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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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

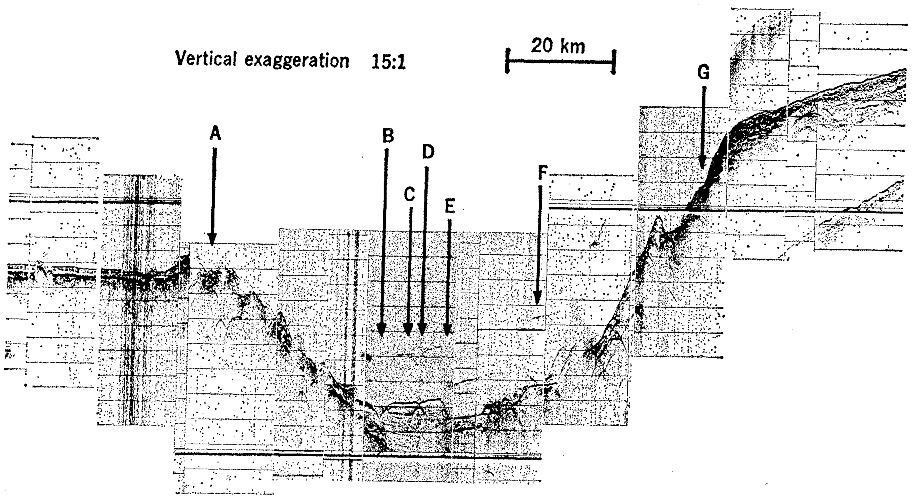
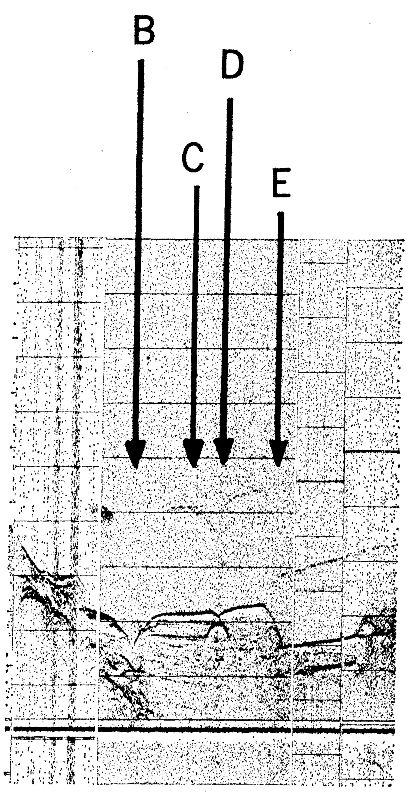


Fig. 1. (Top) Acoustic reflection profile across the Chile Trench off Valparaiso, at 33°15′S. Scale lines are 0.4 second apart; the two-way travel time to the outgoing pulse at the bottom of the record is 8 seconds. *A*, Slope break; *B*, channel (deepest point in trench); *C*, slope break; *D*, minor erosional channel; *E*, normal fault; *F*, small sediment platform; *G*, perched sediments. (Bottom) Enlargement of middle section of the profile shown above.



series of subparallel ridges and troughs on the landward slope have been interpreted to be the result of compressional folding and uplift of that fill (*2*). Yet, a mere 50 km northeast of the last example of fill compression, the southern end of the Kermadec Trench has a clean V-notch profile (*2*).

The sudden transition has been attributed to the upbuckling of trench floor sediments that has blocked a submarine channel and diverted the sediment transport to the east in recent time (*2*). However, the V-notch is 0.8 km deeper than the flat-lying sediments near the last upbuckled zone. Either the deep V-notch was not present before the fill channel was blocked, or sediment that should have flowed into it has disappeared. In both cases, a substantial volume of crustal material must have been subtracted from the trench floor in recent time.

A similar transition between type I and type II occurs in the Peru-Chile Trench at the latitude of Valparaiso. Hayes (*5*) presents many bathymetric profiles of the trench in conjunction with gravity data. These show that the flat floor present just south of Valparaiso is not seen in a profile about 90 km farther north. The selected acoustic reflection profiles of other authors (*1, 2*) confirm that the change in appearance of the bathymetry is due to sediment fill in the southern portion of the trench. The sediments are either flat-lying (*1*) or dip somewhat landward (*2*), with increasing angles of dip at depth. This suggests that the oceanic crust is being steadily downwarped by the weight of encroaching continental material, and the occasional observation of buckled sediments at the base of the continental slope is consistent with either sediment compression or seaward slumping of material (*4*). The quantity of sediment in the trench has been correlated with the rainfall of the coastal and Andean zone, but other changes occur in the overall tectonic picture at the latitude of Valparaiso: for example, the depth of the Benioff seismic zone seems to decrease abruptly south of Valparaiso (*6*). Although the present-day level of precipitation is low in the main Andean range, evidence of heavy glaciation and rapid erosion is commonplace throughout. Thus, a reduced rate of sediment supply for the northern part of the trench may be contributory to the absence of sediment fill on its floor but is unlikely to be the sole cause. A mechanistic distinction between type I and type II trenches therefore remains valid as a working hypothesis.

A high-resolution acoustic reflection profile was recently obtained across the transition zone off Valparaiso during the SEAPAC expedition (R.V. *Oceanographer*). A carefully processed version, pieced together from tape playbacks, is reproduced in Fig. 1. The profiling system employs a short-pulse attraction-type electromagnetic sound source that has an energy spectrum peaked at 150 hz. The returns have been enhanced by means of amplitude leveling and pulse-shape correlation. The profiler is intermediate in capability between 3.5 khz piezoacoustic devices and air-gun or arcer systems (20 to 50 hz). The following deductions can be made from the original record, and most can be confirmed by examination of the reproduction (Fig. 1):

1) Hemipelagic sediments seaward of the trench appear to vanish at the slope break *A* of the outer wall. The true slope angle of "wall" is 4°.

2) The deepest point in the trench is a channel cut through the fill at the base of the seaward wall, point *B*. The deeper reflectors are continuous across the cleft.

3) Turbidite bedding is detectable to 0.8 second beneath the sediment surface, and it exhibits steadily increasing landward dip with depth. The maximum slope is about 1°.

4) The top surfaces of the sediment show increasing seaward dip toward the land side of the trench, with a definite slope break at point *C*.

5) Buried reflectors are also curved upward, but with no well-defined slope break.

6) A minor erosional channel is present below point *D*.

7) There is a substantial (240 m) normal fault at point *E*. The surface slope of the sediment fill is unchanged across it.

8) A small sediment platform at

point F on the landward slope has a similar dip angle (½°) to the sediment on the trench floor. It is also at very nearly the same absolute level as a small shelf on the seaward wall of the trench.

9) Perched sediments at point G show that sediment migration into the trench has been active in recent time.

10) Some coherence in the subbottom reflectors on the broad bench at a depth of 1500 m (not the continental shelf proper) indicates folding in the older sediments but a conformal surface buildup.

The most immediately striking features revealed by the profile are the two erosional channels at points B and D. That they are channels is clear from the acoustic signatures, which are characteristic of channels observed by a wide-beam acoustic sounder. Their existence is confirmed by the narrow-beam echo sounder trace obtained at the same time as the profile. The conclusion that they are due to erosion rather than to tensional rifting is based on the absence of any gradient discontinuity in the curved subbottom reflectors below B, and the separation between the surface gradient discontinuity at C and the channel at D. The floor of the trench slopes northward along its length; between profiles 18 and 19 of Hayes (*5*), there is an average gradient of 0.004. Net turbidity flow transport should, therefore, be strongly northward irrespective of local contributions of sediment from the continent. The presence of erosional channels requires *both* strong longitudinal transport in the trench *and* the removal of obstacles or sills which caused the original layered ponding. Thus, the trench floor to the north of the observed point must have deepened relative to it, much as is required by the previous observations in the Hikurangi Trench (*2, 4*).

Thus far the interpretations have merely led to the deduction that the trench floor must be able to deepen, or to sink vertically, at least in a type II trench. The profile also shows two major features that offer strong clues as to the *mechanism* involved in this sinking. These are the upward curvature of all subbottom reflectors in the trench fill, and the clear normal fault downthrown 240 m on the landward side. There are two ways of lowering a surface point relative to its surroundings: *bending* of neighboring material by downbowing, and *shearing* of the material with a substantial vertical component in the shear. Bending corresponds to the classic concept of ocean floor "underthrusting" (*7*), and shear corresponds to graben formation or a "sinkhole" effect, as discussed by Malahoff (*3*) from morphological evidence and by Lliboutry (*8*) from mechanical considerations. The gravity fault evidence from the Japan Trench (*9*), cited by Malahoff (*3*) as evidence of normal faulting in the oceanic lithosphere, is a natural result of the downbowing of that lithosphere and stretching of the upper surface. The faults are not systematically downthrown landward, as required by the mechanism of Lliboutry (*8*), but merely introduce a stepped unevenness in the seaward slope of the trench.

In the distorted sediment of the transition zone off Valparaiso, there is direct evidence of a sinkhole (downbowing of reflectors) and of the presence of shear that has taken place *on the trench floor*. Both observations are consistent with a shear mechanism for the downward transfer of oceanic lithosphere (*8*). That the whole oceanic plate is involved in this shear, and not merely the surface layers subjected to stretching, is confirmed by the abrupt slope break on the seaward side of the trench. The tendency for the oceanic plate to break abruptly without significant initial downbowing may be peculiar to the most active (type II) part of the Peru-Chile Trench. This circumstance may be responsible for the remaining oddity of the Fig. 1 profile: the *seaward* sloping units of sediment fill between E and F. In the western Pacific trenches, downbowing of the oceanic plate is the dominant mechanism until the trench axis is reached, and it provides an intrinsic landward tilt to any surface of significant age. The seaward tilt observed here confirms Malahoff's suggestion (*3*) that the point of most rapid surface vertical motion is at the axis of the trench.

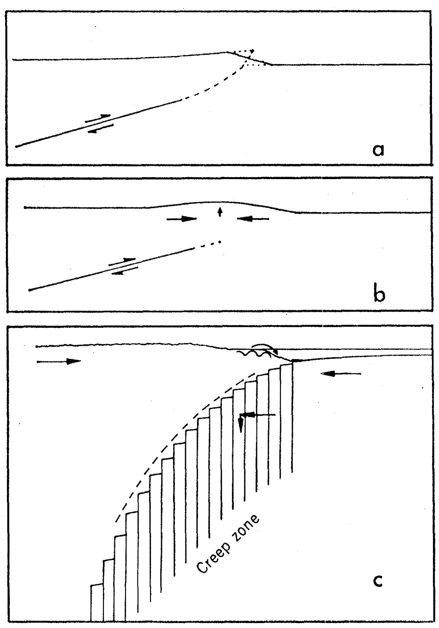


Fig. 2. (a) Surface expression of a shallow dip-thrust fault. The plane of the break curls toward the surface to achieve the minimum energy condition. (b) A system functionally equivalent to the one shown in Fig. 2a but in relatively incompetent material. The thin end of the wedge is plastically compressed instead of slipping on the underlying material. (c) Combination of the mechanism illustrated in Fig. 2b with Lliboutry's shear mechanism for foundering of oceanic lithosphere. Compression causes coastal uplift and folding on the shelf. The trench is primarily formed by material sinking into the hole left by the lithosphere, partly by initial downwarping of the oceanic plate by weight of compressional uplift. The continental slope is maintained by combined erosional transport and slumping toward the trench. The dashed line is a locus of shear above the descending plate, probably confined to a layer of relatively soft material sucked down by the trench.

To understand how the sinkhole on the floor of the trench can be rapidly transformed into surficial folding and uplift on the continental side, it is useful to examine the surface expression of a thrust fault. In a situation where a thrust fault of shallow dip is generated at some depth and approaches the surface, the plane of break tends to curl upward toward the surface to minimize frictional energy loss. The phenomenon is illustrated in Fig. 2a and has been observed in nature (*10*). The continuation of a recognizable break is to be expected in a competent rock formation; in softer material, it might be expected that the fault proper would merely peter out and that the thin end of the wedge would crumple in compression. This mechanism is illustrated in Fig. 2b, and it can be seen that it is functionally similar to the high-angle faulting in Fig. 2a, in that a surface bulge is produced at the end of the fault. It might be argued, therefore, that trench formation, particularly of the downbowed kind, is merely the response of the oceanic plate to loading by the weight of the upthrust material and the stress due to the thrust itself. This explanation would be acceptable if the motion were finite but limited, as are the continental thrust faults discussed by Link and

Walters (*10*). The mechanism would not produce steepening of the oceanic lithosphere into a Benioff zone; instead, there would be a substantial overall mass excess in the neighborhood of the trench. Where gravity data across an entire oceanic trench system have been published (*11*), the positive anomaly inside the island arc is not substantially larger in overall mass equivalence than is the sharp negative anomaly due to the trench itself.

The introduction of the Lliboutry shear-collapse mechanism for the oceanic lithosphere allows an explanation of both the rapid steepening of the lithosphere into a Benioff zone and the lack of a mass excess in the trench region. In the generalized trench mechanism sketched in Fig. 2c, the oceanic plate is initially somewhat downbowed by the transmitted shear (not true of the Chile Trench north of Valparaiso). At or near the trench floor, failure in shear occurs and the surface of the oceanic lithosphere begins to steepen downward. This subtracts material from the surface and can produce normal faults downthrown toward the land side, as observed in Fig. 1. The thin wedge of continental material encroaching upon the trench moves with the trench at its edge but with the continent at its base; it is, therefore, strongly deformed in compression, and its surface tends to rise by folding (typically) or by localized thrust faulting. The soft upthrust material is rapidly transported back toward the trench by sea-level erosion and slumping. The continuing downward shear of the underlying oceanic plate may be responsible for the concave slopes observed on the island arc sides of some western Pacific trenches (*12*). Shear of the thrust-fault type is required between the oceanic lithosphere and the continental plate proper, probably taking place (typically) in a zone of relatively soft material originating in the trench floor. It is important to note that the concentration of the thrust shear in a zone of heterogeneous soft material is not inconsistent with the existence of earthquakes that exhibit substantial source stresses (*13*). Indeed, if the large-scale differential stresses generated by global tectonic motion are small, as appears to be the case from the small overall gravity anomalies observed at sources and sinks, it is *only* in a heterogeneous material that the necessary local stress concentration can occur.

The data and arguments presented here do not, naturally, extend to the interpretation of seismic source mechanisms in the Benioff zones proper. However, the shear-failure mechanism for the oceanic plate is not inconsistent with the earthquake mechanisms commonly derived for the upper parts of Benioff zones (*7, 14*). These suggest longitudinal compression of the sinking lithosphere; the preexisting vertical shear zones provide a ready mechanism for the necessary deformation to occur by plain shear. If noncreep deformation is much easier in the vertical direction than in any other, it is even possible that stresses applied in other directions will result in vertical-shear earthquakes; the apparent alignment of the source mechanisms could be due as much to the anisotropy of the lithosphere as to real alignment of the applied stresses.

In conclusion, it is interesting to apply the shear failure hypothesis to the "typing" of trenches into those without apparent floor deformation (type I) and those empty of sediment (type II). As far as surface effects are concerned, the most important consequence of the hypothesis is the concentration of gross tectonic activity immediately landward of the onset of shear failure. Thus, type I trenches should have their points of failure well inland of the topographic axis of the trench, and only upthrusting, folding, and slumping are to be expected on the landward slope. Net surface mass anomalies should be positive over the region seaward of the failure point, but there should be a negative anomaly, at least of the Bouguer gravity, over the "sinkhole" region. On the other hand, the principal gravity anomaly and surface intercept of the Benioff zone should fall within the morphologic trench for a type II trench.

Published data for the highly active type II trenches tend to confirm the shear hypothesis description (*7, 11*). Most significantly, comprehensive hypocentral locations are available for the Hikurangi Trench off New Zealand (*15*) extending into the transition zone between it and the Kermadec Trench. Over most of its length, the Hikurangi Trench is clearly type I (*4*), and the surface intercept of the Benioff zone is some 100 km inland of the topographic trench. Bouguer gravity minima coincide with the surface intercepts of the Benioff zone and are consistent with a thick fill of lighter material over the point of shear failure. The northernmost profile of Hamilton and Gale (*15*) is over the transition zone, where the trench begins to deepen. Here, the locus of hypocenters begins to trend over toward the trench axis, which suggests that the point of failure of the oceanic plate is shifting closer to the topographic axis as the Kermadec Trench is approached.

Thus the principal difference between type I and type II trenches is the position of the locus of shear failure of the oceanic plate relative to the topographic axis of the trench. The type I trenches may be characterized by relatively slow convergence rates and an excess of sialic material, such that the seaward transport of material by compressional uplift, erosion, and slumping exceeds the rate of convergence. On the other hand, the type II trench has a convergence velocity exceeding the rate at which surface material can encroach on and fill the "sinkhole" depression at the point of shear failure, so that a deep empty trench is maintained. It should be noted that cause and effect are not properly resolved by these arguments: a dichotomy remains between continental compression and mountain building on the one hand, and self-propagation of "foundering" oceanic lithosphere on the other. The morphological differences between trenches do, however, appear to be the mechanical conseqences of different convergence rates, lithosphere thicknesses, and, no doubt, local asthenospheric properties.

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