The Discovery of Thirteen Hydrothermal Vent Fields and associated Polymetallic Massive Sulfides in the Central Indian Ocean

by

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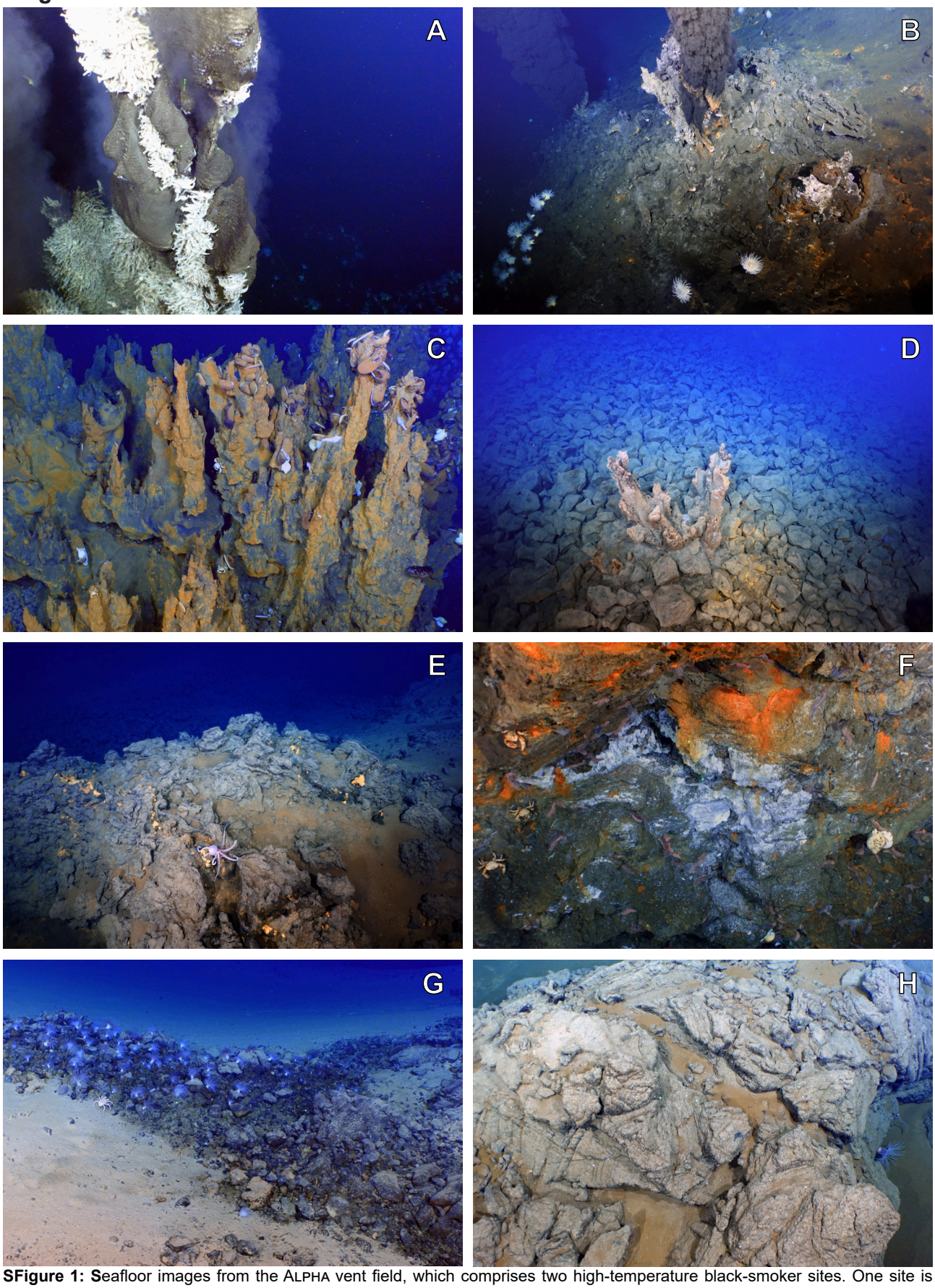
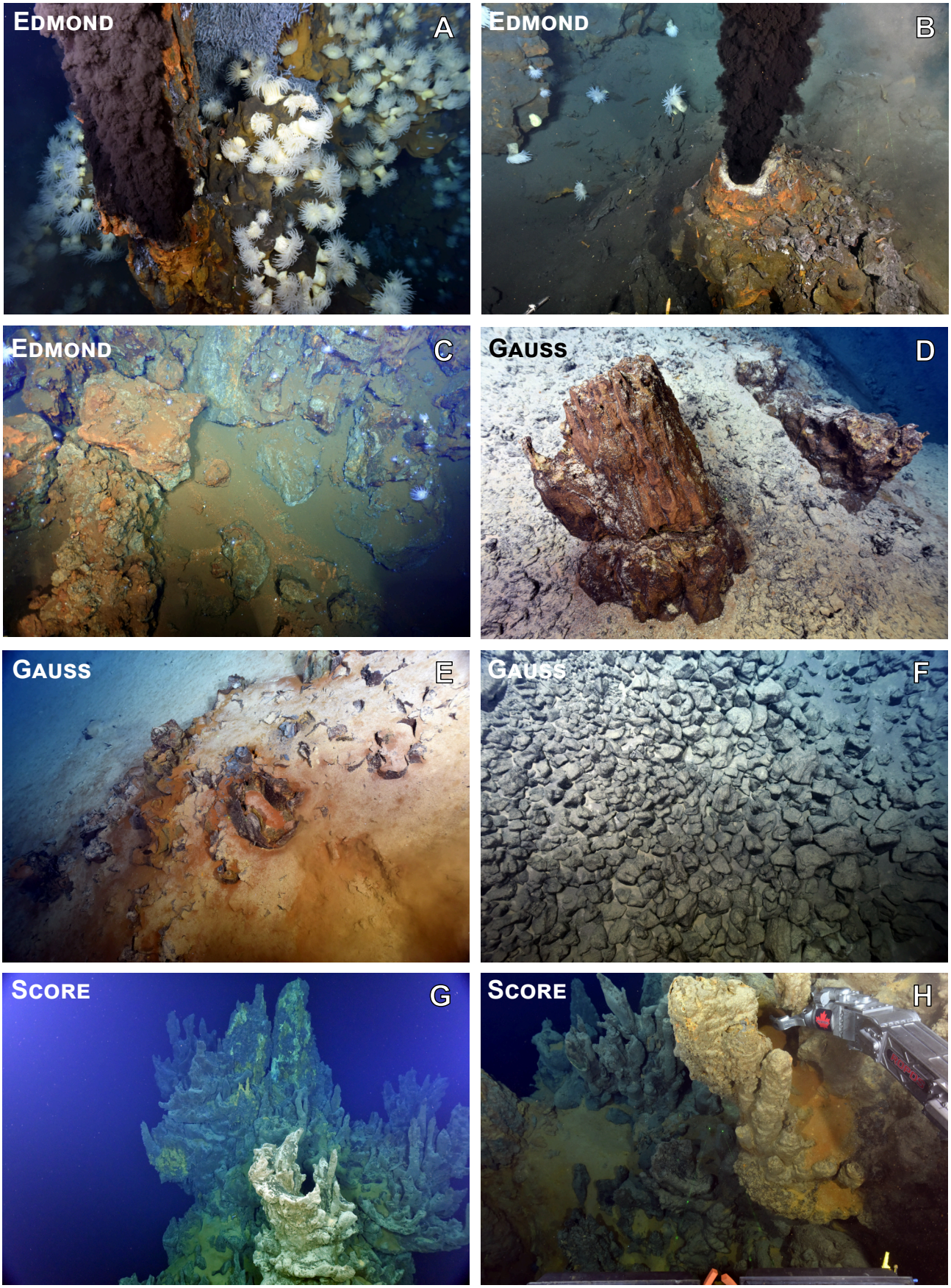
Supplemental Figures 1 - 14

SFigure 1: ALPHA vent field



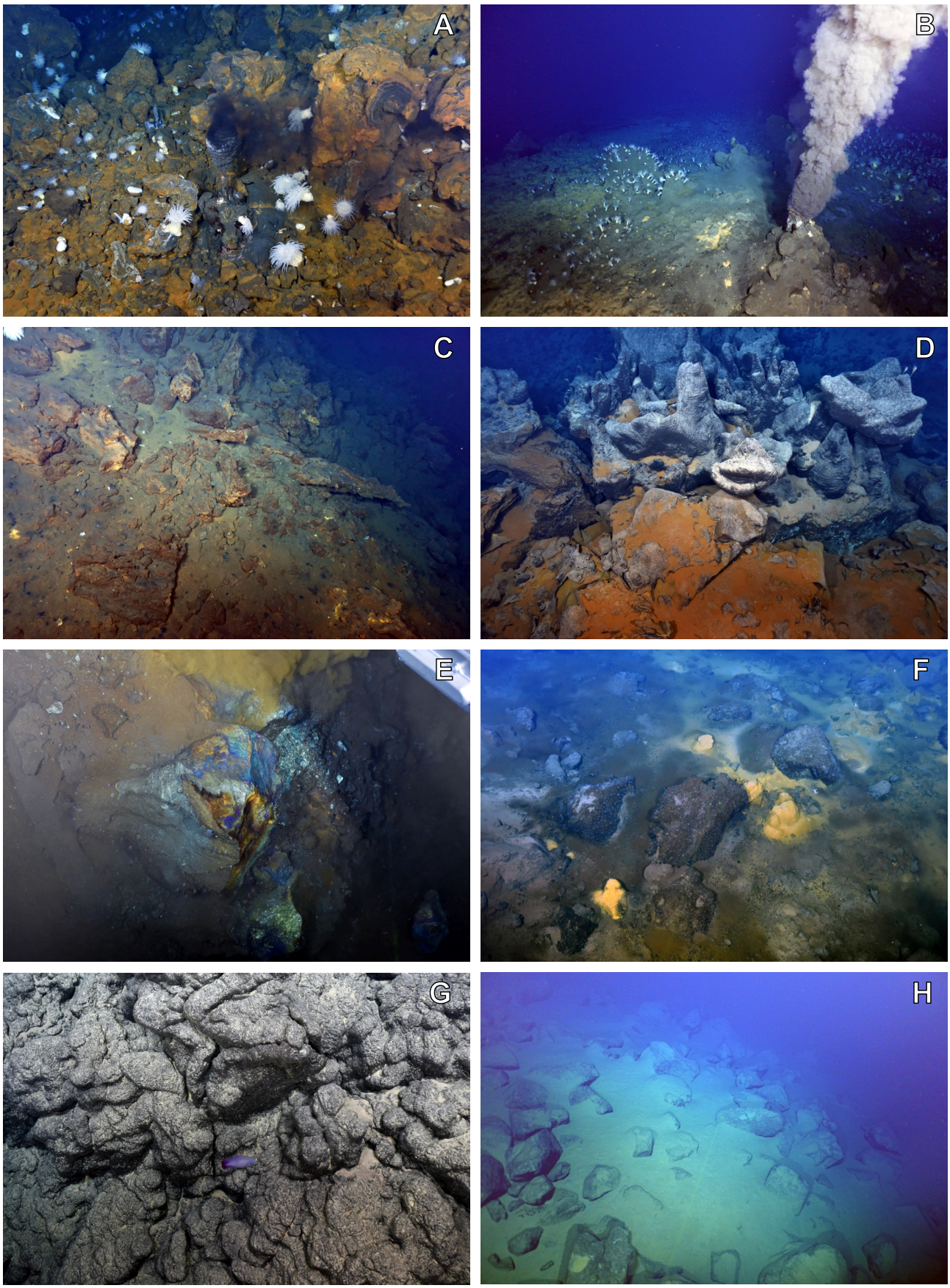
SFigure 1: Seafloor images from the ALPHA vent field, which comprises two high-temperature black-smoker sites. One site is characterized by a large chimney complex with typical vent fauna (A), whereas at the second site black-smoker fluids discharge either through openings in the seafloor or from small chimneys, without typical vent fauna (B). Inactive sites include organ-pipe-like chimneys (C), small isolated chimneys in talus flows (D), hydrothermal crusts overlying hydrothermal sediment (E, H), and Fe-oxide deposits in the periphery of the hydrothermal field (F). At some sites, diffuse hydrothermal discharge appears to follow hidden fissures in the seafloor (G).

SFigure 2: Edmond, Gauss and Score vent fields



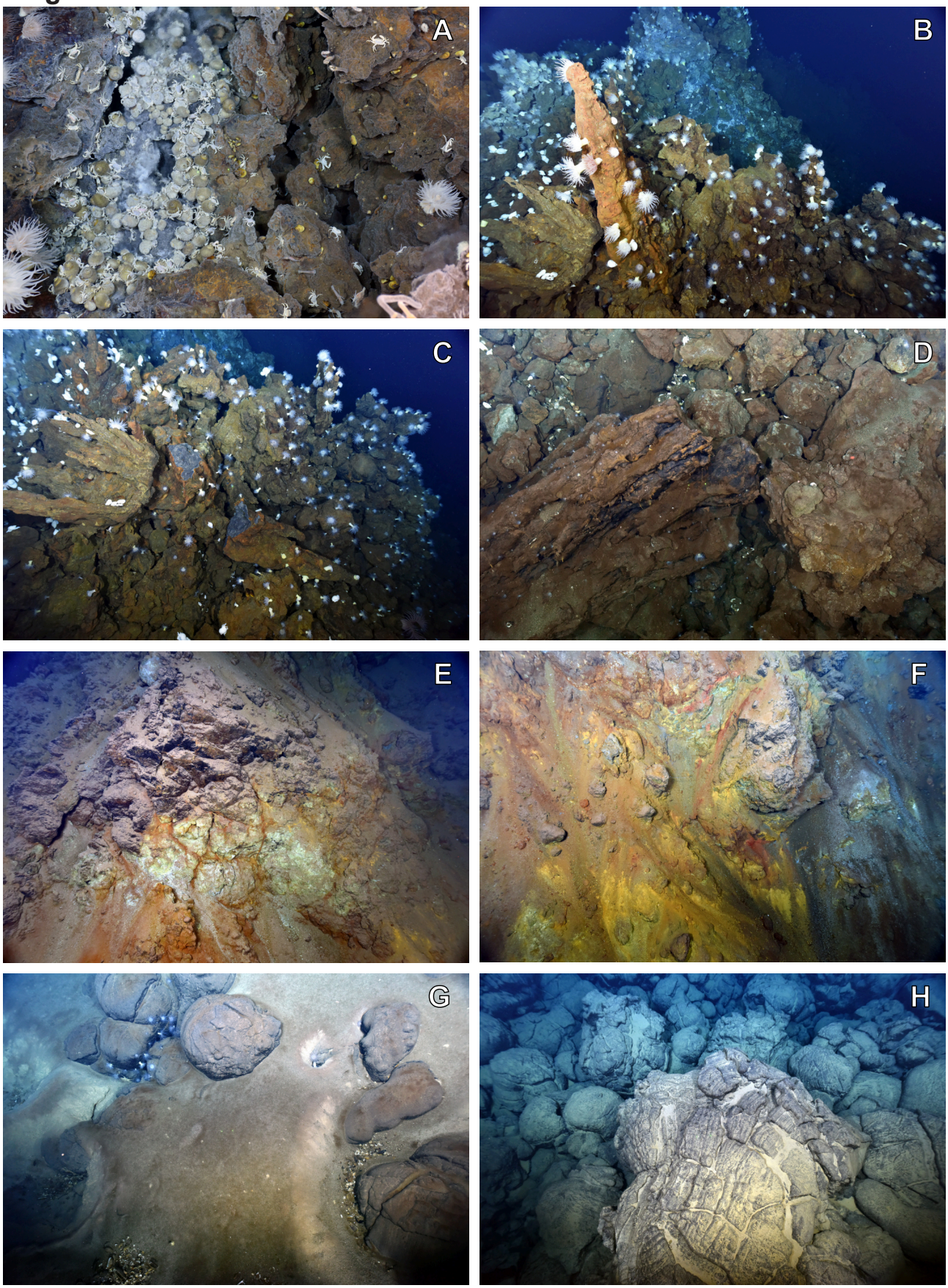
SFigure 2: Seafloor images of the vent fields Edmond (active), Gauss, and Score (inactive), located on two normal faults ~1000 m apart and likely part of the same hydrothermal convection system. Edmond features a large chimney complex emitting high-temperature black smoker fluids with typical vent fauna (A) and solitary chimneys at the base of the active mound (B). Sulfide blocks and talus occur near the active mound (C). At Gauss, strongly altered sulfide blocks and talus, partly covered by hydrothermal sediment, occur along basaltic talus slopes (D–F). Score is situated on the same steep fault-controlled slope and hosts inactive but intact large candelabra-like chimneys (G, H), indicating a more recent shutdown of hydrothermal activity than at Gauss.

SFigure 3: KAIMANA vent field:



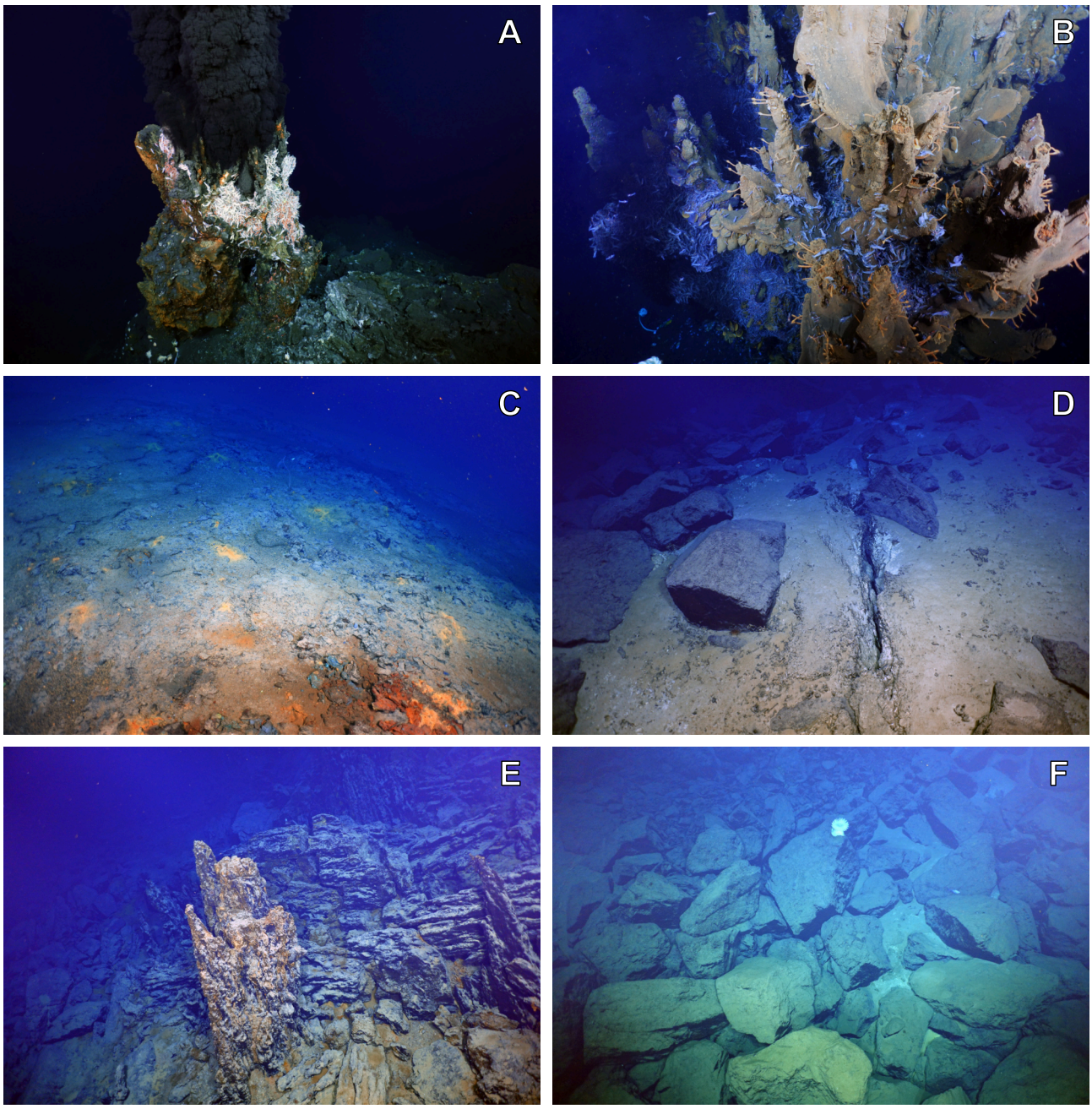
SFigure 3: Seafloor images from the KAIMANA vent field. The field is located on cross-cutting faults, and consists of active and inactive sites. Massive sulfide mounds are generally flat (compared to other vent fields) and contain of single or groups of small to larger-sized smokers (A, B) emanating high-temperature fluids. Copper- and Zinc-rich sulfide talus occurs at both, active and inactive sites (C-E). At the latter inactive smaller chimneys are still preserved (D).Host rock geology is characterized by exhumed blocky talus of plutonic rocks (gabbro, harzburghite) variably sediment-covered and coated Fe-Mn crusts (F-H).

SFigure 4: SURYA vent field:



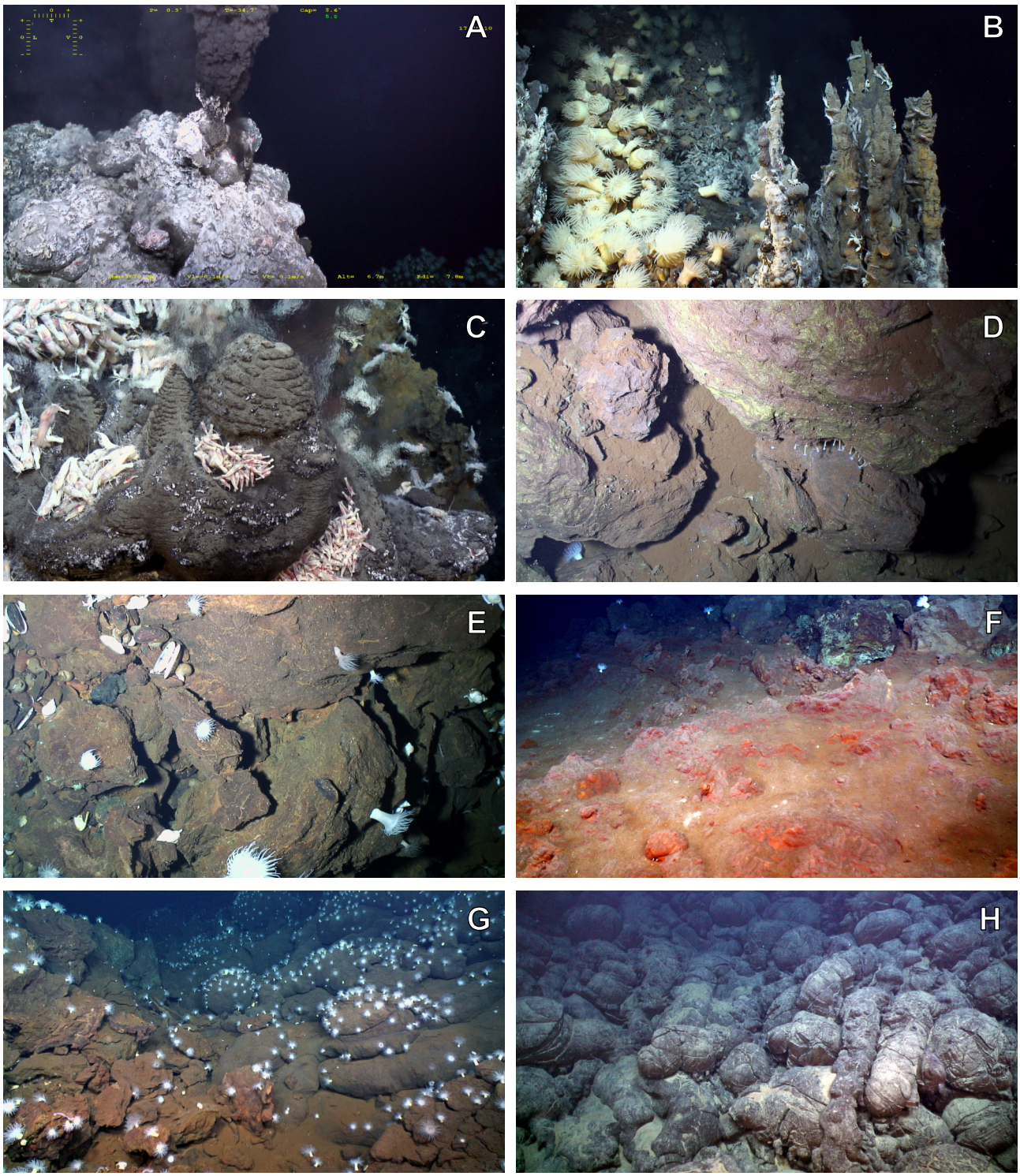
SFigure 4: Seafloor images from the SURYA vent field, located in the first SEIR segment south of the Rodriguez Triple Junction. The main site forms elliptical hydrothermal mound composed of basaltic and sulfide talus. Venting of diffuse, clear low-temperature venting (up to 31 °C) occures mainly through cracks / fissure of sulfidic talus (A). Small, inactive chimneys are scattered across the mound (B, C). Sulfide debris ís still well-preserved (C, D) and composed of Cu-Fe-Zn-sulfides. Erosional processes led to exposure of the stringer zone of SURYA (E, F). The presence of hydrothermal sediments is limited basal areas of the mound, where they occur in vicinity to pillow-type basalts (G, H).

SFigure 5: SOORAJ vent field



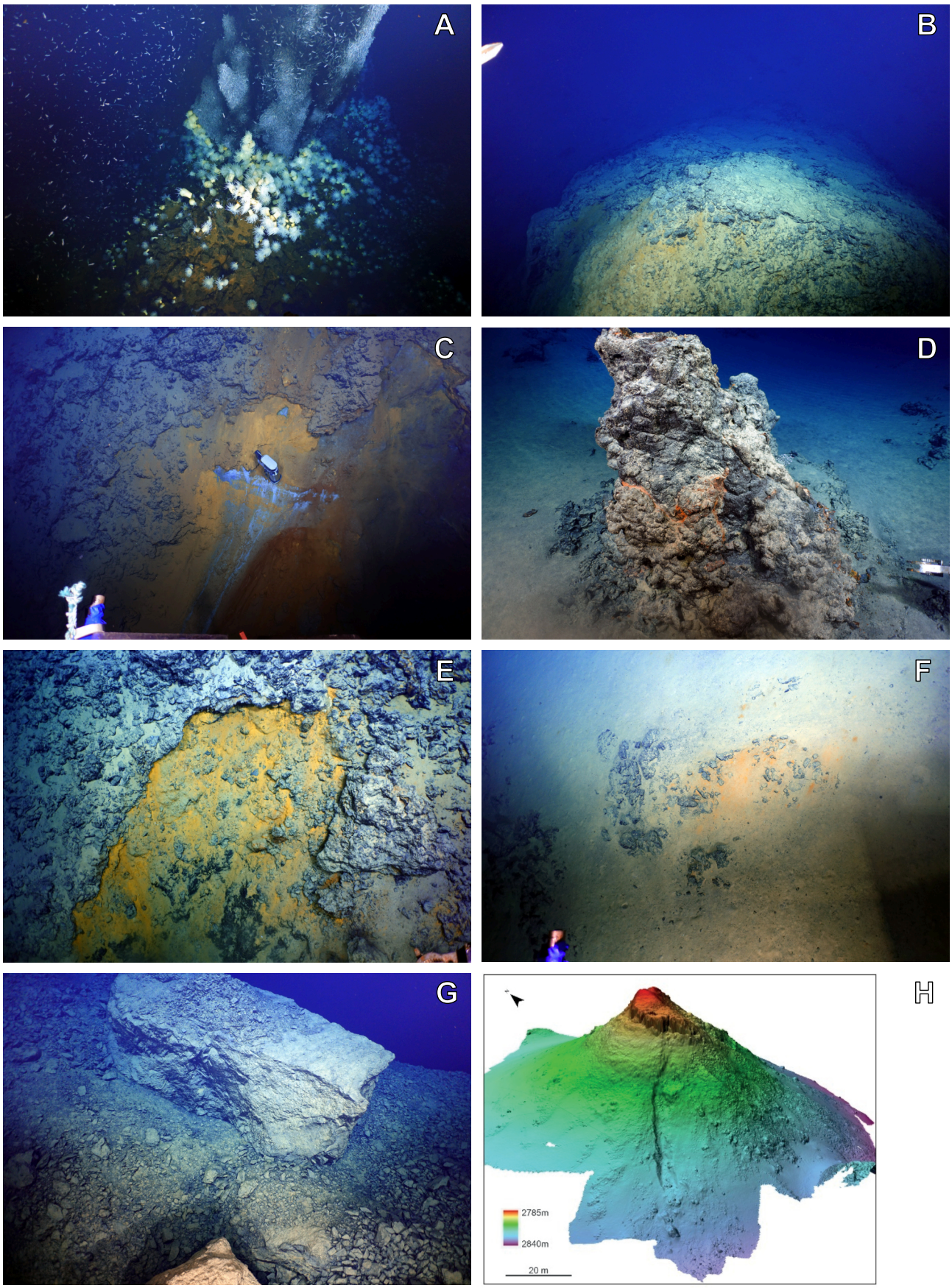
SFigure 5: Seafloor images from the SOORAJ vent field consisting of two high-T vent sites (A, B) with one central mound with a chimney complex at its top venting black smoke and hosting the typical vent fauna (A). There is a third active site with diffusely venting low-T fluids and widespread hydrothermal crusts, Fe-staining and pieces of atacamite (C) being located about 150 m to the SW of the central mound seen in (B). On the other side of the central mound inactive chimneys and hydrothermal precipitates occur along open fissures (D) and in-between blocky talus (E). Blocky talus cover the slopes around SOORAJ indicating plutonic rocks as host rocks of this hydrothermal field (F). A conceptual sketch of the SOORAJ field is shown in (G).

SFigure 6: PELAGIA vent field



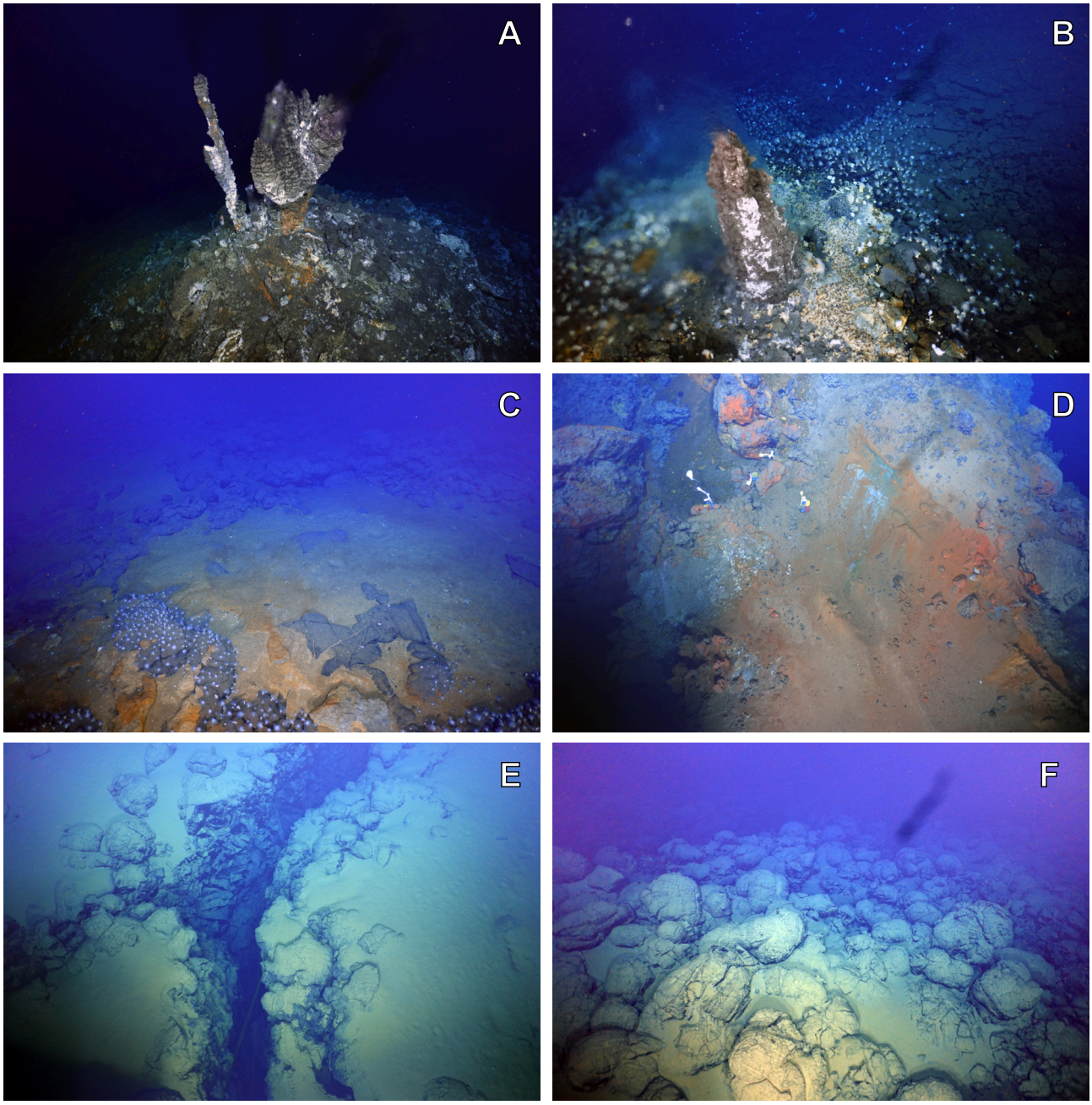
SFigure 6: Seafloor images from the PELAGIA vent field, located on the down-faulted western side of an active ridge-parallel fault within the central axis of the Southeast Indian Ridge. Active venting occurs at three closely spaced vents along the northern margin of a small sulfide mound, as well as on the adjacent fault-derived talus, through black smokers (A and B). Clear fluids also vent from beehives (C). Inactive chimneys and fragments of chimneys are scattered across the surface of the mound (D and E). In some areas, silica has precipitated alongside FeOOH, forming red-coloured solidified aggregations and sediments (F). Sulfide talus and chimney debris dominate the mound (G) and extend onto a fault scarp. The surrounding substrate consists of pillow lavas and basaltic talus (H), which are derived from a neighbouring minor pillow volcano.

SFigure 7: Jim vent field



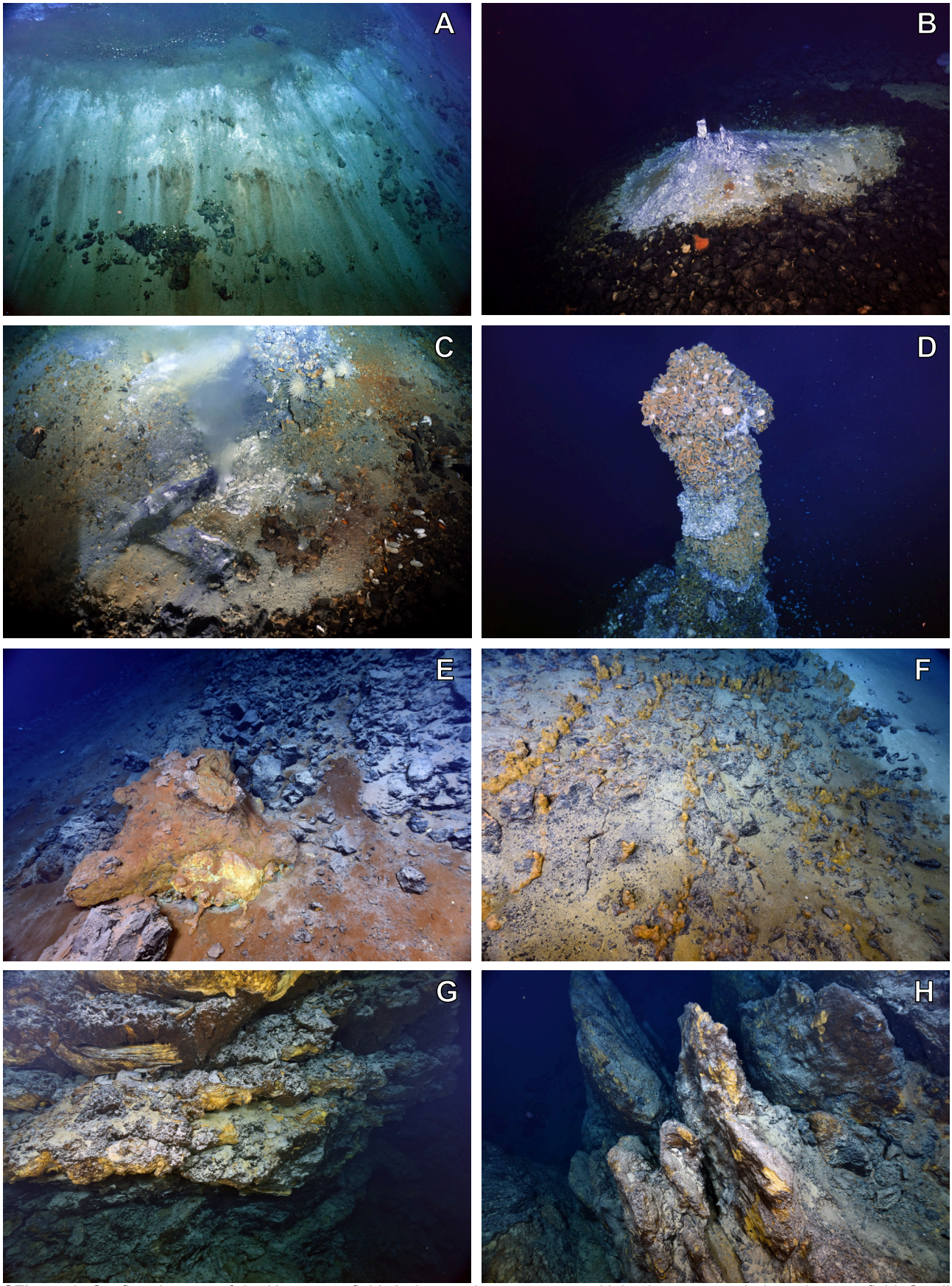
SFigure 7: Seafloor images of the Jim hydrothermal field. This field has one actively venting, high-temperature black smoker site with typical vent fauna (A) and one with low-T (ca. 10°C), diffusely venting site (C). All other 13 sites are inactive. Most of the hydrothermal sites form crusted mounds with massive sulfides occurring under a Fe-Mn oxide, silica-rich crust (B, C, E). A 3D model of such a mound (Jim site 4b) is also shown (H) based on photogrammetric data. Only a few chimney remnants were observed (D) indicating that hydrothermal activity has ceased in most sites a long time ago. Host rocks of the Jim field are mostly plutonic rocks (G) and serpentinized ultramafics.

SFigure 8: New Sonne vent field



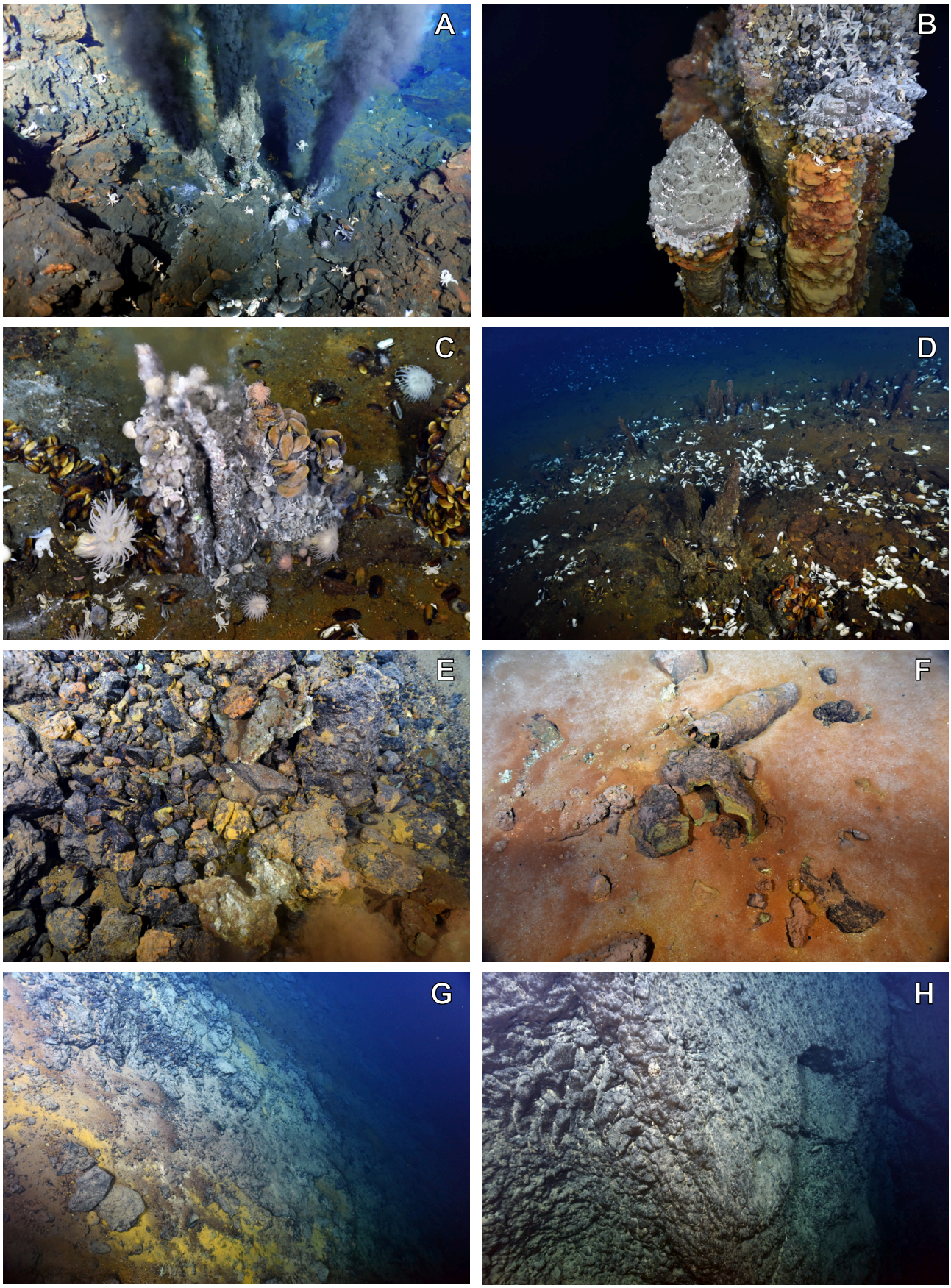
SFigure 8: Seafloor images of the New Sonne vent field with active chimneys and associated vent fauna (A, B), diffuse venting, low-T Fe-oxyhydroxide precipitates, and associated anemones (C), weathered and oxydized sulfide mound with recolonization experiments (D), active extensional tectonics creating open fissures (E), and slightly sediment-covered ambient pillow flows (F). Along a fault scarp a larger part of the stockwork underneath this hydrothermal field was exposed (G).

SFigure 9: HUNA vent field



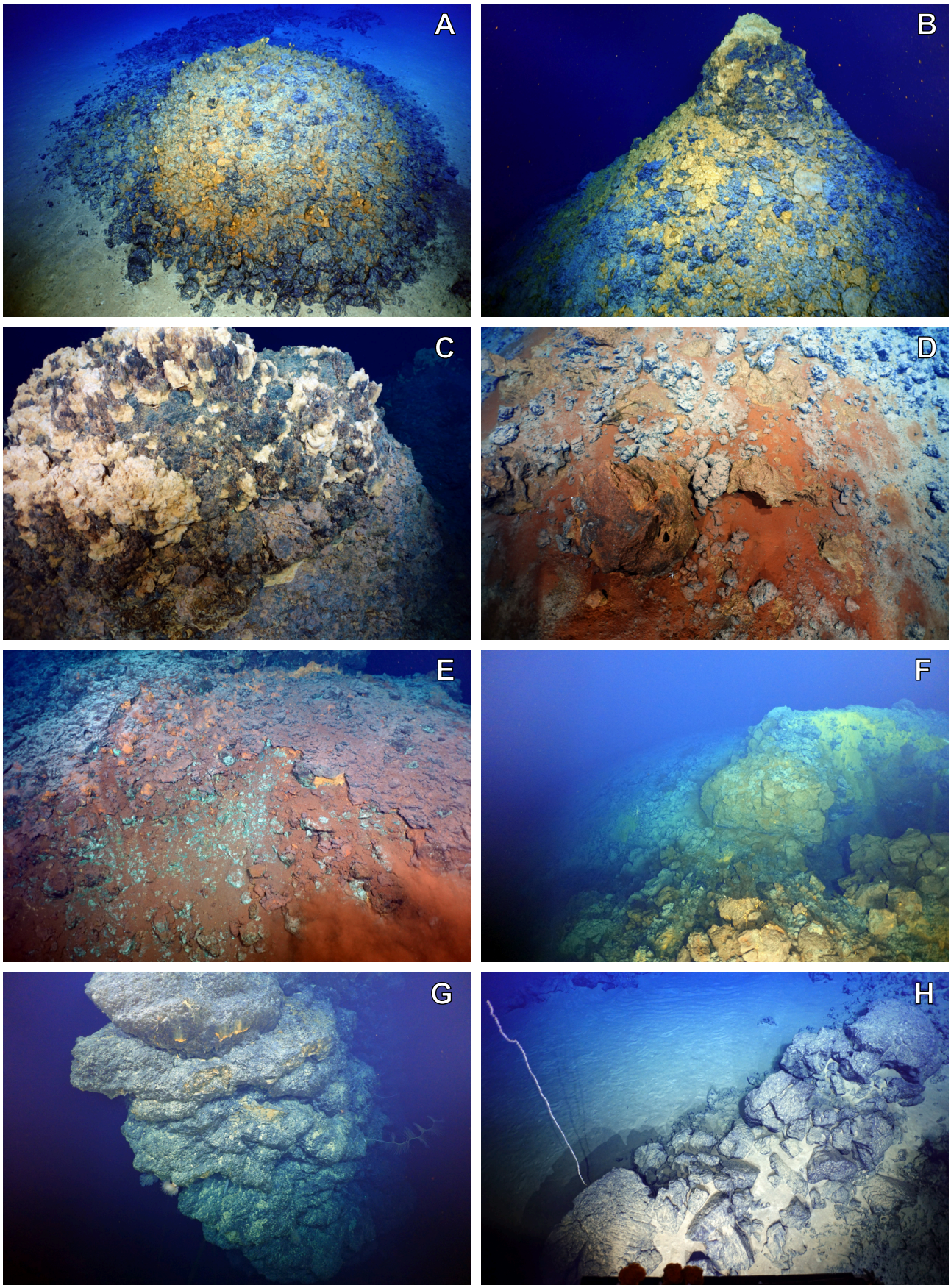
SFigure 9: Seafloor images of the HUNA vent field. Active venting occurs at multiple sites scattered along the vent field. Small silica chimneys emit clear hot fluids, which lead to the formation of larger mounds (A) and patches (B, C) on basaltic talus. These mounds and patches are almost entirely composed of unconsolidated silica. Large inactive smokers and sulfidic talus are preserved on sulfide mounds (D and E), which in turn are partly overlain by silica material formed after the sulfide mineralisation. Of particular note are the occurrences of inactive silicic micro-smokers that cut through Fe-Mn crust-covered sediments (F) and huge, shelved silica structures (up to 30 m high) composed of silica intercalated with minor FeOOH (G, H).

SFigure 10: PENUMBRA vent field



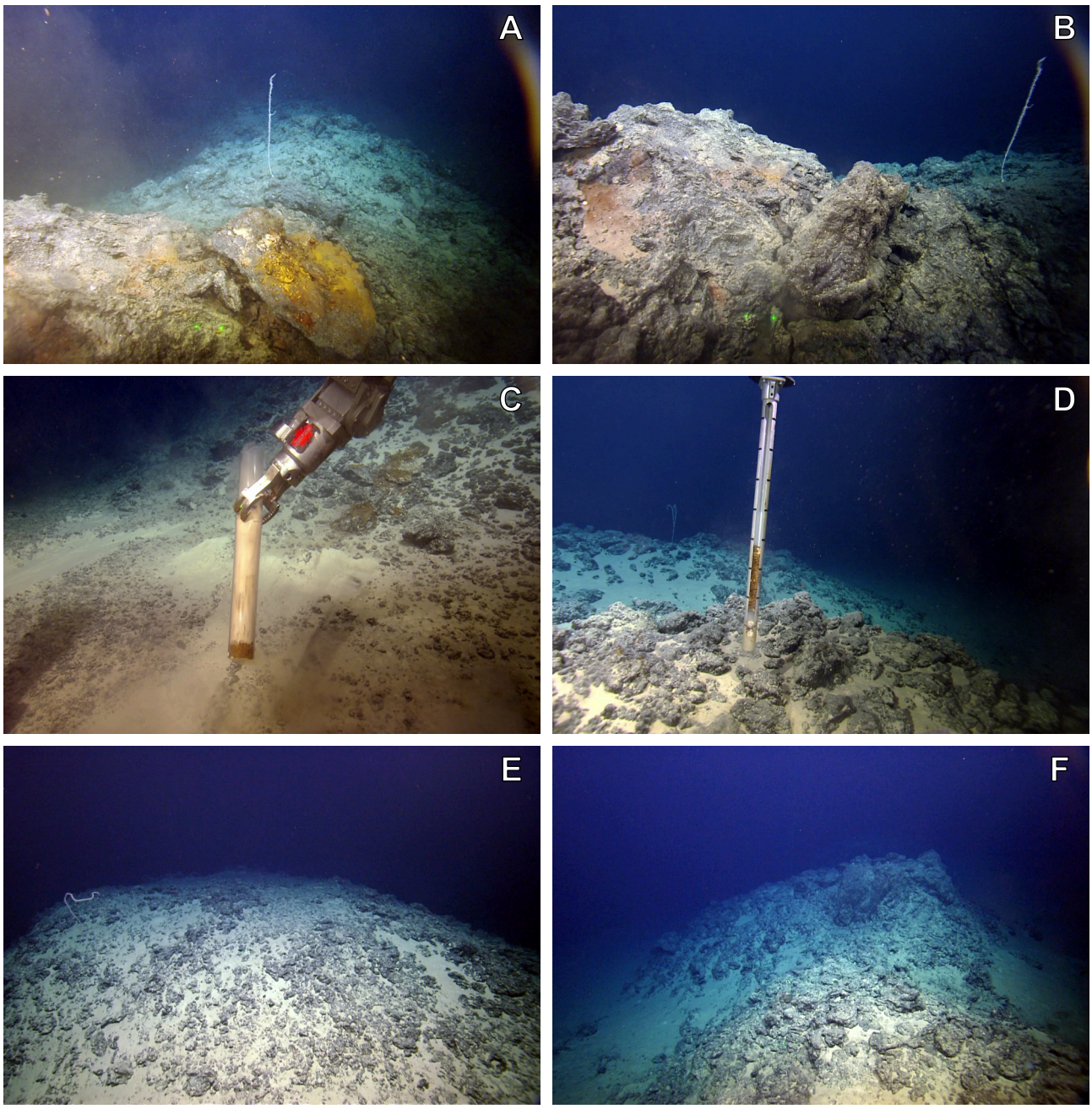
SFigure 10: Seafloor images of the PENUMBRA vent field show active hydrothermal venting at multiple sites, including black smoker chimneys, chimney complexes and zones of diffuse discharge (A–C). Inactive sites include smaller, partially degraded chimney structures and sulphide talus (D–F). Sulfide talus and oxidised hydrothermal sediments are widespread on the plateau and terrace surfaces (F and G). Pillow lavas and basaltic talus in the vicinity are usually covered by thick Fe-Mn crusts (H).

SFigure 11: LUX vent field



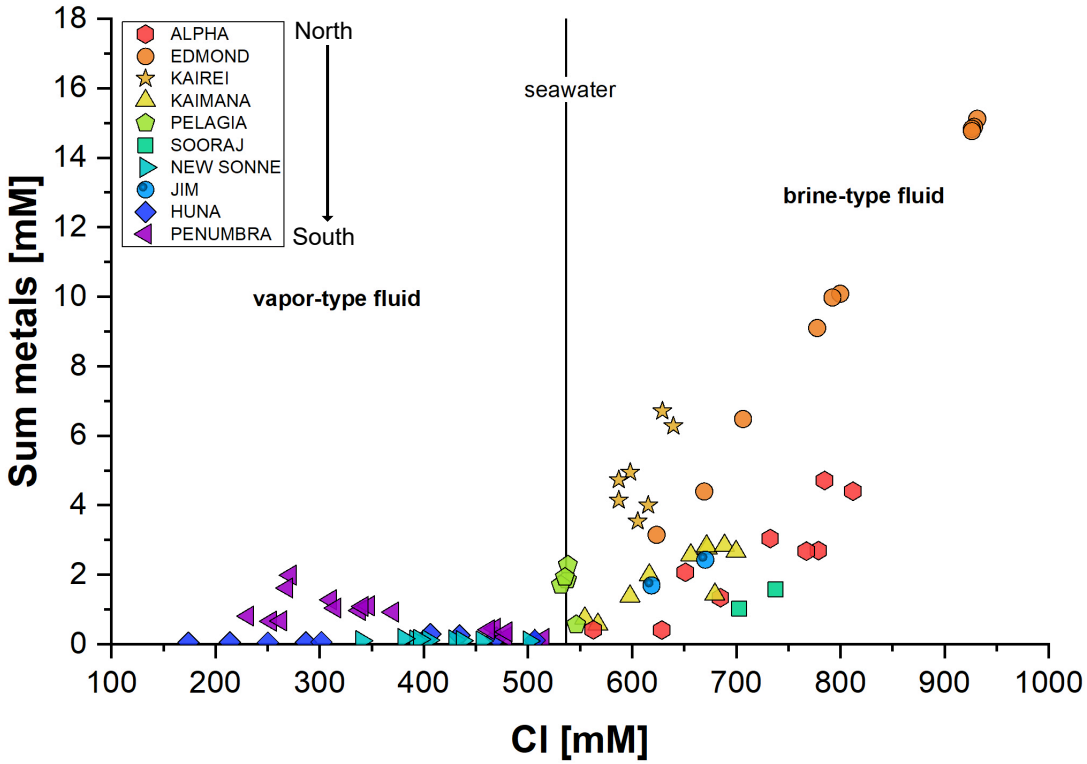
SFigure 11: Seafloor images of the Lux hydrothermal field showing inactive crusted mounds typical of the area. The mounds are generally small and composed of yellowish hydrothermal sediments (A, B); locally, pelagic sediment is incorporated into Fe–Mn oxide crusts (C). Larger mounds host Fe-oxyhydroxide chimneys and crusts (D) and greenish Cu-rich material (atacamite) (E). A large fissure exposing oxidized massive sulfides indicates active extensional tectonics (F). An unusual large inactive chimney in the northwest of Lux consists mainly of silica with minor Fe-oxyhydroxides and pyrite (G). Pillow lava outcrops along fault-related bathymetric steps bounding most mounds (H).

SFigure 12: UMBRA vent field



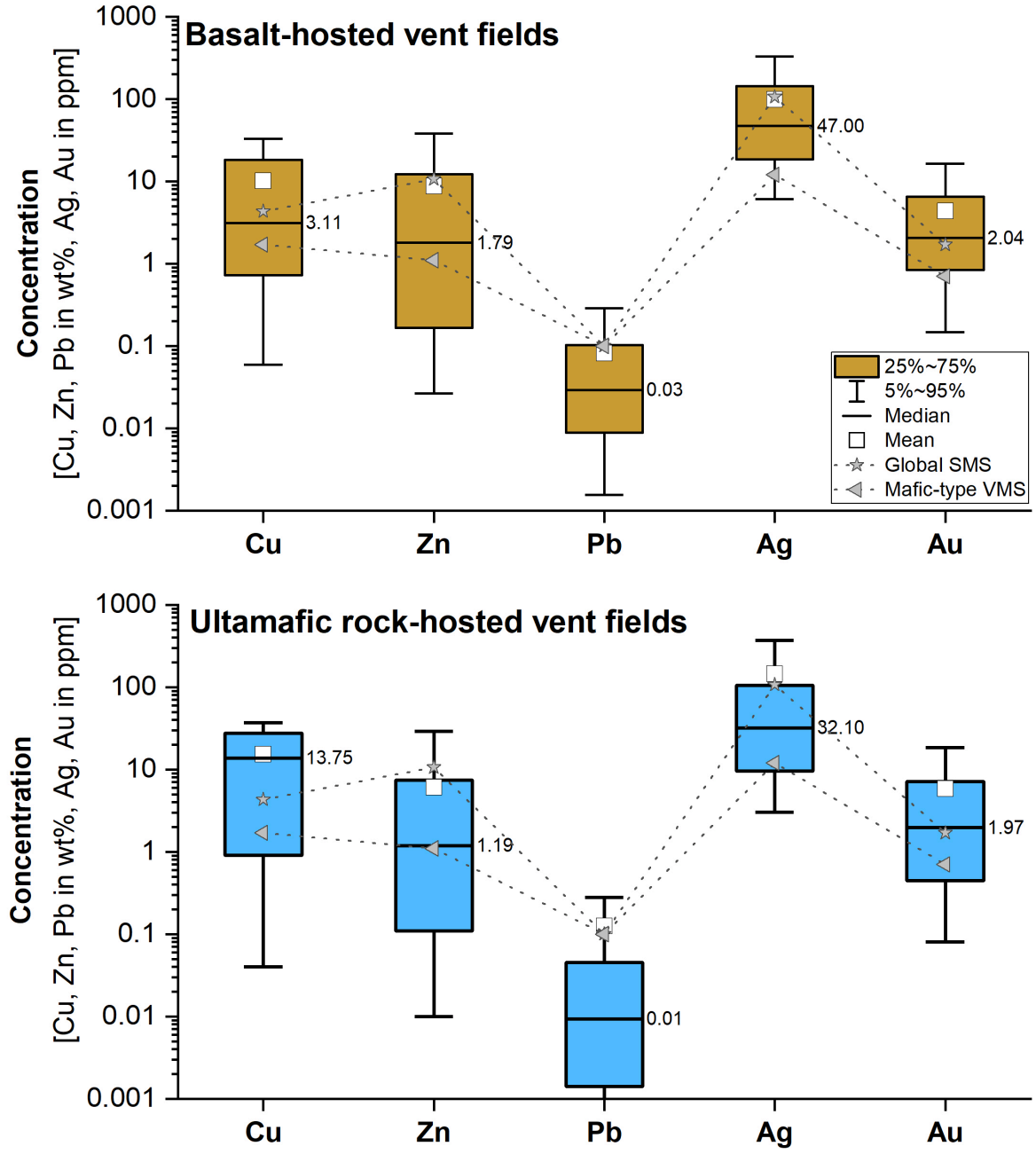
SFigure 12: Seafloor images of the UMBRA hydrothermal field showing Fe-stained sediments underneath an oxide crust from graben shoulders in which UMBRA occurs (upper row) as well as small crusted mounds (10 – 20 m across up to 5 m high) from the middle of the graben floor (lower and middle rows). The mounds consist of nontronite- and goethite-rich clay with varying share of pelagic background sediment as well as Fe-oxyhydroxide and manganese oxide crusts as detected from sampling with push cores (middle row). The graben in which UMBRA occurs is 150 m wide, 600 m long and 10 m deep.

SFigure 13: Fluid chemistry



SFigure 13: Bivariate plot of chlorine vs. summed metal concentrations (Fe+Mn+Zn+Cu) in hydrothermal fluids sampled from the active vent systems. The plot exhibits a distinct differences between metal-Cl-rich brine-type fluids sampled from vent at ALPHA, EDMOND, KAIREI, KAIMANA, SOORAJ vent field located along the Central Indian Ridge and northernmost areas of the Southeast Indian Ridge, and the metal-Cl-poor vapor-type fluids in the NEW SONNE, JIM, HUNA and PENUMBRA field along the Southeast Indian Ridge.

SFigure 14: Whole-rock chemistry



SFigure 14: Box-whisker plots of whole-rock geochemical data of collected seafloor-surface samples (N > 500). The plots show the concentrations of Cu, Zn, Pb (in wt%), Ag and Au (in ppm) for the basalt-hosted vent fields (yellow-colored boxes) and ultramfafic rock-hosted vent fields (yellow-colored boxes). The dotted lines with symbols present the median concentrations in worldwide seafloor SMS (star symbol) occurences and landbased mafic VMS-type deposits (triangle symbol; data source: references 32 and 33)