Figure F1. Down-looking sonar image taken inside the pit crater atop the Upper Cone during the camera survey to position Site U1528. The midpoint of the pit crater is determined by the outer arcuate reflectors, which show a near-circular shape. The crater narrows at the bottom and becomes more rectangular. Each ring on the sonar has a 7.5 m radius.

Figure F2. Detailed bathymetry of Brothers volcano and surrounding area showing the location of sites drilled during Expedition 376. Contour interval = 200 m. Modified from Embley et al. (2012).

Figure F3. Interpreted seismic section of Line Bro-3 and projected location of Site U1528 30 m northeast of the line. Proposed Site UC-2A was the alternate site.

Figure F4. Reentry system and casing installation, Hole U1528B. Major components, formation conditions, and associated drilling depths (mbsf) are depicted. The possible bend in the casing string, which formed upon inadvertent drilling-in close to the pit crater wall, caused the reentry system to fail. mbsl = meters below sea level.

Figure F5. TDCS BHA used for coring Hole U1528C. Total length = 17 m. From Miyazaki et al. (2014).

Figure F6. A. Assembled TDCS core barrel on the rig floor, Expedition 376. (Credit: Yuichi Shimmoto, IODP). B. Close-up image of the TDCS polycrystalline compact diamond (PDC) bit during a precoring function test (Credit: Yuichi Shimmoto, IODP).

Figure F7. Drilling assembly consisting of mud motor, bi-center underreamer, and pilot drilling bit, Expedition 376. After Graber et al. (2002).

Figure F8. Reentry system and casing installation, Hole U1528D. Major components and associated drilling depths (mbsf) are depicted.

Figure F9. Hydrothermal plume being expelled from the reentry funnel during third reentry, Hole U1528D.

Figure F10. Drill string components damaged from downhole corrosion. A. Parted end of drill pipe (laid out on the rig floor) recovered from Hole U1528D after losing the lowermost ~172 m of drill string including the BHA during drilling operations upon the seventh reentry (Credit: Tobias W. Höfig, IODP). B. Heavily corroded latch sleeve, recovered from the last coring attempt in Hole U1528D, showing native sulfur and sulfate encrustations that resulted from interaction with highly acidic, S-rich fluids rising through the drill string (Credit: Stephen Midgley, IODP).

Figure F11. Lithostratigraphic summary, Holes U1528A, U1528C, and U1528D.

Figure F12. Representative macroscopic samples, Igneous Unit 1, Holes U1528A and U1528C. A. Polymict dacitic lapilli tephra with blocks/bombs; insets show a spherical grain of native sulfur enclosed by a vesicle. B. Polymict lapilli tephra. C. Bread-crust texture of clast.

Figure F13. Representative clasts from Igneous Unit 1 impregnated in epoxy resin and prepared as a thin section, Hole U1528A. A–B. Perlitic texture in a volcanic clast cut by secondary alteration minerals in (A) plane-polarized light (PPL) and (B) cross-polarized light (XPL). C, D. Crystals of plagioclase present in the matrix of this pyroclastic sediment in (C) PPL and (D) XPL.

Figure F14. Stratigraphic correlation, Hole U1528D. Note the distinction between altered lava (Subunit 2b and Unit 3) and altered volcaniclastic sediments. The primary mineralogy is better preserved in altered lava than in altered volcaniclastic rocks. The macroscopic and microscopic textures are also distinct. Yellow = intervals with a strong H_2S odor.

Figure F15. Representative macroscopic samples from Subunit 2a, Hole U1528D. A. Tuff-breccia with poorly sorted angular to subrounded clasts. B. Darker clasts of least-altered, vesicular plagioclase-phyric dacite separated by hydrofracture filled by fine rock debris. C. Clast-supported lapillistone with highly altered porous dacite clasts with alteration halos. D. Highly altered lava crosscut by hydrothermal veins.

Figure F16. Representative photomicrographs of Subunit 2a, Hole U1528D. A. Polymict volcanic clasts. B. Volcanic clasts. C, D. Formerly plagioclase-pyroxene-magnetite–bearing glomerocryst with pyroxene pseudomorphically replaced by secondary minerals; magnetite (Mt) is being altered to pyrite (Py). Shown in (C) XPL and (D) Refl. (reflected light). Cpx = clinopyroxene. E. Increased alteration results in pseudomorphs after plagioclase (Plag). F. Volcanic clasts with a darker alteration rim and lighter core.

Figure F17. Representative macroscopic samples from Subunit 2b, Hole U1528D. A. Moderately altered, plagioclase-phyric dacite lava. B. Matrix-supported monomict lapilli-tuff. C. Matrix-supported monomict lapilli-tuff with blocks/bombs. D. Highly altered volcanic rock.

Figure F18. A, B. Subunit 2b (Hole U1528D) plagioclase (Plag) and originally also pyroxene-phyric dacite with large glomerocrysts dominated by zoned plagioclase. shown in (A) PPL and (B) XPL. Cpx = clinopyroxene. Note that the secondary minerals form pseudomorphs after pyroxenes, but the plagioclase and volcanic texture appear unaltered apart from cracks filled with secondary minerals. C, D. Similar features encountered in Core 22R. Shown in (C) PPL and (D) XPL.

Figure F19. Representative macroscopic samples from Subunit 2c, Hole U1528D. A. Clast-supported lapilli-tuff. B. Clast-supported lapilli-tuff. C. Clast-supported lapillistone. D. Altered volcaniclastic rock.

Figure F20. Representative microscopic samples of Subunit 2c, Hole U1528D. Images illustrate the increasing loss of any primary volcanic texture throughout this unit. A, B. Clearly visible volcanic clasts with pseudomorphs after plagioclase. Shown in (A) PPL and (B) XPL. C, D. Relict clast in a strongly altered matrix composed of secondary minerals in (C) PPL and (D) XPL. E, F. An example where all primary volcanic textures are lost in (E) PPL and (F) XPL.

Figure F21. Representative macroscopic samples from Igneous Unit 3, Hole U1528D. A. Moderately altered, plagioclase-pyroxene-phyric dacite. B. Highly altered volcanic rock. C. Intensely altered volcanic rock. D. Completely altered volcanic rock.

Figure F22. Relatively unaltered dacitic lava in Igneous Unit 3, Hole U1528D. A, B. Trachytic groundmass texture with aligned plagioclase microlites and glomerocrysts of plagioclase (Plag) and Fe-Ti oxides and partially altered clinopyroxene (Cpx). Shown in (A) PPL and (B) XPL. C, D. Glomerocryst with twinned but unzoned plagioclase, a pseudomorph after pyroxene, and Fe-Ti oxides. Shown in (C) PPL and (D) XPL.

Figure F23. Results from pXRF analyses performed on Site U1528 rock powders showing low K_2O and Rb concentrations of altered volcanic rocks from Site U1528 relative to unaltered dacite recovered from Sites U1527 and U1529.

Figure F24. Results from pXRF analyses on rock powders, Site U1528. Depth-dependent variations of Ti/Zr values and Rb concentrations illustrate the impact of alteration on the dacite protolith. Small arrows = intervals with fresh plagioclase phenocrysts preserved (Figure F14).

Figure F25. Stratigraphic column, Site U1528. Macroscopic and mineralogical observations and variation in dominant alteration type based on XRD, thin section, and hand specimen description.

Figure F26. Representative cores from alteration types observed at Site U1528. A. Type I. B. Type II. C. Type III. D. Top: Type IV crosscutting Type II. Bottom: Type IV crosscutting Type III.

Figure F27. Two prominent native sulfur morphologies. A. Crystalline (orthorhombic) sulfur. B. Globular spheres of native sulfur.

Figure F28. Alteration Type I, Hole U1528A. A. Native sulfur globule infilling vesicle in slightly altered dacite clast. B. Representative clast and gravel material with some clasts exhibiting moderate alteration.

Figure F29. Alteration Type II, Hole U1528D. A. Blue-gray matrix containing unaltered plagioclase phenocrysts with patches of white alteration containing silica and the occasional open vug. B. Dark blue-gray matrix crosscut by a network of fine silica-pyrite veins.

Figure F30. Progressive alteration of plagioclase (XPL), Site U1528. A. Unaltered plagioclase (Plag) with pseudomorphed clinopyroxene (Cpx-pseudo). B. Resorption of plagioclase: plagioclase core rimmed by illite and anhydrite (Anh). C. Pseudomorphed plagioclase replaced by natroalunite (Nal), silica, and gypsum (Gyp) in Alteration Type III.

Figure F31. Alteration Type II, Hole U1528A. A. Natroalunite (Nal) forming the dominant matrix phase. B. Progressive replacement of plagioclase by natroalunite (outlined by dashed green line) and a pyroxene phenocryst pseudomorphed (Cpx pseudo) by a rim of clay, anhydrite (Anh), and pyrite (Py). C. Pyrite preferentially forming along crystal boundary (red dashed line) during alteration of clinopyroxene (Cpx).

Figure F32. Progressive oxidization of titanomagnetite (Ti-mt) to pyrite (Py), Alteration Type II, Site U1528. A. Pyrite mantle around titanomagnetite. B. Near-complete replacement of titanomagnetite by pyrite. C. Complete replacement of titanomagnetite by pyrite. Inset: high-magnification image of pyrite exhibiting skeletal texture. Shown in reflected light (RL).

Figure F33. Alteration Type III, Hole U1528A. A. White matrix surrounds gray, zoned clasts. B. Localized narrow veins of dark anhydrite with lighter halo.

Figure F34. A. Clast/matrix boundary, Alteration Type III, Hole U1528A. Clast is smectite rich, whereas matrix is rich in pyrophyllite (Pyro), quartz (qtz), and natroalunite (Nal). Cris = cristobalite. Plagioclase (Plag) in a clast is pseudomorphed (pseudo) by natroalunite. B. Matrix material showing intergrowth of pyrophyllite, quartz, and natroalunite with smectite (Smec). C. Plagioclase crystal replaced by pink-gray smectite.

Figure F35. Pseudomorphed plagioclase and pyroxene in clasts, Alteration Type III, Site U1528. A. Natroalunite (Nal) and quartz pseudomorphing plagioclase. B. Plagioclase glomerocryst pseudomorphed by anhydrite (Anh), natroalunite, and clay. Gyp = gypsum, smec = smectite. C. Pyrite (Py) associated with possibly leucoxene. Pyro = pyrophyllite. Shown in RL.

Figure F36. Alteration Type III, Site U1528. A. Natroalunite (Nal) pseudomorphing plagioclase cut by an anhydrite-pyrite (Anh-py) vein (dashed red line). B. Anhydrite-gypsum (Anh-gyp) vein cutting a gypsum-natroalunite pseudomorphed plagioclase phenocryst. C. Large granular anhydrite-gypsum vein truncating a smaller gypsum vein. Pyro = pyrophyllite, qtz = quartz, Native S = Native sulfur.

Figure F37. Matrix and clasts cut by a network of pyrite-rich veinlets, Alteration Type III, Site U1528. A. Pyrite (Py)-anhydrite vein cutting altered smectite (Smec)- and natroalunite (Nal)-rich matrix. Vein shows a millimeter-scale, white, silica-rich alteration halo. B. Vug infilled with anhydrite (Anh) and euhedral pyrite. C. Anhydrite exhibiting dissolution features in a smectite-pyrophyllite (pyro) matrix. Qtz = quartz.

Figure F38. Alteration Type IV, Site U1528. A. Type IV alteration overprint with preservation of Type II brecciated texture. B. Discrete alteration pathways with well-developed vuggy texture cutting and enclosing clasts of Type II alteration. C. Veins of Type IV cutting Type III. Center of the vein is infilled with native sulfur (Native S).

Figure F39. Contact between Alteration Types III and IV, Site U1528. A. Alteration halo at contact between Type III and Type IV. Pyrite becomes progressively less abundant with proximity to Type IV contact due to destruction of pyrite (RL). B. Increased abundance of microcrystalline silica, native sulfur (native S), and minor natroalunite (Nal) in Type IV, relative to dark matrix material of Type III (transmitted light).

Figure F40. Box outlines area containing latest drusy anhydrite in an open vug (376-U1528D-18R-2, 68–69 cm; 140.7 mbsf).

Figure F41. Types of FIs, Hole U1528D. A. Type 1a. B. Type 1b. C. Type 2; complex FIs in anhydrite with multiple anisotropic daughter minerals that are probably sulfates. D. Type 2; complex FIs, immiscible sulfur-bearing fluid in anhydrite. E. Type 2; complex FIs, sulfur in gypsum FI. F. Type 3; vapor-filled FI with daughter minerals. $T_{h(l)}$ = temperature homogenized to liquid, diss = dissolultion, $T_{h(l)}$ = temperature homogenized to liquid.

Figure F42. Range (blue lines) and median (red dots) of fluid homogenization temperatures with depth compared with the Schlumberger wireline measured temperature (dashed green line), Hole U1528D. Black dotted line is boiling point curve (BPC) calculated for 3.5 wt% NaCl at 125 bar. Also plotted are occurrences of gypsum deposits (dep.) and temperature (t) ranges indicated by alteration assemblages at and below 240 mbsf.

Figure F43. Salinity (NaCl wt% equivalent) vs. homogenization (H) temperature and corresponding enthalpy of water (kJ/kg) in the liquid phase, Site U1528. NaCl solubility curve calculated from Bischoff (1991). Also shown is the salinity of seawater (sw). bc = boiling curve

Figure F44. Vein attributes, Hole U1528A. Alteration vein dip inset: histogram of vein dips with 10° bins. Black curve = expected distribution of a random set of vein dips sampled by a vertical borehole (see Structural geology in the Expedition 376 methods chapter [de Ronde et al., 2019a]). There is a large range in dip magnitude, an acme in vein thickness, and a decrease in vein density from 45 to 65 mbsf.

Figure F45. Vein morphologies, Hole U1528A. A. Anhydrite-filled vein with anastomosing shape. Vein formed between clasts and not through them. B. Irregular anhydrite vein meandered between clasts. C. Irregular composite vein filled with anhydrite, gypsum, and native sulfur. Thickest portion of vein is deflected around volcanic clasts; however, some veins penetrate into clast. D. Volcanic (Volc.) clast on the left in C (XPL). Vein outer margin is filled with anhydrite (Anh); median line is partially filled with native sulfur (S). The vein also contains gypsum (Gyp). A previous gypsum vein (top left of image) is cut by the thicker anhydrite-gypsum-native sulfur vein. The growth habit of the earlier gypsum vein is subvertical and in two parts, whereas the anhydrite-gypsum-native sulfur vein has a more irregular growth habit.

Figure F46. Volcanic fabric intensity and dip angle, Hole U1528D.

Figure F47. Examples of volcanic fabrics, Hole U1528D. A. Steep volcanic fabric defined macroscopically by the alignment of vesicles. B. Volcanic fabric defined macroscopically by aligned vesicles. C. Steep volcanic fabric defined by the alignment of plagioclase. D. Steep volcanic fabric defined by aligned plagioclase microlites and to some extent phenocrysts (Plg) (PPL). Upcore is to the top of the page. Mtx = matrix.

Figure F48. Volcanic fabrics in different volcanic clasts, Hole U1528D. A. Interval with several volcanic clasts, each with a volcanic fabric with a distinct orientation. White arrows = clasts with fabrics. B. Clasts whose fabrics are not obvious, masked by alteration. C. Fabrics within clasts evident in thin section when not macroscopically obvious (as in B). Many clasts have a fabric, but fabrics do not share a common orientation (black arrows are parallel to fabric apparent dip).

Figure F49. Alteration vein attributes, Hole U1528D. Several intervals have a large range in dip angle; others have a more limited range and steep dip. Alteration vein dip inset: histogram of vein dips in 10° bins. Black curve is the expected distribution of a random set of vein dips sampled by a vertical borehole (see Structural geology in the Expedition 376 methods chapter [de Ronde et al., 2019a]). Vein dips are positively skewed. Vein thickness inset: histogram of vein thickness in 0.2 cm bins. The vast majority of vein dips are between 0 and 0.2 cm thick.

Figure F50. Alteration vein types, Hole U1528D. A. Uniform vein with a thin halo filled with anhydrite and pyrite. B. Intersecting veins: one steep, the other subhorizontal. At the intersection is a vug of anhydrite. C. Discrete vein surrounded by discontinuous halo (extreme left side of piece). D. Network vein with less disrupted host rock (near bottom of image) to completely replaced protolith (top of image) is example of the highest vein density.

Figure F51. Fracture attributes, Hole U1528D. Fracture dip inset: histogram of fracture dips in 10° bins. Black curve is the expected distribution of a random set of fracture dips sampled by a vertical borehole (see Structural geology in the Expedition 376 methods chapter [de Ronde et al., 2019a]).

Figure F52. Total sulfur (TS) and TC determined by elemental analyzer, together with TOC, Site U1528. Visual estimates of pyrite and native sulfur abundances (in vol%) are also shown for comparison.

Figure F53. A. S (SSO_4) vs. Ca measured in leach solutions (mM), Site U1528. The regression line close to unity suggests that the Ca/S ratio in leached material is similar to pure anhydrite $CaSO_4$. B. Sr vs. Ca in water-soluble mineral (predominantly anhydrite) showing two different trends suggesting different compositions and potentially origins of anhydrite in the samples.

Figure F54. Downhole variations of immobile or poorly mobile trace element Zr and element oxides TiO_2 and Al_2O_3 and values of Zr/Ti and Y/Zr, Site U1528. Horizontal dashed lines = depth intervals marked by major geochemical changes and alteration types, as discussed in the text. Vertical gray shaded area = compositional range for unaltered dacites from Igneous Unit 1 of Hole U1528A and Site U1529 and represents 2σ from the average value. Only ICP-AES data are reported except for pXRF-generated data. Geochemical data are reported for comparison with the degree of alteration and macroscopic estimates of rutile, plagioclase, augite, and Fe-Ti oxide in each core.

Figure F55. Downhole variations of major element oxides CaO, K_2O, MgO, Fe_2O_3, and SiO_2, Site U1528. Horizontal dashed lines = depth intervals marked by major geochemical changes and alteration types, as discussed in the text. Vertical gray shaded area = compositional range for unaltered dacites from Igneous Unit 1 of Hole U1528A and Site U1529 and represent the 2σ from the average value. Only ICP-AES data are reported except for pXRF-generated data. Geochemical data are reported for comparison with the degree of alteration and macroscopic estimates of smectite and illite in each core.

Figure F56. Downhole variations of trace elements (Ba, Sr, and Mn) and total sulfur (S), Site U1528. Horizontal dashed lines = depth intervals marked by major geochemical changes and alteration types, as discussed in the text. Vertical gray shaded area = compositional range for unaltered dacites from Igneous Unit 1 of Hole U1528A and Site U1529 and represent the 2σ from the average value. Only ICP-AES data are reported except for pXRF-generated data.

Figure F57. Chemical enrichment factors for Alteration Types I–IV. Each enrichment curve was obtained by calculating the average composition of each alteration type and normalizing to the average composition of the least-altered dacites recovered from Igneous Unit 1 of Hole U1528C and Site U1529. Data for total sulfur are not shown due to the extremely high enrichment factor >100.

Figure F58. Pore space gas concentrations, Holes U1528A, U1528C, and U1528D. Dotted line in ΣCO_2 panel = bicarbonate concentration range in the bottom seawater. Yellow shaded zones (I–V) = positions of possible subseafloor hydrothermal fluid flow.

Figure F59. Measured concentrations of (A) Mg vs. Na, (B) Cl, (C) Br, (D) Si, (E) K, (F) ΣSO_4, (G) Ca, (H) Sr, and (I) ΣH_2S for BFs sampled in Hole U1528D compared with other published compositions of acid-sulfate fluids. Lines = extrapolated source fluid compositions for species exhibiting conservative behavior. 2σ errors are shown or are smaller than the symbols. SW = seawater.

Figure F60. AF demagnetization experiment showing univectorial decay in Sample 376-U1528D-23R-1, 124–126 cm, from Igneous Unit 2. Sample shows a decrease of NRM to ~20% of its original value and a stable primary magnetization for AF >10 mT.

Figure F61. TD experiment in Sample 376-U1528D-12R-3, 90–92 cm, from Igneous Unit 2. Sample shows a complex TD curve with peaks appearing at temperatures greater than ~400°C, suggesting the transformation to different magnetic minerals with increasing temperature.

Figure F62. AF demagnetization experiment showing univectorial decay in Sample 376-U1528D-48R-1, 107–109 cm, from Igneous Unit 3. Sample shows coercivities similar to those in Unit 1 (Figure F60) and a stable primary magnetization for AF >10 mT.

Figure F63. TD experiment in Sample 376-U1528D-63R-1, 17–19 cm, from Igneous Unit 3. Sample shows a relatively intense NRM before demagnetization, typical of the less altered samples from Site U1528. The magnetic overprint from drilling and coring is reduced after heating at temperatures greater than ~200°C, leaving a stable primary magnetization component with univectorial decay.

Figure F64. Intensity of NRM before demagnetization and inclination from PCA after AF and TD experiments (376-U1528D-55R-1, 12–14 cm, with anomalous positive inclination of ~69°, is not included). Black vertical lines = inclinations of a GAD with normal and reversed polarities of 55° and −55°, respectively, at the latitude of Brothers volcano.

Figure F65. Physical properties, Holes U1528A and U1528C. *P*-wave velocity values are the mean for each measurement.

Figure F66. Physical properties, Hole U1528D. *P*-wave velocity values are the mean for each measurement. Data from Hole U1528A (Figure F65) are included as gray symbols for reference.

Figure F67. MAD and *P*-wave velocity data for discrete samples, Holes U1528A, U1528C, and U1528D. Lines show best fit from linear regression.

Figure F68. *P*-wave velocity and anisotropy, Holes U1528A, U1528C, and U1528D.

Figure F69. Results of 18 h NGR analyses to assess relative abundances of radiogenic isotopes in Sections 376-U1528A-9R-1 (top) and 376-U1528D-48R-1 (bottom). ^{40}K accounts for a relatively higher proportion of observed counts in Section 48R-1.

Figure F70. Thermal conductivity of 50 samples compared to alteration type and mineralogy, Site U1528.

Figure F71. Sequence of operations for the series of downhole measurements and sampling in Hole U1528D conducted directly after completing the hole. Pump rate (black lines), cumulative pumped volume (blue line), and the time interval for each downhole measurement (green lines) are shown. See Table T21 for the start and end times of each measurement.

Figure F72. Temperature measurements acquired in Hole U1528D with (A) the LEH-MT on the HTTC tool string and (B) the ETBS tool.

Figure F73. Temperature heat-up profiles (temperature vs. time; orange) for each ETBS measurement, alongside the operation sequence, depth (gray), and pumping rate (blue), Site U1528. A. Run 1. B. Run 2. C. Run 3.

Figure F74. HTTC downhole measurements summary, Site U1528. NGR = natural gamma ray measured downhole with the total spectral gamma ray (HSGR) and on whole-round cores with the WRMSL. cps = counts per second.

Figure F75. Comparison of core and downhole measurements, Site U1528.

Figure F76. Whole-round samples collected for microbiological analyses, Site U1528. Red arrows point to samples selected from highly fragmented core pieces. (Continued on next page.)

Figure F76 (continued).

Figure F77. Identification of microbiological (MBIO) samples relative to igneous units and alteration types, Site U1528. Reduced size samples represent samples that were too small to provide the 20–40 g of material necessary for DNA and RNA extraction. Incomplete samples represent samples that were too small to provide subsamples for both DNA and RNA; only DNA samples were preserved. Possible lateral hydrothermal fluid flow zones were determined by higher concentrations of H_2 (see Geochemistry).