Reports

Geologic Setting of the Apollo 14 Samples

Abstract. *The Apollo 14 lunar module landed in a region of the lunar highlands that is part of a widespread blanket of ejecta surrounding the Mare Imbrium basin. Samples were collected from the regolith developed on a nearly level plain, a ridge 100 meters high, and a blocky ejecta deposit around a young crater. Large boulders in the vicinity of the landing site are coherent fragmental rocks as are some of the returned samples.*

The Apollo 14 lunar module (LM) landed in the Fra Mauro region at 3°40′19″ south, 17°27′46″ west, about 390 km south of the crater Copernicus and 550 km south of Montes Carpathus, which form the southern rim or boundary of the Mare Imbrium basin. In contrast to the Apollo 11 and Apollo 12 missions, where the landing was made on the relatively dark plains of the lunar maria, the Apollo 14 landing was made on a rolling highland with distinctly higher albedo than the maria. The Fra Mauro region of the lunar highlands is characterized by a complex pattern of hummocks, ridges, and small craters; the ridges are radial to the center of the Mare Imbrium basin and are as much as 30 km long and 5 km wide. Closely spaced large shallow craters up to 100 km in diameter, which are typical of the southern lunar highlands in the region from Ptolemaeus south to Tycho, are lacking. They are believed to have been covered in this region by a blanket of ejecta derived from the Mare Imbrium basin when it was excavated by impact early in the history of the moon (*1*). The

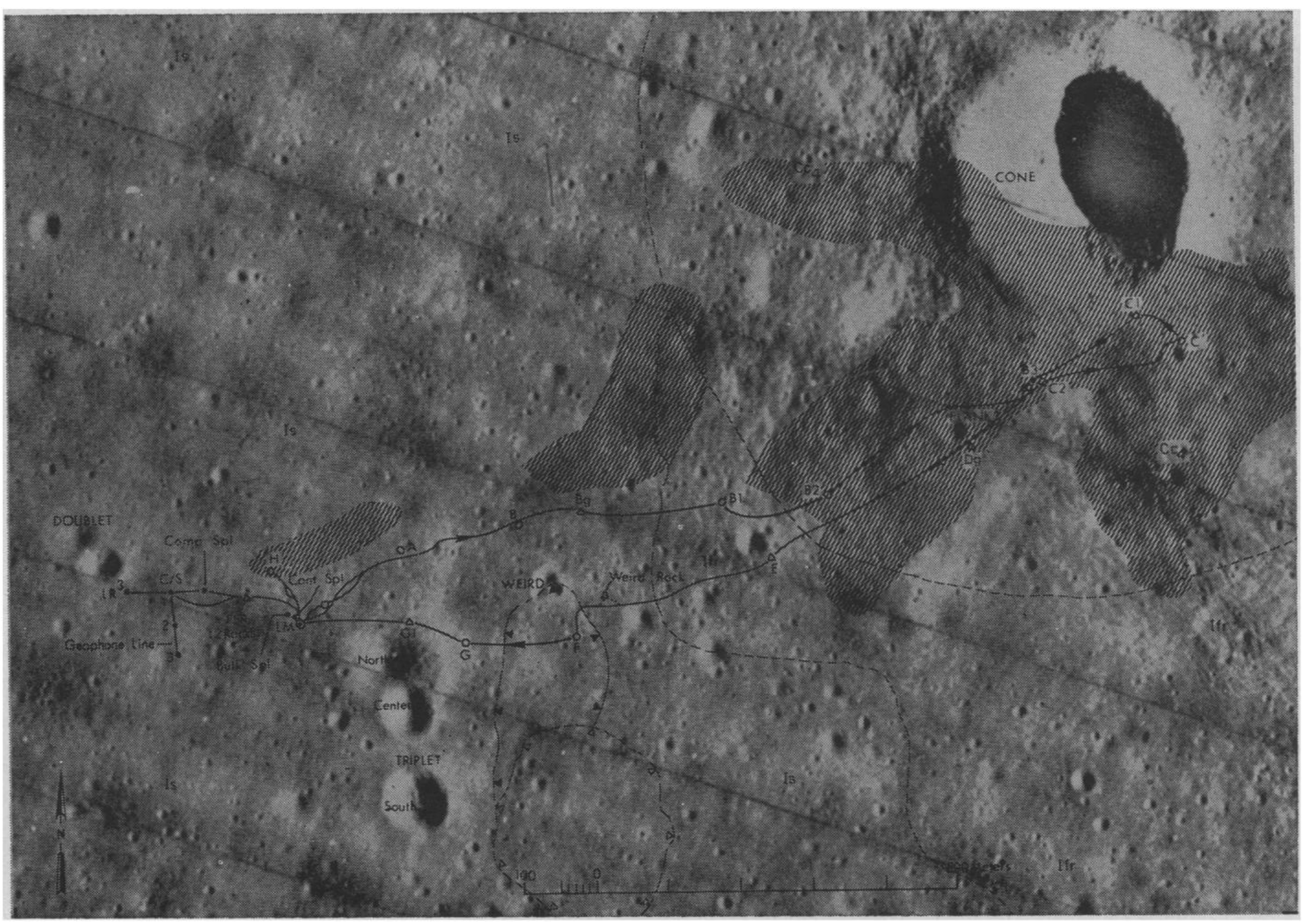

Fig. 1. Map of major geologic features in the Apollo 14 traverse area. The origin of the geologic units is described in the Apollo 14 preliminary mission maps (*5, 6*). Crater names used during the mission are informal. *Cc_4*, continuous ejecta blanket of Cone Crater; hatched area, bouldery ray deposits of Cone Crater; *Is*, smooth terrain material of the Fra Mauro Formation; *Ifr*, ridge material of the Fra Mauro Formation; long and short dashes, contact (long dashes where contact is approximately located; short dashes where the location is inferred without local evidence); solid and dashed line with solid triangles below, foot of scarp (bounds small mesa; triangles point down slope; short dashes where the location is inferred); solid and dashed line with open triangles below, edge of hill (long dashes where the edge is approximately located; short dashes where the location is inferred; triangles point down slope); heavy solid line, traverse route for EVA 1 and EVA 2; ○B, panorama station; △G1, station without panorama; *C/S*, Apollo Lunar Surface Experiments Package central station; *LR^3*, laser ranging retroreflector; *FSR*, football-sized rock; ● *Cont Spl*, contingency sample; *Comp Spl*, comprehensive sample; *Dg*, grab sample at station D.

impact occurred north of the landing site in terrain that probably resembled the present lunar highlands. The hummocky deposit thins to a feather edge 150 km south of the LM landing point in the vicinity of the crater Bonpland. It forms a broad belt surrounding Mare Imbrium and has been designated the Fra Mauro Formation (*2*).

Photogeologic evidence indicates that the Fra Mauro Formation is older than the lunar mare material. The radial deposits and structures surrounding the Mare Imbrium basin are truncated and overlapped at many points by material of the maria, including that at the Apollo 11 and Apollo 12 landing sites. Several large craters, including Archimedes and Sinus Iridum, are younger than the Mare Imbrium basin and older than the mare material, which suggests that the time span between the excavation of the basin and the flooding of the basin by mare material was appreciable (*3*). Finally, the crater density on the Fra Mauro Formation is greater than that anywhere on the maria. The number of craters between 400 m and 1 km in diameter is three to five times greater in the Fra Mauro region than in the vicinity of Tranquillity base, and five to seven times greater than around the Apollo 12 landing site. Craters in this size range on the Fra Mauro Formation are mostly old-appearing, circular, pan-shaped craters with slightly raised rims or irregular shallow depressions. Combined with the hummocky topography intrinsic to the Fra Mauro Formation, they form a complex undulating surface with considerably more local relief than is found on the maria.

Much of the information that follows is taken directly from the preliminary science report on Apollo 14 by the Apollo Lunar Geology Investigation Team (*4*). There are three major topographic and geologic units at the landing site (Fig. 1): (i) a nearly level plain in the western half of the landing area, whose relief is due mainly to overlapping shallow craters 20 to at least 200 m in diameter; (ii) a north-south trending ridge approximately 100 m high in the eastern half of the site; and (iii) a blocky ejecta deposit which surrounds Cone Crater, a young crater with a diameter of 340 m located at the crest of the ridge. The traverse made during the first period of extravehicular activity (EVA 1) was confined to the level plains unit; during EVA 2 the astronauts crossed the plains unit and climbed the ridge to within 20 m of the rim of Cone Crater (Fig. 1).

All of these units consist of fragmental material, the regolith, at the surface; but this material is more finegrained in the western part of the site than in the Cone Crater ejecta. Samples and photographs were taken at various

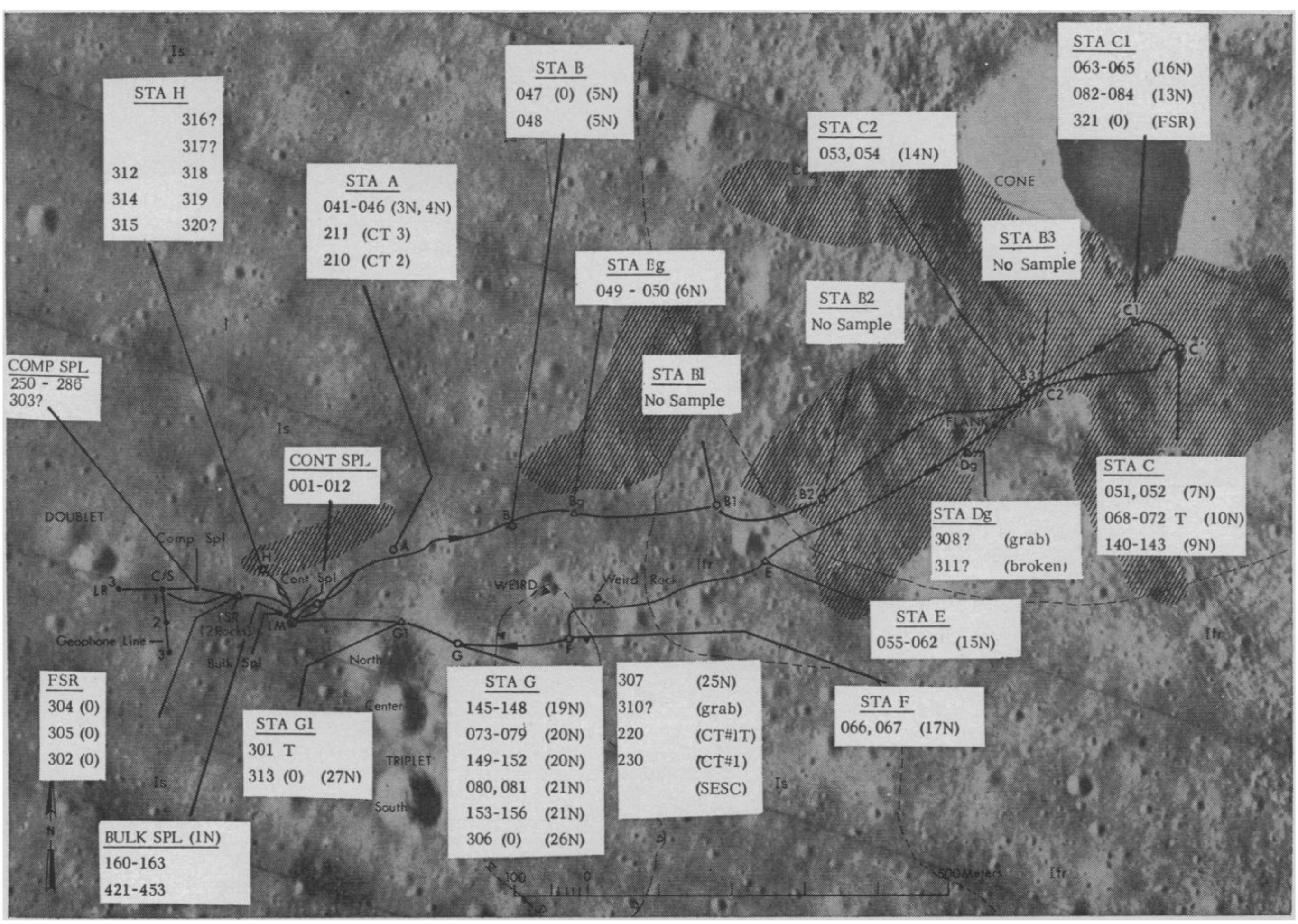

Fig. 2. Traverse map showing sample locations. Traverse and station symbols are the same as those used in Fig. 1. *STA*, Station; *bag 6N*, prenumbered sample bag; *307*, sample for which location is "known" by reference to sample bags used at the time of collection; *306 (0)*, sample for which location and lunar orientation are known; *318 (T)*, sample for which location is tentative, based on identification of sample in lunar surface photographs; *310 (?)*, sample for which location is tentative, based on description by the astronauts, the process of elimination of known samples, or the possibility of sample mixing during transfer between or within weigh bags; *(grab)*, sample that was not photographed before sampling or put into prenumbered bags; *CT#1T*, core tube No. 1 with a tab (not "tentative"); *SESC*, special environmental sample; *CONT SPL*, contingency sample; *COMP SPL*, comprehensive sample.

stations along the traverse (Fig. 2). All of the samples were collected from the surface or shallow subsurface of the regolith; many are probably fragments that were ejected from Cone Crater. The western part of the area is characterized by gently rolling surfaces at scales of a few meters superposed on the larger relief caused by old, large subdued craters. The surface is densely pockmarked with craterlets from a few millimeters to a few centimeters in diameter. Rock fragments larger than a few centimeters in diameter are rare in the western part of the site and become progressively more abundant toward Cone Crater. Near the rim of Cone Crater, the fragmental surface material ranges in size from particles too small for resolution with the naked eye to boulders 10 m in diameter. Smaller boulders are scattered over much of the ridge unit and extend onto the plains unit as discontinuous ray-like extensions of the Cone Crater ejecta. The surface of this deposit is also characterized by small hummocks at scales ranging from a few centimeters to a few meters. Small craterlets are common but not so abundant as in the western part of the area. Although the ejecta surface of Cone Crater is younger than the plains unit and ridge unit surfaces, the rounding of the boulders in the ejecta by micrometeorite impact indicates that the craterlets should be

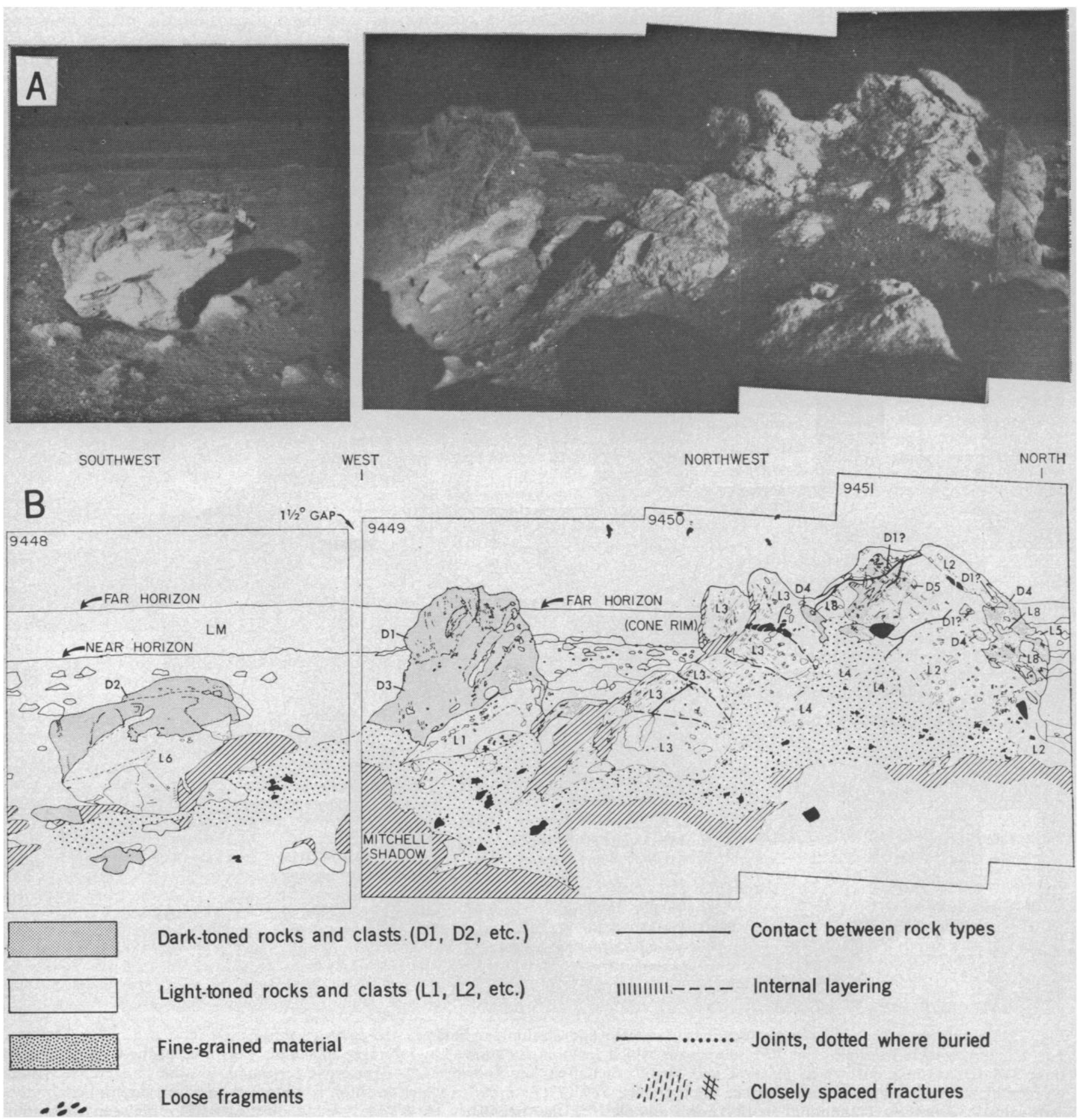

Fig. 3. (A) White rocks near the rim of Cone Crater. [NASA photographs AS14-68-9448 to AS16-68-9415] (B) Sketch map of white rocks.

as abundant on the Cone Crater ejecta as in the western part of the area. The craterlets are probably less abundant on the ejecta than in the plains unit largely because their development is inhibited by the more coarse-grained material of the Cone Crater ejecta.

Most of the large boulders have fillets of lunar fines and fragments banked against their sides (Fig. 3, A and B). The size of a fillet is commonly proportional to the size, the degree of rounding, and possibly the friability of the host rock.

Of the other craters visited during the geologic traverses, only the small crater at station C′ has abundant blocks on its rim and these appear to be reworked Cone Crater ejecta. The rest of the small youthful craters have raised rims containing only a slightly greater number of blocks than the surrounding regolith. Some of these blocks are agglomerations of lunar soil ranging from clods to strongly indurated rocks that were lithified by recent impact. The lack of blocky rims around small young craters indicates that the regolith at Fra Mauro base is more than 5 m thick. North Triplet Crater has a slightly raised rim and a mature-appearing rim deposit; fragments larger than 1 cm are more abundant at this crater than in the surrounding regolith but large blocks are sparse. The relative ages of the major craters along the geologic traverses are listed according to relative age, oldest to youngest, as follows: (i) the crater designated North Triplet and the moderately subdued 50-m crater east of station F; (ii) Cone Crater, Flank Crater, and the sharp 45-m crater at station E; and (iii) the sharp 30-m crater at station C′.

Most samples collected along the traverses have had a complicated history of ejection and tumbling. Many are uniformly covered with glass-lined impact pits. The large boulders in the Cone Crater ejecta blanket, on the other hand, have been abraded by impact but have probably not been turned over since their ejection. These boulders were ejected from depths to about 60 m, the approximate depth of the crater, and are samples of local bedrock at the site of Cone Crater.

The collected samples consist predominantly of fragmental rocks which vary significantly in their degree of induration and in the proportions and character of their included fragments. The more coherent fragmental rocks are similar in appearance to the large boulders in the Cone Crater ejecta blanket in having both light and dark clasts and in containing sets of closely spaced fractures like those observed in photographs of the boulders (Fig. 3, A and B); they are probably typical of bedrock in the vicinity of Cone Crater. Many of the large clasts in the boulders appear to be made up of smaller clasts, as are many of the clasts in the Apollo 14 lunar samples (*5*). The rocks appear to have had a complex history of brecciation and lithification. As stated above, regional studies indicate that the Imbrium impact occurred in a highly cratered terrain similar to the present lunar highlands. The fragmental rocks within fragmental rocks in the boulders and the Apollo 14 lunar samples suggest such a history of multiple impacts. Many of the clasts in the coherent breccias in the Cone Crater ejecta were probably derived from fragmental rocks formed by pre-Imbrian cratering events, including basin-forming events, and were refragmented and deposited by the Imbrium event. Lithification probably occurred during or shortly after deposition. The fractures in the boulders, and the glass coatings and fracture linings in some Apollo 14 lunar samples, were probably formed, at least in part, as a result of local impacts such as the Cone Crater event, after the Fra Mauro Formation had been deposited and lithified.

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7. Photo-relief base was prepared by Topographic Command, U.S. Army. This report was prepared under contract T-65253G from the National Aeronautics and Space Administration. Publication authorized by the director of the U.S. Geological Survey.

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Tectonic Movement in the Chile Trench

Abstract. *An acoustic reflection profile across the Chile Trench off Valparaiso shows the trench floor to have a substantial sediment accumulation that is far from flat-lying. The morphology is transitional between the flat-lying sediment fill to the south (labeled a type I trench) and the bare V-notch character farther north (labeled type II). A sharp seaward slope break, downbowed reflectors, and a landward downthrown normal fault suggest that the oceanic lithosphere is failing in shear. This mode of failure is more consistent with the observed features of trenches and Benioff zones than is the concept of bending and underthrusting.*

The relationship between trench morphology and the mechanism of crustal subduction has been discussed extensively (*1–3*). Many sections of trench floor consist of flat-lying turbidites apparently undisturbed by tectonic movement; yet, in other places, there is no trace of sediment accumulation at the bottom of the trench, even where the oceanic crust carries a substantial layer. Thus, there appear to be two distinct types of trench: one in which sediment can accumulate relatively undisturbed for substantial periods of time, and another in which sediment is actively removed. In a few places a single trench system changes from type I (filled) to type II (empty), and data are available for two of these transition zones. Since the mechanism involved in maintaining a type II trench may be observed in action at the transitions, some deductions can be made about the principal mode of failure in a sinking oceanic lithosphere.

The Hikurangi Trench (off North Island, New Zealand) has been investigated in some detail near the transition zone between it and the Kermadec Trench, a well-known type II feature (*2, 4*). Not only does the Hikurangi Trench contain large quantities of flat-lying sediment fill, but a