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35. SERPENTINITE-BRECCIA LANDSLIDE DEPOSITS GENERATED DURING CRUSTAL EXTENSION AT THE IBERIA MARGIN[1]

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ABSTRACT

Three serpentinite-breccia units, pre-Late Cretaceous to late Barremian in age, were recovered from Subunit IVA (369.9-484.2 m below seafloor in Hole 899B), one approximately 95 m thick, and two less than 20 m. The three are similar and are interpreted to be bedded tabular units. Each contains angular fragments, many displaying jigsaw/crackle textures, set in a matrix apparently generated by fragmentation of the clasts. Sorting is generally absent, but larger boulders tend to occur in the upper half of the thickest unit. Minor internal deformation zones or slip zones occur. All these features are common in subaerial giant landslide deposits, and the serpentinite breccias are interpreted as being equivalent submarine deposits, generated by slope failure on a nearby large serpentinite fault scarp. Giant landslides are a typical feature of regions undergoing rapid extensional deformation, and such deposits may be relatively common in strongly faulted submarine extensional environments. The basement topography at the time of formation of the serpentinite units probably differed significantly from the present topography buried beneath the Iberia Abyssal Plain. As a result, the location of the source serpentinite escarpment is unknown. However, the large size of some of the fragments included within the serpentinite indicates that it was probably within a few kilometers of Site 899. The aggregate width of the belt of mantle serpentinite exposed in the Late Cretaceous at the Iberia Margin was at least 20 km. Most of this belt is now buried beneath the sediments of the Iberia Abyssal Plain.

INTRODUCTION

Ocean Drilling Program (ODP) Site 899, on the Iberia Abyssal Plain, was drilled during Leg 149, an east-west transect of sites, to examine the nature of the ocean/continent transition on the Iberia Margin. Sawyer, Whitmarsh, Klaus, et al., (1994) record shipboard observations made during Leg 149; this volume summarizes the postcruise results and conclusions drawn from the work. Three serpentinite-breccia units, pre-Late Cretaceous to late Barremian in age, form part of Subunit IVA (369.9-484.2 m below seafloor [mbsf]) in Hole 899B, one approximately 95 m thick, and two less than 20 m thick. This account draws on the shipboard description of the breccias (Shipboard Scientific Party, 1994) and discusses several possible origins for the units. We conclude from observational and chemical evidence that the breccias formed as large landslide deposits, probably derived from unstable scarps exposed during extensional faulting during the Early Cretaceous opening of the north Atlantic.

SUMMARY OF THE SITE 899 SERPENTINITE BRECCIAS

The Upper, Middle, and Lower Breccia Units are similar poorly sorted polymict breccia units containing mostly serpentinite clasts. In each case, all the recovered material consists of broken rock; there is no obvious distinction between "clasts" and "matrix". The grain size ranges from large boulders more than a meter in diameter to microscopic. Back scatter imaging suggests that the particulate fabric extends into the 10-µm range. Thin section and macroscopic observations show that many of the clasts are minutely shattered. Nevertheless, the rocks are highly indurated, apparently from diagenetic cementation, possibly involving the authigenic precipitation of smectite. The smaller fragments can be seen to be angular, and this is particularly apparent in thin section, but the degree of rounding of the larger boulders is unknown. Fragments are generally equidimensional, where this can be ascertained.

Superficially, the breccias show little systematic evidence of internal stratification or layering. Local grain size zoning was observed in the interval 899B-23R-2, 92-106 cm (Shipboard Scientific Party, 1994, fig. 36) and rare internal sharp boundaries also occur (e.g., in intervals 899B-19R-1, 59cm and 899B-28R-1,126-128 cm; Shipboard Scientific Party, 1994, fig. 41). The only evidence of sorting is a slight tendency for larger clasts to occur preferentially in the mid- to upper part of the Upper Breccia Unit (Shipboard Scientific Party, 1994, fig. 13). More than 95% of the clasts in the Breccia Units are serpentinite. They vary slightly in composition and, although the rocks were almost completely serpentinized prior to brecciation, both olivine- and pyroxene-rich variants can still be identified. More critically, the serpentinite fragments appear to have been variably oxidized and calcitized prior to their incorporation into the breccia. In the central and lower parts of the thicker breccia unit it is possible to identify fragments of both "fresh" dark green and yellow-brown variably oxidized serpentinite. Small fragments of magnesium-rich metaigneous rocks are the only other clast-type present in the breccias. A striking feature of the units is the fractured or "jigsaw" nature of many of the clasts (Shipboard Scientific Party, 1994, fig. 35) and the presence of disaggregated grains with fragment trails, suggesting that the process of fragmentation was active during the last stages of emplacement.

Internal shear zones are present within the breccia unit. Such zones are not major features, usually a few centimeters wide, crudely planar, and are indicated by grain-size reduction, (e.g., 899B-16R-1, 121 cm, and 899B-28R-1, 110-128 cm, [Shipboard Scientific Party, 1994, fig. 41]). Folded flow textures (Shipboard Scientific Party, 1994, fig. 39) occurring near the bases of the units suggest that in

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places a measure of ductile flow was involved in the emplacement of the units.

The lower boundary of the breccia unit was not well recovered, and neither were the rocks beneath the breccias. These rocks appear to consist of accumulations of mixed blocks of serpentinite, micro-gabbro, and basalt set in sediments of various lithologies. The sediments do not contain mineralized veins, are relatively uncompacted, and also lack significant cementation. In some cases there is evidence for deformation within these sediment intervals, but there is no unequivocal evidence that the deformation was associated with the emplacement of the breccias.

POSSIBLE ORIGINS FOR THE BRECCIA UNITS

Brecciated rock textures are common, and may be associated with in situ deformation of rock (e.g., from hydrofracturing), cataclastic deformation in tectonic shear zones, mass flow deposits such as landslides or rock falls, and various other causes. Despite the varied environments of formation, common textural characteristics may recur. For example, angular and fractured clasts are common features in brecciated units dominated by a variety of brittle processes. Fortunately, some diagnostic characteristics permit the multiple possibilities to be constrained. We here examine these characteristics in the context of the origin of the breccia units at Site 899.

In Situ Brecciation

Crystalline and highly indurated rocks exposed to significant stresses and fluid pressures may display extensive brittle deformation, resulting in intense in situ brecciation. Basement cores recovered at Site 897 and Site 900 (Sawyer, Whitmarsh, Klaus, et al., 1994) contain abundant brecciated zones accounting for up to 70% of a given core. Texturally, these rocks are distinguished by angular clasts of locally derived basement rock embedded in a calcite-rich matrix. Clast sizes range from microscopic to more than 10 cm in diameter, and there is a general absence of structure, either sedimentary or tectonic. Most importantly, the brecciated zones are characteristically heterogeneous, with large volumes of relatively undisturbed, in-place basement rock, surrounded by disrupted brecciated zones. The relative homogeneity of the serpentinite breccias at Site 899 and the uniformly fragmented and disrupted nature of the particles precludes the possibility that they were formed by in situ brecciation processes. However, the picture is complicated by occurrence in the largest breccia unit of clear evidence for secondary calcite veining and repeated hydrofracturing of the breccia unit after it was formed (Morgan and Milliken, this volume).

Cataclastic Shear Zones

Brittle shear zones and fault gouges have been described frequently (e.g., Rutter et al, 1986; Chester and Logan, 1987), and they exhibit a range of textures and structures, controlled in large part by lithology and the mode of deformation. Serpentinite fault gouges display certain features in common with other examples (e.g., Hoogerduijn Strating and Vissers, 1994), including discrete zones of shear localization and grain size reduction, fracture arrays, and planar foliation. Serpentine, however, is very sensitive to elevated temperatures and pressures, and will deform ductilely at temperatures as low as 300°C (Evans, 1977). Under frictional heating conditions induced along shear zones, serpentine will tend to develop distinct foliation and shear fabric (e.g., Hoogerduijn Strating and Vissers, 1994). The complete absence of such textures in the serpentinite breccias at Site 899 argues strongly for low temperature, brittle deformation.

Talus Accumulations

Recent submersible observations of the textures, superficial features, and processes on active submarine talus cones (Whipple and Naidoo, 1991; Juteau et al., in press) have emphasized that large talus deposits can be formed under marine conditions adjacent to submarine scarps. These deposits include "energetic rockfalls." Indeed, we suspect there may be a complete spectrum of deposits from talus accumulations, formed by mass wasting over a significant time period, to rock avalanche deposits formed by sudden catastrophic failure and the deposition of large volumes of brecciated rock. Unfortunately, the evidence required to categorize the members within this spectrum of deposits is largely lacking. Talus accumulations are often of limited lateral extent, whereas landslide deposits can be extensive and of tabular morphology. Although we have no data on the lateral extent of the three Site 899 serpentinite breccia units, we prefer to interpret them as bedded units because they are intercalated with fossiliferous sediments and span a considerable time period. We are not aware of mass wasting talus deposits in which the fragments display the crackle and jigsaw textures. Such textures characterize landslide deposits and are also found in the Site 899 breccias.

Diapiric Extrusion

Diapiric origins for serpentinite breccias have been proposed in a variety of settings, many related to subduction zones (e.g., Fryer and Fryer, 1987), and are attributed to the buoyancy of water-saturated serpentinite. Lockwood (1972) termed these brecciated masses "serpentinite protrusions." The extrusive products, "sedimentary serpentinites," are more frequently observed and typically display a highly sheared texture, with clasts of serpentinite entrained within a foliated serpentine mud matrix (e.g., Lockwood, 1971a; Carlson, 1984; Phipps and Ballotti, 1992; Fryer and Mottl, 1992). Such deposits demonstrate the very ductile flow behavior of wet, fragmented serpentinite. Superficially similar foliated, sheared serpentinite was recognized in cores from sediments above the serpentinite at Site 897 (e.g., in the interval 897C-65R-2, 90-97 cm) and also mixed with sediments at Site 899 (e.g., in the interval 899B-31R-2, 32-37 cm). All these examples, and in particular the well-described Quaternary examples recovered on ODP Leg 125 (Fryer and Mottl, 1992) display a foliated character distinct from the brittle-textured breccia units under consideration.

Mass-flow Deposits

Bedded units in this category include a spectrum of types ranging from debris-flow deposits, commonly with a mud matrix, to rock avalanche deposits with a cataclastically generated matrix. Many deposits termed "olistostromes" probably fall into this category (Abbate et al., 1970) and this term has been widely applied to serpentinite-rich masses in the Appenines. Olistostromes often contain giant clasts and a well-defined clast/matrix dichotomy is invariably present—a feature missing in the breccia units considered here. Yarnold (1993) has clearly distinguished debris-flow deposits from rock-avalanche or landslide deposits and outlined their characteristics when formed under *subaerial* conditions. Our observations at Site 899 show many similarities with subaerial landslide deposits and the major features of these units are summarized below. Fortunately, the origin of some of these deposits is unambiguous—their formation was observed. Unfortunately, rock-avalanche deposits have been mainly described in terms of their large-scale features, whereas the Site 899 serpentinite breccias are, of course, only known from the description of a single vertical core, making the comparison difficult.

CHARACTERISTICS OF ROCK-AVALANCHE DEPOSITS RESULTING FROM GIANT LANDSLIDES

Geometry

Typically such deposits, where unconfined, are sheetlike or tonguelike. The long dimension may exceed 15 km (Watson and Wright, 1969) and units may be from a few meters to several hundred meters thick. Volcanic debris-avalanche deposits may be even larger, and extend for over 100 km where constrained in valleys, and cover areas exceeding 2000 km^2 (Siebert, 1984; Stoopes and Sheridan, 1992).

Grading/Sorting and Ghost Stratigraphy

As most descriptions of landslide deposits are of undissected Quaternary units, few descriptions contain detailed quantitative information on internal grading and or sorting. Most units appear to be non-graded. However, Cruden and Hungr (1986), showed a single section through the Frank slide in Alberta to be reversely graded. Krieger (1977) also refers to a general coarsening upward in both the Escabrosa and lower Martin megabreccias. Notwithstanding the apparently chaotic nature of most avalanche deposits, the relative position of the source lithologies may be preserved during transport in large volume deposits, generating a "ghost stratigraphy." This is the case in the Blackhawk slide (Shreve, 1968) even though material was transported for distances of up to 8 km. In the even larger Saidmerreh slide deposit, blocks of Asmari Limestone are prominent in the upper part of the deposit above Eocene debris, reflecting the original stratigraphic relations (Watson and Wright, 1969).

Clast Characteristics

Deposits of this type invariably contain angular to subangular fragments, although clast roundness may vary with the lithology or clast size. Clast composition is largely a function of the nature of the rocks in the source area. The amount of foreign material entrained during transport is typically minimal. As a result, deposits derived from large, uniform rock masses such as granites and serpentinite bodies are often mono-lithologic. Material within large-volume deposits is normally intensely fractured, with the development of "jigsaw" or "crackle" textures. Mudge (1965) noted that even relatively small units may show clast fracturing. Shreve (1968), describing blocks from the Blackhawk slide, noted that some were severely shattered, but that the constituent fragments were displaced only by a few centimeters. Clast size is highly variable, but very large clasts, greater than 100m in diameter, may be preserved (Watson and Wright, 1969).

Matrix

The matrix typically results from the cataclastic fragmentation of the source rocks and may make up 90% of the deposit. Little quantitative information on the matrix grain size characteristics is available, but coarse- to medium-grained sand-size material is common.

Internal Slip Surfaces and Contact Relations

Yarnold (1993) notes that giant landslide deposits "commonly contain discrete internal slip surfaces" marked by deformation and shear along zones of the order of 100 mm thick. These zones are common in the lower Martin megabreccia (Krieger, 1977) and appear to represent zones of considerable movement within the slide. The base of such deposits may be associated with considerable disturbances of the underlying rocks if the latter were unconsolidated at the time of the emplacement of the slide deposit. This deformation may take the form of scouring and "bulldozing." In large deposits, flowing over poorly consolidated sediments, this deformation may extend to a depth of 5 m. Krieger (1977) notes that the distal end of the El Capitan landslide "plowed into the underlying sediments, compressing them into folds." Much attention has been paid to minor topographic features on the upper surface of giant landslide deposits. However, it is probably sufficient to note here that such upper surfaces are typically highly irregular, hummocky, or ridged.

DISCUSSION

The above summary of the characteristic features of subaerial rock-avalanche deposits resulting from giant landslides, clearly indicates many similarities between the Site 899 serpentinite breccias and such deposits. These similarities include the presence in both of (1) angular fragments with jigsaw/crackle textures, (2) a general lack of sorting, compatible with very rapid, essentially instantaneous formation, but with larger boulders occurring near the upper surface of the units, (3) a matrix generated by fragmentation of the clasts and a size continuum between the clasts and matrix, and (4) internal deformation zones or slip zones. In addition, rock-avalanche deposits are generally tabular units that are surprisingly extensive. Observation at Site 899 and the general stratigraphic framework for Unit IV show the serpentinite breccias to be interbedded with sedimentary units. Biostratigraphic ages suggest a normal stratigraphic succession and therefore the breccias are most simply interpreted as normal bedded units. Overall, the similarities are sufficiently striking to warrant interpreting the serpentinite breccias as rock-avalanche deposits resulting from giant landslides. This interpretation raises a number of issues and these are considered next.

Large subaerial landslides are generated in areas of significant topographic relief. Many have been reported from fold-mountain belts, particularly in regions such as the South Island of New Zealand and the European Alps where glacial erosion has generated over-steepened slopes along the sides of glacial valleys (Craw et al., 1987). However, large landslides are also particularly common in regions of extensional tectonics, slope failure often being associated with active fault scarps. There are many accounts of such deposits from the Basin and Range province in the southwestern United States although only in some cases (e.g., Woodford and Harriss, 1928; Longwell, 1951; Burchfiel, 1966; James et al., 1993) can megabreccia deposits be directly demonstrated to have a landslide origin.

The Iberia Margin was a region of extensional tectonics at the time of emplacement of the serpentinite breccia units, and, by analogy, their generation in this area at that time was to be expected. The presence of single rock-avalanche deposits as thick as 90 m requires considerable relief with perhaps 500-m- or even 1-km-high fault scarps comparable to those found in the Basin and Range province at the present time. Basement relief on this general scale exists at present beneath the sediments of the Iberia Abyssal Plain. However, the present basement relief cannot have generated the serpentinite breccia units as the units now form the *top* of one of the basement highs, whereas they must have formed at the *foot* of a major escarpment. This in turn implies significant deformation in the area after the formation of the breccia units and prior to the start of the deposition of the sediments that mantle the basement. A similar problem arises in the interpretation of the mass flow deposits of Unit IV recovered in Holes 897C and 897D. One possibility at both Site 897 and Site 899 is that an extensive (possibly tabular but unconstrained) deposit on a fault block terrace was subsequently back-rotated, raising the leading edge to create the existing topographic highs. Unfortunately, we cannot accurately document the bedding and show it to be tilted. A more fundamental problem is whether the breccia units were formed in a subaerial or submarine environment. All the published accounts of giant avalanche deposits cited above describe rock units that were thought to have been emplaced in subaerial conditions. Indeed, some authors consider that entrapped air was an important element contributing to the fluidity of the rock avalanches, thus accounting for their tabular nature. However, the presence of fine-grained sediments between the Site 899 serpentinite breccias, and the occurrence in the sediments of marine microfossils strongly suggests that the breccias were emplaced in a submarine environment. Certainly, submarine landslides do occur (Lipman et al., 1988; Moore et al., 1989; Cochonat et al., 1990; Holcomb and Searle, 1991) and possibly pore waters or entrapped seawater contribute to the fluidity of the rock avalanches and explain in some cases the long distances traveled. Tucholke (1992) has presented persuasive geomorphological evidence for the occurrence of a massive submarine rockslide in the rift-valley wall of the Mid-Atlantic Ridge. However this unit has not been drilled and the internal textures and fabric of this submarine rockslide are unknown. It is noteworthy that the region is again one of extensional deformation. We agree with Tucholke who argued that "there is no a priori reason why flowslide-like phenomena should not occur in the submarine realm."

The striking similarity of the fabrics developed in the submarine serpentinite breccias to fabrics developed in demonstrably subaerial deposits is perhaps surprising. The high fluidity of the deposits suggests that, in both environments, they were emplaced in a fluidized state. An explanation of the similarity may be that the fundamental process involved in the fluidization is independent of the properties of the medium, water replacing air in the submarine environment. Melosh (1979) has proposed that large landslide deposits may suffer "acoustic fluidization" induced by a transient strong acoustic wave field, and shows that acoustically fluidized debris may behave as a newtonian fluid with a viscosity in the range of 10^5-10^7 P. Such an explanation can also account for the long runout landslides on the moon (Howard, 1973), where neither water nor air can have been effective in generating the fluidized mass.

The source for the serpentinite breccias was presumably a fault scarp exposing massive serpentinite. Such a source would naturally explain the serpentinite bulk composition of the breccia composition and the absence of sedimentary, pelitic-metamorphic, or granitic clasts. Serpentinites are structurally weak and particularly susceptible to slope failure along escarpments. The trace-element data presented in the Site Report (Shipboard Scientific Party, 1994, table 8) indicate that the bulk composition of the serpentinite was similar to that of the serpentinite exposed at Site 897. The similar bulk composition of source and breccia indicates that probably little material was entrained during the flow and emplacement of the breccia units—another characteristic feature of rock avalanche deposits. More importantly, drilling at Site 899 suggests that during the early extensional history of the Iberia Margin, serpentinite did not just form a narrow ridge close to the ocean/continent transition, but outcropped along a zone perhaps as wide as 20 km—the approximate distance between Sites 897 and 899.

Large serpentinite escarpments also occur in transform fault zones and serpentinite breccias, somewhat similar to those being considered here, have been recovered from some of these zones. Bonatti et al. (1974) described a dredged suite of ultramafic-carbonate breccias from the Romanche and Vema fracture zones in the equatorial Atlantic. The samples are quite varied in texture and, in most, the volume occupied by calcareous cement is roughly equal to that occupied by serpentine. The original authors argued that the textures indicated that the samples were brecciated prior to calcitization and that the brecciation was probably tectonic in origin. This is certainly possible, but we note that in situ brecciation of serpentinites at Site 897, an area selected as not being close to a fracture zone, is interpreted as generating rocks with more than 50% calcium carbonate. Some of the extensively calcitized rocks there show no evidence for prealteration brecciation of the serpentinite; the brecciation is interpreted as an integral part of the calcitization process (Morgan and Milliken, this volume).

In contrast, in a wide-ranging review, Lockwood (1971b) suggested that many fragmental serpentinite units were deposited very rapidly by submarine landslides, mudflows or turbidity currents. Later, Bonatti et al. (1973) described some "sedimentary serpentinites" from the Mid-Atlantic Ridge and concluded that they were indeed of sedimentary origin and that they were probably emplaced by gravity sliding, slumping, and turbidity current transport of serpentinite debris originating from the upper parts of ultramafic transverse ridges at the Romanche Fracture Zone. Most of the dredged samples described are finer grained than the very coarse breccias at Site 899.

Bonatti et al. (1974) also stressed the similarity of rocks described from the Romanche and Vema fracture zones to ultramafic breccias found in ophiolite occurrences in the Apennines and the South Pennine nappes of eastern Switzerland. The description by Bernoulli and Weissert (1985) of relations near Davos, Switzerland are very reminiscent of relations at Site 897 with sediments overlying brown calcitized, brecciated serpentinites, in turn overlying green massive serpentinites. The Davos breccias are described as polyphase in origin and forming in a transform zone. Barrett and Spooner (1977), describing similar ophiolitic breccias from the East Ligurian Apennines, considered that most of the breccias represent talus accumulations at the base of major submarine fault scarps. In both of these areas, the ophiolites may indeed include landslide deposits, but in situ and tectonic brecciation were probably also active processes.

As noted above, the Upper Breccia Unit in Hole 899B also contains a small proportion of clasts of metamorphosed magnesium-rich igneous rocks (Shipboard Scientific Party, 1994, Fig. 17). These clasts are described in detail by Cornen et al. (this volume). The rocks can be interpreted as medium- to fine-grained metamorphosed basalts. Some large landslide deposits preserve the original stratigraphy in the sense that relative position of the source lithologies may be preserved during transport and deposition. However, an examination of the data on 158 clasts in the Upper Breccia Unit (Shipboard Scientific Party, 1994, table 6) suggests that the metamorphic clasts are randomly distributed throughout the unit. The metamorphic clasts tend to be small in size, perhaps because the source material was highly fractured. Thus, although a "ghost stratigraphy" cannot be demonstrated, the most likely explanation is that the altered basalts formed a thin veneer on top of the serpentinite escarpment and that the rocks became mixed with the dominant serpentinite lithology during the emplacement of the breccia unit. Elsewhere in the breccia source region, this veneer of volcanic rocks may have been missing, as the source serpentinite appears to have been variably oxidized and calcitized before becoming incorporated into the breccia.

Interestingly, no gabbro or mafic cumulate rock fragments have been found in the serpentinite. Thus, at the time of formation of the serpentinite breccia, the crustal section in the source region was already highly attenuated. The extension had generated an escarpment that exposed highly metamorphosed basaltic rocks, probably from at least one kilometer below the original eruptive surface. These apparently rested as a thin veneer directly on mantle rocks, without any intervening gabbros. Whereas this might have been a depositional contact, this condensed stratigraphy was more likely also the result of extension eliminating any intervening gabbros and cumulate rocks.

SUMMARY AND CONCLUSIONS

The following are critical features of three serpentinite breccia beds within Unit IV, Hole 899B: (1) the fragments are angular and many display jigsaw/crackle textures; (2) sorting is generally absent, but larger boulders tend to occur in the in the middle and upper part of the thickest unit; (3) the breccia matrix appears to be generated by fragmentation of the clasts and there is a size continuum between the clasts and matrix; (4) minor internal deformation zones or slip zones occur, particularly along the margins of large blocks; and (5) the breccias are interpreted as being tabular, bedded units. All these features are common in subaerial giant landslide deposits, and the serpentinite breccias are interpreted as being equivalent submarine deposits, generated by slope failure along large nearby serpentinite fault scarps. Giant landslides are a typical feature of regions undergoing rapid extensional deformation, and such deposits may be relatively common in faulted submarine extensional environments. The basement topography at the time of formation of the serpentinite units clearly differed significantly from the present topography buried beneath the Iberia Abyssal Plain. As a result, the location of the source serpentinite escarpment is unknown. However, the large size of some of the fragments included within the serpentinite indicate that it was probably within a few kilometers of Site 899 and that the aggregate width of the belt of mantle serpentinite exposed in the Late Cretaceous at the Iberia Margin might have been 20 km.

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