The landing of the NEAR-Shoemaker spacecraft on asteroid 433 Eros

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The NEAR-Shoemaker spacecraft was designed to provide a comprehensive characterization of the S-type asteroid 433 Eros (refs 1–3), an irregularly shaped body with approximate dimensions of 34 × 13 × 13 km. Following the completion of its year-long investigation, the mission was terminated with a controlled descent to its surface, in order to provide extremely high resolution images. Here we report the results of the descent on 12 February 2001, during which 70 images were obtained. The landing area is marked by a paucity of small craters and an abundance of 'ejecta blocks'. The properties and distribution of ejecta blocks are discussed in a companion paper[4]. The last sequence of images reveals a transition from the blocky surface to a smooth area, which we interpret as a 'pond'. Properties of the 'ponds' are discussed in a second companion paper[5]. The closest image, from an altitude of 129 m, shows the interior of a 100-m-diameter crater at 1-cm resolution.

The main goal of the Near Earth Asteroid Rendezvous (NEAR) landing was to capture images of Eros at extremely high resolution, potentially improving the resolution by a factor of 10 over the best images (resolutions of about 0.3 m per pixel) acquired during the low-altitude flyover on 28 January 2001 (ref. 6). The imaging sequence consisted of two parts. First, two 6-frame monochrome mosaics were acquired following the first of five braking manoeuvres and used by the navigation team to calculate the timing shift for the final burns and the initiation of the final imaging sequence. The second and primary part of the descent imaging consisted of a continuous set of frames that began just before the start of the second braking manoeuvre and continued uninterrupted through the three remaining burns until 15 min after the predicted time of contact with the surface, to allow for the latest probable landing time in the event of over-burns that would cause the spacecraft to stay aloft longer.

The sequence contained monochrome images (760 nm) with image spacing that alternated between 20 and 45 s. Images were returned to Earth immediately using a new method in which the images were buffered in real-time and then played back while the next set was being acquired. All images were shuttered using an exposure of 15 ms to limit smear. Here we summarize the major insights about the surface of Eros obtained from the images. More detailed analyses of specific observations are provided in accompanying contributions describing ponded deposits[5] and ejecta blocks[4].

The selection of the landing site was dictated by several practical considerations that are summarized in the legend to Fig. 1. One aim was to land the NEAR spacecraft in a region where details of surface modification by ejecta and downslope movement of regolith could be studied. We hoped to land in the vicinity of one of the enigmatic 'ponds' discovered during the 28 October 2000 low-altitude flyby[6] and viewed at even better resolution (0.5 m) in late January 2001. The location of the landing site, within the 9-km depression Himeros, is shown in Fig. 1 (arrows). Several reconstructions of the final trajectory yield estimates of the landing location, which differ by several hundred metres on the surface of Eros. The best solution, supported by the appearance of the surface in the final images, indicates that NEAR landed inside a degraded crater about 100 m in diameter at 35.7° S, 279.5° W. A strong supporting

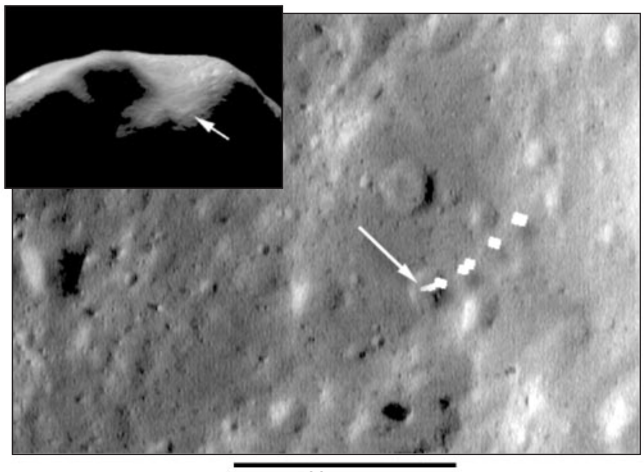

Figure 1 The NEAR landing site (35.7° S, 279.5° W). Outlines of the last ten frames are indicated. The final four images (Fig. 3) fall inside the 100-m-diameter crater indicated by the arrow. The descent trajectory was designed to maximize the number of images of the surface from altitudes below 5 km. Minimizing the impact velocity was a secondary goal. To maximize image downlink capability, the spacecraft had to maintain constant high-gain antenna contact with the Earth. The NEAR-Shoemaker (NEAR) spacecraft has fixed instruments, radio antennas and solar arrays. This limited the possibilities for imager pointing. Because the rotation pole of Eros lies almost in the plane of the asteroid's orbit about the Sun, the solar latitude during February 2001 was at 85° S, with southern latitudes in constant sunlight and northern regions in darkness. Simulations showed that descent trajectories to landing sites along the smaller axis of Eros were less sensitive to orbit determination timing errors than to those on the long axis. The longitude of the touchdown site was selected so that the spacecraft could maintain continuous Earth contact and have the imager pointed at the surface of Eros during descent. Before the descent, the NEAR spacecraft was in a near-circular 34 km by 36 km retrograde orbit. A de-orbit burn of 2.57 m s^{-1} performed on 12 February at 15:14 UTC changed the orbit inclination from 180 degrees to 135 degrees relative to Eros' equator. Four additional braking manoeuvres were pre-programmed to execute at fixed intervals during the 4.5-h controlled descent. The time of impact from Doppler tracking was determined to be 19:44:16 UTC. Post-landing analysis indicated a vertical impact velocity of 1.5 to 1.8 m s^{-1} and a transverse impact velocity of 0.1 m s^{-1} to 0.3 m s^{-1}. The touchdown site was determined to be at 35.7° S, 279.5° W, about 500 m from the nominal site. All times are spacecraft event times in UTC (Coordinated Universal Time). On 12 February 2001, Eros was 2.11 astronomical units (AU) from Earth corresponding to a one-way light time from the spacecraft to Earth of 17 min 34.5 s. Inset, a global view of Eros showing the landing site within the large 9-km depression Himeros. The inset spans 17 km.

argument is that the last image shows that the spacecraft landed on or within a few metres of a pond, a landform known to occur predominantly on the floors of craters[5,6].

At the beginning of the descent-imaging sequence, the geometry was non-optimal for discerning details of surface morphology (high Sun, oblique viewing) but improved as the spacecraft approached the surface. The last views were obtained under ideal illumination (Sun 26° above the horizon) looking almost vertically (16° off vertical). In all, 70 images were obtained during the final sequence over about 37 minutes beginning at a range to the surface of about 7 km (resolution of 70 cm per pixel) and ending at 129 m (resolution of 1 cm per pixel). The camera remained in focus throughout.

As expected from previous lower-resolution views[6], the landing region displayed a subdued appearance, with degraded and apparently filled-in craters dominating the landscape, with abundant evidence of ejecta blocks and regolith. The nature and the size distribution of the ejecta blocks is discussed in detail in ref. 4.

As the spacecraft reached altitudes below 1 km (resolution of 10 cm per pixel or better) local differences in surface texture became evident. The morphology of the surface remained generally blocky

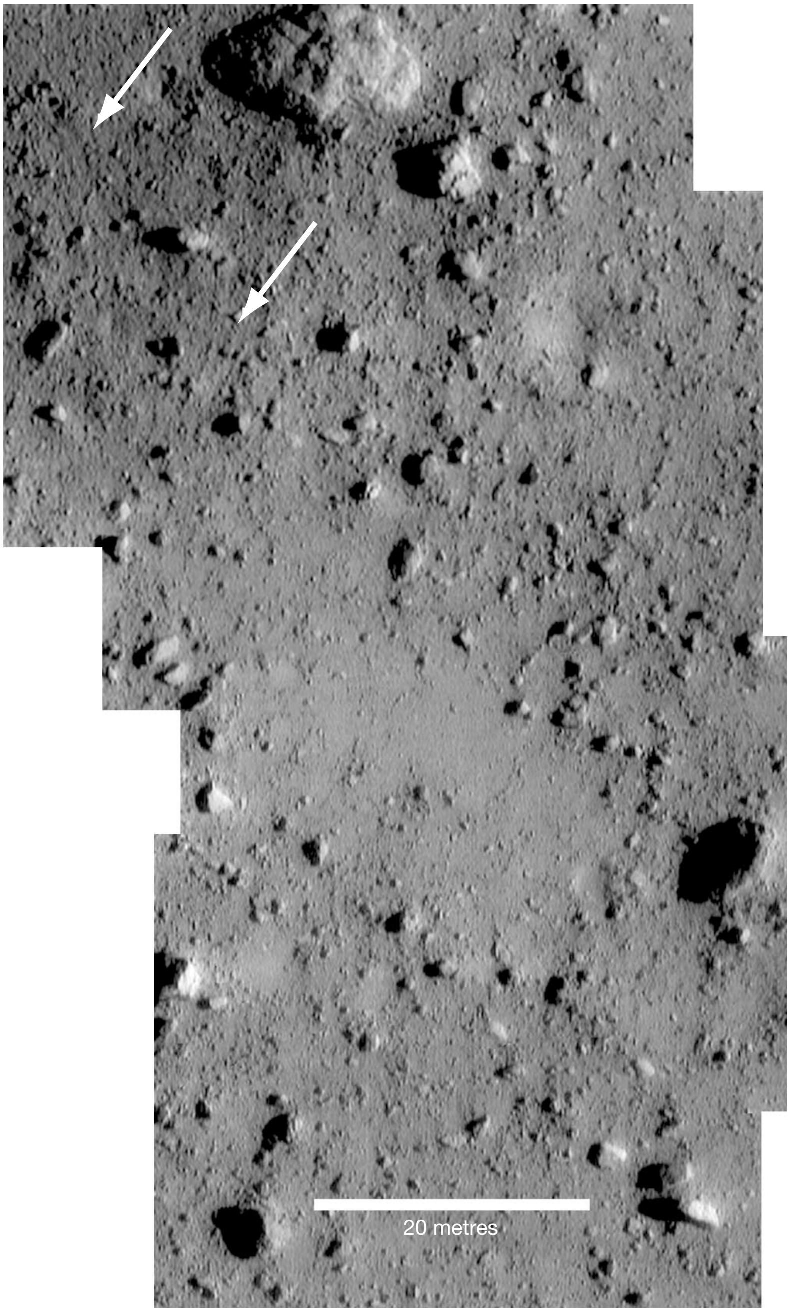

Figure 2 Details of regolith morphology at high resolution. White arrows point to furrow-like lineations with some sinuosity trending from top to bottom in the general direction of the smooth area near the middle of the mosaic. This direction coincides with the general trend of numerous apparent alignments of small rocks and positive relief features at the limit of resolution throughout the mosaic. Images MET 157416658, -678 and -743. Average range, 900 m (resolution of 90 cm per pixel). The NEAR camera, the MSI, covers the spectral range from 400 to 1,000 nm and has a 2.25° by 2.90° field of view[13,14]. The 244 by 537 charge-coupled device (CCD) has rectangular pixels that subtend 0.95 m by 1.61 m at 10 km. All descent images were obtained through filter 3 centred at 760 nm. Resolutions quoted in this paper correspond to the short dimension of the pixel.

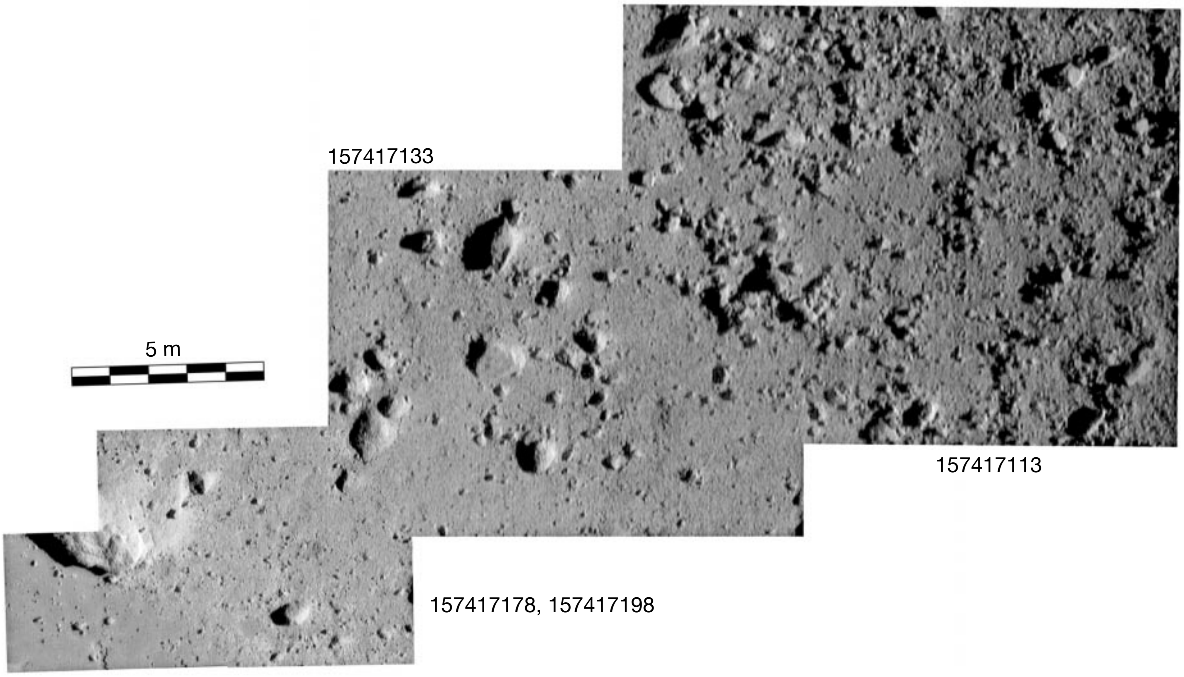

Figure 3 Last four images of the descent sequence, showing the floor of the crater indicated by the arrow in Fig. 1. A gradual transition from a blocky morphology (upper right) to a smooth 'pond' deposit (bottom left) is evident. A 5-m scale bar is included. The best estimate places the actual landing site some 7 m to the left edge of the mosaic. Mosaic of frames MET 157417113, -33, -78 and -98. The spacecraft (with solar panels deployed) is about 6 m across. Although telemetry ceased when the spacecraft landed, carrier lock was maintained indicating that NEAR had survived and was still operational. Telemetry was later restored, and it was determined that NEAR was resting on the tips of two solar panels and the bottom edge of the spacecraft's body. Although the mission was scheduled to end on 14 February 2001, NASA decided to extend the mission by 14 days to gather additional γ-ray spectrometer and magnetometer data. On 28 February, commands were sent to place the spacecraft into a hibernational mode. NASA may try to contact NEAR one more time in September 2002 when NEAR is back in sunlight and Eros is only 0.64 AU from Earth.

but smoother, more block-free areas appeared (Fig. 2). Some of these relatively block free areas have smooth textures, while others appear to be furrowed by linear markings which have characteristics suggestive of downslope displacement of surface material. The sinuous furrows (arrows in Fig. 2) trend in a direction that would move material into the flat, smoother area in the middle of the mosaic of images. This direction coincides with the trend of apparent alignments of small rocks and other positive relief features. One problem is that views from other directions and under different lighting conditions are not available, making it difficult to exclude the remote possibility that some of the apparent alignments are artefacts of the shadowing under the prevailing specific lighting and viewing conditions[7]. Rock fragments down to scales of tens of centimetres are seen to be buried partially in a finer regolith. In many cases very intricate textures can be discerned on the surfaces of the blocks, including pitting, planar fractures and at least one example of a small crater.

The very last sequence of images (Fig. 3) shows a definite transition from a blocky surface (upper right) to a very smooth area (lower left). We interpret the smooth area as a 'pond' and consider the observed transition as a strong clue that the spacecraft landed inside a crater[5,6]. Several unusual morphological features can be seen in the last images (Fig. 4). First, the very smooth (at a scale of 1 cm) texture of the pond deposit at lower left. Second, the occurrence of several collapse pits within the deposit (arrows a and b in Fig. 4A). The smaller ones are about 5 cm across. The largest (arrow a) has several stubby extensions. In all cases the morphology of these pits suggests collapse by removal of subsurface support. Their depth can be estimated at 1 to 2 cm.

All of the larger ejecta blocks in this region are partially buried. In a few cases there may be debris aprons around individual rocks and in one case (arrow c in Fig. 4A) there is clearly a moat-like depression around part of the periphery of a 1-m boulder. Such depressions suggest compaction of a fine textured material, perhaps by a process related to the one responsible for the formation of the pits. There are hints of subtle channel-like depressions (arrow d in Fig. 4A) trending from upper right to lower left in a direction consistent with transporting fine material into the pond area. The transition between the very smooth pond deposit and the surrounding area is fairly abrupt, occurring on a scale of 10 to 20 cm.

It is difficult to compare the detailed regolith morphology of Eros with observations of other asteroids owing to the lack of images of a comparable resolution. The best Galileo views of S-asteroids Gaspra and Ida had resolutions of 60 m per pixel and 30 m per pixel, respectively and were limited to only small fractions of the surfaces[8,9]. The lack of images at metre resolution of Gaspra and Ida precludes any useful comparisons of the average surface density of ejecta blocks or the size distribution of blocks on Eros and the two S-type asteroids studied by Galileo. Data for Mars' satellite Phobos at resolutions of about 3 m per pixel show block populations in the vicinity of the large crater Stickney which are comparable to those on Eros[10].

Nothing comparable to the flat 'pond' deposits has been noted on Gaspra, Ida or Phobos, even though Phobos coverage is certainly adequate to show such features if they were present[10]. Filling in of depressions by finer regolith has been observed on Mars' satellite Deimos but the morphology of such deposits is very different from that of the ponds on Eros[11].

A most remarkable characteristic of the area in which NEAR landed is the scarcity of small craters. The cause remains to be determined[12], but could be related to the transport of regolith into local sedimentary basins[5]. Alternatively it could be due to blanketing by ejecta from a relatively recent large impact[4]. The preservation of copious ejecta blocks suggests that in recent epochs in this region of Eros small craters are more likely to be obliterated by burial than by erosion. □

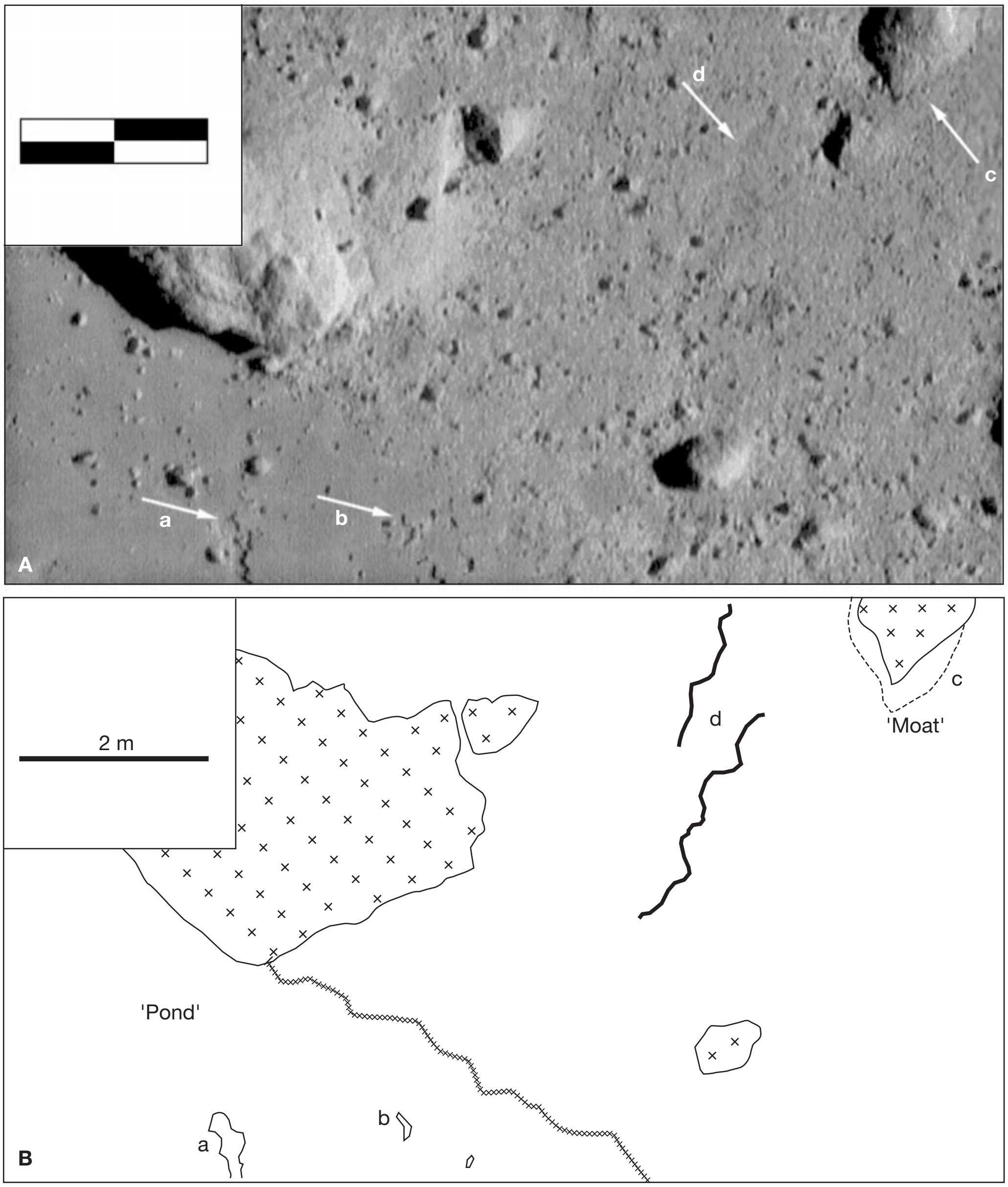

Figure 4 Geological interpretation of the landing site. **A**, NEAR's last two images: details of pond with collapse features. These frames have an average resolution of 1.4 cm. Two enclosed collapse pits are indicated by arrows (a and b) in the smooth pond deposit. Arrow c points to a moat-like depression around a metre-sized boulder. Arrow d marks a subdued, somewhat sinuous, channel-like depression which trends in the general direction of the pond deposit. Mosaic of frames MET 157417178 and -98. Range and resolutions are 167 m (1.6 cm per pixel) and 129 m (1.2 cm per pixel), respectively. Scale bar, 2 m. **B**, Sketch map of **A**. Blocks are outlined with cross filling. Boundary between pond and rougher surface is marked by crossed line. Two sinuous depressions are shown by heavy, solid lines (d). Collapse features are outlined within the pond (a and b).

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