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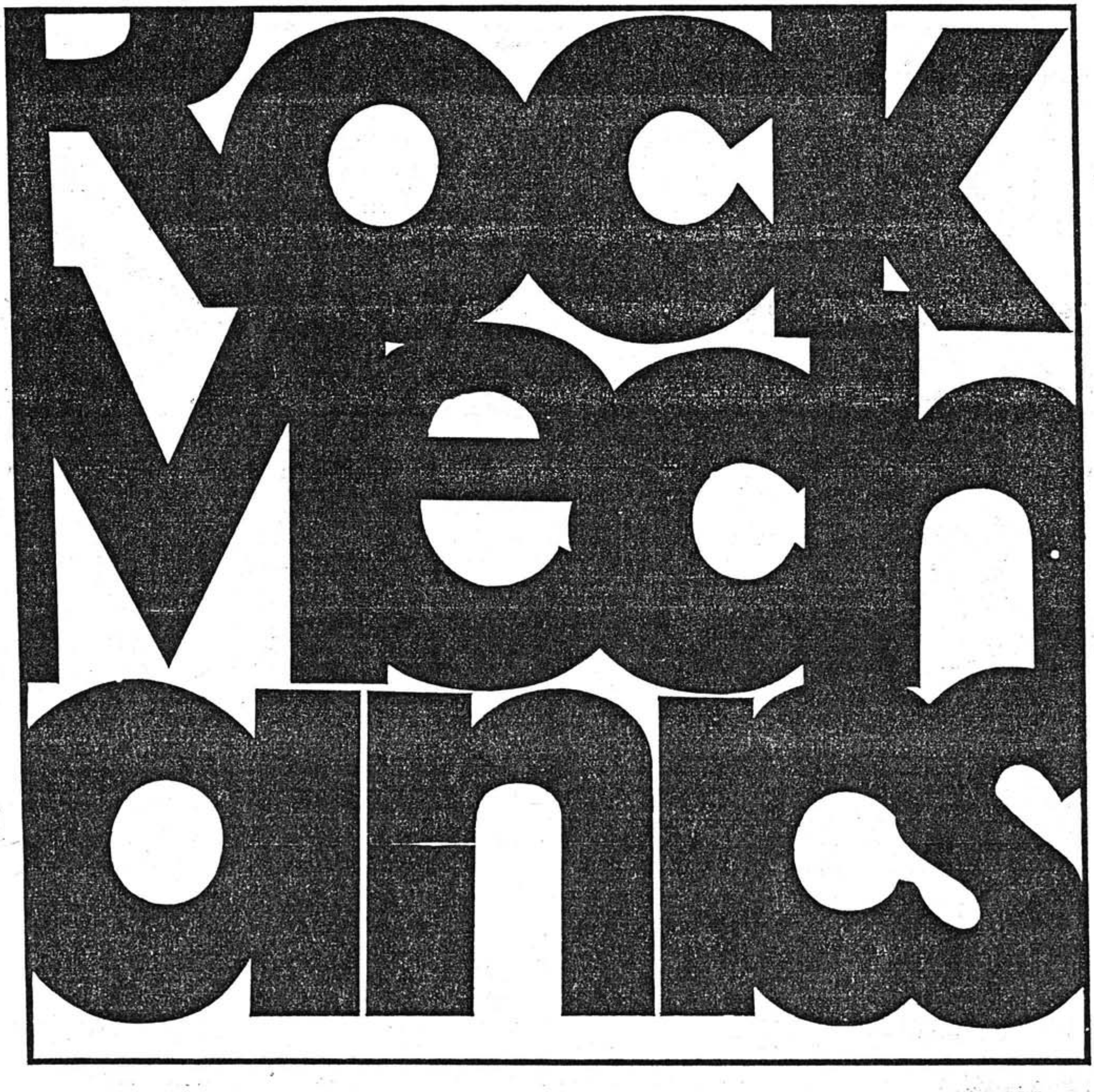

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THE BURST OF A WALL IN A HIGHWAY TUNNEL DURING CONSTRUCTION

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The Burst of a Wall in a Highway Tunnel During Construction

By

P. Lunardi

With 18 figures

Summary – Zusammenfassung

The Burst of a Wall in a Highway Tunnel During Construction. In this note, one of the many instability phenomena which may occur in an underground work jobsite, is duly considered and described. This event, consequent on the rough and sudden pressure relief of the rock mass corresponding to the excavation section, has occurred during the construction of Gran Sasso Highway Tunnel in the Central Apennines.

The detailed geological and structural reconstruction, the analysis of the phenomena previous to the event and of those actually occurred, as well as considerations about the statics of the phenomenon which generally occur during tunnel excavation, have allowed to include the observed failure within elastic-brittle phenomena.

Moreover, supposing a hydrostatic stresses state, it has been possible to interpret such a phenomenon applying the Kastner-Fenner method.

By the study of such event, rather unusual considering the involved dynamics, it has been possible to point out the importance of the fractures occurring subvertical and subparallel to the tunnel axis, above all when they isolate rock volumes of the same size of the excavation section.

Verbruch in einem im Bau befindlichen Autobahntunnel. Im Bericht wird eines der vielen Instabilitätsphänomene behandelt sowie über andere berichtet, die bei einem Untergrundbau vorkommen können. Dieser Vorfall, Ergebnis eines plötzlichen und unvorhergesehenen Spannungsausbruches des Gesteins an der Aushubstelle, ereignete sich beim Bau des Autobahntunnels im Gran Sasso-Massiv im Zentralapennin.

Die geologische und strukturelle Detailkonstruktion, die Analyse der Ereignisse, die dem Vorfall vorangegangen sind und jener die ihn gekennzeichnet haben, die statische Betrachtung der Vorkommnisse, die sich allgemein beim Aushub eines Tunnels ereignen können, haben dazu geführt, diesen Typ von Bruch in den Bereich der Elasto-Sprödigkeit einzuordnen.

Außerdem war es bei Annahme eines hydrostatischen Verhaltens der Spannungen möglich, den Spannungszustand um den Aushub nach der Theorie Kastner-Fenner auszulegen. Die Erforschung dieses Ereignisses, welches wegen seiner Dynamik in der Tat ziemlich außergewöhnlich war, hat dazu geführt, die Bedeutung der subvertikalen und subparallelen Unstetigkeiten gegen die Tunnelsektion in den Vordergrund zu stellen, speziell wenn diese an der Stelle des Aushubprofiles Gesteinsmengen in der Größenordnung der betreffenden Sektionen isolieren.

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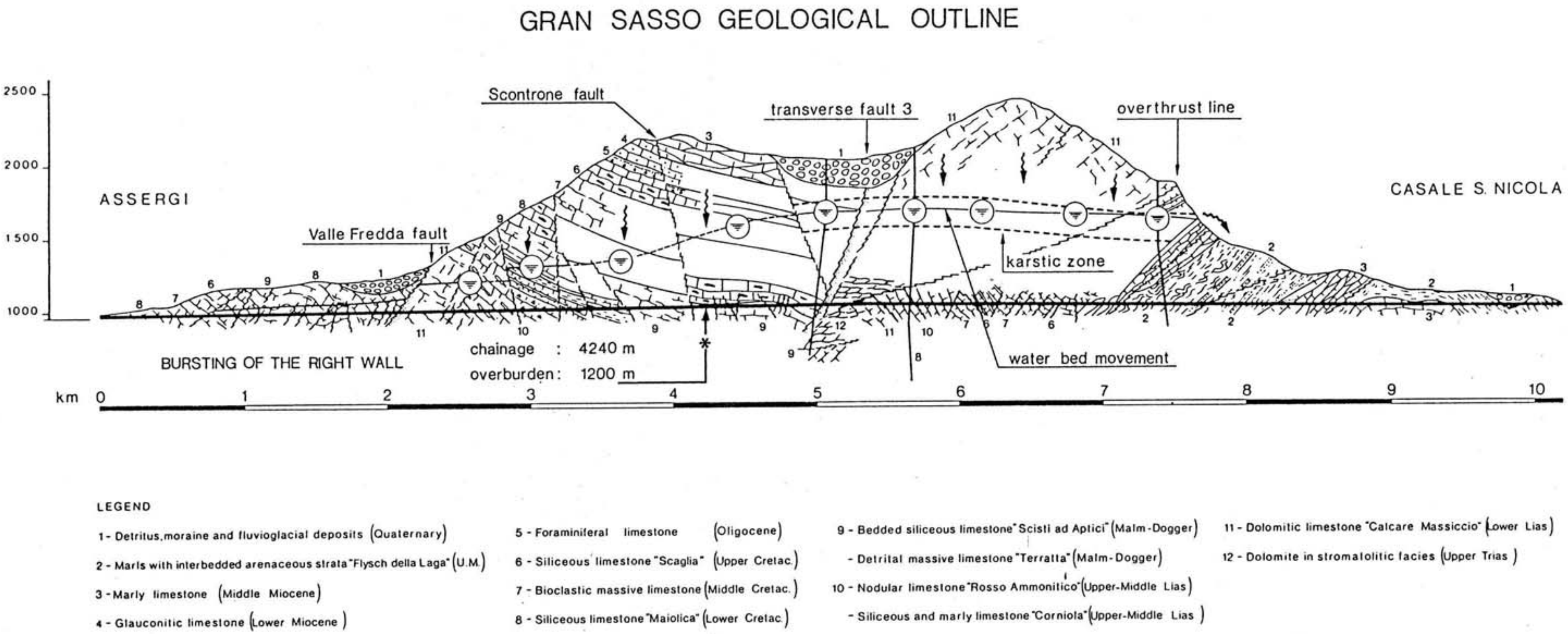

Fig. 1. Gran Sasso geological profile
Gran Sasso Tunnel: Geologisches Längsschnittprofil

The Burst of a Wall in a Highway Tunnel During Construction

One of the most feared phenomena of instability occurring in underground excavation is that following the sudden and unexpected pressure relief in the rock along the excavation line. Such a phenomenon of brittle failure of the rock loaded up to its ultimate strength σ_{gd} is evidenced by a violent and sudden release, with consequent ejection into the opening, of more or less considerable masses of rock, accompanied by loud blasts.

Low intensity stress-relief phenomena occurred at different locations in the tunnel such as: in the marl formation under overburdens of the order 200 to 450 m (between chainage 1900 and 2100) and in the limestone formation under overburdens from 1100 to 1200 m, where the rock mass was quite massive and almost impervious (3800 to 4200 m from the Casale portal and 4100 to 4500 m from the Assergi portal).

Such phenomena were manifested by local uniform rock releases at the heading and of rock slabs at the spring line, or by shotlike sounds, coming from the surrounding mass, which could be clearly heard only when the works were suspended (Fig. 1).

The afore mentioned pressure-relief phenomena were not a threat to the stability of the tunnel, but they always slowed down the works due to the precautions which had to be taken, namely: the use of more strict safety measures for workers at the heading and the length reduction of the excavation cycle. The pressure relief phenomena can be of large or small dimensions, as compared with the tunnel section, only occasionally they may affect the entire opening.

Such an unusual event did actually happen during the excavation in a zone of cherty limestone ("Scisti ad Aptici"), under an overburden of the order of 1200 m.

Reference is made to the burst of the right wall of the left tunnel, at chainage 4238, which occurred in the "Scisti ad Aptici" formation.

Structural-geological features

The "Scisti ad Aptici" formation, which the tunnel encountered, on the Assergi side, at chainage 4075 m, in the right hand carriageway and at chainage 4085 m in the left hand carriageway, is separated from the preceeding formation by a normal fault, with a few tens of meters throw. The "Scisti ad Aptici" formation is a detrital and biofragmental, fine to medium, seldom coarse and often of rather uniform grain size, limestone. It is thinly layered (10 to 30 cm and exceptionally 1 to 2 m thick layers): 5 to 10 cm thick layers and nodules of wheathered, whitish chert are frequently interbedded. Constant strike, nearly parallel to the tunnel axis, and 25° to 30° dip toward the left wall (Fig. 2), occur.

From the tectonic viewpoint, closely spaced faults are present, both crossing and subparallel to the tunnel axis (Fig. 3), with very small throws. From the hydrological point of view, low overall permeability ($K = 10^{-7}$ m/sec) have been recorded, excluding a few well defined zone where concentrated inflows or heavy dripping occurred, feeded by lateral intake areas.

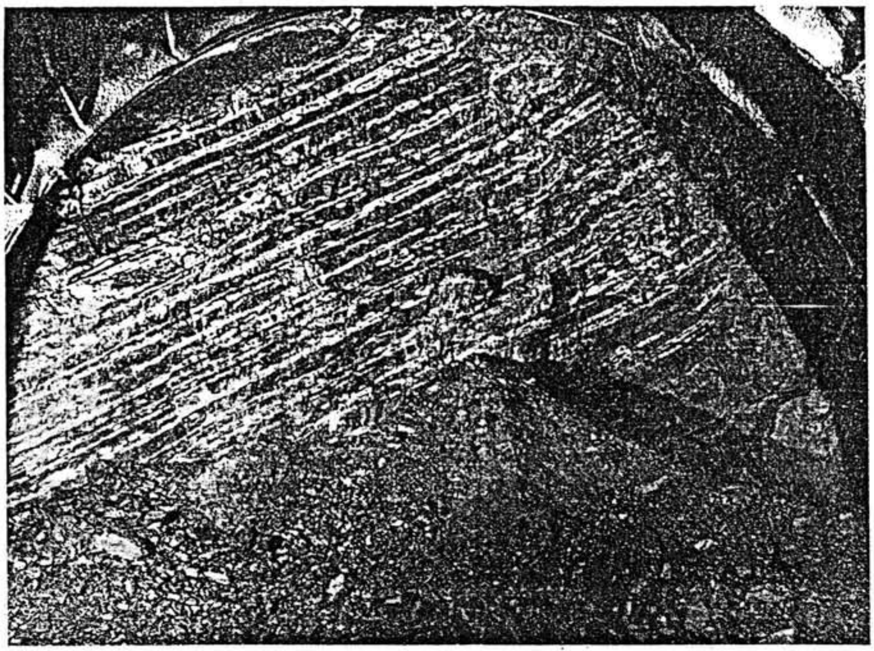

Fig. 2. Heading in the "Scisti ad Aptici" formation
Tunnelbrust im Schiefergestein

This occurred along the whole right hand wall of the right tunnel, as shown by the results of boreholes SA22 and SA24, that recorded discharges up to 40 l/sec under hydrostatic heads of the order of 12–16 atm. By comparison, 5 to 10 l/sec were recorded in boreholes SA19 and SA23 located in the left wall of the left tunnel, where the bedrock appears very compact and almost dry.

The above mentioned boreholes, in addition to hydrological and lithological, supplied information concerning the jointing of the rock, based on R.Q.D. (Rock Quality Designation) evaluations.

R.Q.D. values zero or near zero have been reported in the whole examined area. This can be logically ascribed to the natural jointing of the rock subjected to very high triaxial stresses, as well as to coring disturbances, being the rock thinly stratified with nodules of harder material (like chert) inside.

Description of the phenomenon

Having left behind the lower Malm formation, with boundary at chainage 4085 m, the excavation was carried out by 2 m long cycles and systematic erection of temporary support formed by coupled NP 180 ribs and about 10 cm thick shotcrete. As the excavation progressed, the following phenomena were observed:

- progressive permeability decrease in the rock mass;
- progressive R.Q.D. decrease, down to zero;
- phenomena of instability at the heading, manifested by popping of rock slabs also of large size.

Such releases occurred unexpectedly, generally accompanied by loud blasts with consequent ejection of material.

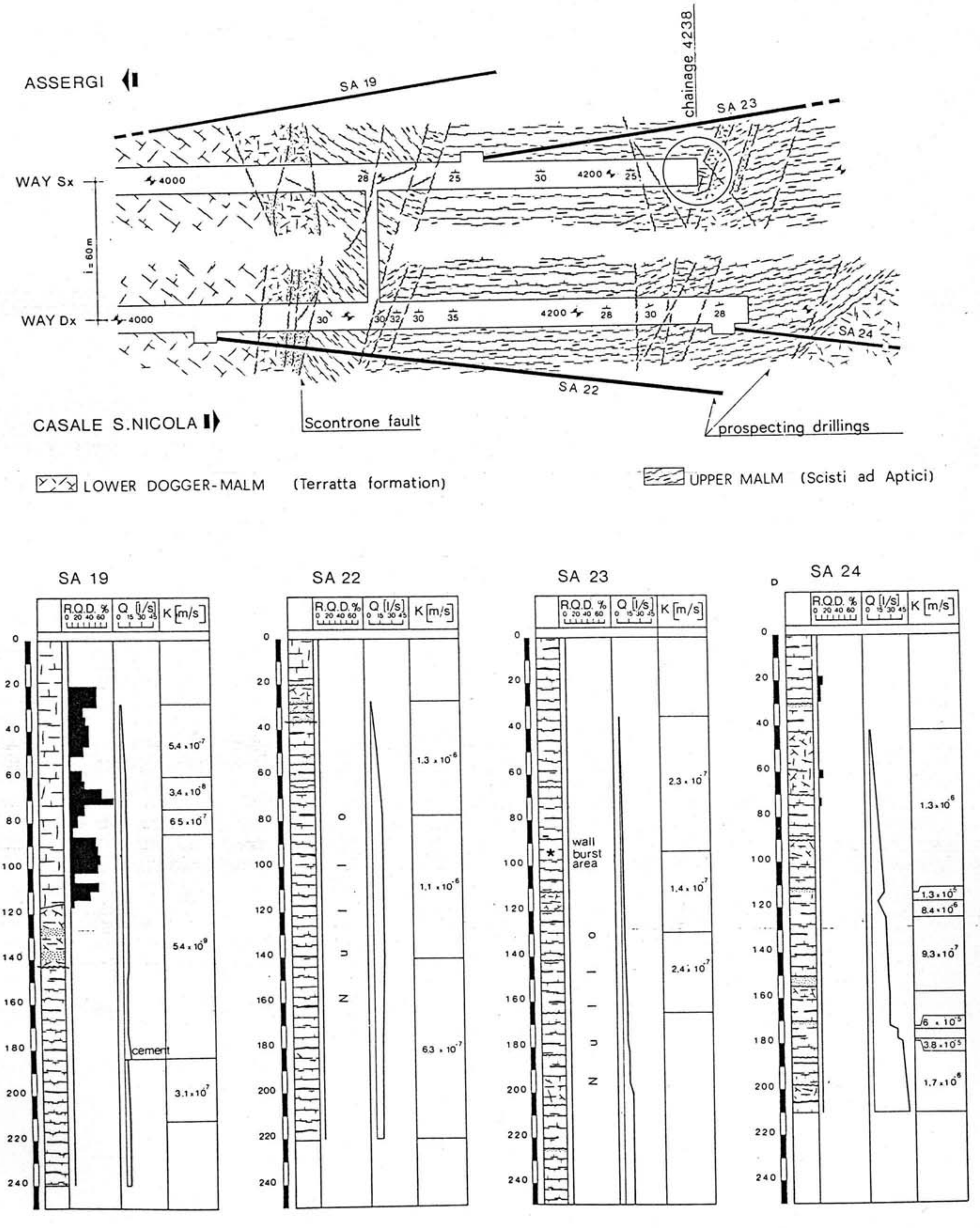

Fig. 3. Bursting of the wall; geological map and logs of the boreholes drilled in the "Scisti ad Aptici" formation

Bergschlag an der Ulme; geologisch-stratigraphischer Grundriß der Bohrlochsondierungen im Schiefer "Scisti ad Aptici"

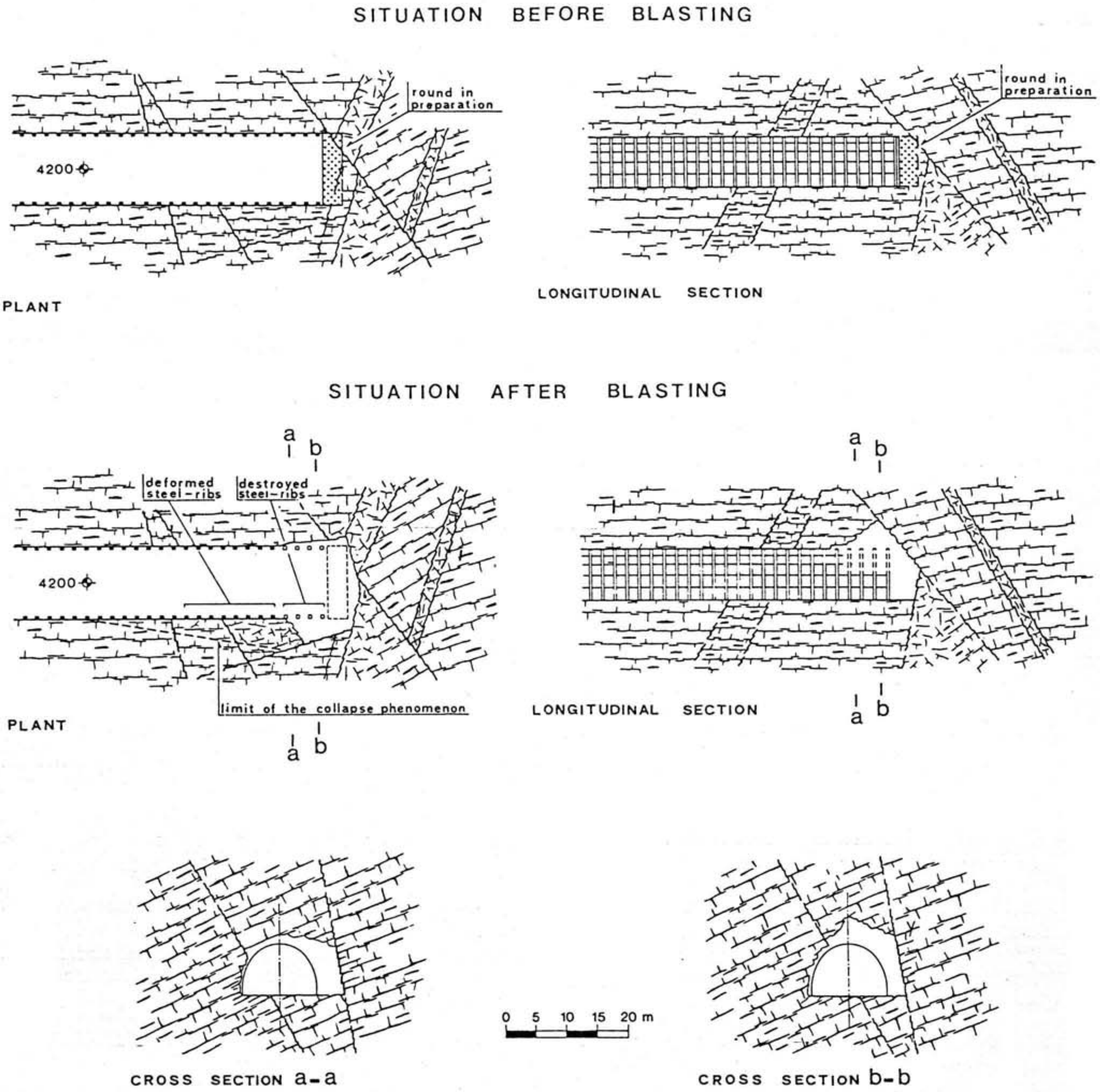

Fig. 4. Burst of the wall; left hand carriageway – "Scisti ad Aptici" formation; geological structural surveys in the burst area
Bergschlag an der Ulme des linken Tunnelrohres im Schiefer; geologische und gefügetechnische Beobachtungen an der Erscheinungsstelle

Failures took place along joints, rather than along bedding planes, with more or less conchoidal surfaces, intersecting bedding planes and involving apparently stable layers.

At chainage 4240 m in the left tunnel, under overburden of 1200 m, a singular geostructural feature occurred, represented by a dense interlacement of faults (Fig. 4); after about 15 minutes from shooting rounds, a sudden and violent ejection of a body of rock took place, from the right wall of the tunnel (Fig. 5).

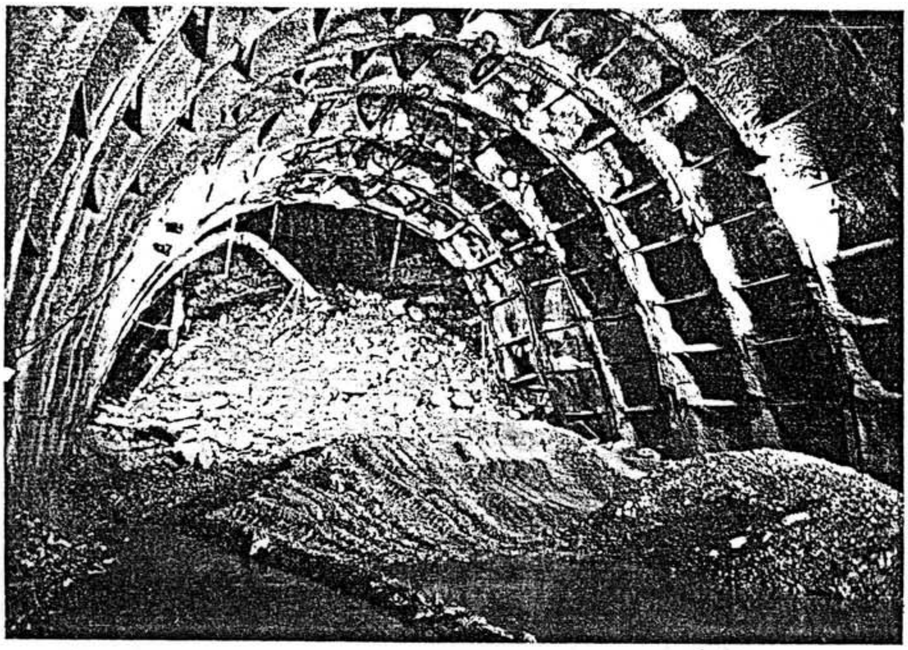

Fig. 5. Condition of the heading after burst; clear diffused laceration in the support
Zustand der Tunnelbrust nach dem Abschlag; es ist eine allgemeine Zerrissenheit des Ausbaues zu bemerken

The burst of the wall and consequent ejection of material into the opening caused, consequently, rock release at the crown, extending till the left spring line and involving a volume of rock of several hundreds of cubic meters.

This phenomenon, which had its acme near the heading, in a few meters long stretch, propagated along the right wall, which completely collapsed for a 40 m long stretch, supported by steel ribs and shotcrete (Fig. 6 and 7).

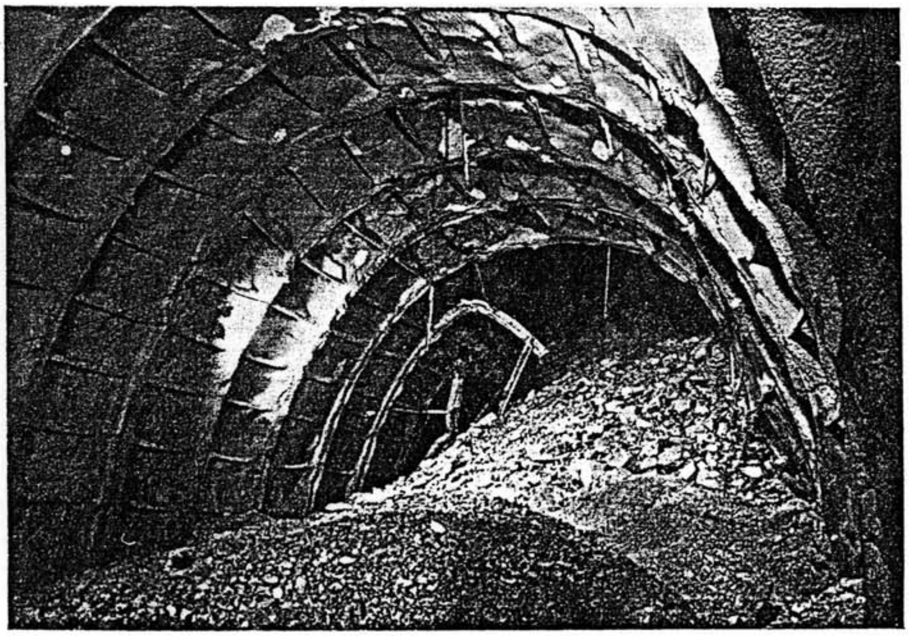

Fig. 6. Condition of the two walls at the burst area: – right wall: collapsed and bulged; – left wall: practically undisturbed
Zustand der Ulmen vor der Brustzone: – rechte Ulme: geknickt und angeschwollen; – linke Ulme: praktisch ungestört

Fig. 7. Heading in the burst area
Tunnelbrust im Vortrieb

Such an accident caused the complete destruction of the last four ribs (Fig. 8 and 9) and the warping, under axial loads, of other eight ribs (Fig. 10), the extensive tearing of the shotcrete layer and the failure of the rock surface immediately beneath the shotcrete, in the area near the heading.

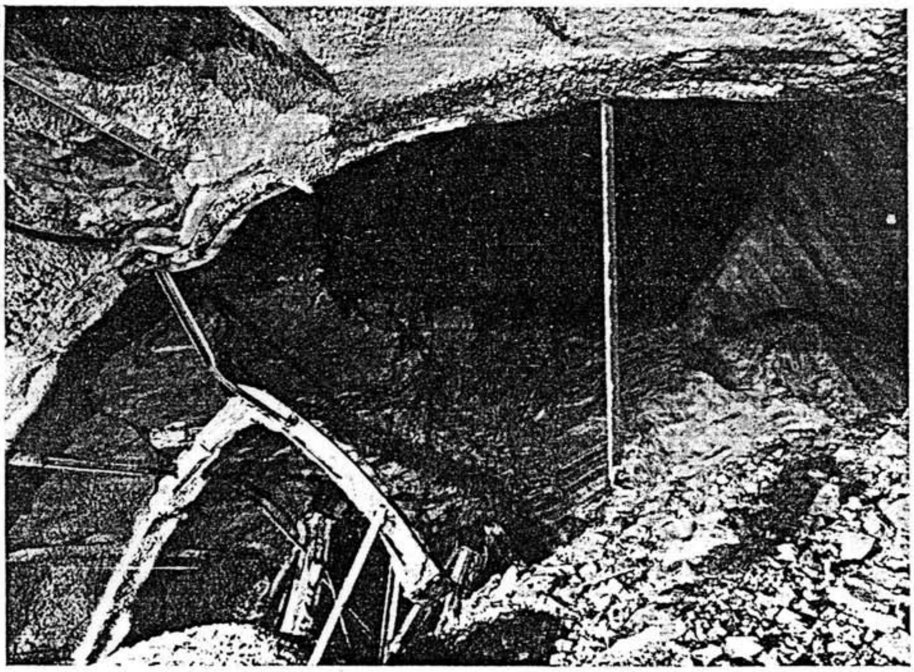

Fig. 8. Details of destroyed ribs
Ausschnitte des zerstörten Ausbaues

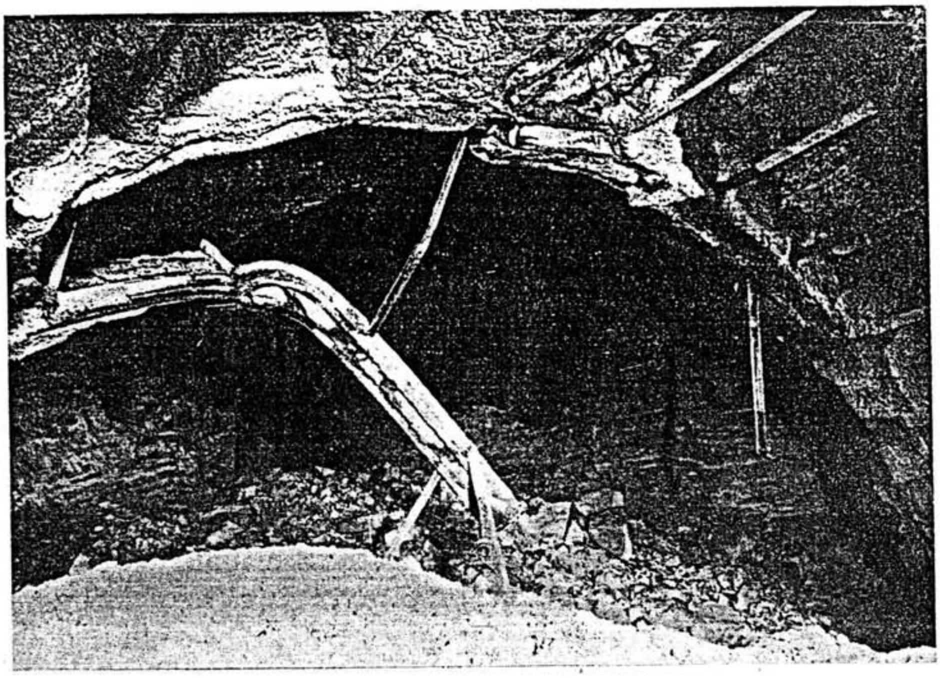

Fig. 9. Details of destroyed ribs; on the background, fault plane with marked oxidation traces
Ausschnitte des zerstörten Ausbaues; im Hintergrund sieht man die Glättung der Störung mit Oxydationsspuren

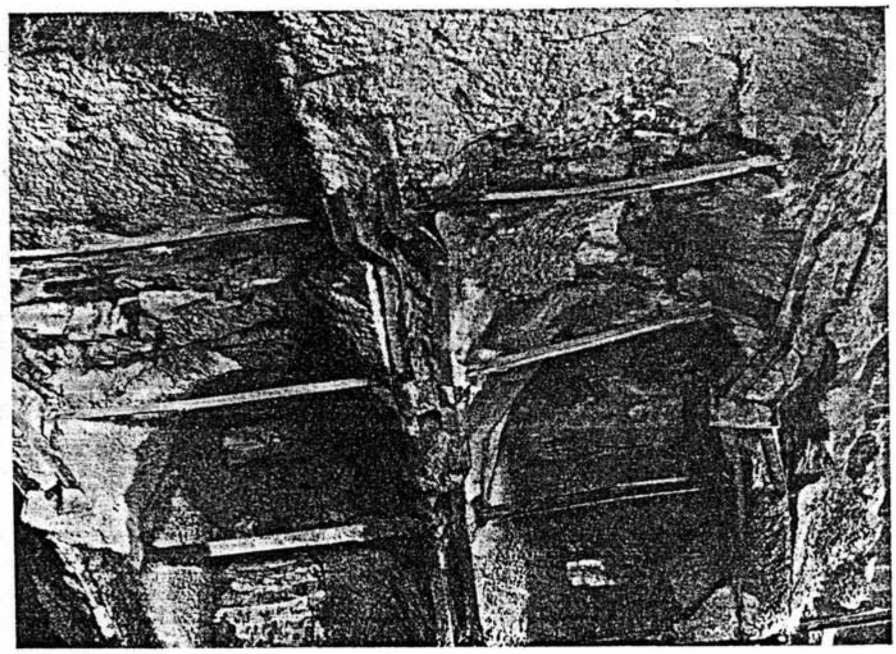

Fig. 10. Detail of warped ribs behind the burst area
Ausschnitte der verformten Stahlbögen vor der Brustzone

Trial interpretation of the phenomenon

Based on the experience and observation of the phenomena, usually occurring in tunnelling, the following conclusions can be drawn:

a) When a tunnel is excavated, the natural state of stress of the rock mass undergoes changes.

If the modulus of elasticity of the rock is high enough, the elastic deformation consequent to the new state of stress are very small and develop immediately after excavation, before erecting temporary supports. Such operation, necessary to protect the workers, cannot either alter the state of stress produced by the excavation of such a rigid mass or substitute the containment exerted by the rock removed by a round.

b) On the other hand, inside the mountain rock undergoes vertical pressures induced by the overburden and by residual tectonic stresses: deformation is opposed by the surrounding rock mass, preventing expansion.

The confinement increases the rock strength.

When an opening is created the surrounding mass is free of expanding, but toward the opening, only, with consequent decrease of strength. As long as the tangential stress along the excavation is smaller than the strength of the rock ($\sigma_t < \sigma_{gd}$), the system is stable, deformations being within the elastic limit. When the overburden is such that $\sigma_t < \sigma_{gd}$ the walls of the tunnel fail.

Broadly speaking, the failure is similar to that shown by the sides of a cubic sample under a press; the expansion of the upper and lower faces being prevented by friction. The walls of the opening will tend to become circular. The cylindrical vault which forms at the periphery of the excavation opposes rock mass deflections toward the opening, thus increasing the rock strength, again.

c) Different types of failure can take place, according to how rigidly the rock mass stands against the applied stresses:

If it is very rigid (sound and massive rock with good mechanic properties) the rock mass, loaded up to its ultimate strength σ_{gd}, fails in a brittle way ("decoesione") suddenly and abruptly returning, with a violence proportional to the load gradient, the energy stored while overstressed. Such "decoesione" failures occur at well defined points, rather than along the entire excavation line, inducing slight deformation, unless large volumes or rock are involved, whose residual strength decreases till a merely frictional strength (elastic-fragile behaviour: Fig. 11).

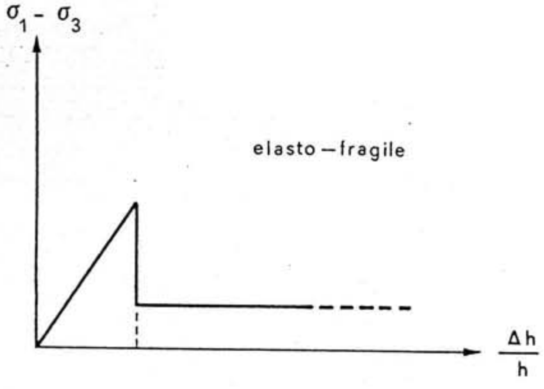

Fig. 11. Diagram 1
Diagramm 1

If low-rigidity rock occur (rock undergone to tectonic actions or of poor mechanical properties) the rock mass, stressed to its ultimate strength σ_{gd}, undergoes ductile failure, returning, with slow and smooth deformations, the energy stored while overstressed; these deformations take place along the entire excavation line, more or less homogeneously according to the anisotropy of the rock mass. The resulting deformations can be large; if adequately controlled by erecting appropriate support (bolting, shotcreting), they are such as to allow the rock mass to maintain rather good residual strength, exerting in its turn an increasing and progressive supporting action (in connection with the temporary lining) which ensures the excavation stability (elastic-plastic behaviour: Fig. 12).

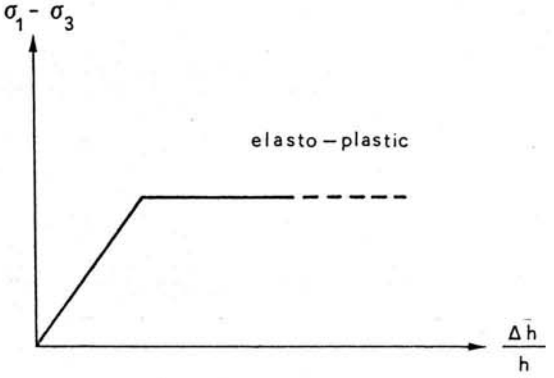

Fig. 12. Diagram 2
Diagramm 2

Based on these observations and on the dynamic development of the phenomenon, it seems resonable to classify the described failure as elastic-fragile. Moreover, if λ ratios are assumed, of the order of one, considering the high overburdens present, the Kastner-Fenner theory can be used (Fig. 13c), for the interpretation of the phenomenon.

We thus observe that:

– the occcurrence of a subvertical fault, quasi parallel to the axis of the tunnel could have altered the σ_t distribution around the opening, as compared to an ideally elastic distribution (homogeneous and isotropic medium). Consequently, the natural stress migration and radial redistribution would have been prevented, within the rock mass;

– the discontinuity produced by the fault could have caused a stress concentration on a body located near the wall and isolated from the rest of the rock mass (the thickness of the body was thinning as the excavation advanced). As a consequence, all these contemporary actions could have impared the stability of the wall, which through a series of sudden and violent collapses reached a new structural shape and thus a new equilibrium.

In conclusion the failure would have evolved through a sequence of stages, which could be summarized as follows:

a) Upon shooting rounds, the radial confining pressure, provided by the rock present at the heading, changed from $\sigma_3 = 300$ kg/cm^2 to $\sigma_3 = 0$;

b) The state of stress at the wall, changed from triaxial to monoaxial, and increased (*Terzaghi*) starting from its minimum value $\sigma_1 = 300$ kg/cm^2;

c) In the time lag (about 15 minutes) elapsed between the ignition of rounds and the burst, σ_1, underwent an increase from $\sigma_1 = 300$ kg/cm^2 to a maximum $\sigma_1 = 600$ kg/cm^2 value, calculated based on the Kastner approach. This corresponds to the average stress acting on the rock body isolated by the fault.

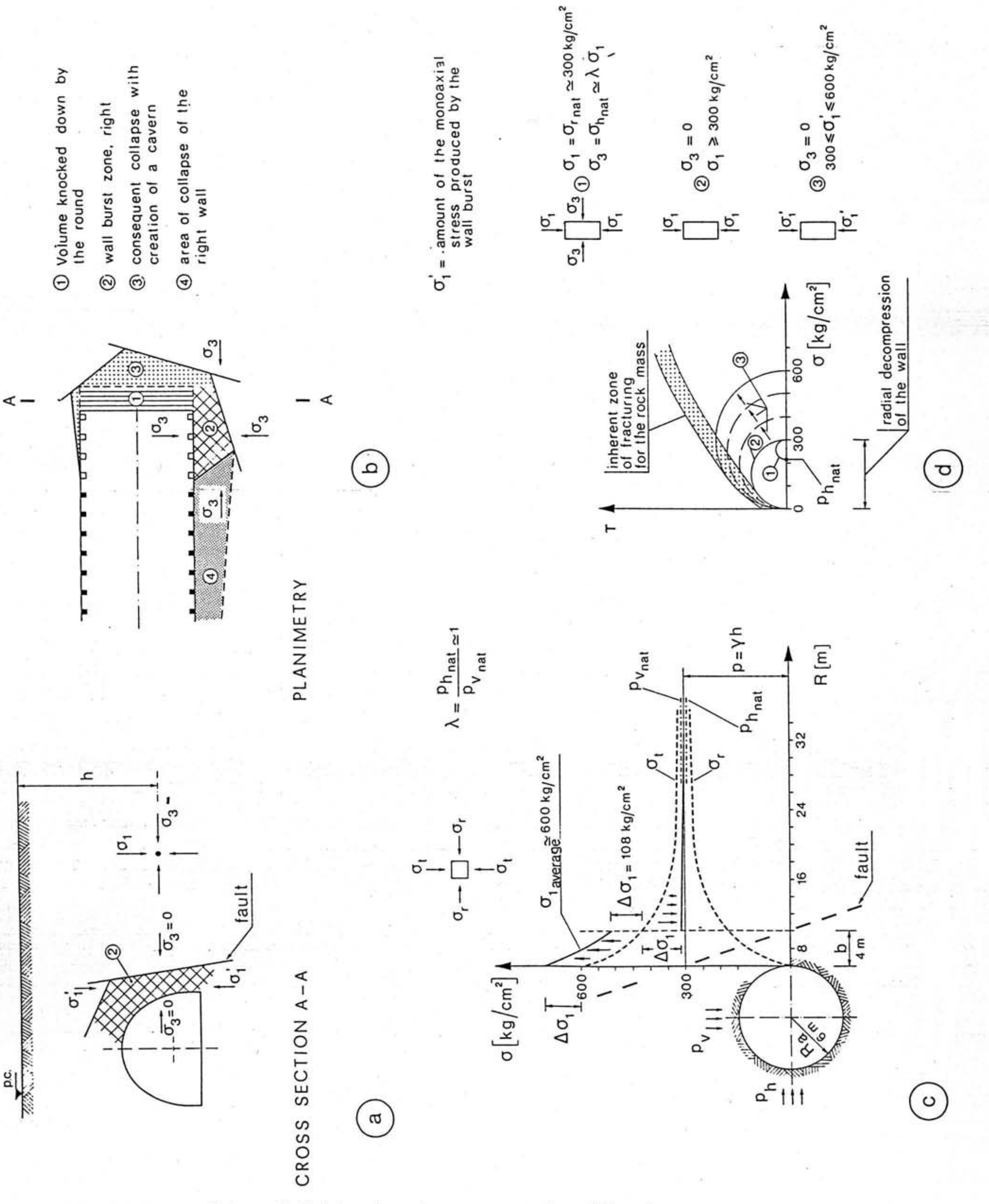

Fig. 13. Burst of the wall; left hand carriageway – statics of the phenomenon
Bergschlag an der rechten Ulme des linken Tunnelrohres; Erklärung der Erscheinung durch den Spannungszustand in der Umgebung

It follows that the stress $\sigma_1 = \sigma_{gd}$, which caused the burst, can be assumed as ranging between $\sigma_1 = 300$ kg/cm^2 and $\sigma_1 = 600$ kg/cm^2. Based on this consideration, in addition with the fact that elastic-brittle failure occurred, the phenomenon can be represented on the σ versus τ *Mohr's* diagram, as reported in Fig. 13d.

Final Conclusions

Based on the previous analyses, it seems possible to conclude that the burst of the tunnel wall occurred because a nearly prismatic body of rock, isolated by faults and of dimensions of the order of the opening, was loaded up to its ultimate strength σ_{gd}, estimated between 300 and 600 kg/cm^2.

The failure was elastic-fragile as confirmed by the abrupt and violent development of the phenomenon, as well as by the occurrence of frequent subvertical fractures, present in the right wall and totally absent in the left wall (Fig. 14, 15, 16 and 17) of the tunnel.

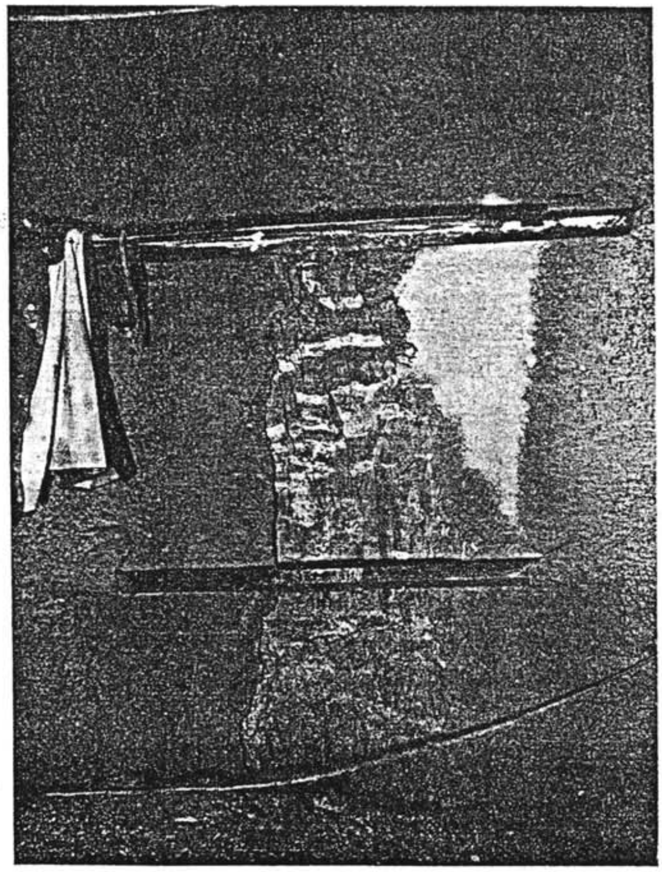

Fig. 14. Right-hand wall; condition of limestone about 20 m from burst area
Rechte Ulme: Zustand des Kalksteines (etwa 20 m vor der Brust)

The failure though not causing any harm to the personnel, caused large damages to temporary lining due to the high energy released by the burst (certainly

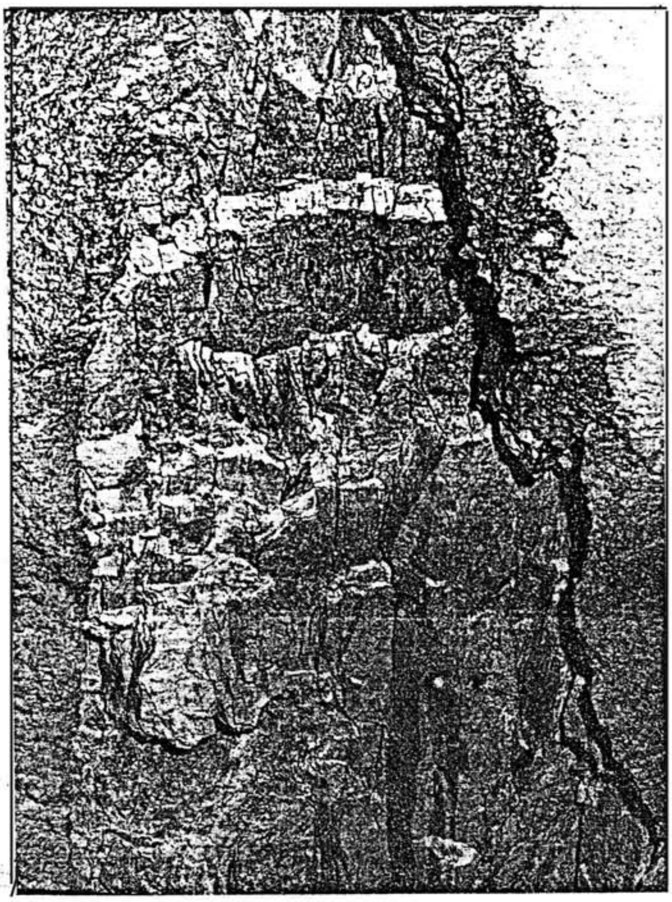

Fig. 15. Right-hand wall; details of collapsed material with marked subvertical pressure-relief fractures
Rechte Ulme: Ausschnitte des zusammengebrochenen Felses; man kann subvertikale Entspannungsklüfte erkennen

tens of times larger than an usual round). It could not be easily foreseen, though some symptoms showed, as described, a certain fatigue of the rock mass. The failure has however shown that:

a) when similar states of stress occur it is important to check that local discontinuities do not isolate bodies of rock near the excavation, with dimensions of the order of the tunnel section;

b) discontinuities occurring subvertical and subparallel, to the tunnel axis play a determinant role in limiting the sizes of rock bodies near the wall; especially if radially located, to respect to the opening, they preclude stress migration and redistribution at the contour;

c) in the case under examination, either smaller or larger volumes, to respect to the tunnel section would not have probably caused the wall to burst so violently.

Safety precautions were taken to continue the excavation in the "Scisti ad Aptici" formation in both tubes, after chainage 4238 m left hand tunnel. The most effective measures, which allowed safely tunnelling, avoiding instability, were either the reduction of the unsupported height of the wall (heading-bench

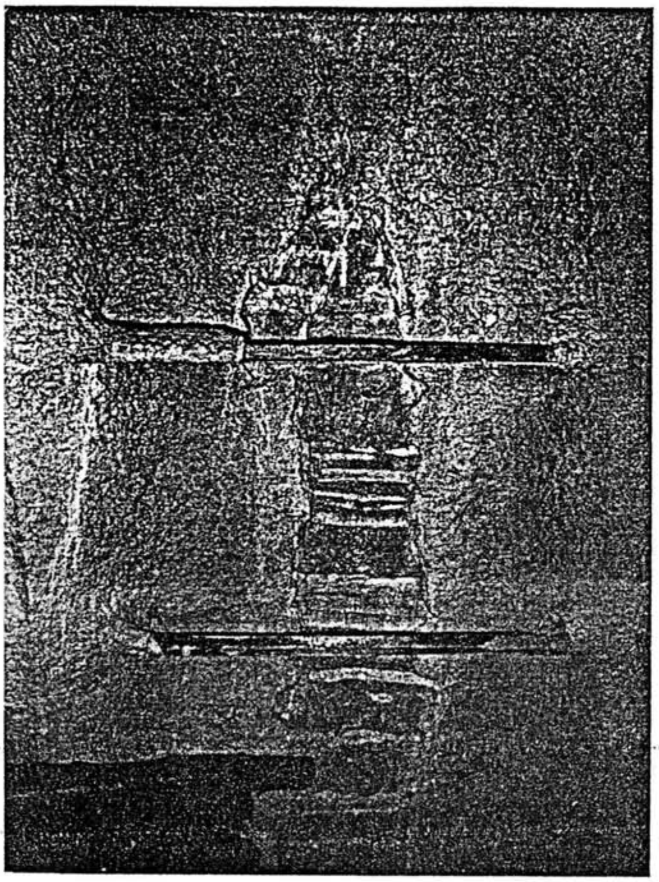

Fig. 16. Left-hand wall; condition of limestone about 20 m from burst area
Linke Ulme: Zustand des Kalksteines (etwa 20 m vor der Brust)

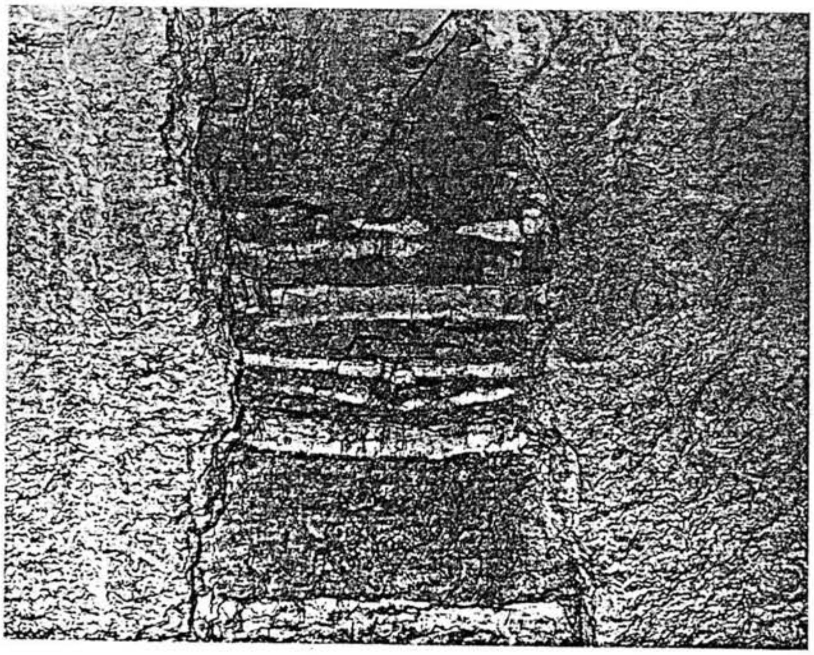

Fig. 17. Left-hand wall; details of limestone with flint layers undisturbed by burst
Linke Ulme: Ausschnitte des ungestörten Kalksteines (mit erkennbaren Feuersteinschichten)

method: Fig. 18), and the accurate and systematic survey, by experienced personnel, of joints and faults affecting the whole section and their three dimensions recording.

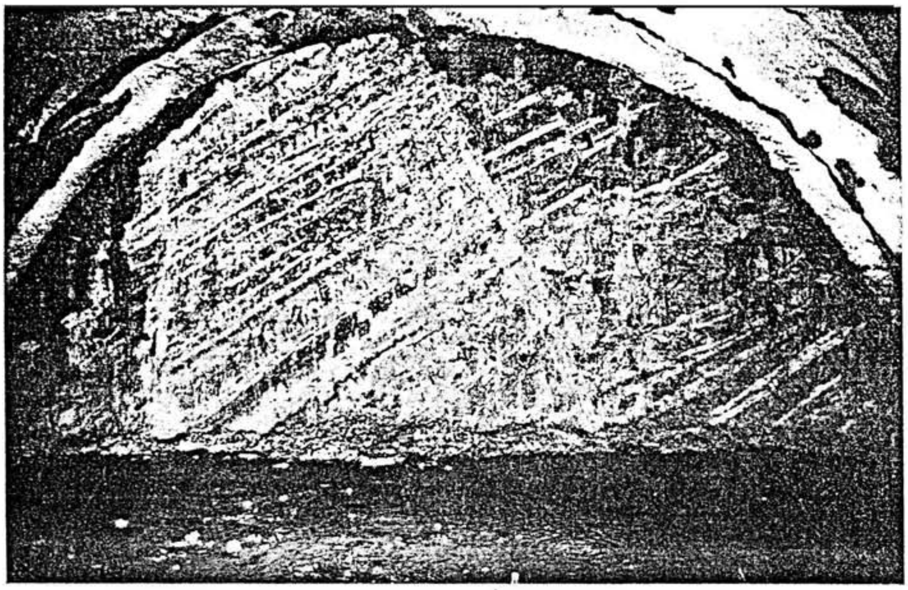

Fig. 18. Heading-bench after chainage 4240; "Scisti ad Aptici" showing a fault subparallel to the tunnel axis
Halbquerschnittvortrieb (bergseitig vorgetriebene Länge 4240 m); der Schiefer zeigt Spuren der Störung, die subparallel zu der Tunnelachse liegt

Address of the author: Prof. Ing. *Pietro Lunardi,* School of Engineering, University of Florence, Piazza San Marco 1, Milano, Italy.

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