thick, hot and dry rind of mantle diaper supplied substantial basaltic volcanism where as the wet core of diapers produce lavas during 2006 eruption.

3.7 The cinder cone and recent ash cover

The central cinder cone on Barren Island has existed for the past 220 years at least, and must be described as polygenetic. In the time between the historic eruptions, which ended in 1832, and the first of the recent eruptions, in 1991, Barren Island's cinder cone managed to survive erosion, testifying to the general rule that cinder cones are well sorted and highly permeable, which means slow erosion because of little surface runoff (Segerstrom 1950; White et al., 1997). This cinder cone lost half its original height during the 1991 eruption (225 m above sea level at the end of the eruption), but grew higher and steeper again during the 1994–95 and 2005–06 eruptions, so it now rises well over 400 m above the sea. It is already active in a new eruption—so far only of tephra—that began in 2008. If activity persists, new lava flows are not unexpected.

Fine ash from the 1991 eruption, after the associated aa flows were erupted, reportedly covered the flows, and the rest of the volcano around the cinder cone was under ash up to 3 m thick. This was quickly removed by rain from over the 1991 flow as reported by Shanker et al. (2001). The possibly syn-caldera ash beds as well as the ash blanket deposited during the historic and recent eruptions are now deeply gullied (Figs. 3.8e). Fall of fine ash can also cause gullying of older, previously stable, landscapes (Segerstrom 1950, 1966). However, the recent eruptions have also deposited a large amount of dark grey ash and cinders on the southern and southeastern side that when incandescent burned part of the thick forest (Fig. 3.2c).