Visibility of Fault Strands in Exploratory Trenches and Timing of Rupture Events

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M.G. Bonilla, J.J. Lienkaemper
U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025

ABSTRACT

Many estimates of seismic risk depend crucially on how well the date of faulting events can be determined from the stratigraphic position of fault strands exposed in exploratory trenches. However, fault strands cut by trenches may seem to die out where they are in fact only poorly expressed, or they may actually die out. Such ambiguity can lead to misinterpretation of the time of the most recent displacement and also of the recurrence interval between faulting events. To investigate the frequency of occurrence and other characteristics of strands that falsely appear to die out or that actually do die out, more than 1200 fault strands were analyzed. For strands associated with individual faulting events, 45 percent could not be visibly traced in the trench walls to the ground surface that existed at the time of faulting; for reverse and strike-slip faults, the number exceeds 70 percent. Thus, any apparent upward termination of a fault strand that is thought to indicate the date of a faulting event requires critical examination and corroboration from other evidence. Nonvisibility (i.e., dieout upward, obscure segments, and dieout downward) is more common on strike-slip and reverse faults than on normal faults and is more common in soil horizons than in clay and gravel. Nonvisibility occurs on strands that have had large (> 1 m) as well as small displacements.

INTRODUCTION

The upper parts of many fault strands that have ruptured the ground surface in historic time are not visible in exploratory trenches (Bonilla, 1973; Cotton et al., 1976, 1982). Little is known of the frequency of occurrence or of the factors affecting such nonvisibility. Nonvisibility of fault strands can affect determination of the time of the most recent and earlier displacements on faults. It thus affects evaluations of regional seismic risk as well as engineering-geology evaluations of the risk of surface faulting at particular sites. To investigate this problem, we studied many published and unpublished trench logs and their accompanying reports. We also examined in the field nearly half (52) of the trench exposures in the United States that were included in this study. We gave preference to trenches that crossed faults having historical surface displacements, and we selected logs on the basis of our judgement of their quality (primarily amount of detail), and availability. We scanned more than 1000 logs and selected 163 for study—72 on strike-slip faults, 50 on normal faults, 40 on reverse faults, and one on a fault of unknown type. The logs were from the United States, Nicaragua, New Zealand, Algeria, Japan, Peru, Guatemala, and Israel. About half of the exposures were on fault segments that have had surface rupture in historic time.

Various factors that might affect the visibility and nonvisibility of fault strands were considered. These include type of fault, amount of fault displacement, material penetrated, thickness of bedding, age of most recent displacement, rotation of pebbles, and presence or absence of fissures, gouge, slickensides, and breccia. We calculated the frequency of occurrence of the various features compared to the total number of fault strands or exposures, and we determined standard deviations, assuming binomial variance. The differences in frequencies were tested at the 0.05 level of significance using standard methods (see, e.g., Weinberg et al., 1981).

This report summarizes only the relation of fault type, fault displacement, and material penetrated to nonvisibility. A brief preliminary summary of the results has been published (Bonilla and Lienkaemper, 1988); the supporting data and detailed results, including the effects of the other factors, will be published elsewhere[1] .

SPECIAL TERMS

Some special terms adopted for this study are illustrated in Figure 1. "Dieout up" and "dieout down" refer to the process or condition in which a fault strand ends or seems to end upward or downward, and is not visible at the time of trenching in a layer that existed at the time of faulting. To avoid considering strands that end upward because they are covered by younger deposits, the data on dieout up are restricted to strands for which the position of the ground surface at the time of faulting is known or can be reliably inferred.

The term "obscure segment" is applied to part of a known fault strand where the strand is not clearly visible in a trench wall. Fault segments that have contrasting materials across them are excluded from the obscure category, even if the fault trace is indistinct. Faulting in the segment must be known from fault displacement of materials above and below the segment, from historical records of rupture of the ground surface, or from statements made in the report accompanying the trench log. Obscure segment applies to a fault strand or deformation that is known to be present but is not clearly visible. Dieout up and dieout down also include strands that actually terminate in beds older than the faulting.

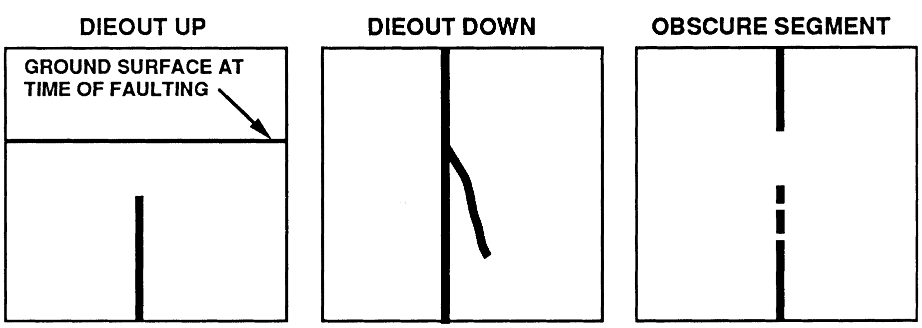

Figure 1. Schematic cross sections showing dieout up, dieout down, and obscure segment.

[1] Bonilla, M. G., and Lienkaemper, J. J., 1991, Factors affecting the recognition of faults exposed in exploratory trenches: U. S. Geological Survey Bulletin 1947, 54 p.

“Nonvisibility” and “nonvisible” were adopted as general terms that include obscure segments, dieout up, and dieout down.

DIEOUT UP

About half of the trench exposures were on faults that had ruptured the ground surface during historical events, but in many of the exposures the fault strands could not be traced to the ground surface. An example of dieout up on the San Andreas fault is shown in Figure 2. An investigator who did not know that surface rupture occurred at the site in 1906 could have concluded, on the basis of the trench alone, that the most recent event was older than the upper part of the exposed section. This example emphasizes the fact that knowledge of the characteristics of dieout up, such as its frequency of occurrence on various types of faults and in various materials, provides useful background for fault investigations.

A determination of whether dieout up occurred could be made for relatively few strands because the position of the ground surface at the time of faulting must be known. Dieout up occurs on 45 percent of these strands (Fig. 3A). The incidence of dieout up on normal faults (<20%) is distinctly lower than on reverse or strike-slip faults, and the difference is significant at the 0.01 level. The high (>70%) incidence of dieout up in the reverse and strike-slip groups is surprising. The high incidence may be partly explained by the fact that several of the exposures with dieout up were concentrated in two moderately small areas, and another exposure had many subsidiary strands that die out upward. When these data were reduced to one randomly selected exposure in each of the small areas and the exposure with many subsidiary strands was removed, the percentages shown in Figure 3A decreased to 67 for strike-slip faults and 61 for reverse faults. Even these somewhat smaller percentages indicate that the possibility of dieout up should always be carefully evaluated. No significant differences in dieout up related to the amount of displacement on the strand or to material penetrated were found. The depth of dieout up (i.e., the distance from the ground surface at the time of faulting to the top of the visible part of the strand) ranges from a few centimetres to a few metres. Thus, a thick, apparently unfaulted upper section in a trench wall does not necessarily mean that the section is unaffected by faulting.

OBSCURE SEGMENTS

Information on the occurrence of obscure segments is pertinent because it supplements the limited data on dieout up. Furthermore, an obscure segment at the top of a fault strand may lead to the false conclusion that the faulting is older than the material above the visible part of the strand. Of all the fault strands examined, 14 percent have one or more obscure segments (Fig. 3B). Obscure segments are distinctly less common on normal faults than on strike-slip or reverse faults, but the difference between strike-slip and reverse faults is not significant at the 0.05 level. Most of the obscure segments occur on strands that have small displacements, but about 20 percent occur on strands having displacements greater than 1.0 m. Thus, a large displacement on a strand provides no assurance that an obscure segment will not be present. Many obscure segments have a

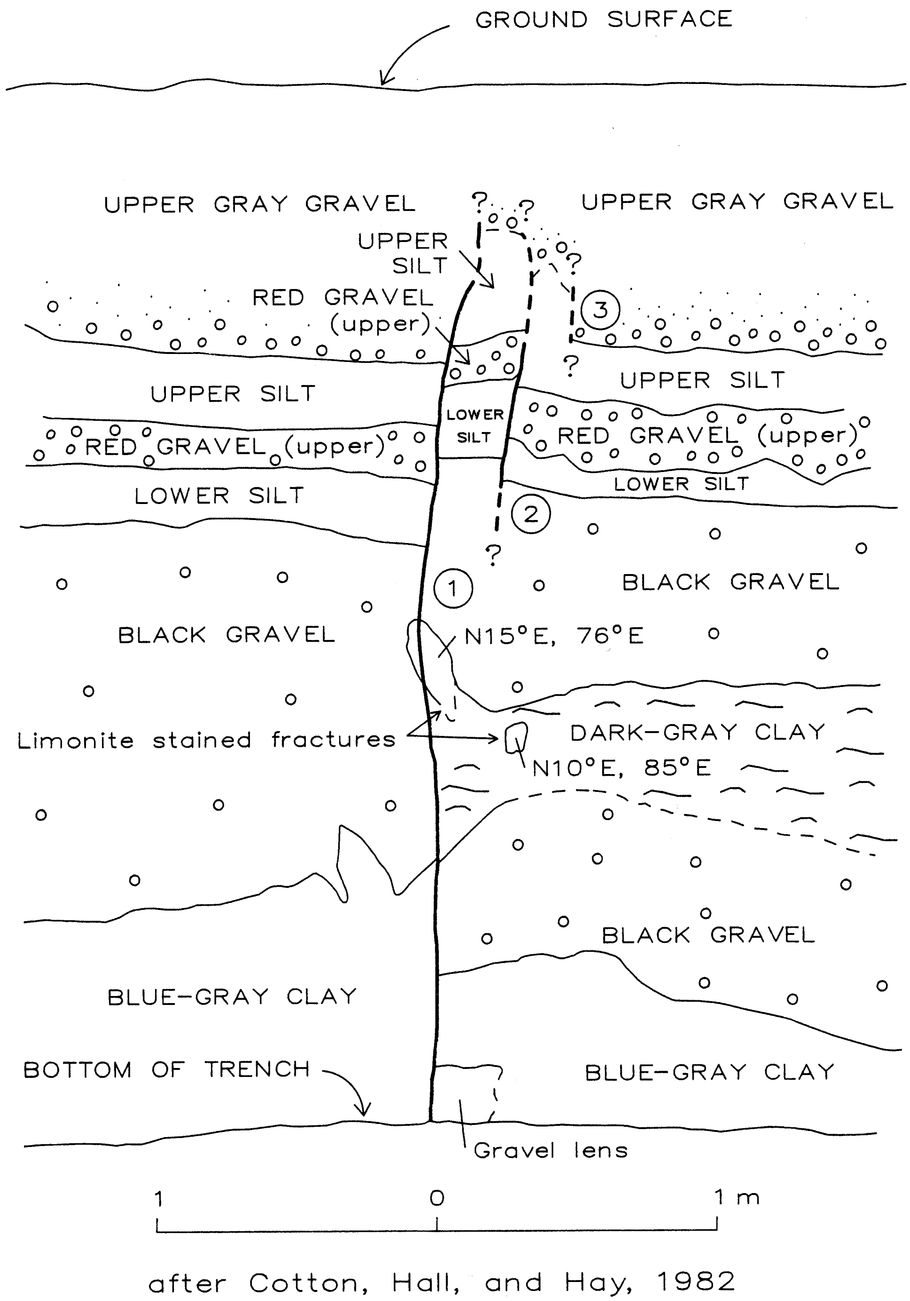

Figure 2. Log of trench on San Andreas fault at place where ground surface was ruptured by more than 4 m of strike- slip displacement in 1906. Fault strands visible in lower and middle parts of this trench and several parallel trenches were not traceable to ground surface. Modified from Cotton et al. (1982).

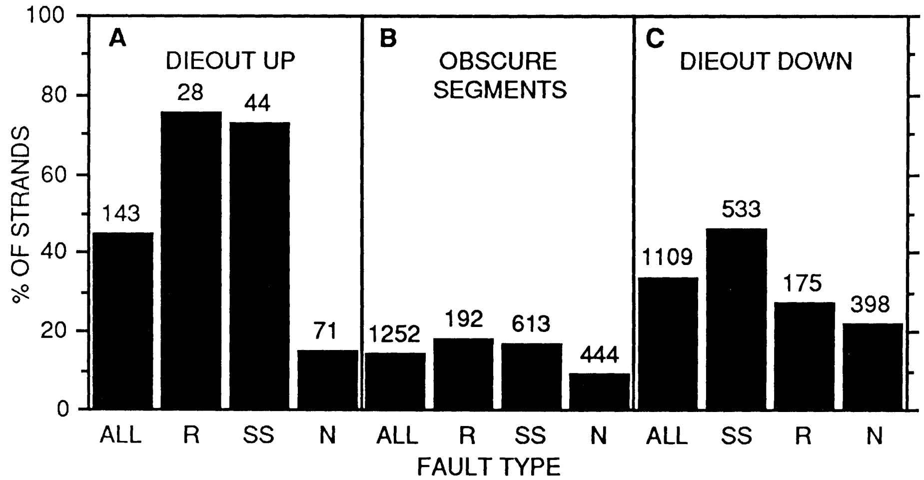

Figure 3. Frequency of occurrence of dieout up (A), obscure segments (B), and dieout down (C). Percent refers to strands that die out upward, have obscure segments, or die out downward in given fault-type groups compared to all strands in respective groups. Fault types: R = reverse; SS = strike slip; N = normal. Numbers above columns are total number of strands in each group.

substantial length (as measured in the trench wall); 18 percent of them are longer than 1.0 m. Thus, a long reach without clearly visible faulting does not prove the absence of faulting. Taking into account the frequency of occurrence of various materials cut by the trenches, we find that obscure segments occur most commonly in sand, followed by soil horizons, silt, clay, and gravel.

DIEOUT DOWN

Dieout down is not directly applicable to dating fault displacements, but its characteristics provide data that apply to dieout up. In dieout down, the faulting is unquestionably younger than the material in which the die out occurs. As shown in Figure 3C, dieout down occurred on 34 percent of all strands that do not join more important strands (i.e., strands having larger displacements) when traced downward. A significantly larger fraction of strands die out down on strike-slip faults than on other types of faults, but the difference between normal and reverse faults is not significant at the 0.05 level.

A likely place for a fault trace to end is at a bedding plane, where mechanical properties of the materials may change. At least 17 fault strands, distributed among nine strike-slip fault exposures and one normal-slip fault exposure, end downward at a bedding plane. On the strike- slip faults, the displacement could have transferred to undetected bedding-plane slip. Dieout *upward* at bedding planes undoubtedly occurs also, giving the false impression of a fault strand capped by a bed younger than the faulting.

In general, the incidence of dieout down is higher on strands having small displacements than on strands having large displacements. A few strands having more than 1.0 in of strike slip die out down. The incidence of dieout down is greater in soil horizons and silt than in sand, clay, or gravel.

GENERALIZATIONS ABOUT NONVISIBILITY

This study has shown that the type of fault and the materials involved are the principal factors related to nonvisibility (i.e., dieout up, obscure segments, and dieout down). The effects of fault type are summarized in Figure 4. We have divided the data into principal strands and subsidiary strands because too few data are available for certain combinations of strand type and nonvisibility type. For principal strands (Fig. 4A), the frequency of dieout up is higher on strike-slip and reverse faults than on normal faults, but strike-slip and reverse faults do not differ significantly. However, the three fault-type groups differ significantly in the frequency of occurrence of obscure segments—strike-slip faults are highest, reverse faults are intermediate, and normal faults are lowest. No significant differences were found in the frequency of dieout down related to fault type, but there are few data.

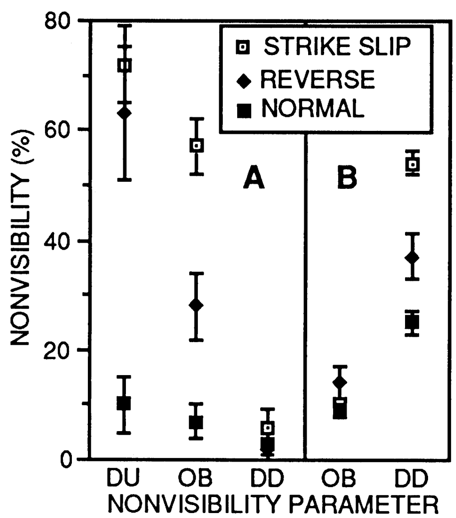

Figure 4. Frequency of occurrence of nonvisibility on various types of faults. A: Principal strands; B: subsidiary strands. DU = dieout up; OB = obscure segments; DD = dieout down. Vertical lines show standard deviations.

For subsidiary strands (Fig. 4B), the only significant differences in nonvisibility among the fault-type groups are in dieout down, the incidence of which is highest on strike-slip faults, intermediate on reverse faults, and lowest on normal faults. No significant differences among fault types were found for the obscure segments, and too few data are available for comparisons within dieout up.

Figure 4 indicates that problems with visibility are generally more common in strike-slip faulting than in reverse or normal faulting. Several factors may contribute to this lower visibility. In general, the bedding of the sediments exposed in the trenches has a low dip, and therefore individual beds are more likely to remain in contact and present fewer tectonically produced lithologic contrasts across the fault after strike-slip displacement than after dip-slip displacement. Dip-slip faulting is also more likely to be recognizable because of distinctive scarp- derived rubble and colluvium that become incorporated in the section. Furthermore, wide fissures along fault strands produced during normal-slip faulting are commonly made visible by infillings that contrast with their surroundings, or they are preserved as open cracks. Figure 4 shows that where significant differences exist, the incidence of nonvisibility is greater for reverse faults than for normal faults. It is possible that this too is related to a greater tendency to produce large tensional openings during normal faulting.

The effects of material type on nonvisibility are summarized and compared in Figure 5, which takes into account the frequency of occurrence of the various materials. Because data on dieout up were too few to make significant distinctions among material types, the comparisons are based only on obscure segments and dieout down on combined principal and subsidiary strands. For both obscure segments and dieout down, soil horizon (including buried fossil soils) has a high ranking, and clay and gravel have relatively low rankings. The probable explanation for the high incidence of nonvisibility in soil horizons is that the commonly massive but fractured, blocky nature of soils makes it difficult to detect fault strands. The modifications that occur in soils as the result of root growth and decay, moisture changes, temperature changes, and the activity of invertebrate and vertebrate animals (including humans) also obscure faulting. Gravel is unique in that it can reveal faulting by the rotation of pebbles. Whether the clay in the exposures has more distinct bedding than the sand and therefore tends to reveal faulting was not investigated.

The descriptions of materials given in the trench logs differ greatly in the amount of detail, and simplified classes were adopted in order to include all the data. For example, silty sand, clayey sand, and clean sand were grouped as sand. This simplification may have affected the positions of various materials in Figure 5: e.g., clayey sand may more closely resemble clay than it does clean sand in its response to faulting. Figure 5 does, however, represent typical behavior for the variety of materials represented in our sample.

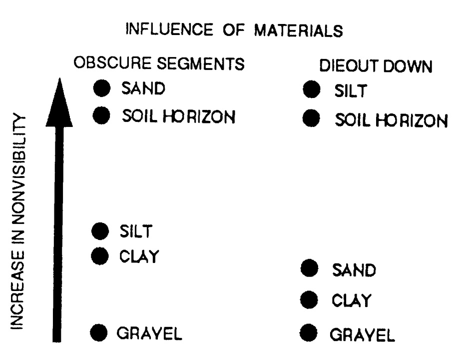

Figure 5. Comparison of nonvisibility of fault strands in various materials. Ranking takes into account relative frequency of occurrence of listed materials. Data include both principal and subsidiary strands. Dieout up data are too few to determine any significant contrasts related to material.

ORIGINS OF NONVISIBILITY

Nonvisibility, as we have defined it, can originate in at least three ways: (1) the fault strand, although it may have been visible immediately after the event, has lost its visibility; (2) the fault strand was never visible as a discrete trace because the displacement was distributed over a zone; (3) the fault strand actually terminated by decrease in displacement.

Loss of visibility may result from processes such as bioturbation, human activities, freeze-thaw, shrink-swell, plastic flow in clay, or rearrangement of grains in granular material. Loss of visibility probably explains dieout at some sites where surface rupture has occurred in historic time, including several trenches on the 1906 traces of the San Andreas fault.

Faulting that is distributed across a zone may not be visible because the displacement is in the form of many small ruptures, intergranular movements, or bending of the affected layer. Distributed faulting can be detected if distinct marker horizons have been deformed. Some of the 1971 surface faulting in San Fernando, California, warped the ground surface, but discrete fault strands could not be found in a trench excavated across the fault zone in poorly bedded silty sand (Bonilla, 1973, p. 177). Distributed deformation probably explains dieout up at five exposures on the Hayward and Calaveras faults, where tectonic creep is occurring. The dieout cannot be attributed to either loss of visibility or actual termination, inasmuch as the displacement is currently in progress and reaches the ground surface, where buildings are being distorted. A combination of loss of visibility and distributed deformation probably applies to two sites on the 1952 trace of the reverse-slip White Wolf fault (Cotton et al., 1976).

Laboratory model studies and mine mapping show fault strands that actually terminate as discrete ruptures either upward or downward (Cloos, 1968; Sanford, 1959; Gay and Ortlepp, 1979; Roth et al., 1981; Wallace and Morris, 1986), and bending-moment faults must end upward or downward (Yeats, 1986, p. 68-72). On strike-slip faults, displacement on a particular strand commonly dies out, and the displacement transfers to a separate en echelon strand. Actual termination seems to apply to six strands at four exposures of normal faults, where the lower beds but not the upper beds are visibly displaced. All these occurrences are on subsidiary fault strands.

CONCLUSIONS AND IMPLICATIONS

Fault strands younger than deposits that seem to, or do, overlie them are surprisingly common. This fact must always be considered in interpreting the age of most recent faulting or in deducing the existence and age of earlier faulting events. In the diagram of a trench wall shown in Figure 6, the two fault strands, on a strike-slip fault, formed in one event. Principal strand P, as in many real examples, cannot be traced to the surface because it was never clearly visible or because it has lost its visibility over time. Subsidiary strand S also dies out upward, perhaps because the displacement has diminished, has transferred to an en echelon segment outside the trench, or was largely absorbed in bedding-plane slip. In one real example, a strand similar to S was found to continue upsection when the trench wall was excavated another 30 cm (Cotton et al., 1982). Given the conditions in Figure 6, the mistaken conclusion could be drawn that the most recent event on the principal strand was older than unit D and that an earlier event involving strand S occurred before deposition of unit B.

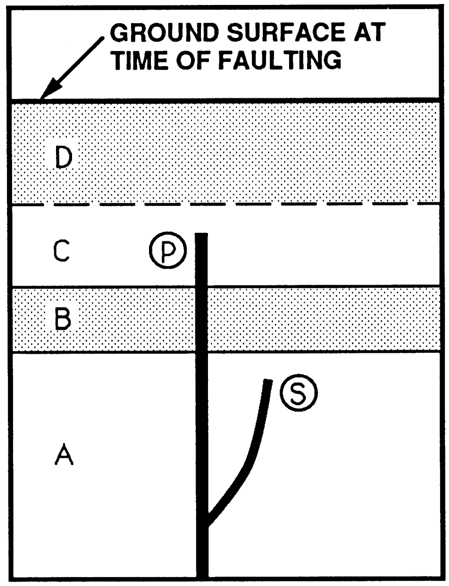

Figure 6. Diagram showing fault strands related to single strike-slip faulting event. A, B, C, D = unconsolidated sedimentary deposits; P, S = fault strands.

Data from upward dieout of fault strands, supplemented by data on obscure segments and downward dieout, show that type of faulting and type of material have important effects on nonvisibility. Strike-slip and reverse faults have a higher incidence of nonvisibility than normal faults. Amount of displacement seems to have little effect on nonvisibility; strands having displacements greater than 1.0 m may not be visible. Obscure segments provide the most data on the effect of material and indicate that soil horizons and sand are correlated with a high incidence of nonvisibility, silt and clay with an intermediate incidence, and gravel with a low incidence. This ranking is partly supported by data on dieout down.

Poorly expressed faulting and actual termination of fault strands may occur on various types of faults, in various materials, and on strands having a wide range of displacements. Therefore, any apparent upward termination of a fault strand that appears to indicate the age of a faulting event requires critical examination and verification. Other exposures of the strand should be examined, and similar terminations of the same age on other strands should be looked for. More trenching may be needed, and if paleoseismic events are suspected, other evidence should be considered, such as the presence or absence of folding, unconformities, scarp-derived rubble or colluvium, small landslides, liquefaction deposits, soft-sediment deformation, fissures, and post-rupture soil formation.

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