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Transcurrent Faults in Continental Areas

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VII. Transcurrent faults in continental areas†

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[Plates 1 to 3]

Seismic fault-plane solutions, displacements observed during historic earthquakes, and an increasing number of geological reports of active transcurrent faults in many parts of the world all suggest that transcurrent faulting is a far more important tectonic process than has usually been recognized. Characteristic features of active transcurrent faults—easily overlooked in the absence of aerial photographs—include: abundant Recent scarps that often show a scissoring relationship to one another; elongate closed depressions; consistently offset streams; and unique rift topography that is remarkably linear over distances of hundreds of kilometres. Thrusts that steepen abruptly with depth typify many transcurrent faults at the base of steep mountain fronts and have led to delays in recognition in some areas.

Most puzzling of the great transcurrent fault zones are those of the circum-Pacific rim, where the relationship between major transcurrent faults of the continental margins and structures of the deep ocean floor is obscure. The Gulf of California is one region that appears transitional in that it combines many attributes of extensional rift valleys with those of transcurrent faults.

Transcurrent displacements, particularly those of large magnitude, add to the attractiveness of the continental drift hypothesis, but demonstrated movements in the circum-Pacific zone are largely parallel to continental margins and thus fail to fit neatly with most theories of orogenesis and drift.

One of the most intriguing results of seismological research in recent years has been the suggestion from the study of earthquake mechanisms that the great majority of the world's earthquakes are caused by transcurrent fault displacements. Many aspects of these fault-plane solutions are still the subject of controversy and debate, particularly with regard to detailed focal mechanisms and their relation to regional tectonic trends, but most seismologists would probably agree that the predominance of transcurrent displacements is a very surprising and unexpected result. In fact, it seems that geologists must draw the conclusion either that (1) the fault-plane solutions are wrong or misinterpreted, or that (2) active transcurrent faults are much more widespread than most geologists have thought in the past. There now seems to be increasing geologic evidence supporting the latter point of view.

If active transcurrent faults are indeed as widespread as is suggested by the seismological evidence, one might well ask why they have not been so generally recognized by geologists. Probably the primary answer is that they simply have not been looked for, or at least most geologists have not been willing to seek out and accept evidence for horizontal displacements on an equal basis with evidence for vertical displacements. There are other important reasons as well: many major transcurrent faults tend to occupy low, alluvium-filled troughs and valleys where they are difficult to detect and where geologic mapping often has not been carried out. The only evidence of faulting in such areas may be physiographic, and this demands the use of aerial photographs that are only slowly becoming

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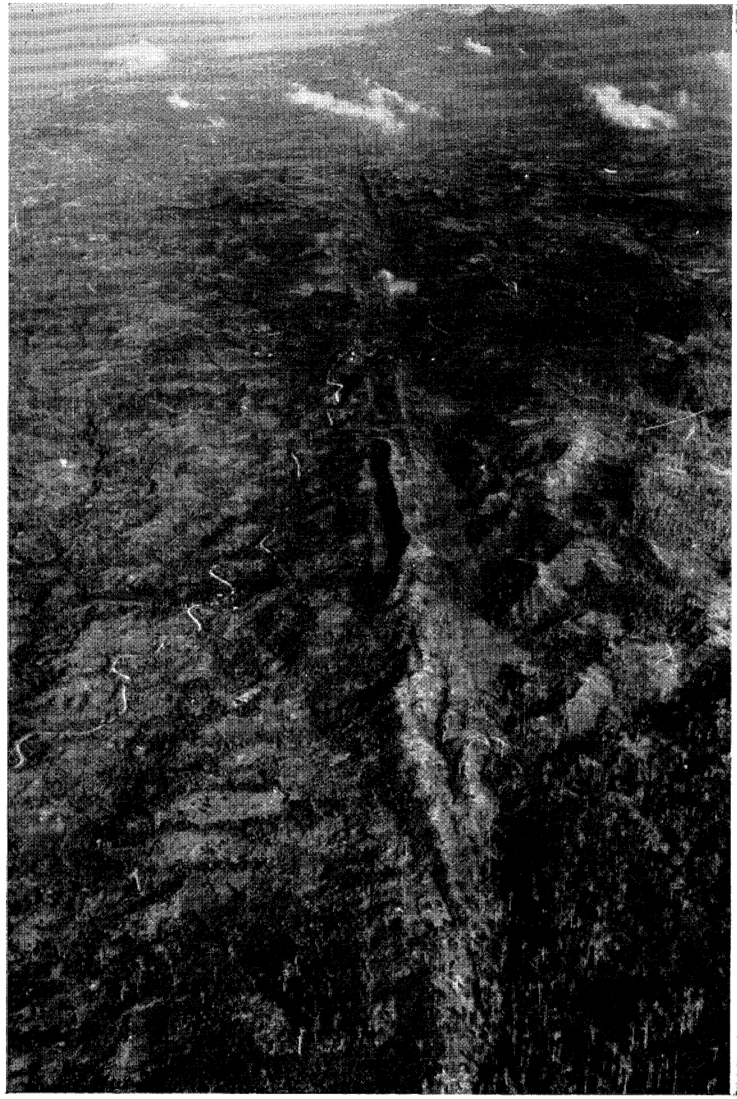

Figure 1. Aerial view northwest along Philippine fault in northern Leyte.

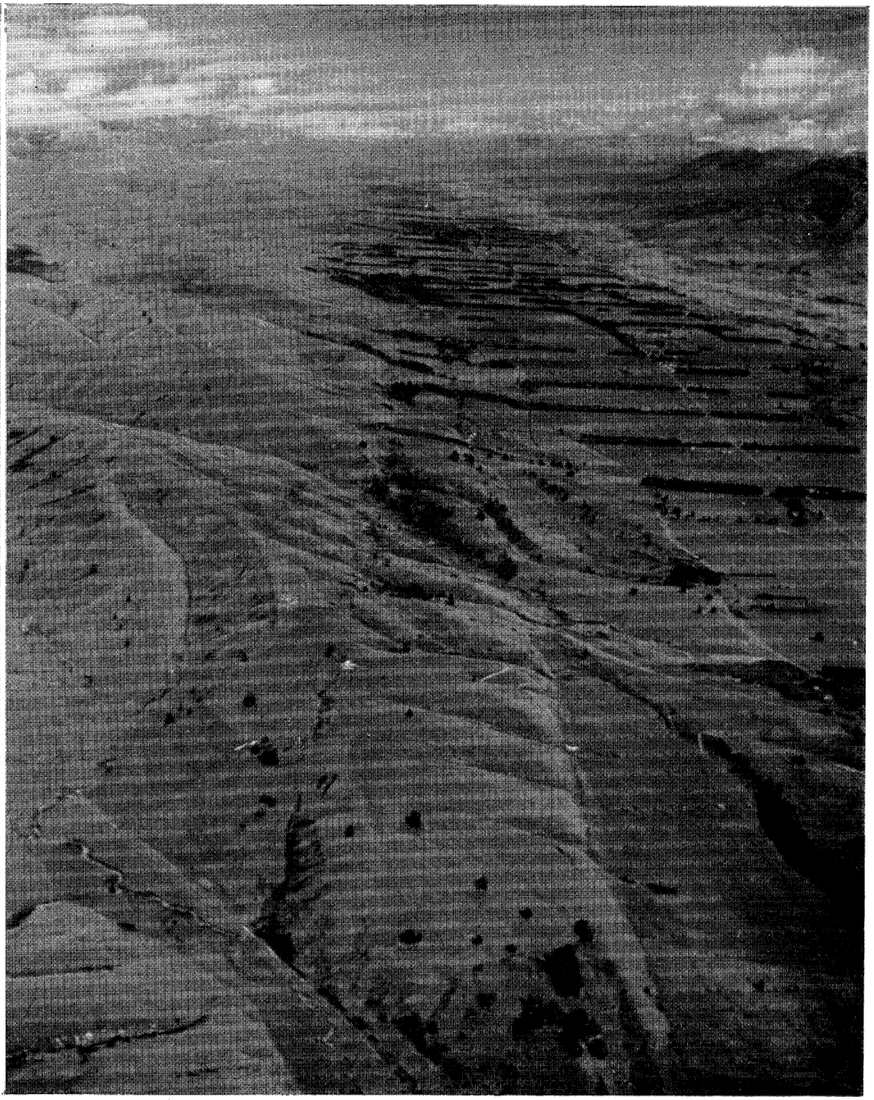

Figure 2. Aerial view southwest along Wairau Valley, southern New Zealand, showing Recent scarps (foreground) along this branch of Alpine fault.

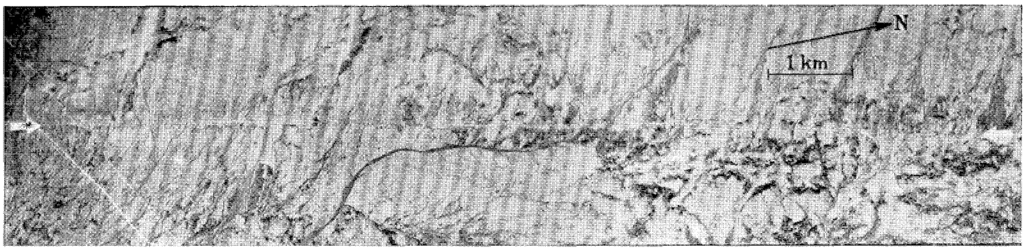

FIGURE 3. Vertical aerial view showing extreme linearity of 12 km length of Atacama fault, 100 km northeast of Antofagasta, Chile.

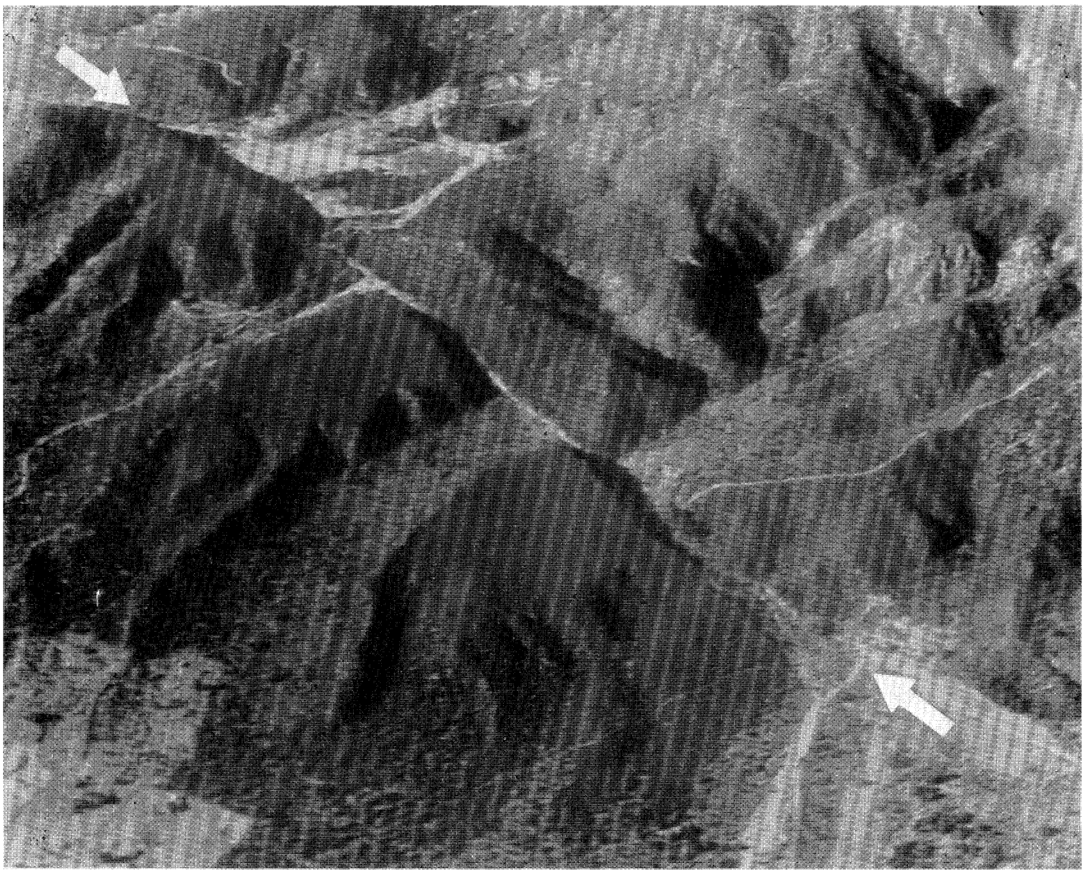

FIGURE 4. Dextral offsets of canyons along San Jacinto fault near Anza, California. Distance along fault between arrowheads is 1·9 km.

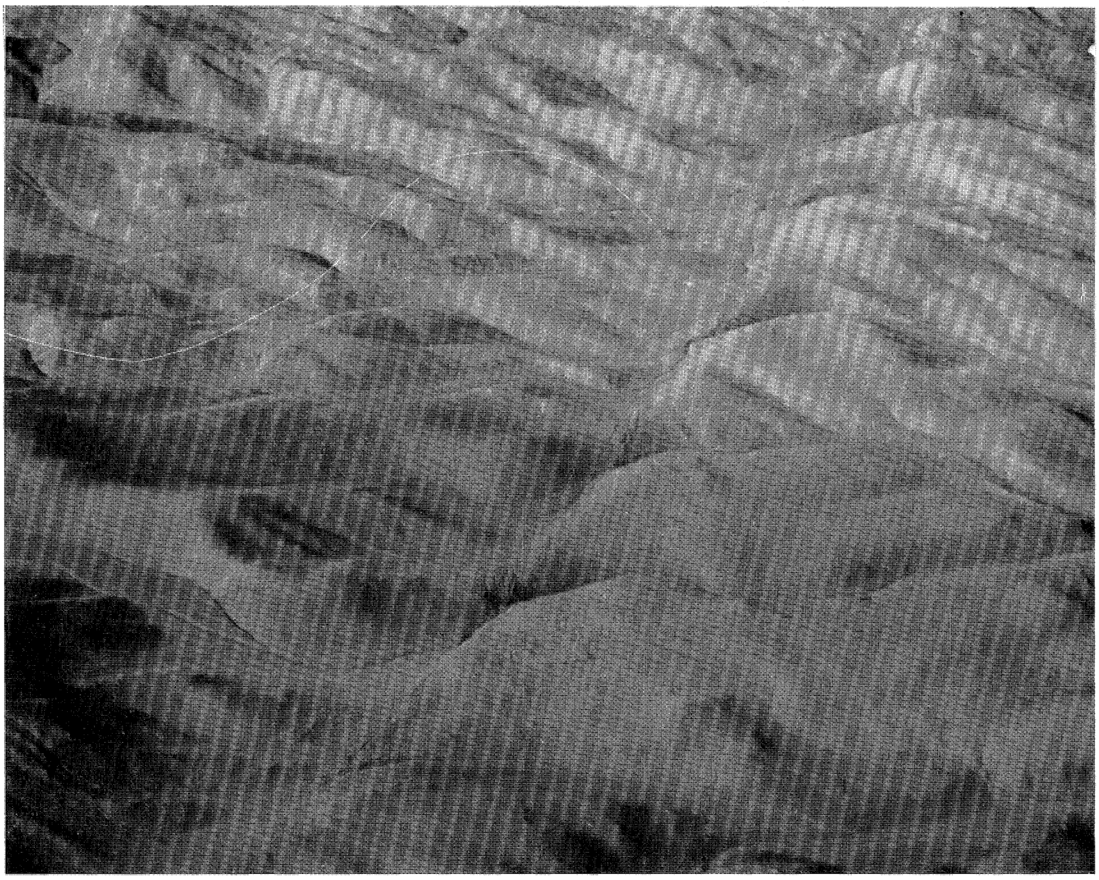

FIGURE 5. Sinistral stream offsets along Camarones fault, which is conjugate to Atacama fault 120 km north of Iquique, Chile. Length of fault shown is about 3·3 km.

FIGURE 6. Rift topography along Atacama fault. View north from near El Salado, Chile. (All the photographs except figure 3 are by author.)

available to geologists in some areas. Another factor is that major transcurrent faults with large total displacements may not become obvious or convincing on a geologic map until very large areas adjacent to the fault have been mapped. This demands vigorous and systematic regional geological mapping programmes that have not as yet been carried out in many parts of the world.

Physiographic evidence for horizontal displacements on active transcurrent faults is a far more powerful and applicable tool than has generally been recognized. Probably the most impressive feature of throughgoing transcurrent faults is their extreme linearity over literally hundreds of kilometres. Linearity of segments of the well known San Andreas and Alpine faults has long been recognized, but segments of the Philippine fault and the Atacama fault of Chile are fully as impressive (figures 1 to 3, plates 1 and 2) (Allen 1962). Although either transcurrent or dip-slip faults might conceivably originate as somewhat sinuous features, continuing horizontal displacements must rapidly tend to straighten a transcurrent fault, whereas a dip-slip fault may retain sinuosity throughout its history of displacement, particularly in areas of heterogeneous surficial rocks. An increasing number of linear fractures on the Earth's surface have now been shown to have histories of horizontal displacement, including many of the oceanic fracture zones (Vacquier 1962; Heezen, Gerard & Tharp 1964), and Menard (1962) has pointed out that the faults of greater length are seemingly associated with greater total displacements. Indeed, we should probably now suspect all exceedingly linear regional fractures of being of transcurrent fault origin until proved otherwise.

Offset stream courses caused by recent horizontal fault displacements are another physiographic feature of faulting whose importance as a reconnaissance tool in establishing sense of movement has not been fully appreciated (figures 4 and 5, plates 2 and 3). Stream offsets seem to survive in a surprisingly wide variety of climates, although aerial photographs are a virtual necessity for identifying them in areas of heavy vegetation. Development and preservation of stream offsets demand a unique environment, not everywhere present along transcurrent faults: there must be sufficient relief so that streams are moderately entrenched, and the fault must cross drainages nearly at right angles rather than follow a stream valley. This last condition is seldom realized, inasmuch as erosion of the pulverized rocks of the fault zone causes most streams to follow the fault rather than to cross it. Only where the fault locally climbs out of a canyon bottom, such as in crossing from one drainage system to another, does it cross numerous closely spaced tributaries. Furthermore, unless the sense of displacement is such that the offsets are in the *uphill* direction, they might just as well be attributed to preferential erosion and stream piracy as to actual fault movement. Examples of such uphill displacements are numerous along the San Andreas fault of California (Hill & Dibblee 1953; Noble 1954) and the Alpine fault of New Zealand (Wellman 1953), and similar arguments have been made for the Agua Blanca fault of Mexico (Allen, Silver & Stehli 1960) and the Philippine fault (Allen 1962). Similar relations have recently been documented along one of the major regional faults of Tien Shan in the Soviet Union (Burtman 1963). Other diagnostic physiographic features of active transcurrent faults include abundant scissoring of recent scarps, and characteristic 'rift topography' in which the fault occupies a broad trough but neither side is consistently higher than the other (figure 6, plate 3) (Sharp 1954).

Most major transcurrent faults are known to be essentially vertical because they cross rugged topography with nearly straight traces, and this verticality is to be expected from the presumed causal stress pattern (Anderson 1951). On the other hand, the surficial expression of many of these faults is locally far from vertical in many places. Wellman 1955*a*) and Suggate (1963) have pointed out that shallow nappe-like structures are common along the Alpine fault at the west base of the southern Alps of New Zealand but that these thrusts steepen very rapidly with depth (figure 7). Likewise, surficial breaks of the San Andreas fault along the south base of the San Bernardino Mountains in southern California dip northward under the range but presumably become vertical at shallow depth (Noble 1932; Allen 1957). Similar relations exist at almost every place in southern California where transcurrent faults delimit the base of a steep mountain front; some of the best examples have recently been mapped by R. V. Sharp along the San Jacinto fault (figure 7). Wellman (1955*a*) pointed out that the rocks associated with the faults of his area were so thoroughly crushed that the surficial thrusting probably was caused by down-slope creep under gravity. Another important causal factor here and elsewhere may be related to the origin of the steep mountain front itself: if, as seems likely, the presence of the mountain front is caused by a local vertical component of displacement along the predominantly transcurrent fault, then vertical motion constrained at depth to a vertical plane must necessarily result in localized low-angle thrusting at the surface, as has been demonstrated analytically and in models by Sanford (1959). Somewhat similar studies have been carried out by Gzovsky (1958). But regardless of caues, it should be noted that

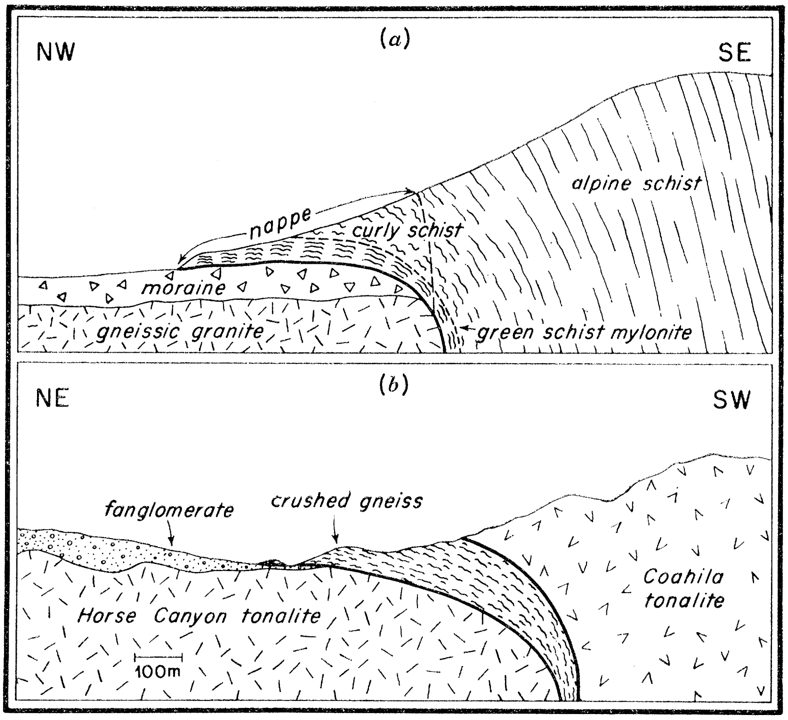

FIGURE 7. Surficial thrusts along predominantly transcurrent faults. (*a*) Diagrammatic section across Alpine fault at base of southern Alps of New Zealand, from Wellman (1955*a*). (*b*) Section across most active branch of San Jacinto fault in Peninsular Ranges of southern California, based on mapping by R. V. Sharp.

these surficial thrusts in many places conceal the major underlying transcurrent faults and indeed have caused delays in recognizing the dominance of horizontal displacements along some branches of the San Andreas; other major transcurrent faults undoubtedly have been—and are being—misinterpreted for the same reason.

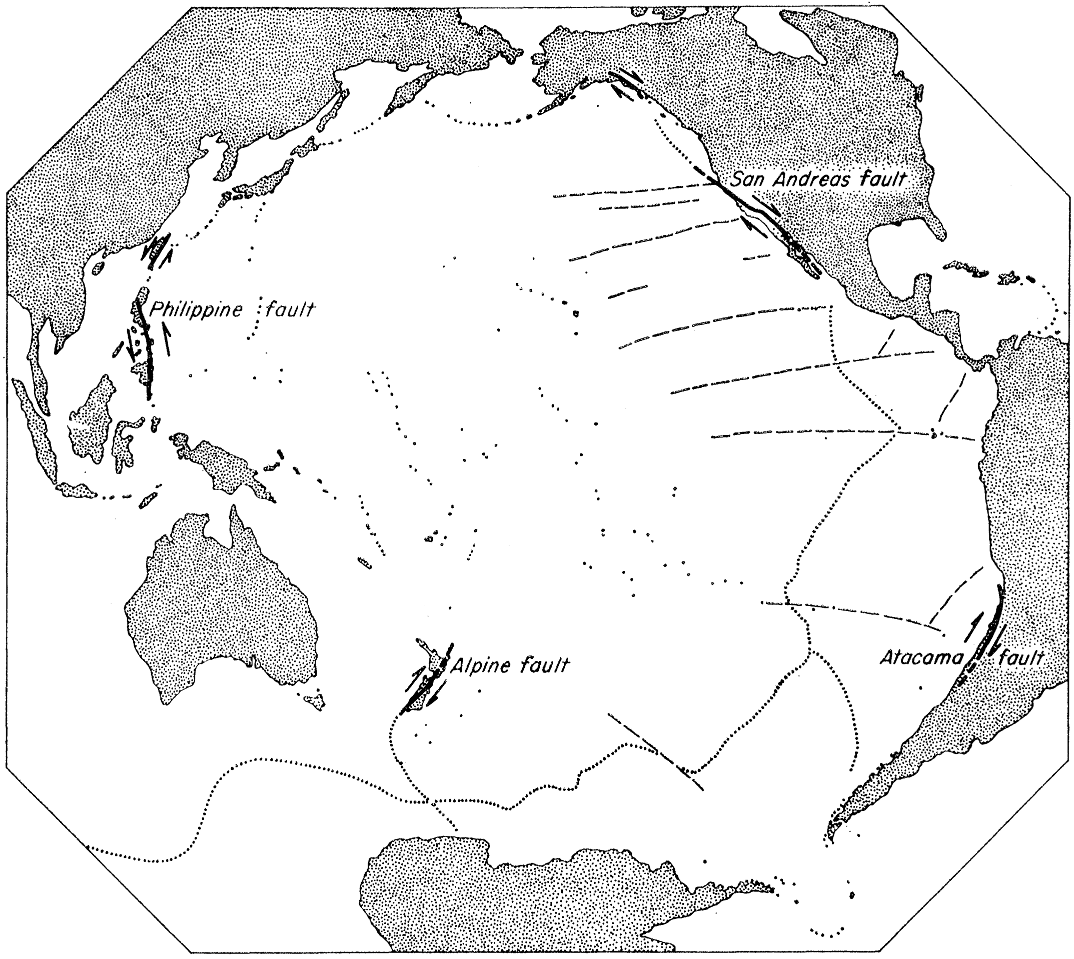

Figure 8. Map of some of the major transcurrent faults of the circum-Pacific rim. Locations of crests of oceanic rises (dotted) and major fracture zones (dashed) are after Menard (1960) and Heezen (1962).

Probably the most puzzling of the great active transcurrent faults are those of the circum-Pacific rim (figure 8), and inasmuch as this is the most active of all mountain-building regions, tectonic processes that are taking place here certainly must fit in to any over-all theory of mountain building and orogenesis. The San Andreas fault of California has been recognized as a throughgoing regional feature since the time of the 1906 San Francisco earthquake (Lawson *et al.* 1908), and it has become clear in the ensuing years that similar and related transcurrent faults dominate much of the rest of coastal California as well. The very similar Alpine fault was later recognized as a major feature of New Zealand (Wellman & Willett 1942), and it is interesting to compare the two regions. Both California and southern New Zealand are dominated by major throughgoing transcurrent faults, yet both regions are very atypical of the rest of the circum-Pacific 'ring of fire' in several important ways: both lack earthquakes of intermediate and deep focus; both lack deep offshore oceanic trenches; and both lack abundant active volcanism. Thus it might be argued that regional transcurrent faults of the San Andreas type are limited to such tectonically unique areas. But the recent documentation of identical fault systems in northern Chile (St Amand & Allen 1960) and in the Philippines (Allen 1962) has now firmly established

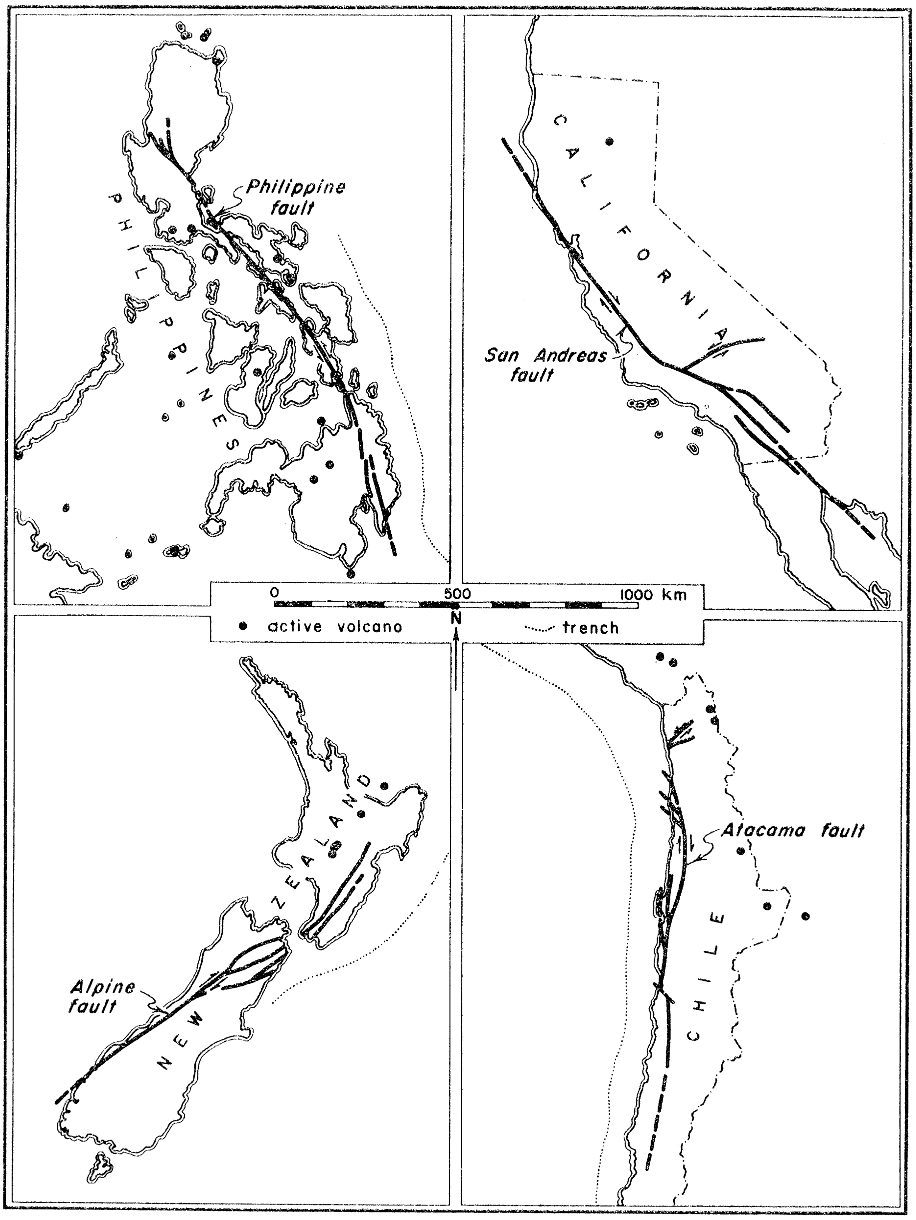

FIGURE 9. Maps at same scale of Philippine, San Andreas, Alpine, and Atacama faults.

that regional horizontal displacements are by no means limited to such atypical areas. Supporting this point of view are the observed ground displacements of horizontal character associated with recent major circum-Pacific earthquakes in Taiwan (Hsu 1962) and Alaska (Tocher 1960)—both in areas where most geologists probably would not have predicted this type of displacement. Likewise, the great earthquake of 1960 in southern Chile is thought to be of dominantly transcurrent character (Benioff 1962; St Amand 1961), although the faulting did not extent on to the land.

The regional transcurrent faults of Chile, California, New Zealand, and the Philippines are all remarkably similar in their apparent length, linearity, degree of activity, and physiographic expression (figure 9). All are parallel to coastlines and thus imply displacements parallel to the circum-Pacific rim. Indeed, the Chilean and Philippine faults are so close and parallel to the adjacent deep oceanic trenches that it is difficult to escape the conclusion that they must to some degree share the same stress system. If the Philippine Islands were slightly more submerged, the trace of the fault would largely be concealed beneath the sea, and it seems likely that similar throughgoing faults of transcurrent character underlie many of the other island arcs that are less well exposed. But whether or not transcurrent faults parallel to coastlines underlie *all* circum-Pacific island arcs is debatable; many of the active faults of Japan, for example, appear to cut across the island-arc structure, and this trend is supported by recent analyses of fault-plane solutions based on surface-wave data (Aki 1964).

In only a few places do major transcurrent faults of the continents tie in directly to features of the deep ocean floor. Perhaps the most instructive of these areas is the Gulf of California, which appears to be part of the East Pacific rise when approached from the south and a part of the San Andreas fault zone when approached from the north (Menard 1960). The East Pacific Rise is thought to be primarily an extensional feature, and this extension is reflected in the Gulf of California's abundant Quaternary volcanism, its shape (Hamilton 1961), its crustal structure (Phillips 1963), and its high heat flow (von Herzen 1963). Yet when the San Andreas fault is traced northward from the Gulf, it loses all aspects of extension and appears to be a purely transcurrent feature across coastal California until it re-enters the deep ocean off Oregon. And the San Andreas fault is the dominant and most active tectonic feature of the California–Nevada region, so it can hardly be dismissed as secondary to more fundamental tectonic processes in the region. It is difficult to escape the conclusion that the continental crust is reacting to tectonic processes in a way different from that of the adjacent deep ocean floors and that perhaps some sort of mechanical decoupling is necessary between the continental and oceanic crusts.

The Gulf of California and the Red Sea have many tectonic similarities, especially in that both represent landward extensions of oceanic rises (Girdler 1962) and both terminate in transcurrent fault zones of probable large displacement (Crowell 1962; Quennell 1959). But in contrast to the simple extensional pattern of the Red Sea, with its single axial fracture zone (Girdler 1962), faults of the San Andreas system form a distinctly en échelon pattern on the floor of the Gulf (Shepard 1950; Rusnak, Fisher & Shepard 1964), and their orientation is not consistent with their being tensional features related to dextral movements across the Gulf (Biehler, Kovach & Allen 1964). It seems reasonable that the distinctive fault pattern of the Gulf should result from stresses related both to the San Andreas fault system and to the East Pacific Rise, but the mechanics of the system is not yet at all clear and again may reflect some sort of decoupling between continental and oceanic crust.

Parts of California southwest of the San Andreas fault are moving relatively northwest at a continuing rate of 3 to 5 cm/y (Whitten 1955, 1961). Analogous rates have been measured in New Zealand (Wellman 1955*b*), and similar movements are presumably taking place along other active transcurrent faults. Thus continental drift—in a limited sense—is taking place before our eyes, and at very finite rates. Such observed horizontal movements of continental crustal blocks, taken together with evidence for very large displacements in the past, certainly add to the attractiveness of the continental drift hypothesis, for they destroy the argument that continental drift of any type is mechanically absurd. On the other hand, the directions of displacement along major transcurrent faults of the circum-Pacific rim are largely *parallel* to the oceanic borders and thus fail to fit neatly with most of the specific hypotheses of convection and drift that have been presented. Most arguments of convection and drift have visualized—in their simplest forms—crustal flow away from the oceanic ridges toward the continental margins, but this does not seem mechanically consistent with horizontal movements within the continental margins at right angles to this direction, as is clearly observed in California and Mexico, Chile, New Zealand, the Philippines, Taiwan, and parts of Alaska. Nor do such transcurrent movements fit any better with most of the more general theories of orogenesis and geosynclinal deformation, which have emphasized compression perpendicular to geosynclinal trends, together with vertical uplift. It appears that we do not as yet have a complete theory of either continental drift or orogenesis that adequately explains the observed transcurrent displacements on continents.

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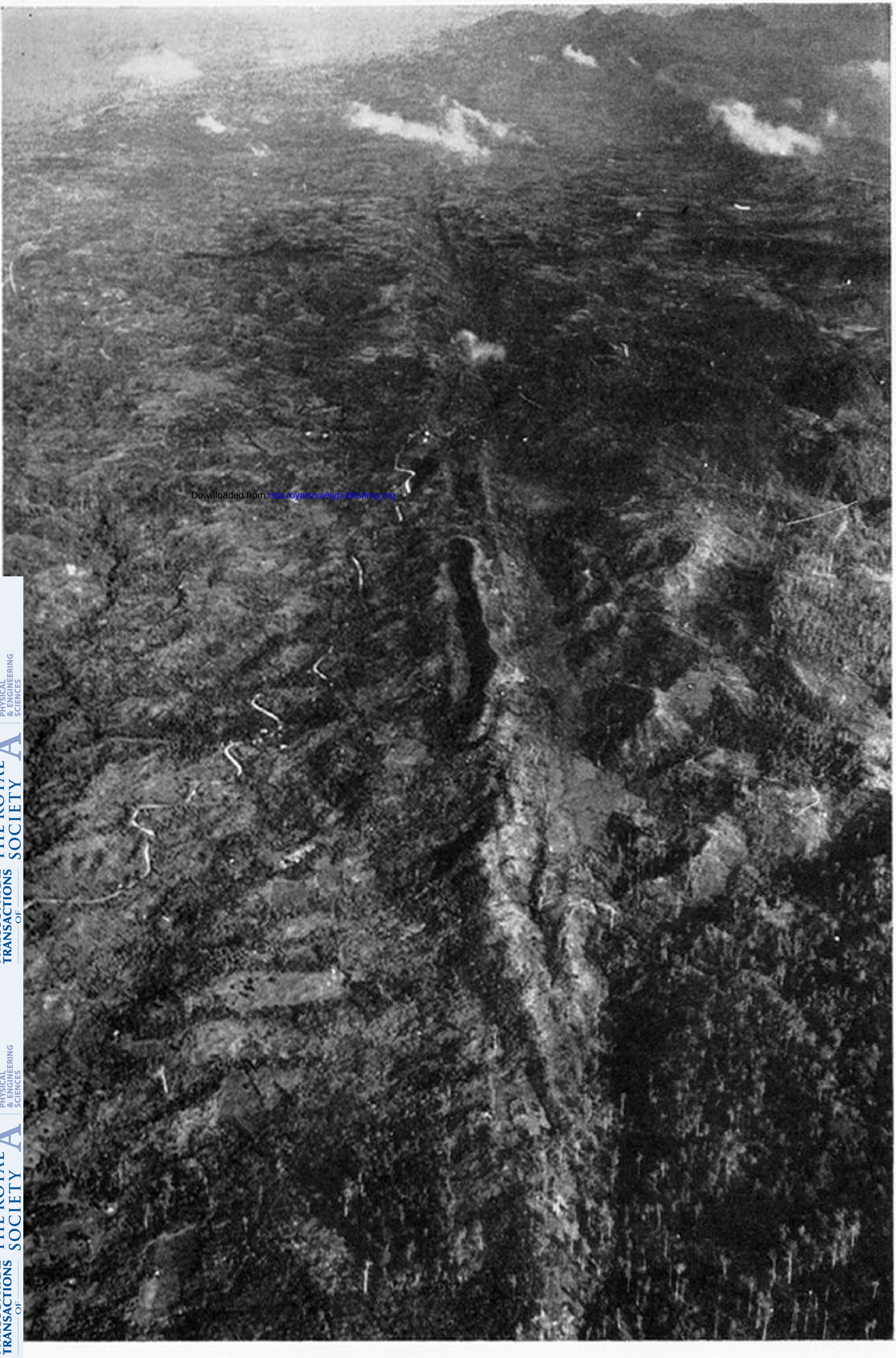
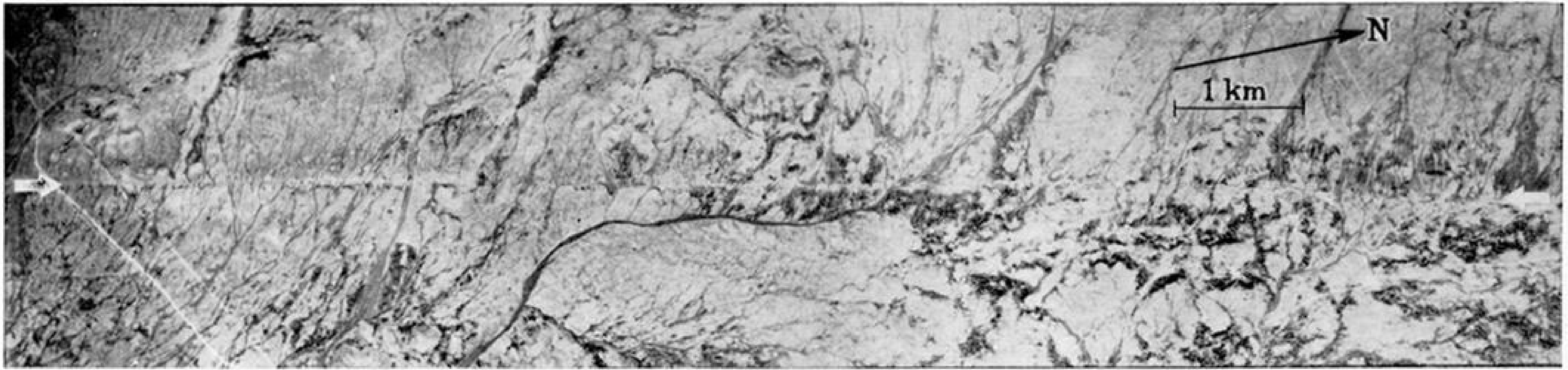


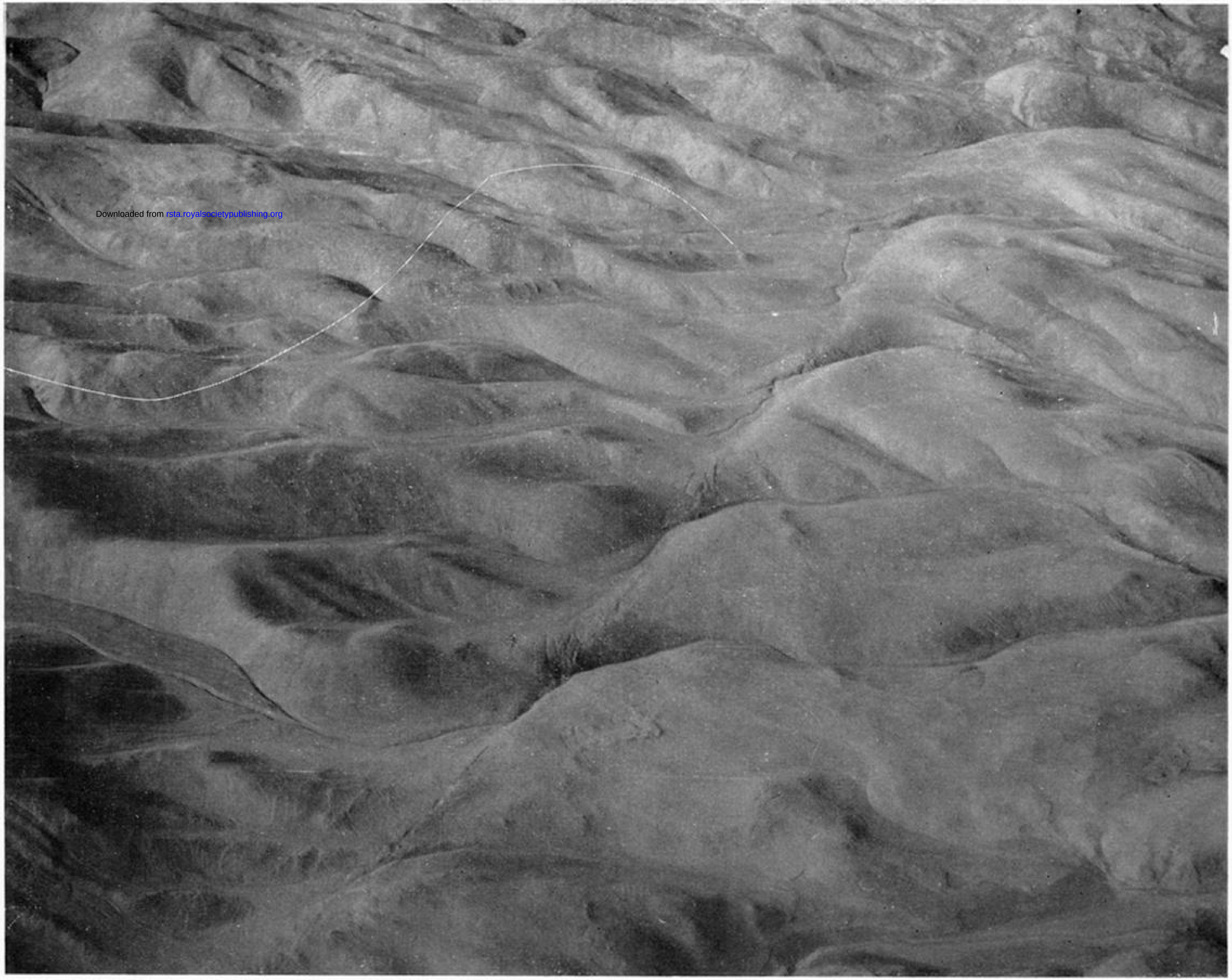
FIGURE 1. Aerial view northwest along Philippine fault in northern Leyte.

FIGURE 2. Aerial view southwest along Wairau Valley, southern New Zealand, showing Recent scarps (foreground) along this branch of Alpine fault.



IGURE 3. Vertical aerial view showing extreme linearity of 12 km length of Atacama fault, 100 km northeast of Antofagasta, Chile.

IGURE 4. Dextral offsets of canyons along San Jacinto fault near Anza, California. Distance along fault between arrowheads is 1·9 km.



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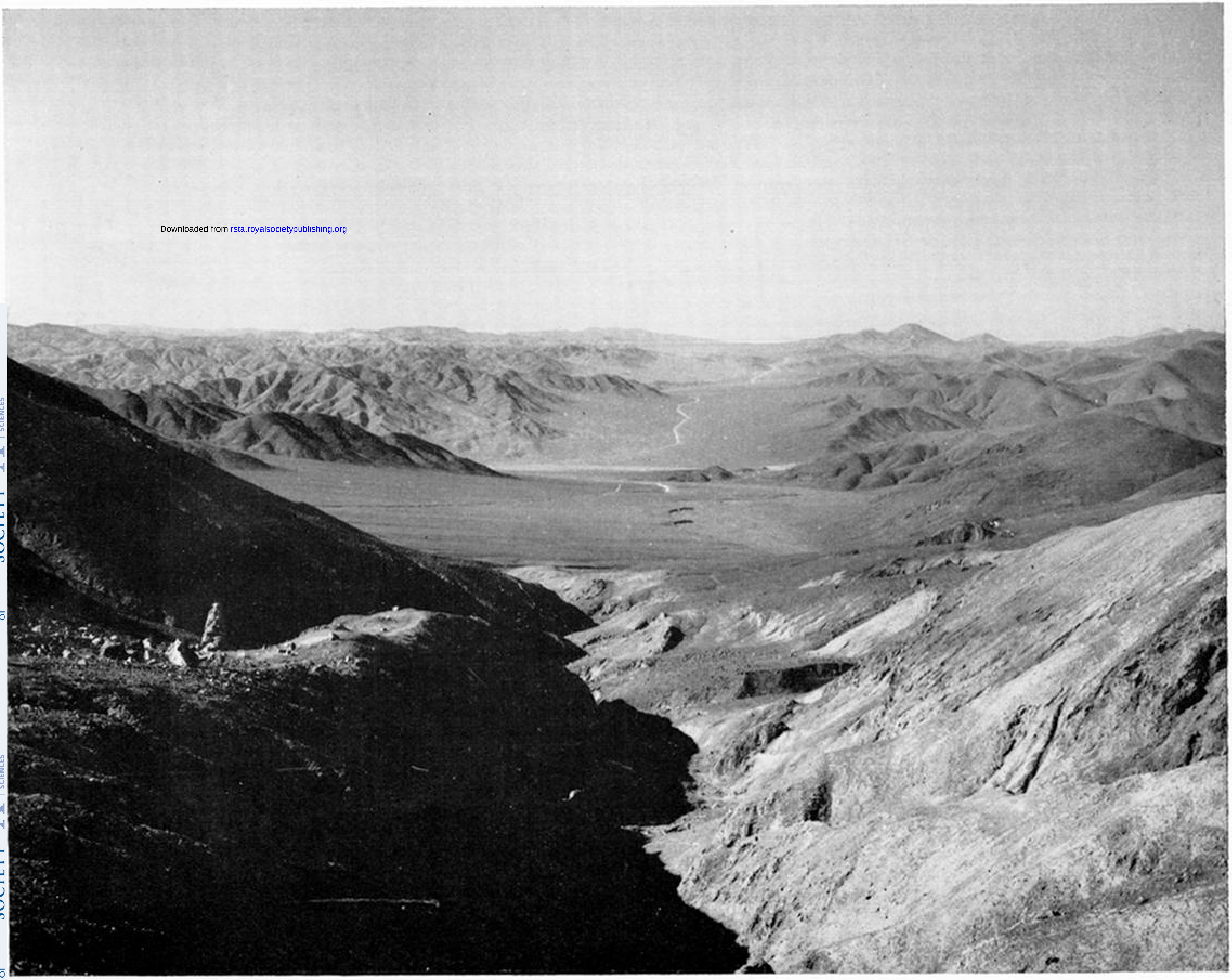

FIGURE 6. Rift topography along Atacama fault. View north from near El Salado, Chile.
(All the photographs except figure 3 are by author.)