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GEOTHERMAL FIELD DEVELOPMENT IN THE EUROPEAN COMMUNITY OBJECTIVES, ACHIEVEMENTS AND PROBLEM AREAS

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ABSTRACT

Achievements and problem areas are reviewed with respect to various engineering implications of geothermal field development in the European Community (EC). Current and future development goals address three resource settings.

(a) low enthalpy sources (30-150°C), an outlook common to all Member states as a result of hot water aquifers flowing in large sedimentary units with normal heat flow, widespread throughout the EC;
(b) high enthalpy sources (<150°C) in areas of high heat flow which, as a consequence of the geodynamics of the Eurasian plate, are limited to Central and South-West Italy and to Eastern Greece;
(c) hot dry rocks (HDR), whose potential for Europe, and also the difficulties in implementing the heat mining concept, are enormous. A large scale experiment conducted at medium depth in Cornwall (UK) proves encouraging though. It has provided the right sort of scientific inputs to the understanding of the mechanics of anisotropic brittle basement rocks.

Development of low grade heat deposits is strongly resource but moreover utilisation dependant under present technological and economic heating standards. This practically restricts commercial exploitation to district heating of large urgan areas whenever exists a dependable aquifer. The most significant development takes place in the Paris Basin with 50 geothermal well pairs (doublet) due to operate by late 1984. This concentration might at a stage cause producing and injector wells to interfere. Other development prospects are shaping in Aquitaine (SW France), Denmark, United Kingdom, Italy and Germany. Many of these aquifers consist of clastic sediments, and therefore arise the problem of reinjecting safely a solid free brine to secure well lifetime and prevent formation invasion by fine particles.

Ten high enthalpy fields have been identified to date of which five, all of the liquid dominated type, have been discovered in the past decade. Yet none of them has moved to commercial production for a variety of technical, economical and environmental reasons.

In particular volcano-tectonic geothermal systems are not fully understood as to their permeability-fracture pattern and their agressive fluid thermochemistry.

Topical R&D actions in the fields of geochemistry, geophysics, reinjection, well stimulation, induced seismicity and reservoir simulation are described whenever they relate to reservoir engineering concerns.

Hot dry rocks. There is a background of seven years of R&D on the topic, since the early modelling and laboratory studies and field experiments at shallow depths which led to the large scale, intermediate depth, test site in Cornwall.

The major questions arisen by the current Cornish project are (a) how to control the growth of a HDR reservoir under strongly anisotropic in-situ stresses and subsequent shear fracturing, and (b) how to reliably assess the volume of fluid filled, artificial and reactivated, joint sets, and the heat exchange are?

1. EC GEOTHERMAL ENVIRONMENTS

Exploration and development of geothermal sources is largely dictated by the geodynamics of the Eurasian lithospheric plate which defines the main European geothermal provinces shown in Fig. 1.

Therefore present and prospective development objectives address three resource settings, namely:

(a) low enthalpy sources. Exploitation of warm water aquifers (30-150°C) is an outlook common to all EC Member states because of the presence of widespread - intracratonic and foredeep - sedimentary basins displaying near to normal heat flow (50 to 100 mW/m^2) and of hydrothermal convection - hot springs - systems of more local occurence in tectonised areas close to border faults of tertiary grabens and to orogenic belts. Highly compartmented tertiary grabens, subjected to distensive transverse faulting, may constitute an objective intermediate between low and high enthalpy uses.

(b) high enthalpy sources. Dry and wet steam resources are limited to those areas, the closing Mediterranean, where the collision of the Eurasian and African plates give rise to typical attributes such as subduction trenches, active volcanic island arcs, marginal basins, anatectic magmatism, extensional horst and graben structures e.g. to Central and South-Western Italy and to Eastern Greece.

(c) hot dry rocks (HDR). So far present projections on the amount of energy ultimately recoverable from natural hot wet sources is limited: 5 million tons of oil equivalent (TOE) per year corresponding to maximum installed capacities of 1,500 MWE (electricity generation) and 7,000 MWT (direct uses) respectively. Not surprising therefore is the considerable interest raised in the EC by the HDR concept of heat mining. Feasible engineering of man made geothermal reservoirs, irrespective of the site specific constraints inherent to natural sources, could multiply by an order of magnitude the EC geothermal reserve.

2. LOW ENTHALPY FIELDS

There are ten or so proven regional aquifers with dependable reservoir performance, among which the Jurassic limestones in the Paris suburban area and Cretaceous sandstones in Aquitaine (South West France) are the most extensively developed for district heating purposes. In the Paris area exploitation of saline waters by means of production-reinjection doublets is the rule whereas in Aquitaine singlet production wells are used instead (fresh water).

Particularly in the first case where about 50 such doublets will be operating in late 1984 there are serious risks of interferring wells with subsequent cooling breakthroughs. In Aquitaine excessive pressure depletions are feared in the near future. Hence the implementation of adequate reservoir management policies becomes urgent and regional simulation of heat and mass transfer is underway to attempt optimizing heat extraction and reservoir lifetime.

In Aquitaine injector wells will be required at a stage to sustain reservoir pressure above the critical matrix 'crushing' threshold. In the Paris basin two alternative strategies are being considered either (a) horizontal wells that allow for larger heat capacities and longer system lifetime, or/and (b) exploitation of underlying Triassic sandstones. The latter depends on procedures for securing reinjection of large quantities of cooled brines over often limited net pay intervals. Two test sites in the Paris Basin experienced severe problems notably sand face bridging due to odd well completions (partial or no gravel packing) and formation invasion by fine particles (see Fig. 2).

Emphasis is placed on developing suitable engineering technologies, through core tests and pilot filtering hardware, for feasibly mastering reinjection in clastic sediments, a geological environment common to many hot water deposits throughout the EC.

3. HIGH ENTHALPY FIELDS

The three dry steam fields of Larderello, Travale and Monte Amiata in Central Tuscany and Northern Latium are a long established geothermal assett with an installed capacity amounting to 440 MWE.

At Larderello the recent reinjection of steam condensates should prove beneficial a practice, as shown in Fig. 3. Elsewhere most problems are posed by liquid dominated sources such as in Torre Alfina (high CO_2 content), Cesano where the thermochemistry of a near saturated brine is very similar to that encountered in the Imperial Valley of California and Latera, a volcano- sedimentary field with a puzzling, fracture dominated, porosity pattern, which penalizes commercial production (and reinjection).

Last but not least, the Mofete and San Vito fields near Naples illustrate the foregoing difficulties to which ought to be added the environmental risk of investigating and developing a field in an active volcanic, seismic and densely populated area. It is a fact of evidence that the development of liquid sources has not progressed at the expected pace.

As a result Community supported research has focused with varying success on the following topic areas:

(a) reinjection and well stimulation. On the Latera field where reinjection of the separated brine is a practical and environmental necessity a series of dry holes were selected as candidates for well stimulation to attempt turning them into commercial injectors. Field procedures combined massive and progressively increasing cold water injection and acid treatment with a view to add the effects of thermal stress cracking, hydraulic fracturing and self propping of induced and/or reactivated fractures. These experiments completed on more or less empirical bases - no back-up by dynamic hydro-mechanical and leaching tests on core - achieved a significant increase of well injectivities, 100 T/h below fracturing pressures (see test and stimulation schedule in Table 1).

(b) well testing. Test hardware using pressurised separators and suitable fluid sampling facilities, are progressively substituted for the standard Russell-James method of testing two-phase flow wells. However, more sophisticated procedures are required to thoroughly appraise well and reservoir performance and fluid behaviour under a variety of thermodynamic conditions.

(c) reservoir simulation. Two - one industry, the other research oriented - computer codes of the 3D two phase flow type were applied to the simulation of the Mofete (liquid) and Travale (steam) fields, the latter benefitting from 10 years long production-pressure histories (Fig. 4). Indeed these complex models are worth using for better comprehending reservoir structure and physics rather than as accurate prediction tools. In fact available pressure temperature sequences are more characteristic of well and very near wellbore flow than of long term reservoir response and boundary influences. Along this line progress is noticed in the implementation of more realistic wellbore two phase flow simulators accounting for CO_2 partial pressure, non condensable H_2S, CH4, and brine evolution.

(d) induced seismicity. The impact of geothermal exploitation on the seismicity of areas with active tectonics and volcanism is monitored by a series of stations in the main fields. At Latera a more refined network using three component seismometers has been installed with a view to detect eventual acoustic emissions generated by well stimulation and water injection operations. After long well shut-ins there is evidence of a fairly intense background seismicity. During injection swarms of events are generated (Fig. 5) with foci locations ordered along two, apparently coherent, tectonic trends.

Until now geothermal exploitation has not, in seismic terms, proven harmful to the environment and seismic monitoring when adequately designed has shown to be a valuable reservoir investigations tool.

(e) geophysics and geochemistry. Integrated geophysical investigations were undertaken on the well documented Travale field chosen as a test site for evaluating the potential of various, conventional and exotic, geophysical techniques in prospecting high enthalpy sources. Some results are not indifferent to reservoir engineers in particular (i) transient electromagnetic recording which applies an IP criterion at great depth. Positive anomalies of amplitude residuals proved strongly correlated with known steam producing zones, which is interpreted as the existence, locally, of polarising mineral bodies formed as consequence of hydrothermal convection e.g. of fracturing (see Fig. 6), (ii) reflection seismics using P and S sources. Contrasts appeared between tight compact and porous fractured rocks especially on S sections structurally more sensitive to shear and fracturation, and (iii) microearthquake recording by a dense array of three component seismometers. There is an organised trend of seismic velocity and attenuation signatures consistent with the model of a fissured reservoir filled at various saturations by either steam or water (Fig. 7). Apart from the usual water rock interactions studied from the fundamental point of view in the laboratory, isotope geochemistry and particularly $^3He/^4He$ ratios provided fascinating clues in perfecting the conceptual model of the Larderello system (heat sources and deep convecting fluid flow paths (shown in Fig. 8 sketch).

Active geochemistry, using a set of five complexed rare earth tracers, combining ideal (non adsorbing) and non ideal (adsorbing) properties has achieved a convincing performance in characterizing a shallow HDR system (Fig. 9). As a matter of fact geochemistry and geophysics, whatever speculative their outcome, often appeared as a valuable tool in conceptual modelling of hydrothermal reservoirs. Yet this opinion is not fully accepted by all specialists.

4. HOT DRY ROCKS

HDR research has associated a variety of early laboratory experiments and model calculations, with field fracturing and circulation tests at shallow depths prior to commissioning the large scale intermediate depth, stimulation project at the Rosemanowes Quarry site in British Cornwall.

Laboratory research dealt with the mechanics and hydraulics of rock fracturing, thermal stress cracking, mathematical and physical modelling of crack propagation and linking on somewhat idealised elastic bodies. Enhancement of fracture conductivity by means of fatigue micropressurisation and chemical leaching by Soda compounds were also studied in some detail.

Preliminary field experiments made it possible (a) to test equipments and procedures - in-situ stress measurements, fracturing and linking processes, fracture detection and microseismic control, and (b) to select the most promising stimulation concept now implemented in Cornwall.

The idea behind this concept is to stimulate large volumes of a jointed rock mass by taking advantage precisely of this basic feature of crystalline and metamorphic basement rocks, by reactivating natural joints. The candidate process combines explosive pretreatment and massive hydraulic fracturing. Unfocused explosives, fired below the plastic limit, are assumed to develop a near wellbore system of radially oriented self-propped fractures resulting in a strong negative skin. The fractures ease the access to the natural joints which is completed by repeated massive pressurisation and venting cycles. This sequence tested successfully at shallow depth is presently being validated at a greater depth (2200 m) under a state of stress representative of target HDR depths.

It is possible to draw of few tentative conclusions from early loop circulation tests:
(a) over 300,000 m^3 of water have been injected in the HDR reservoir and hardly 100,000 m^3 recovered so far;
(b) the system can be circulated at 30 l/s ca. (below 10 MPa WHP) but at the expense of severe losses resulting from, mainly downward, fracture growth away from the recovery well;
(c) because of a peculiar situation where the well axis and the major natural joint strike are misaligned with the maximum in-situ horizontal stress, shearing instead of tension (jacking) appears as the dominant factor in fracture propagation. Alternatively shear triggered an intense microseismic activity which allowed for a consistent reservoir evaluation from foci clustering. Shear fracturing should prevail on most HDR sites because of anisotropic in-situ stresses and the anisotropy in rock strength,a distinctive attribute of basement rocks;
(d) although pressure records tend to indicate natural joint reactivation, reservoir growth has proceeded normal to the minimum horizontal stress and not along a known joint direction. Connections consist of reactivated joints contained by in-situ stresses;
(e) there is evidence, from seismo-acoustic emission and event mapping , hydraulic, thermal and tracer testing of a large stimulated volume (1 km^3 ca.) displaying rock/fluid contact areas of at least 1 km^2. However, neither can seismicity nor tracers define either fluid filled fractures or heat exchange areas. Aseismic (deaf) zones are manifest (Fig. 10) within the pressurised volume and a number of events are triggered far beyond the hydraulically stimulated area in the early fracturing stages. Hence seismo-acoustic mapping can only produce an enveloppe not the stimulated volume proper. Tracers can define adsorbed areas which do not fit necessarily the effective heat exchange area. Tracers on the other hand can best discriminate the main flow conduits of a multipath well connection.
(f) The HDR loop operates as a large volumetric diffusive system between two, weakly connected, performant wells rather than as a connection through a highly conductive fracture.

In summary nothing worked as anticipated. Fractures grew downwards, and not upwards, the major fractures did no propagate along the planes of weakness of the natural joints and there were no indications of channelling and well shortcircuiting whatsoever; The project is very stimulating indeed and has provided already invaluable scientific information.

Stage 2 of the Cornish programme will consist of drilling a third well in order to intersect the main reservoir structure.

An alternative process for stimulating jointed rocks, known as the oriented hydraulic fracturing concept, has been tested in the laboratory and in the field at shallow depth. Validation at greater depth could be given a chance on a second large scale experiment in Central France.

ACKNOWLEDGEMENTS

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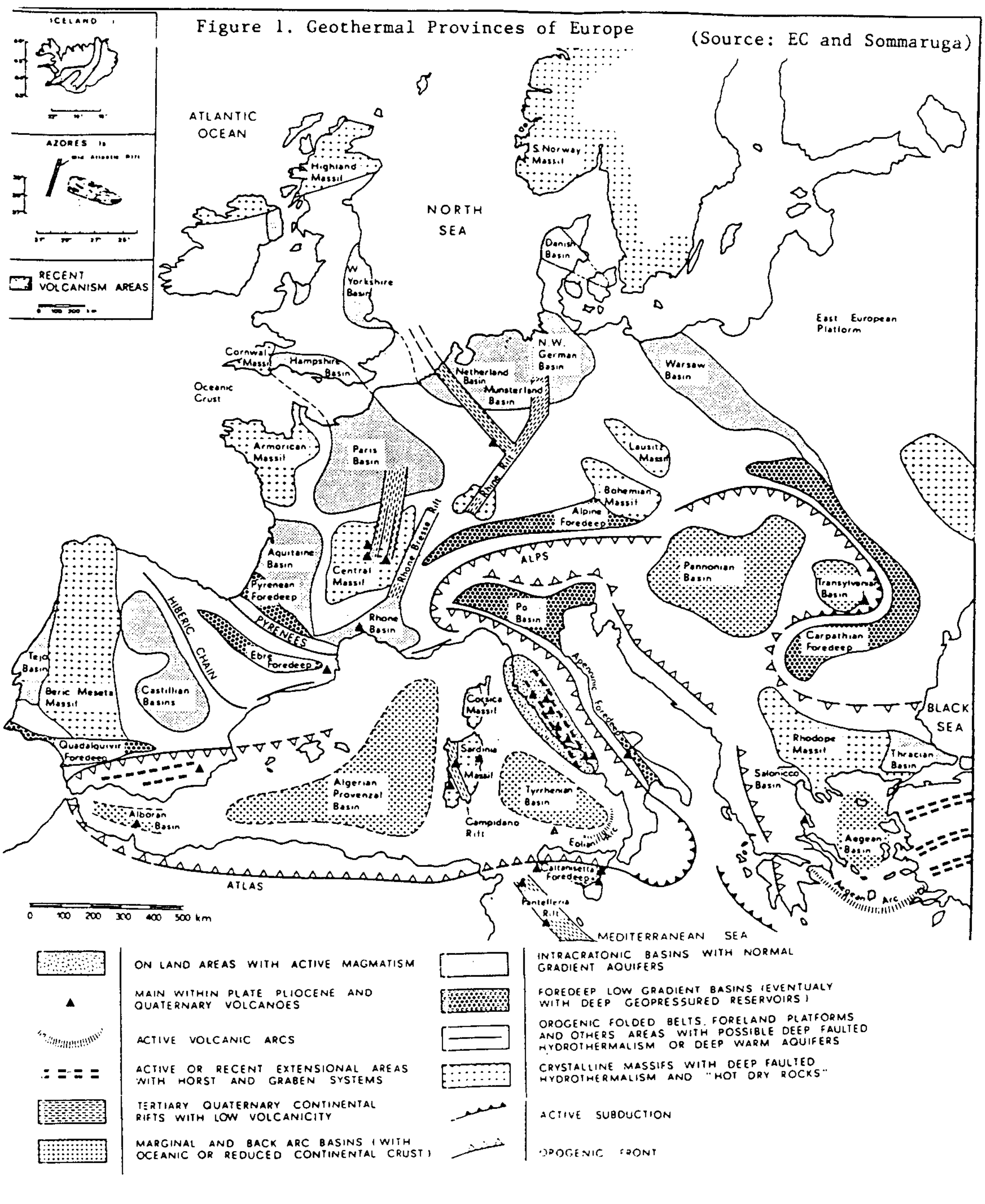
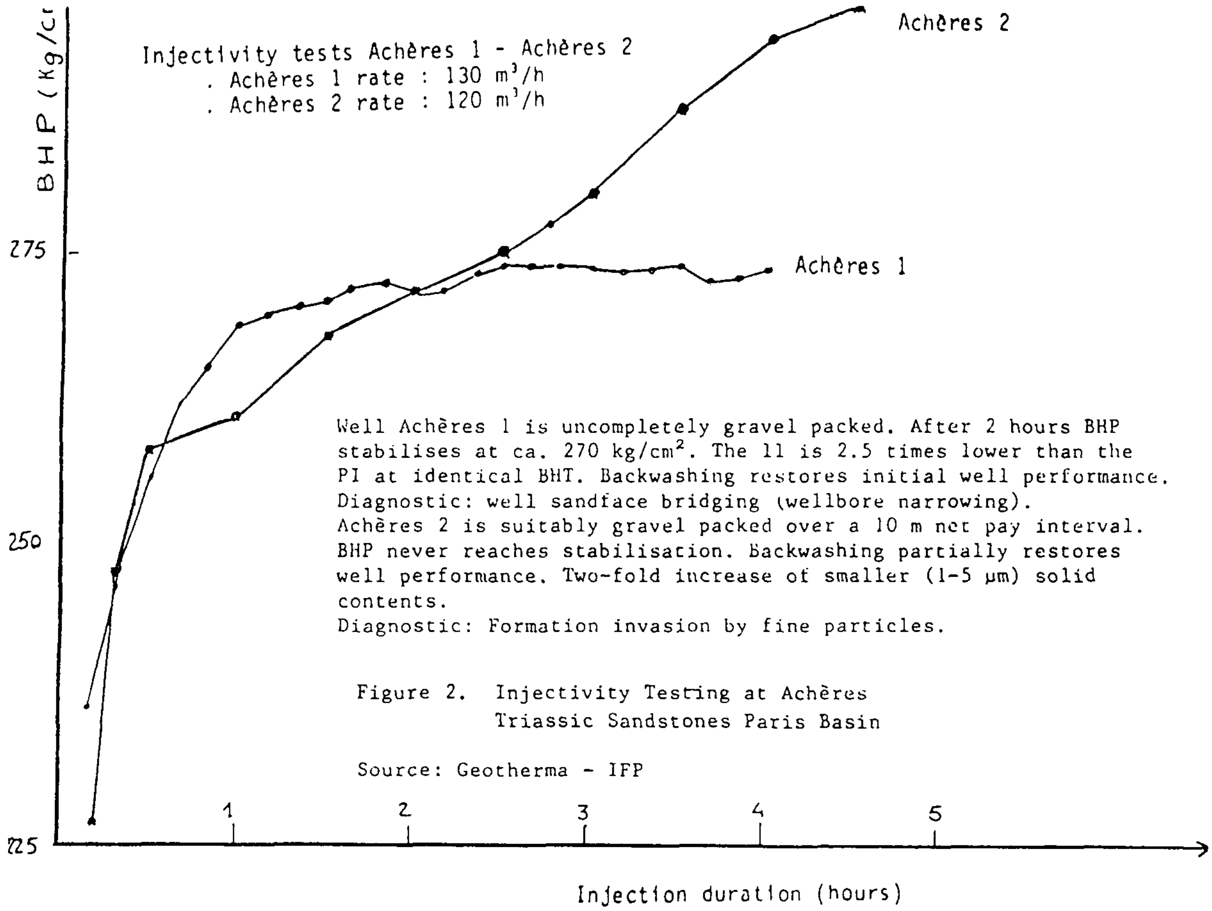


Figure 1. Geothermal Provinces of Europe (Source: EC and Sommaruga)



Source: Geotherma - IFP

Figure 2. Injectivity Testing at Achères
Triassic Sandstones Paris Basin

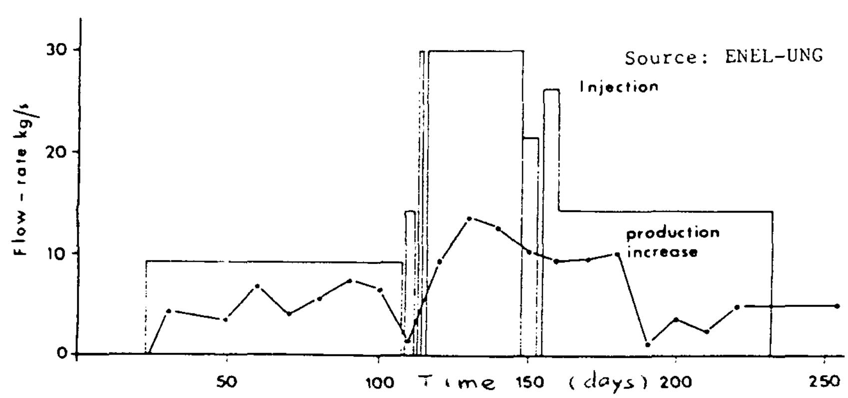
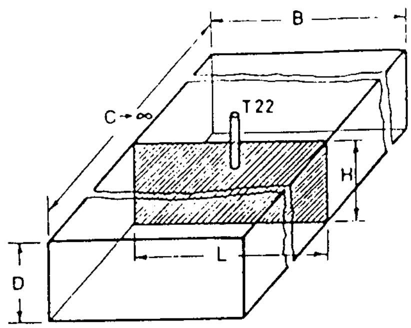
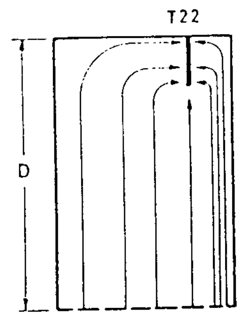


Figure 3 Injection experiment in Larderello.
Condensates are reinjected in a well
at a distance varying from 0.2 to 3 km
to steam producing wells



A)



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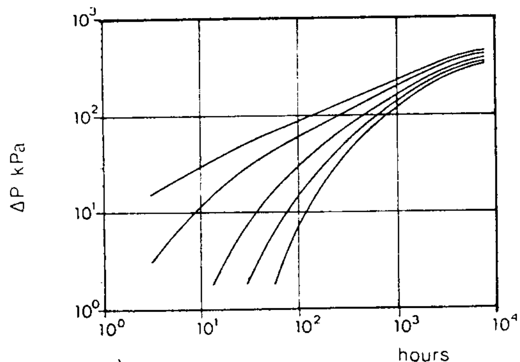
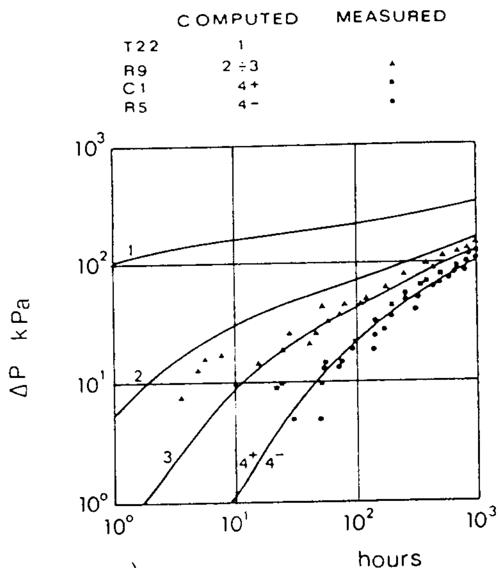


A)

Figure 4 A. Simulation of the Travale Field
Model calibration of well
Pressure Production histories

Source: ISMES



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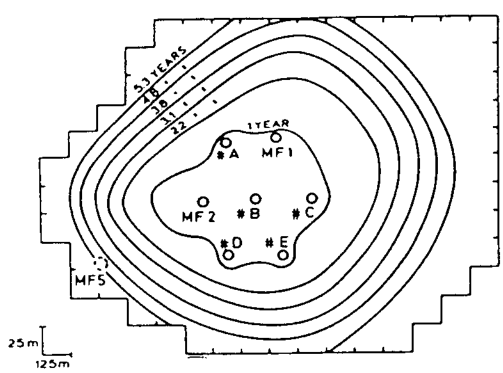
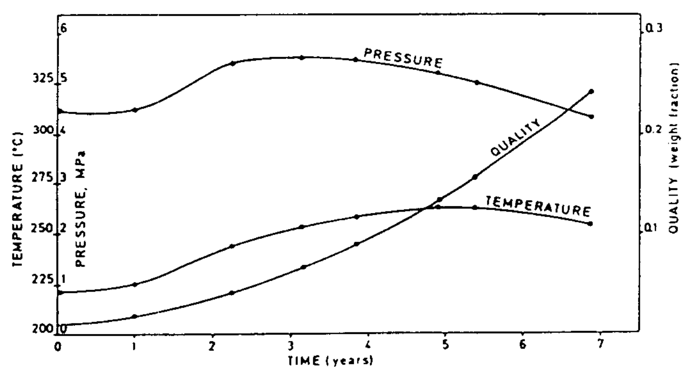


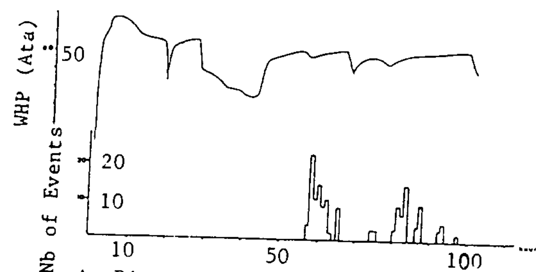


a. Top metamorphic formation.
Model layer n° 12. Evolution of
the flashing front with time.

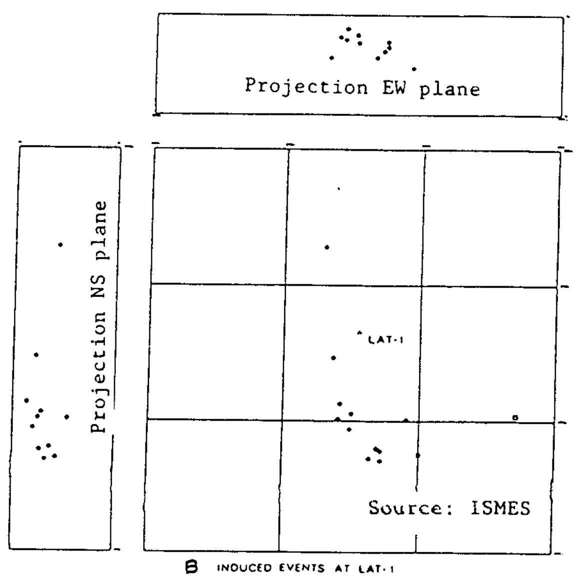
b. Change of well head conditions
for an average well

Source: AGIP

Figure 4 B. Simulation of the Mofete Field.
Case: 7 producers, no injector



A. Distribution of microearthquakes during injection at well L.1



B INDUCED EVENTS AT LAT-1

Figure 5. Induced Seismicity at Latera
Total earthquakes recorded: 148

Only strongest events are shown in Fig. B

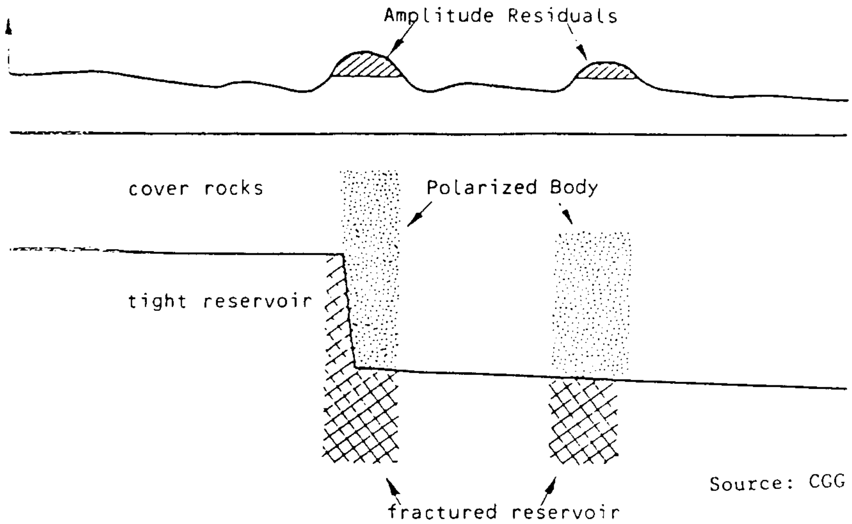


Figure 6 Trasient EM Recording at Travale Interpretative Model, Polarised Bodies are attributed to hydrothermal mineralisation (pyritisation ...).

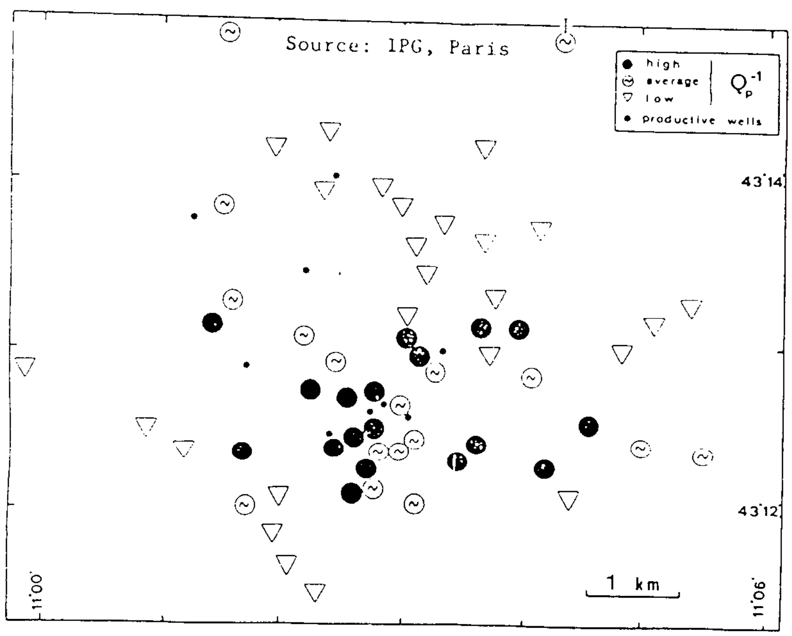


Figure 7 Experimental Seismology at Travale. Mapping of relative **attenuation** Q_P^{-1} of P waves calculated from distant shots. Q_P^{-1} is derived from slopes of spectral ratios respective to the average spectrum (over the whole network) for each individual wave.

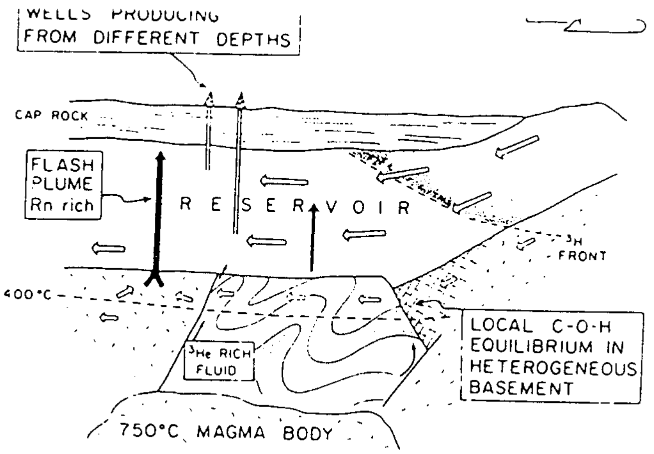


Figure 8 An Updated Conceptual Model of the Larderello Field based on rare gas isotope geochemistry

Source: Univ. of Cambridge

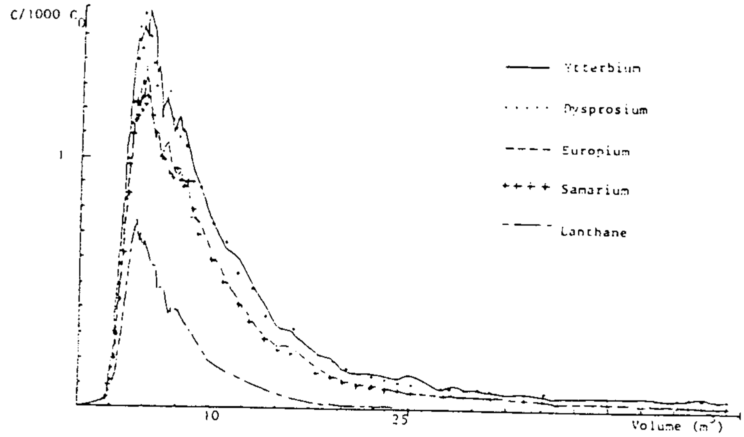
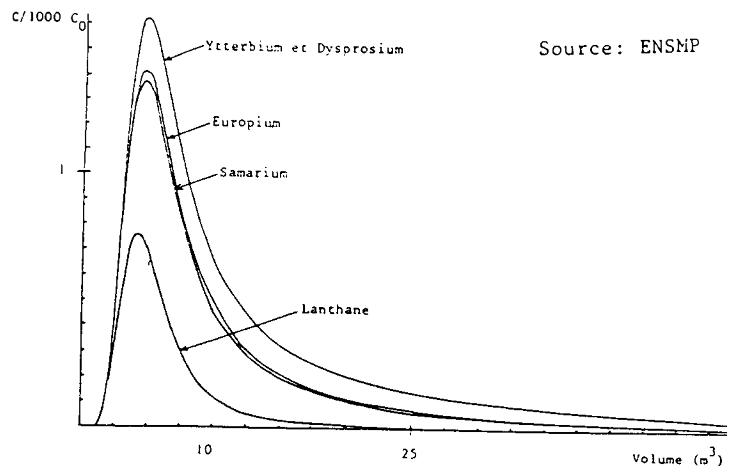
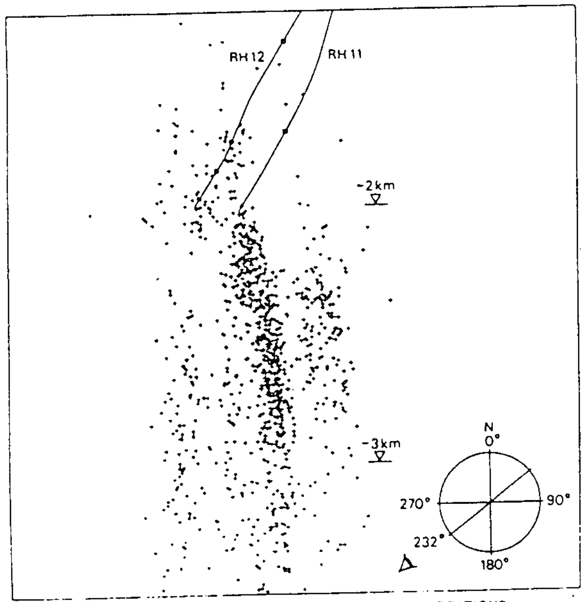


Figure 9a. Experimental tracer restitution curve

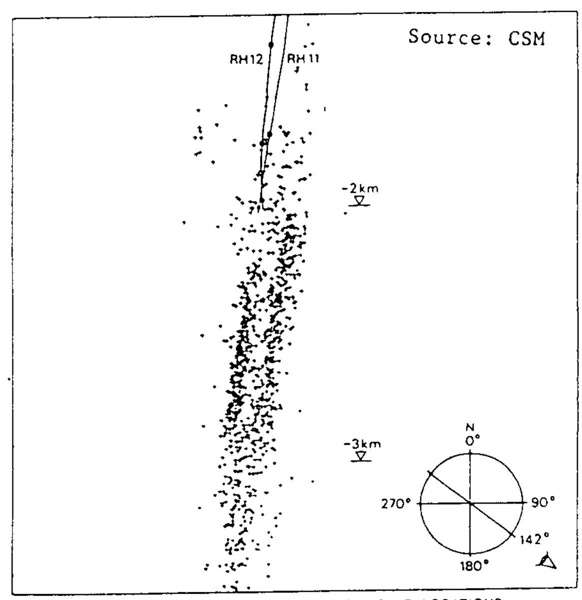


Source: ENSMP

Figure 9b. Model calculated restitution curve



A VERTICAL SECTION SHOWING MICROSEISMIC LOCATIONS VIEWED FROM THE SOUTH WEST



B VERTICAL SECTION SHOWING MICROSEISMIC LOCATIONS VIEWED FROM THE SOUTH EAST

Figure 10 Locations of seismo-acoustic events monitored during fracturing and circulation