



# Geological and geophysical modeling for geothermal assessment: the VIGOR case study of “Guardia dei Lombardi” Area, Campania

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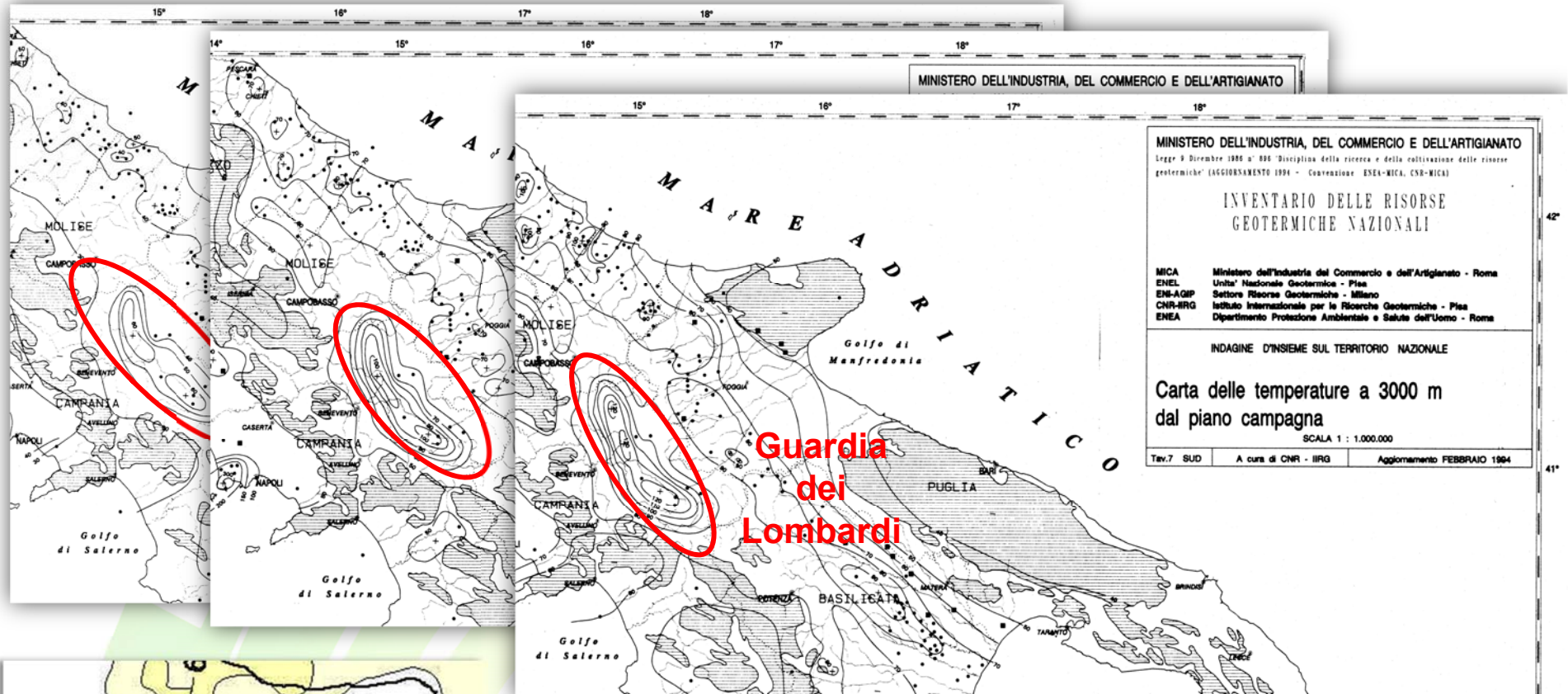


Programma Operativo Interregionale  
ENERGIE RINNOVABILI E  
RISPARMIO ENERGETICO  
2007 - 2013

Una scelta illuminata



# Thermal Anomaly



**Heat Flow  
Up to 90 mW/m<sup>2</sup>**

**Temperature:**  
 -1000 m Tmax 60° C  
 -2000 m Tmax 100° C  
 -3000 m Tmax 120° C

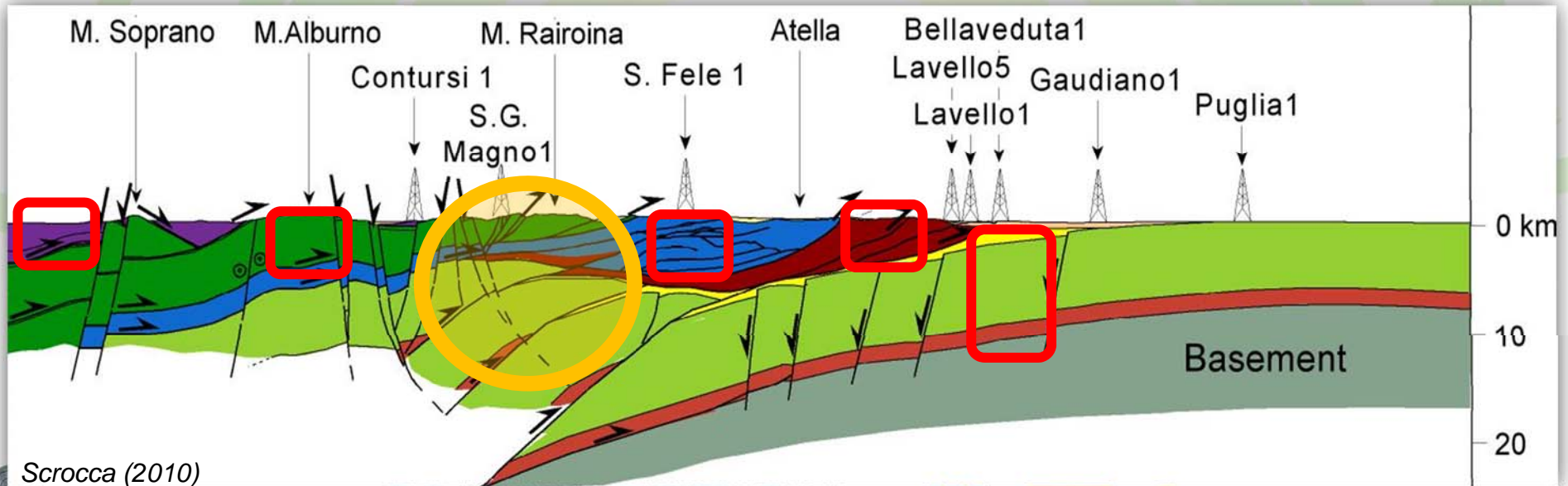
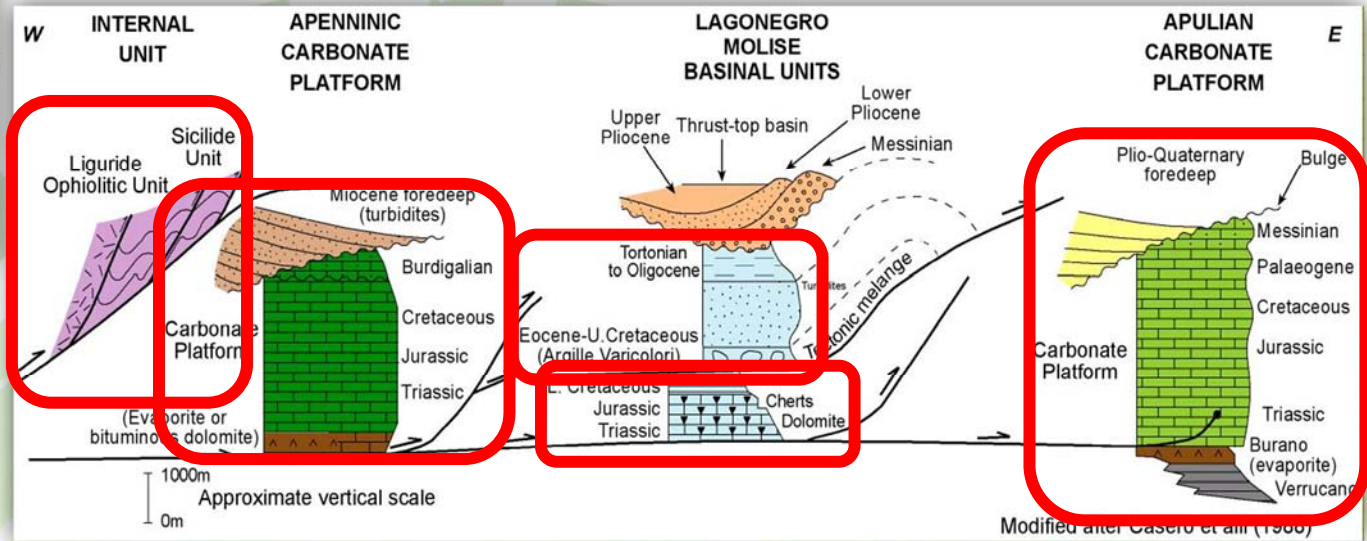
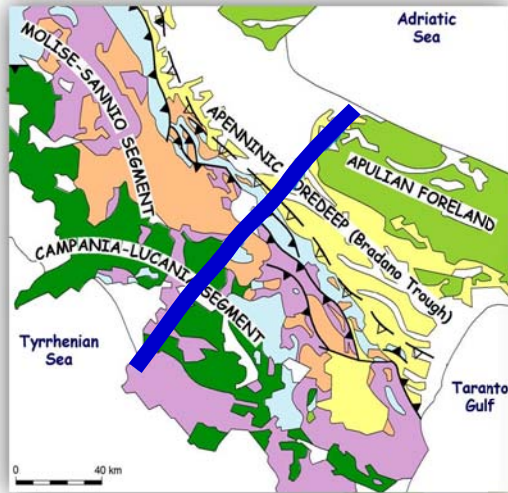
Modified after Della Vedova et al. (2001)

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# Regional Geological Setting

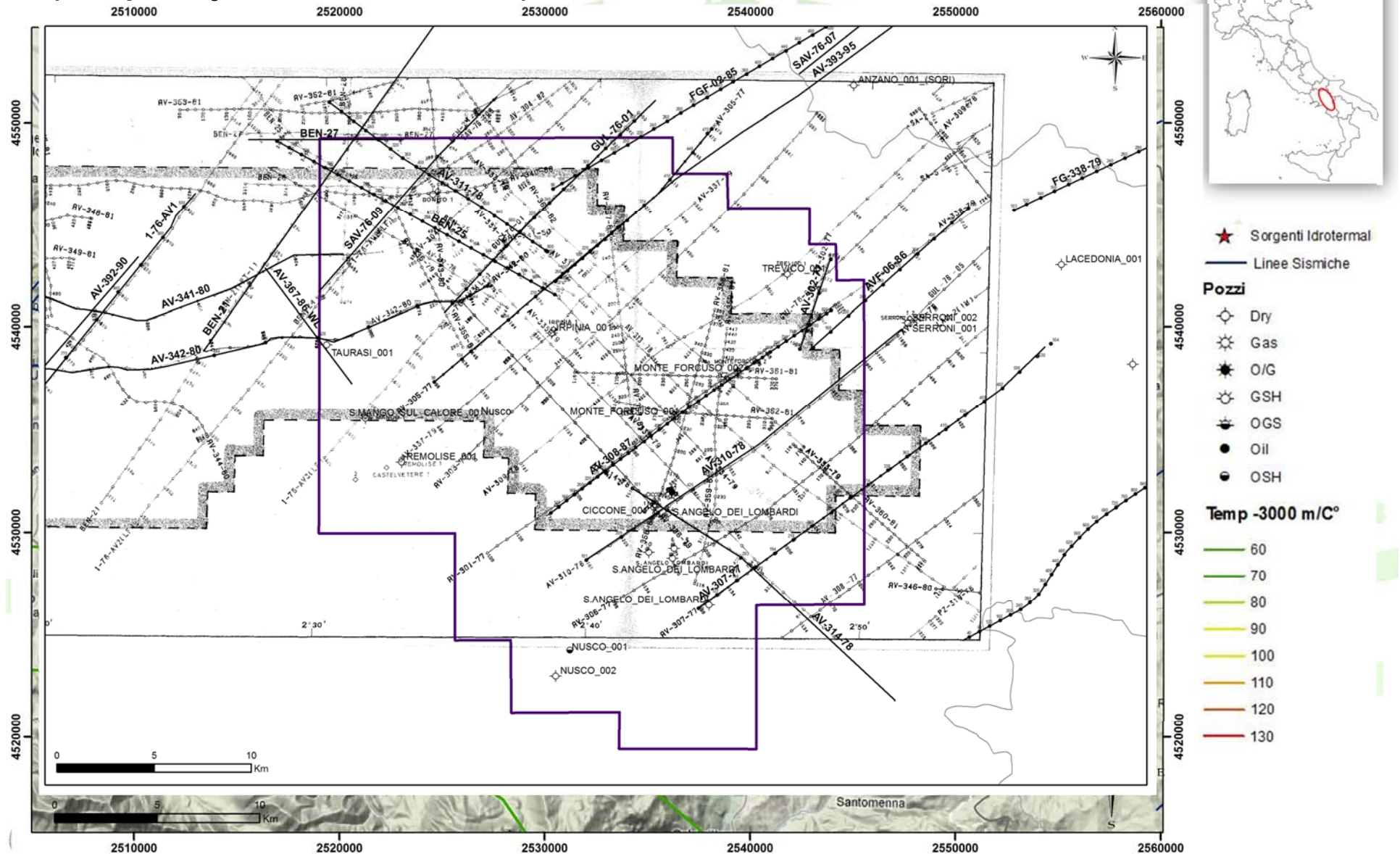


Scrocca (2010)



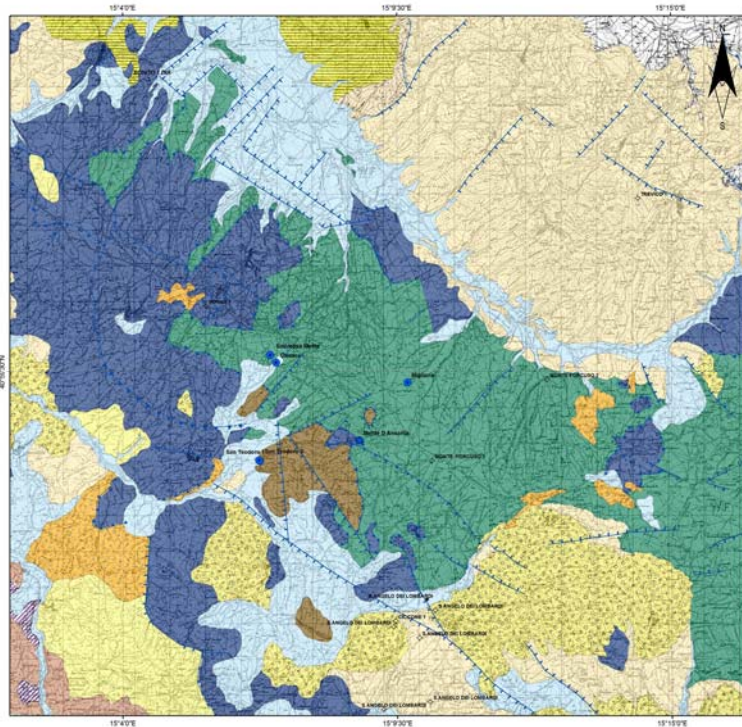
# Guardia dei Lombardi: Subsurface Datasets

Seismic reflection profiles and well data available in the public domain  
(Videpi Project vs ENI database)





# Surface Geology



**Legenda**

- Sorgenti termali
- Mito d'Assisi
- Pozzi
- ▲▲▲▲▲ Sottracimento Inverso
- ▲▲▲▲▲ Sottracimento
- ▲▲▲▲▲ Faglia Inversa
- ▲▲▲▲▲ Faglia Diretta

**Depositi Continentali**  
Età Quaternaria

**Subsistema Scarpella**  
Dacronomi composti da conglomerati e sabbie.  
Età: Pliocene ed olocene

**Sistema Baronia**  
Depositi conglomeratici e sabbiosi, passanti verso falde e depositi argillosi e sabbiosi.  
Età: Pliocene ed

**Molasse Anziano**  
Sedimenti arenaceo-conglomeratici e arenaceo-pellici.  
Età: Messiniano sup.

**Unità Torreda Finamaria**  
Ciprioli (Cinque di anteorde fluvio-lacustre)  
Età: Sarmatiano sup.

**Sistema Vitarnina**  
Depositi arenaceo-conglomeratici e arenaceo-pellici fossiliferi.  
Età: Sarmatiano medio sup. - Alpieniano inf.

**Subsistema Serra Diavolo**  
Depositi arenaceo-sabbiosi a grana media.  
Età: Sarmatiano medio sup.

**Subsistema Pietra Bianca**  
Dacronomi arenaceo-conglomeratici.  
Età: Sarmatiano

**Unità Duania**  
Sedimenti calcareo-sabbiosi.  
Età: Oligocene sup.

**Unità Fattore**  
Depositi alla base costituiti da argille varicolori e calcari  
turchese, passanti verso falde ed alternanze  
calcario-marnose e sabbiose a cemento fossilifero.  
Età: Cretaceo sup. - Liguriano

**Unità Frigento**  
La porzione settentrionale della successione comprende i depositi  
della serie "Lutario-olio-marnoso"  
passanti alla porzione inferiore ad associazioni di Marni  
calcario-clastiche ed argilloso calcario-marnose.  
Età: Triassico medio-Subappenninico medio

**Unità Sicilde**  
Formazioni argillose calcario-marnose arenacee.  
Età: Cretaceo sup. - Oligocene sup.

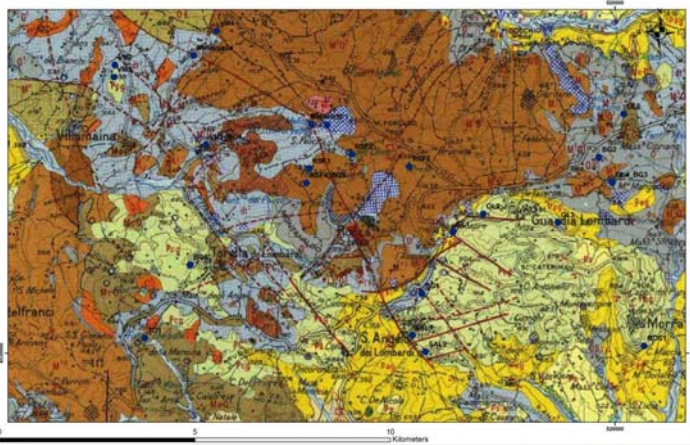
Basi geologica ripresa con modifiche da Di Norsa et al. (2005)

**Regione Campania  
Sito Guardia dei Lombardi  
Carta Geologico - Strutturale**

Validazione del percorso geotermico  
nelle Regioni della Convergenza

Progetto VIGOR: Iniziativa Operativa tra  
MISE, SOGEMIS e CNR - DTA - PIR - PIR  
Energie Rinnovabili e Risparmio Energetico  
2007 - 2013 Linea di attività 1.4 "Interventi  
operativi di gestione"

Field survey  
Critical review  
published maps

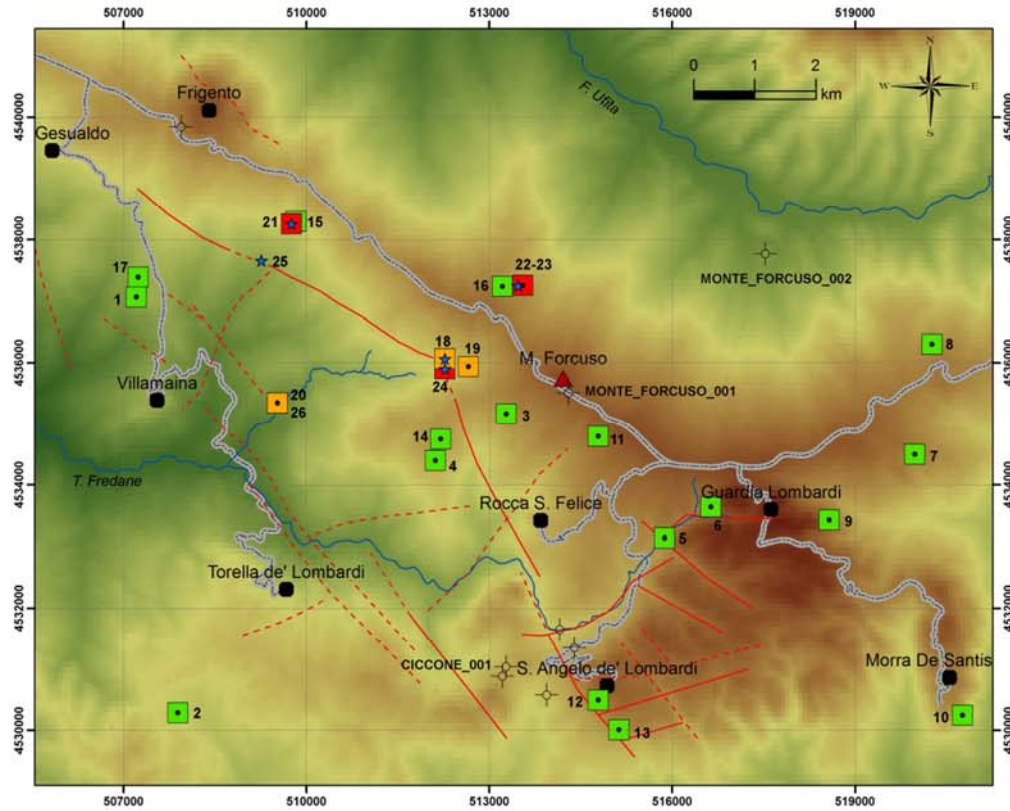


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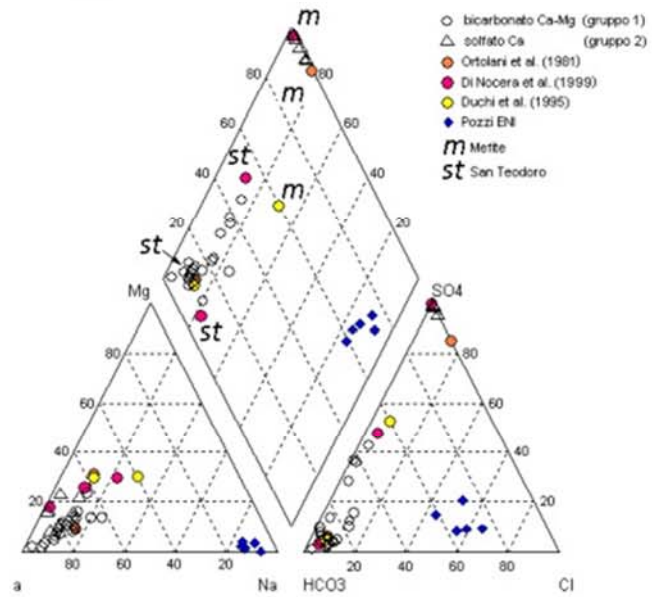




# Geochemistry and Hydrogeology



- ★ emanazioni gassose
- Pozzi
- campioni acqua**
- sottogruppo 1.1
- sottogruppo 1.2
- gruppo 2
- faglie**
- certa
- - - presunta
- quota m s.l.m.**
- 1567
- 289
- idrografia
- strada



Nome	Quota	Portata	pH	T °C	En	Cl <sub>2</sub> mS	O <sub>2</sub>	Na	NH <sub>4</sub>	K	Mg	Ca	HCO <sub>3</sub>	F	Cl	NO <sub>2</sub>	NO <sub>3</sub>	PO <sub>4</sub>	SO <sub>4</sub>	Ca-Mg-HCO <sub>3</sub>	CO <sub>2</sub>	CaCl <sub>2</sub>	CaSO <sub>4</sub>	CaH <sub>2</sub>	CaMg	CaSO <sub>4</sub> -CO <sub>2</sub>	R/Re c			
VMA1_BGS1	450 m	1.85 (1993)	8.11	9	-12	2099	10	39.5		9.4	19	169	350	0.65	16.9	1.1	0.8			244										
VMA3	590 m		6.93	10.9	-22.0	672	4.3	20.0		14.4	6.6	130	466	0.74	13.4	0.9	4.5			16.6										
VMA2	560 m		8.25	6.9	-31.4	723	9	42.3		12.3	12.6	94	345	0.99	32.3	1.6	1.2			56										
VMA4	662 m		7.45	9.9	661.9	716	8.2	24.7		3.6	15.4	111	405	0.72	9.7	0.6	1			52										
Melfonella	576 m	Sargente non garente	3.26	13	-65.7	2832	1.7	51.4	1.55	10.9	29.1	536	940	1.42	10.3	0.8				790		-10.4		97	2.75	10		2.35		
Melfe	750 m		1.93	17.6	9.2	11090	0.6	17.9		46.3	60	595		6.31	12.4	0.9				11.8		1970		-15.41	96.7	1.04	0.25	18	0.43	2.8
RSP1	800 m		8.01	9.5	90.3	1113	11	39.6		4.5	36.1	159	476	0.35	12.2	0.8	0.1			219		-7.79								
RSP2	770 m	0.7 (Marzo 2006)	7	11.1	58.8	532	5.7	13.3	0.05	2.7	7.5	92	349	0.63	8	0.5	5.1			19.7		-0.24								
RSP3	753 m	0.06-0.15 (Nov. 2005 - Dic. 2005)	7.00	12.9	-11.5	555	4.4	28.8		3.1	10.4	84	336	0.73	3	2.7	1.8	1.16		28.7		-7.45								
RSP4_BGS	700 m	0.06-0.10 (Nov. 2005 - Dic. 2005)	7.1	11.6	75.8	630	5	21		1.3	9.6	117	415	0.63	7.5	0.5	1.4			28.4		-7.15								
RSP5	830 m	1.3-3.4 (Ago 1993 - Nov. 2005)	6.90	11.3	135.4	635	6	15.3		2.7	8.1	114	366	0.40	22.6	1.3	5.1	0.46		13.3		-7.69								
GL1	631 m	6-21.5 (Nov. 2005 - Dic. 2005)	7.07	14.4	92.6	490	7.8	11.6		3	3.9	88	287	0.20	15.3	0.9	6.6	0.51		5.5		-8.36								
GL2	1000 m	0.5-2.4 (Nov. 2005 - Dic. 2005)	7.22	13.8	305.8	568	10	14		3.8	3.4	159	488	0.39	23.7	1.3	4.6	0.30		8.3		-8.44								
GL3	940 m		8.81	13	110.1	539	8	11.7		2.4	4.1	330	1013	0.29	15.9	1	6.1	0.51		7.8		-8.25								
GL4_BGS	214 m		6.73	14.5	99.5	752	6	18		8	11.3	123	428	0.42	16.6	1	13.1	1.19		24.1		-6.09								
GL5	300 m		7.01	14.8	97.0	564	14.3			2.9	5.9	100	340	0.43	13.6	1.2	10.6	0.99		9.2		-7.54								
BG1	700 m																													
BG2	800 m																													
BG6	670 m																													
T01	870 m		6.9	12.6	0.1	840	4.8	19.6		10.6	4.8	143	433	0.37	31.2	1.7	55.7	5.1		18.7		-7.31								
T011	873 m		6.84	14	147.8	815	7.1	30		10.1	8.4	129	400	0.37	38.5	2.1	36.2	3.43		41.8		-8.24								
SAL2	750 m		8.92	14.3	135.5	796	9.2	18.2		5.5	2.3	214	610	0.35	39.9	2	13.2	1.23		20		-7.81								
MD51	600 m									32	8.4	100	366	0.39	32.6	1.7	55.4	5.11		46.8		-7.83								

**Modulo di dati per la caratterizzazione geologica**

**DESCRIZIONE SITO**

Località: **Forcuso** Regione: **Abruzzo**

Sezione idrogeologica: **F. Colonna S. Angelo** Comune: **Forcuso**

Località: **Villamaina** Comune: **Villamaina**

Caso idrogeologico: **Villamaina** Capofila idrogeologico: **Forcuso**

Autore del disegno: **ENI** Dipartimento Protezione Ambientale

Cartografia Geologica: **1:50,000**

Quota in m.s.l.m.: **1567** Data del disegno: **1993**

**Descrizione**

Sottogruppo 1.1  Sottogruppo 1.2  Gruppo 2  
 Pozzi ENI  Pozzi privati  
 Pozzi pubblici  Pozzi industriali  
 Pozzi agricoli  Pozzi militari  
 Pozzi industriali  Pozzi agricoli  
 Pozzi militari  Pozzi agricoli

**Mappe**

Carta geologica  Carta idrogeologica  
 Carta idrogeologica  Carta idrogeologica  
 Carta idrogeologica  Carta idrogeologica

**Programma Operativo LE ENERGIE RINNOVABILI**

Una scelta illuminata





# Mefite d'Ansanto: CO<sub>2</sub> Emission



CO<sub>2</sub> (98 vol%)  
with minor amounts of:  
N<sub>2</sub> (1.3 vol%),  
H<sub>2</sub>S (0.33 vol%)  
CH<sub>4</sub> (0.23 vol%)  
(Chiodini et al., 2010)

According to Chiodini et al. (2010), Mefite d'Ansanto is the largest natural emission of low temperature CO<sub>2</sub> rich gases, from non-volcanic environment, ever measured in the Earth (total gas flux 23.1 kg/s - 2000 ton/day)



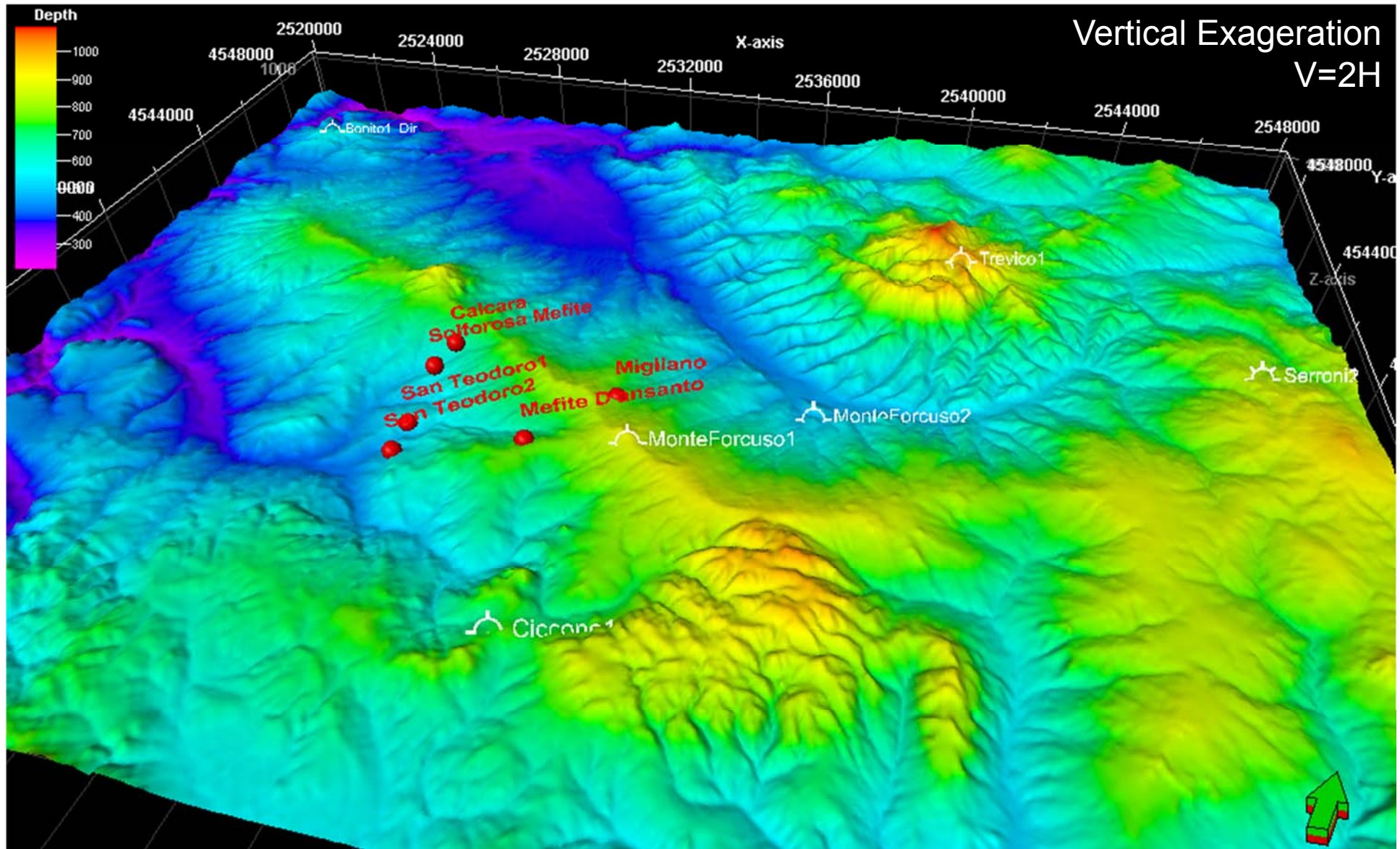
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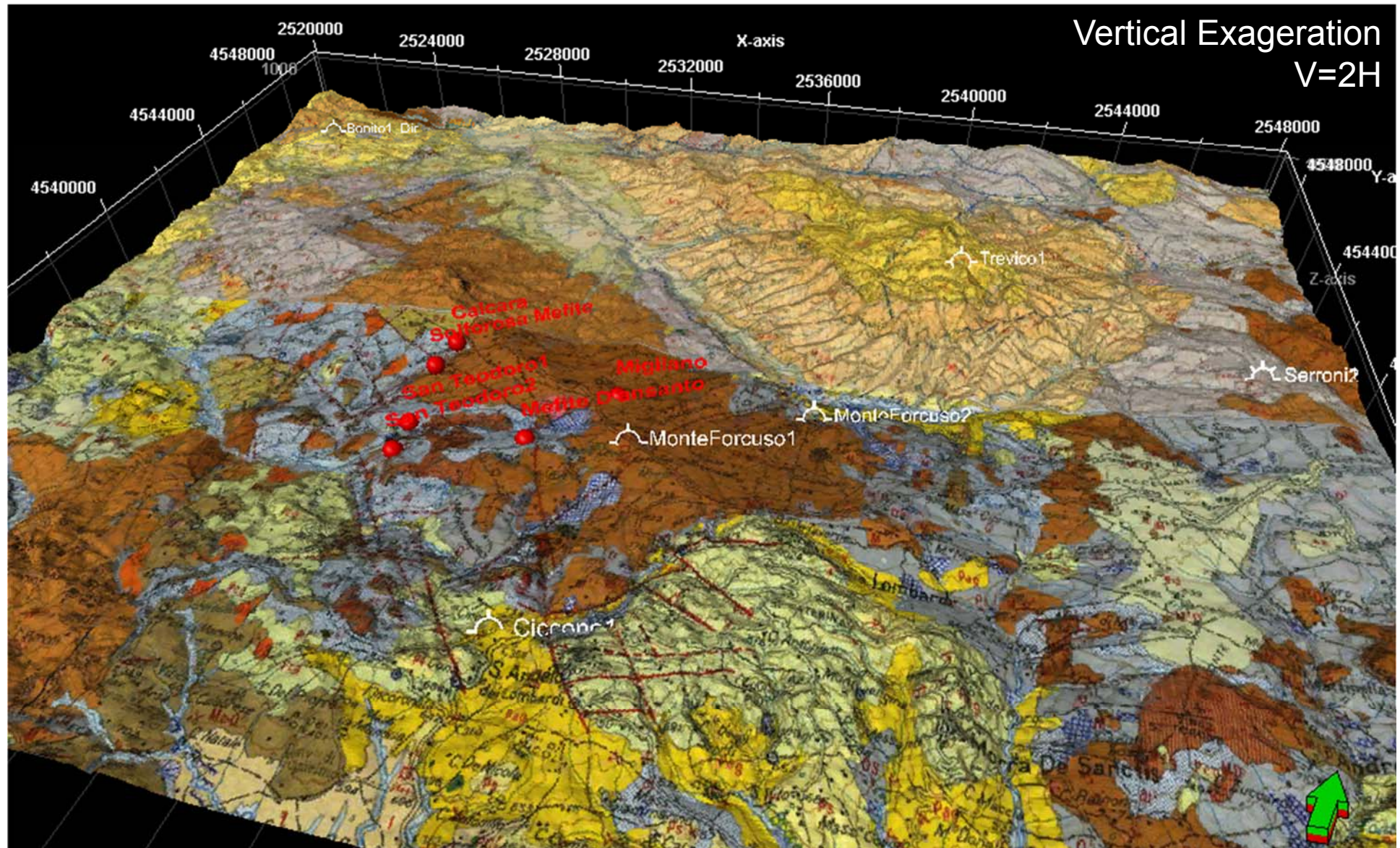
# DEM, Spring and Wells







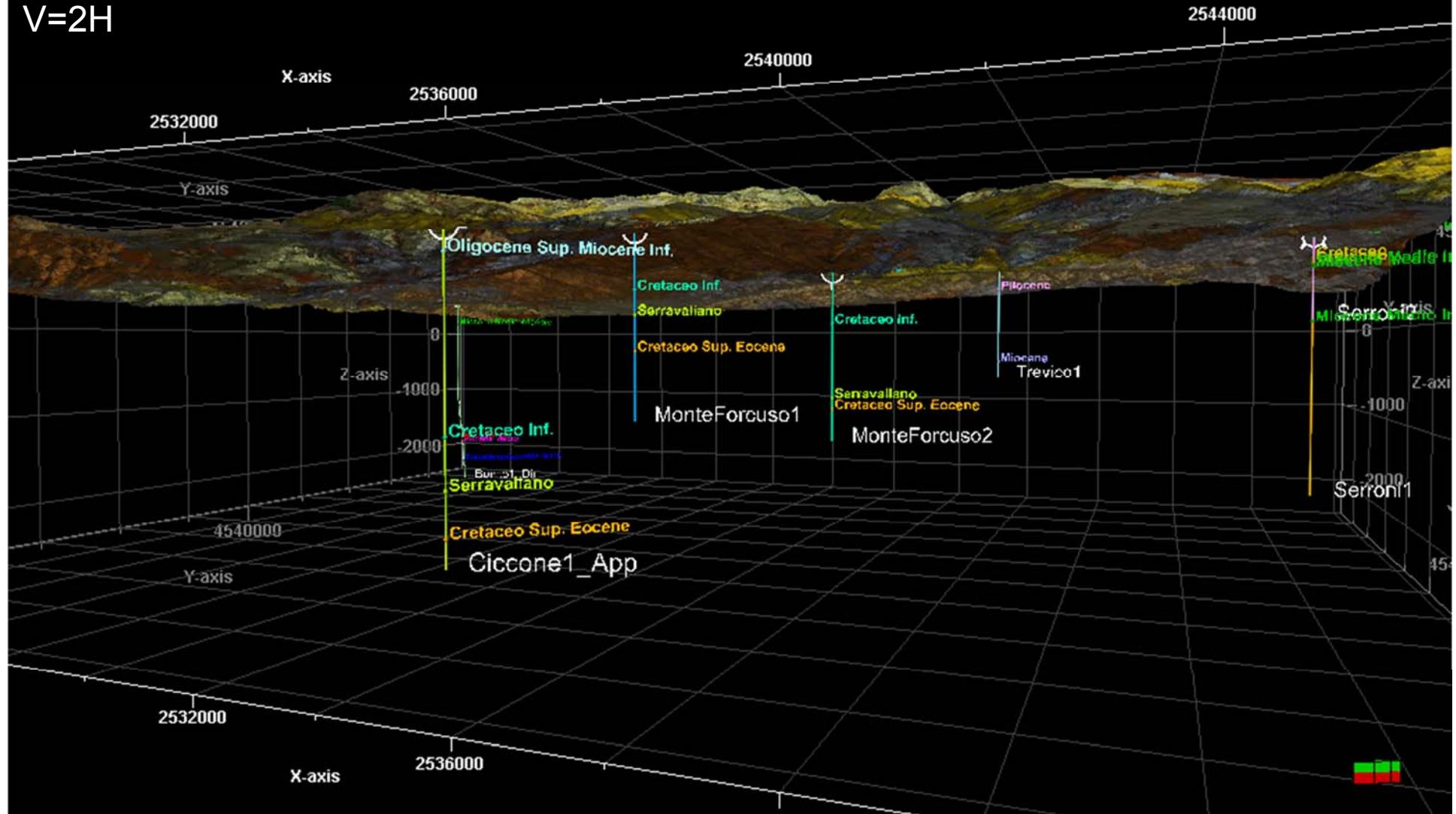
# DEM and Surface Geology





# Well Data: 3D View

Vertical Exageration  
 $V=2H$



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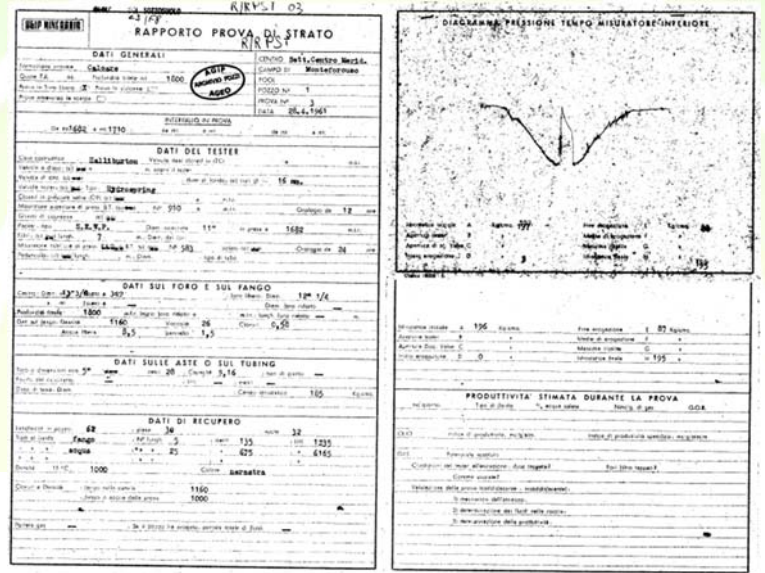
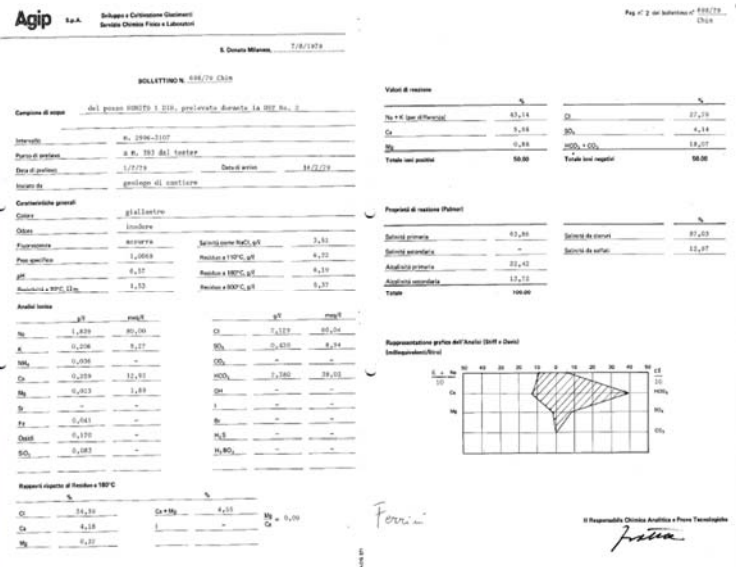
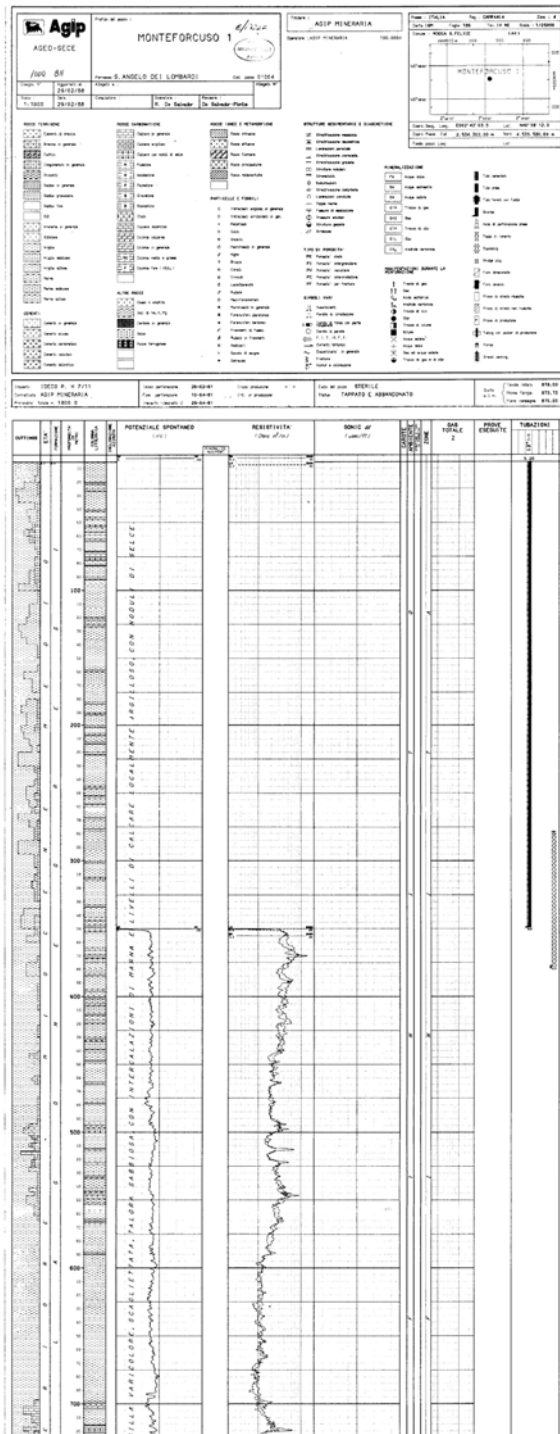
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# Available Well Data

- Composite Logs data
- Technical Reports
- Cores



# Monte Forcuso 1

Operatore: Anno Perforazione: Coordinate X: 2534302 TR: 879  
 Agip 1961 (Gauss Boaga Est) Y: 4535520 TD: 1800 PC: 875

Età	Unità	Carote	Colonna Stratigrafica	Profondità MD(m) SSL(m)	Mineralizzazioni	Assorbimenti & Perdite	Litologia	Descrizione Carote	Prove Eseguite	Temperature	Note
Cenozoico	Miocene	Miocene Superiore? - Pliocene Inferiore? Unità del Torrente Calaggio	<b>COPERTURE</b>	0 - 879			Argilla varicolore scagliettata con intercalazioni di marna e livelli di calcare				il sondaggio ubicato su un alto gravimetrico strutturale gravimetrico, aveva lo scopo di esplorare il substrato calcareo cretaceo. Il pozzo ha attraversato fino a 1128 metri attribuibili alle Formazioni Lagonegresi (Miocene medio-inferiore), costituiti da argille varicolori scagliettate, con livelli di Marna calcareo argilloso localmente con noduli di Selce ed Arenaria quarzo-feldspatica. Le formazioni attribuibili alla Piattaforma carbonatica Apulia interna, costituita da Calcari, Calcari Dolomiti e Dolomie, si estendono da 1128 a 1800 metri ed è attribuibile al Cretaceo Superiore da 1128 a 1500 ed al Cretaceo Inferiore da 1500 a 1800 metri. <b>Risultati Minerari</b> Dalle manifestazioni, dall'analisi dei log e dalle prove di strato il pozzo è risultato mineralizzato ad anidride carbonica nell'intervallo 1128 - 1600 m ed ad acqua dolce e tracce di anidride carbonica nell'intervallo 1600 - 1800 m
		Cretaceo Inferiore		Berrasio/Valangiano Unità Lagonegresi	550 - 785						
Miocene	Serravallo Unità Irpine	Piattaforma Apulia Interna	<b>RESERVOIR</b>	785 - 94			Arenaria quarzosa feldspatica con intercalazioni di marna e di argilla	Carota 1 881-882 m Manifestazioni: Nessuna			1133 - 1155 m Prova di Strato Risultato: CO2  1682 - 1710 m Prova di Strato Risultato: Acqua Dolce & CO2  BIT 75°C at 1778m
				249			Calcare nocciolato ricristallizzato talora dolomitico molto fratturato nella parte superiore	Carota 2 1051-1052 m Manifestazioni: Nessuna			
								Carota 3 1137,7 - 1139,3 m Manifestazioni: Tracce di bitume nelle fratture			
								Carota 4 1303 - 1305 m Manifestazioni: Nessuna			
								Carota 5 1488 - 1490 m Manifestazioni: Nessuna			
								Carota 6 1663 - 1664,4 m Manifestazioni: Nessuna			
								Carota 7 1790,3 - 1792 m Manifestazioni: Nessuna			
				1800 - 921			Wackestone/Packstone talora dolomitizzato alternato a dolomia a grana fine				

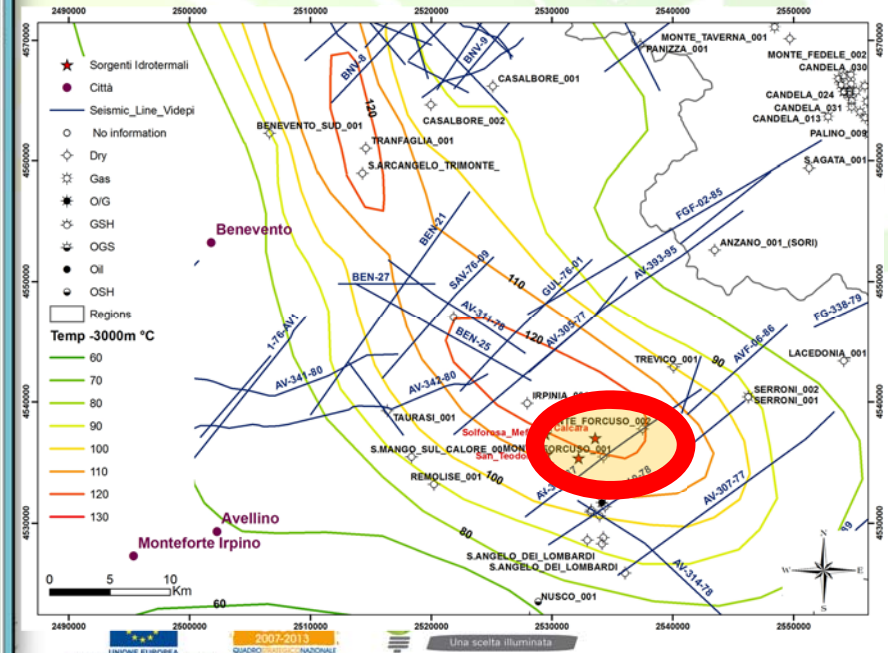
# Well Data Analysis: 1

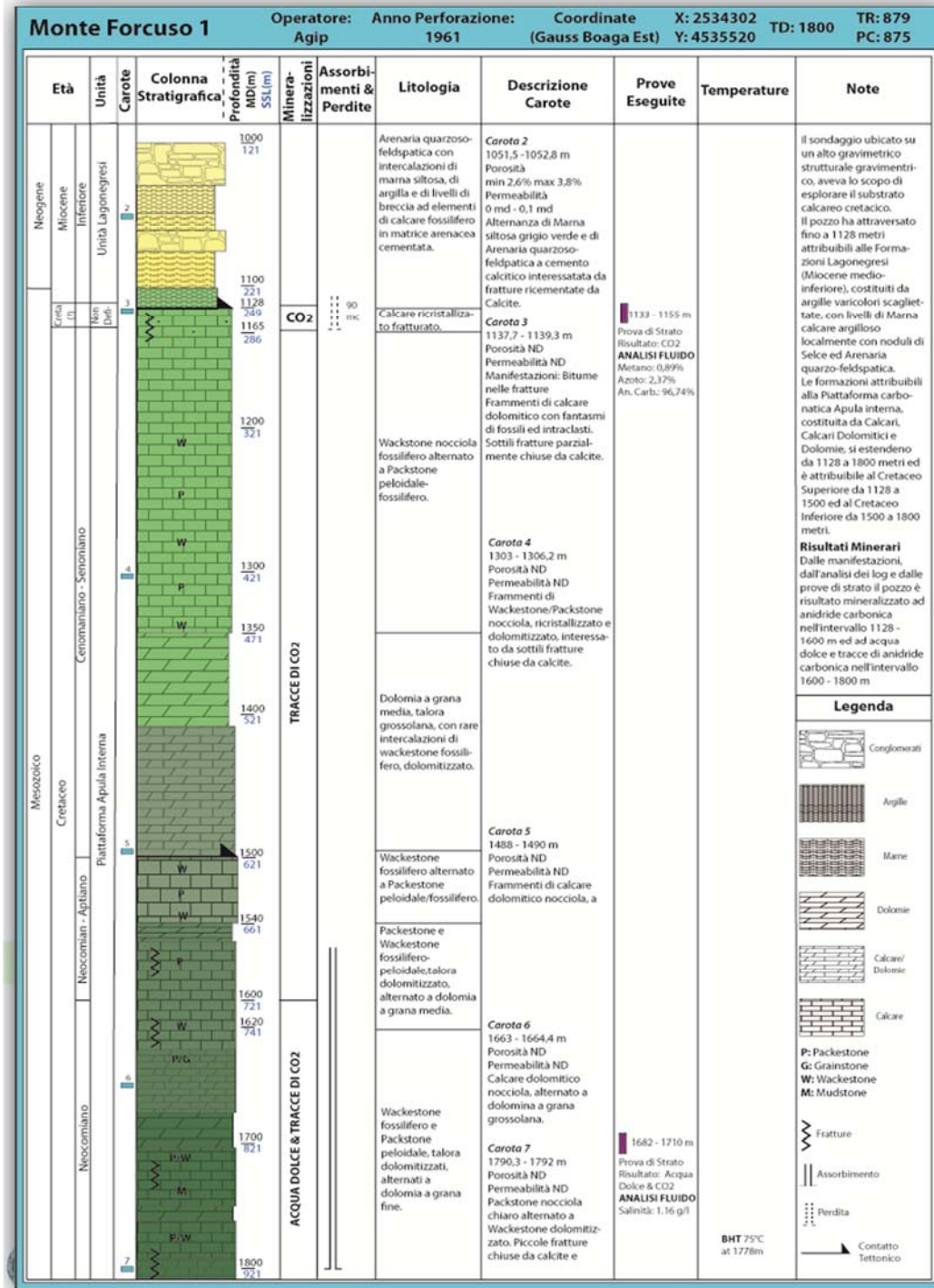
Main geothermal reservoir is made up by fractured carbonates, (Cretaceous-Eocene units of the Apulian shallow water carbonate platform )

Cap rock is formed by mainly shaly formations overlying the geothermal reservoir

**Legenda**

- Calcare/Dolomite
- Argille
- Marna
- P: Packstone
- G: Grainstone
- W: Wackestone
- M: Mudstone
- Fratture
- Assorbimento
- Perdita
- Contatto Tettonico

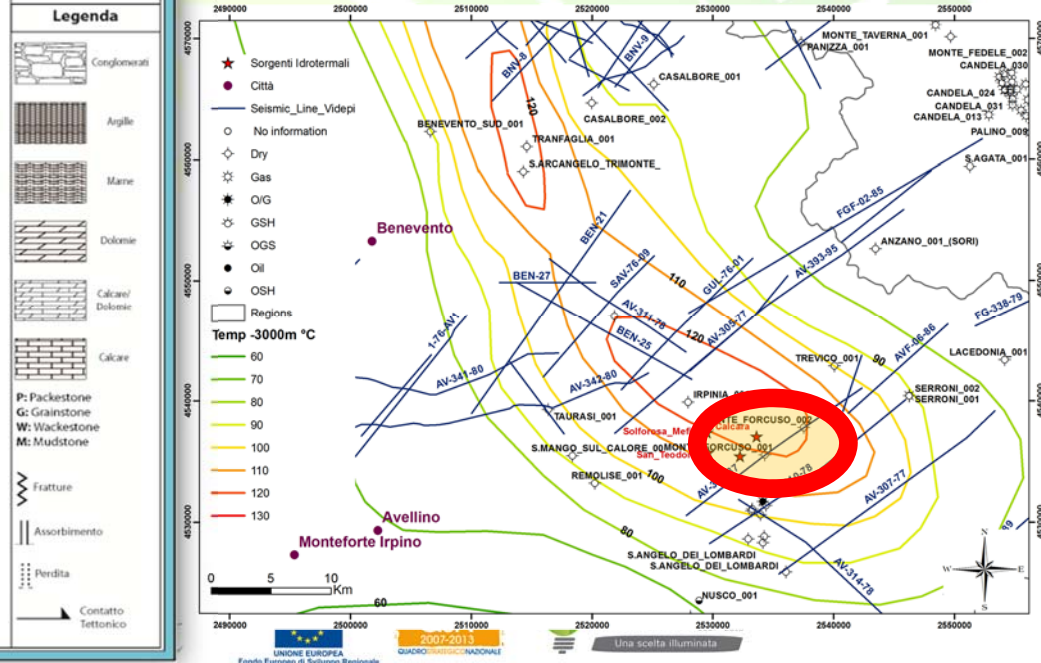




# Well Data Analysis: 2

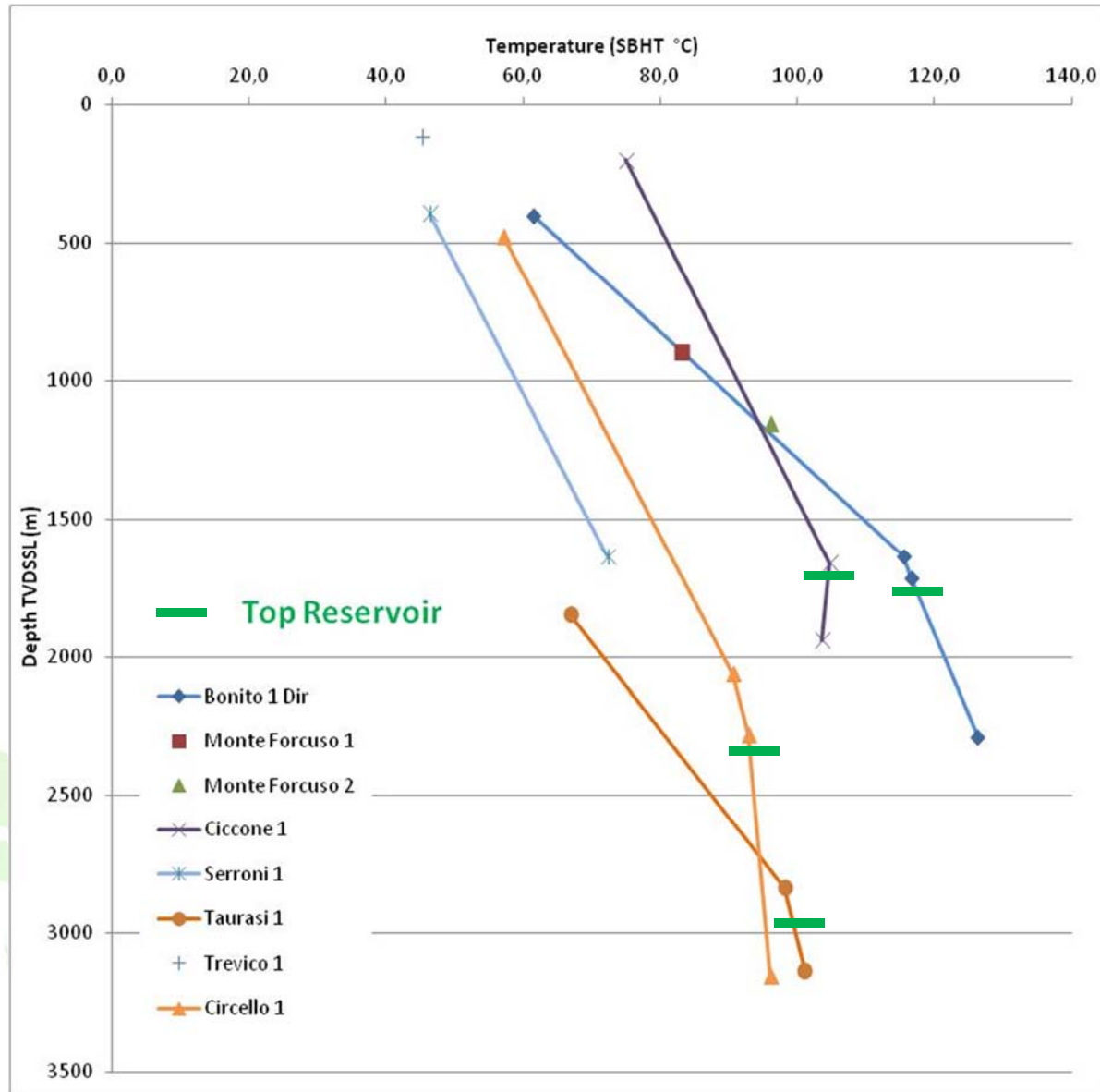
Well data analysis allowed the characterization of the geothermal reservoir

- Stratigraphy
- Temperatures (BHT and corrected SBHT)
- Logs (Resistivity, SP, GR)
- Cores
- Mud Losses
- Well test results
- Reservoir fluids





# Temperature



**Well Temperatures  
(SBHT vs TVDSS)**

**Up to 120-130 °C  
in Bonito 1Dir**

**Geothermometers  
on water samples  
collected from  
thermal springs:  
T reservoir 124°C  
(Duchi et al., 1995)**





# Cores

## ENI GEOLAB (Bolgiano)

3 well available (Monteforcuso 1, Monteforcuso 2 e Bonito 1 Dir)  
Total of 12 cores (16.4 m di recupero) :

### Main Goals:

- Facies and micofacies description
- Improve formation tops interpretation and well correlation
- Characterization of the recognisable fracture systems

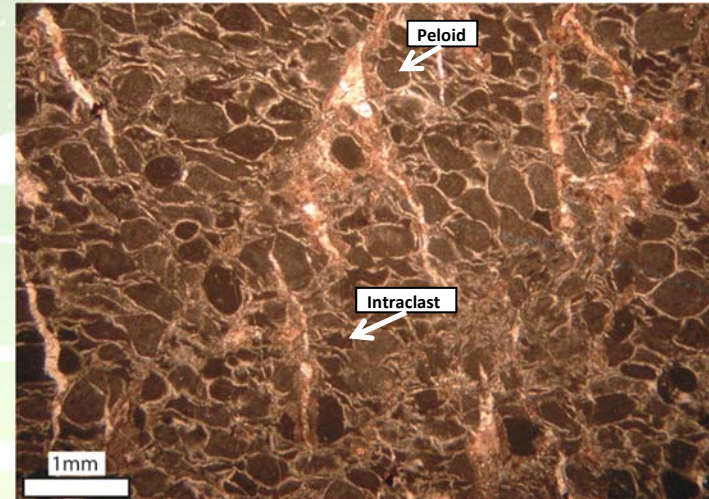
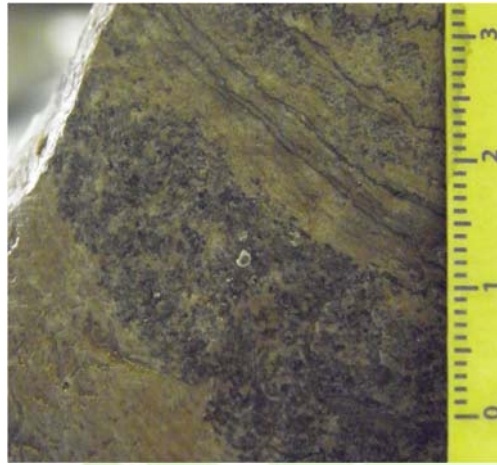




# Cores Facies Analysis

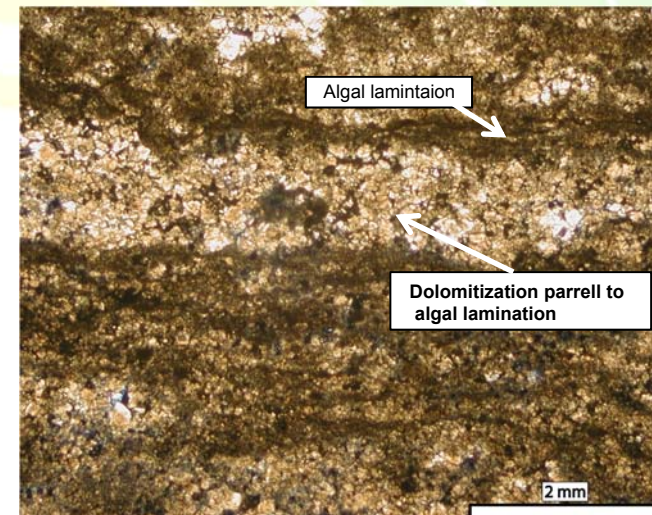
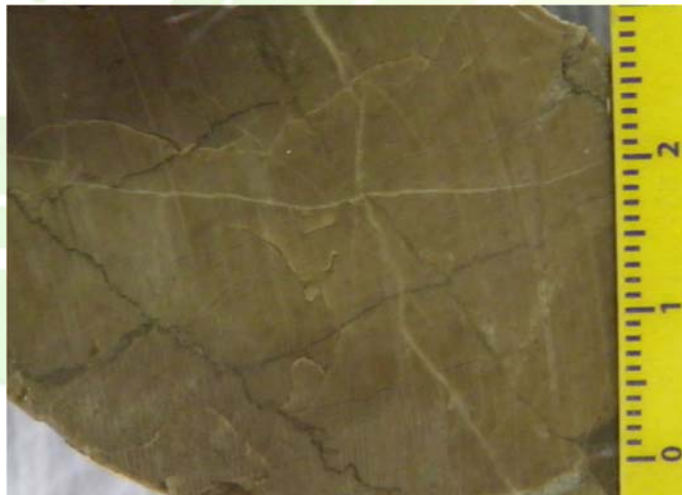
Monte Forcuso 1, Core 5 (1488-1490 m MD)

Shallow water Carbonate (grainstone i, Apulian Carbonate Platform, UpperCretaceous)



Monte Forcuso 1, Core 7 (1790,3-1792 m MD)

Shallow water Carbonate (Laminated bindstone, Apulian Carbonate Platform, Lower Cretaceous)

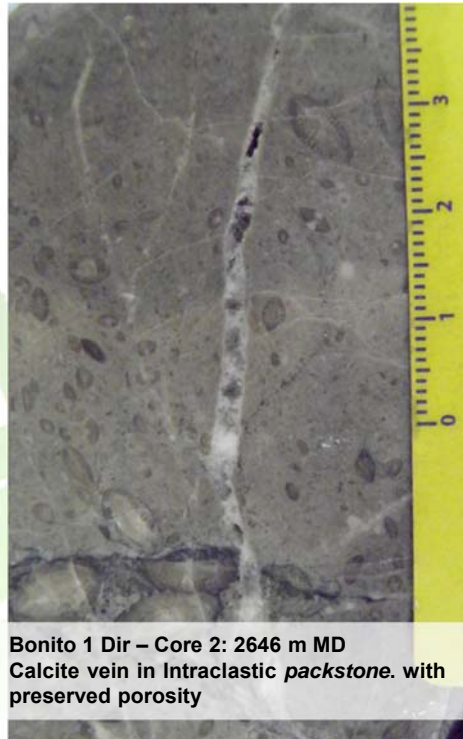




# Core Fractures



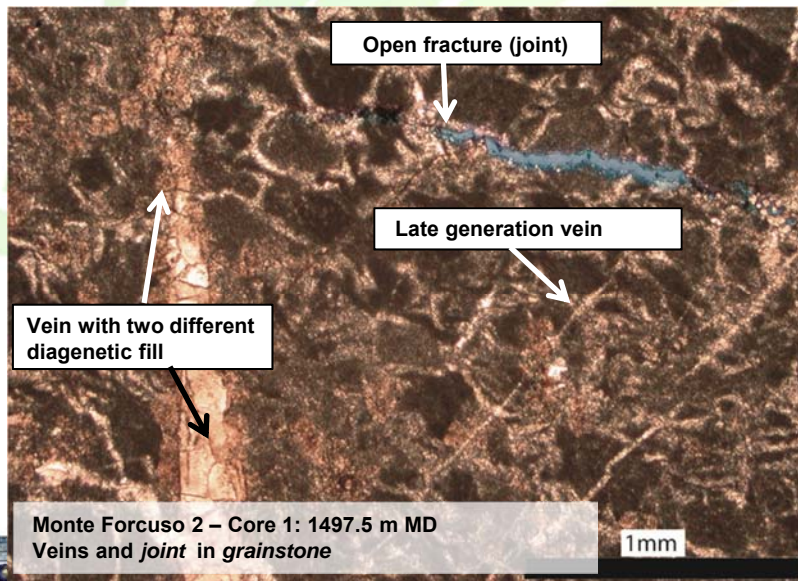
Bonito 1 Dir – Core 6: 3103 m MD (*mudstone – grainstone*)  
Low angle reverse fault with associated damage zone and kinematic indicators (Calcite steps and slickensides)



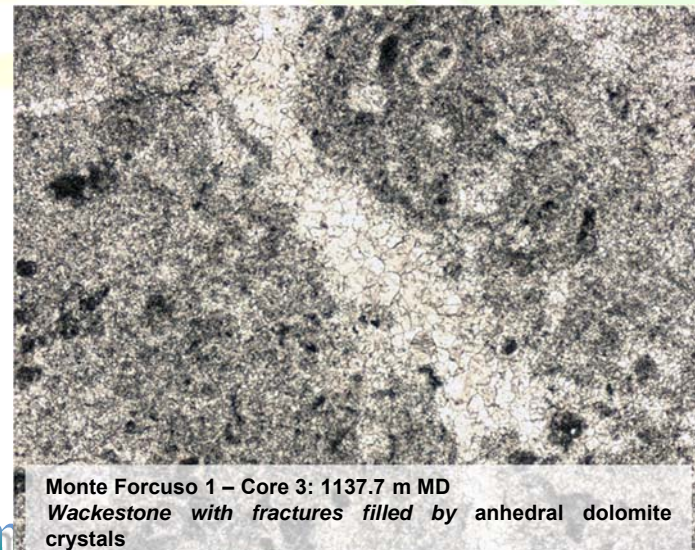
Bonito 1 Dir – Core 2: 2646 m MD  
Calcite vein in intraclastic *packstone*. with preserved porosity



Monte Forcuso 1 – Core 7: 1790.3 m MD  
Pressure solution seams, calcite veins and dolomitised zones (dark areas)

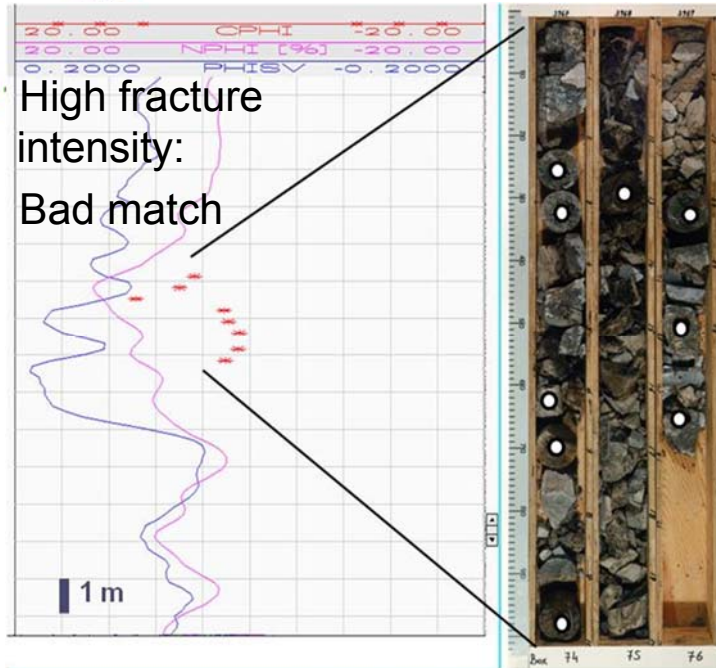


Monte Forcuso 2 – Core 1: 1497.5 m MD  
Veins and *joint* in *grainstone*

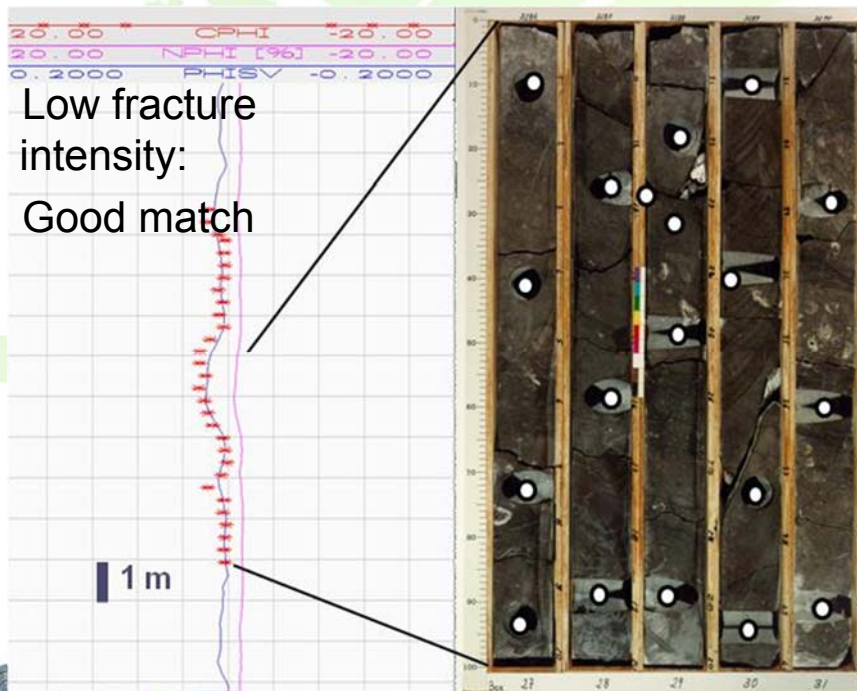


Monte Forcuso 1 – Core 3: 1137.7 m MD  
Wackestone with fractures filled by anhedral dolomite crystals

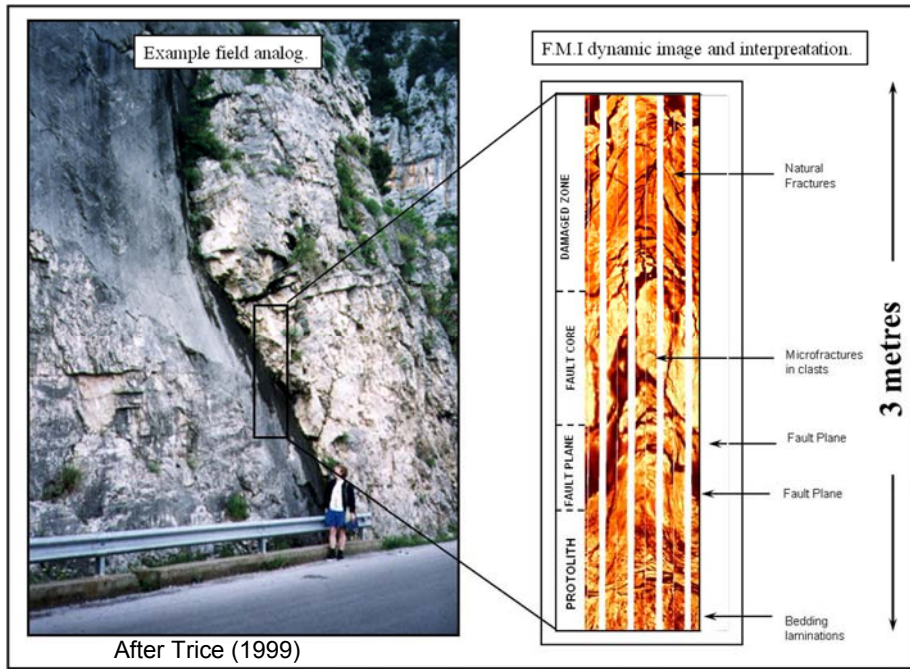
# Fractured Carbonates



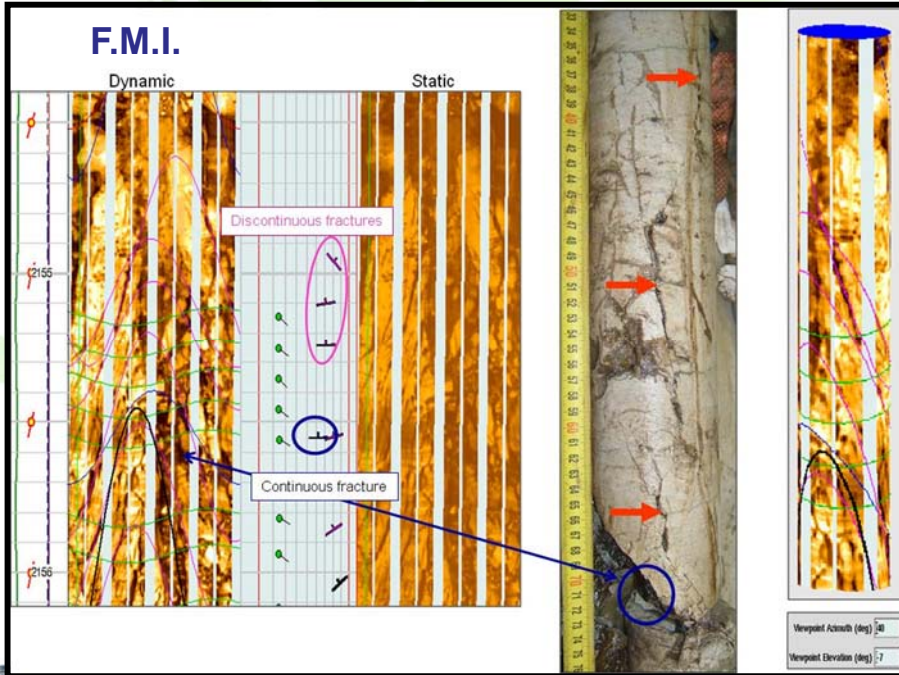
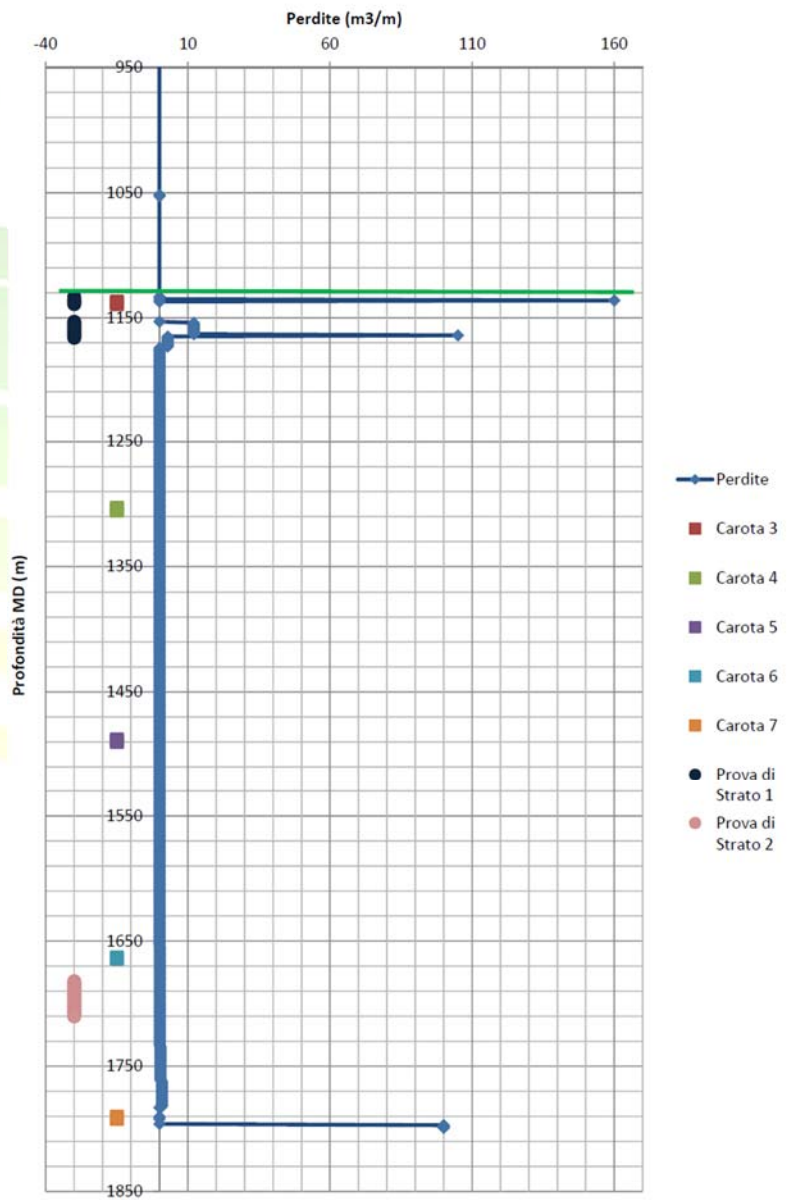
Porosity:  
Logs derived  
vs core measured



# Fractures Detection



## Perdite di Circolazione Monte Forcuso 1

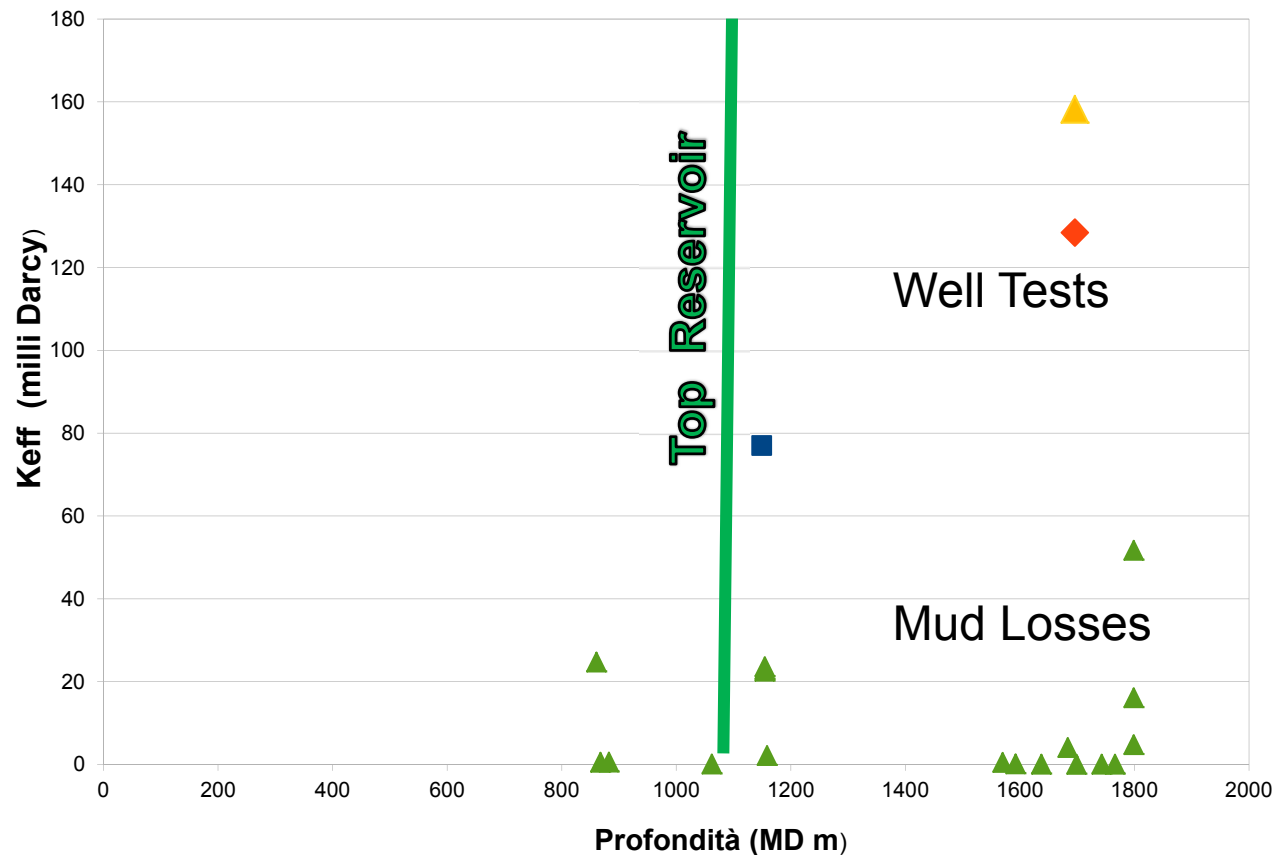




# Permeabilities

Analysis and interpretation of well test results, mud losses logs and core plugs measurements

## Pozzo Monte Forcuso 1



**Core Plugs:**  
Very low  
0.1-5 mD

**Mud Losses :**  
Generally 0.1-20 mD  
Up to 50 mD

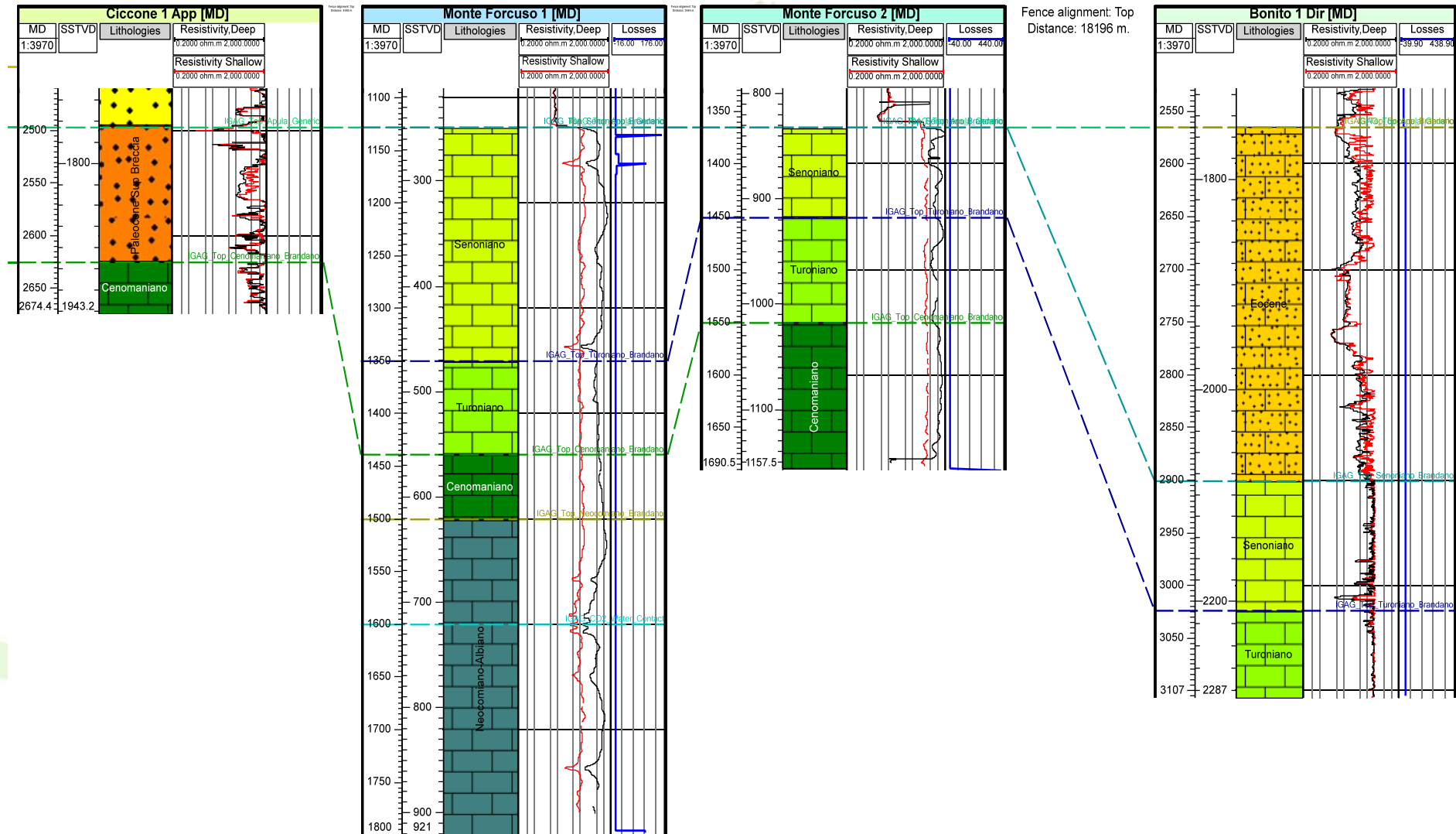
**Well Tests**  
Up to:  
140-160 mD (M. Forcuso 1)  
100-135 mD (Bonito 1 Dir)

**Low matrix permeabilities  
but fractured zones show  
significant permeabilities**



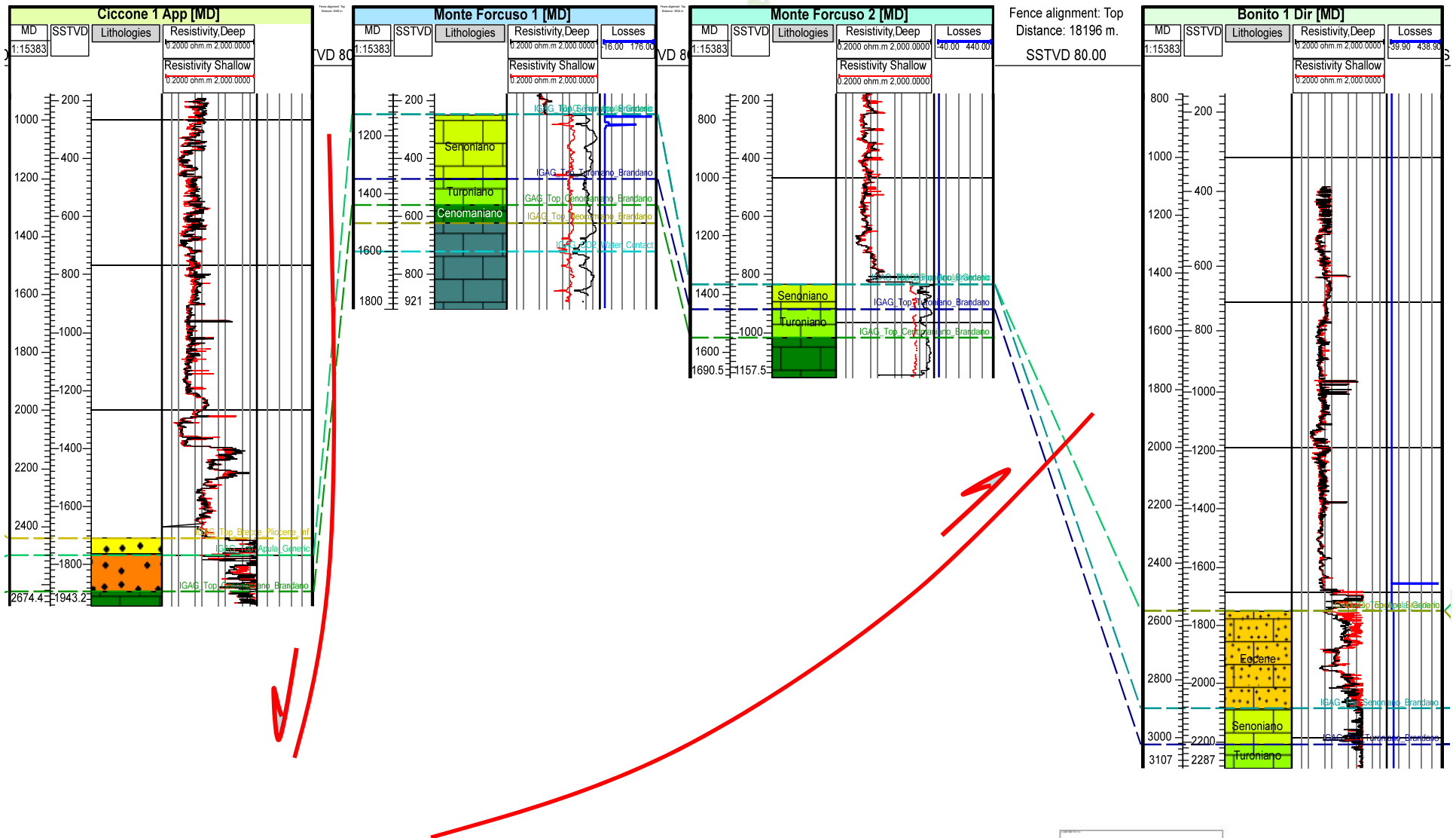


# Well Correlation: 1



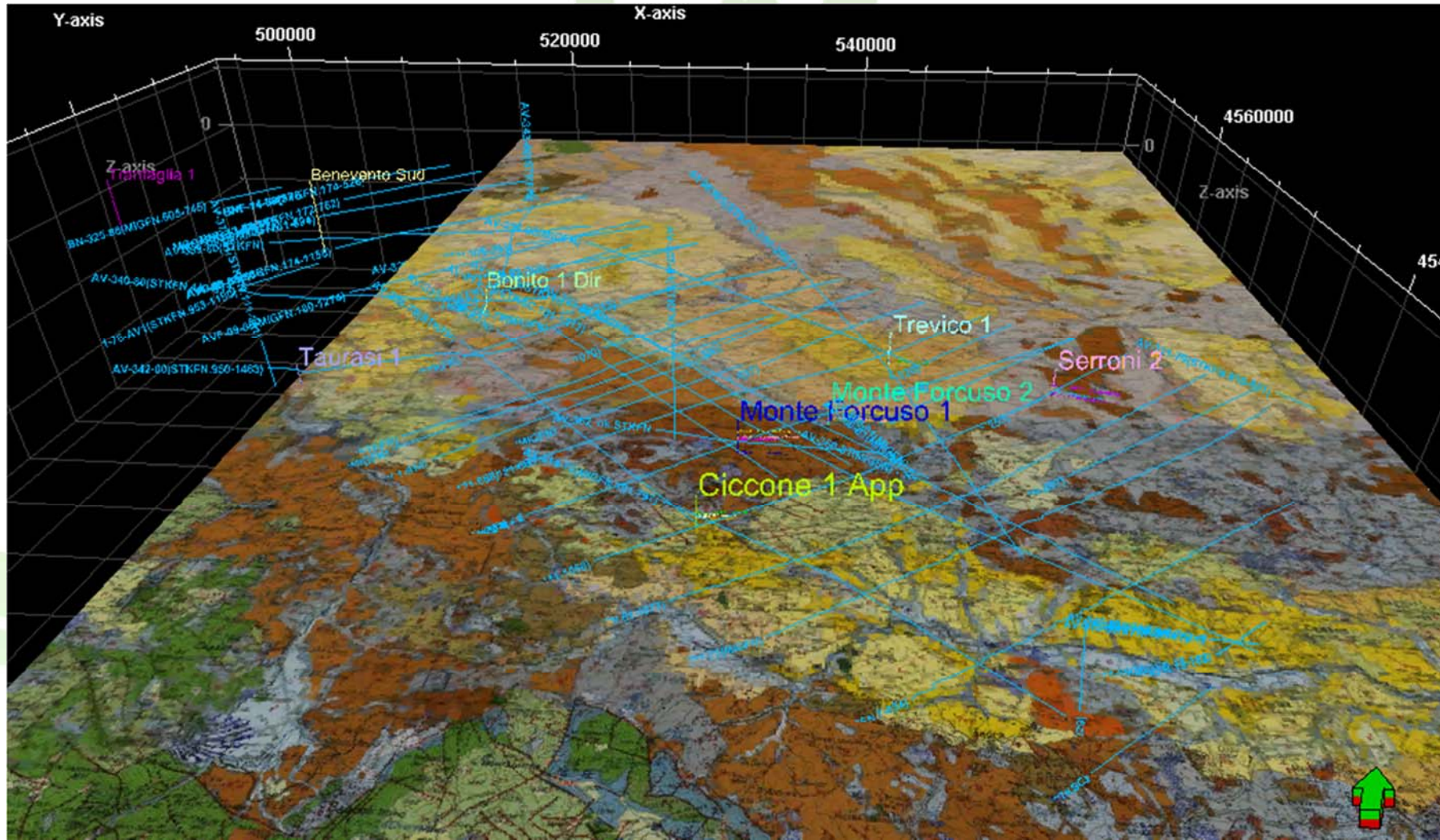


# Well Correlation: 2



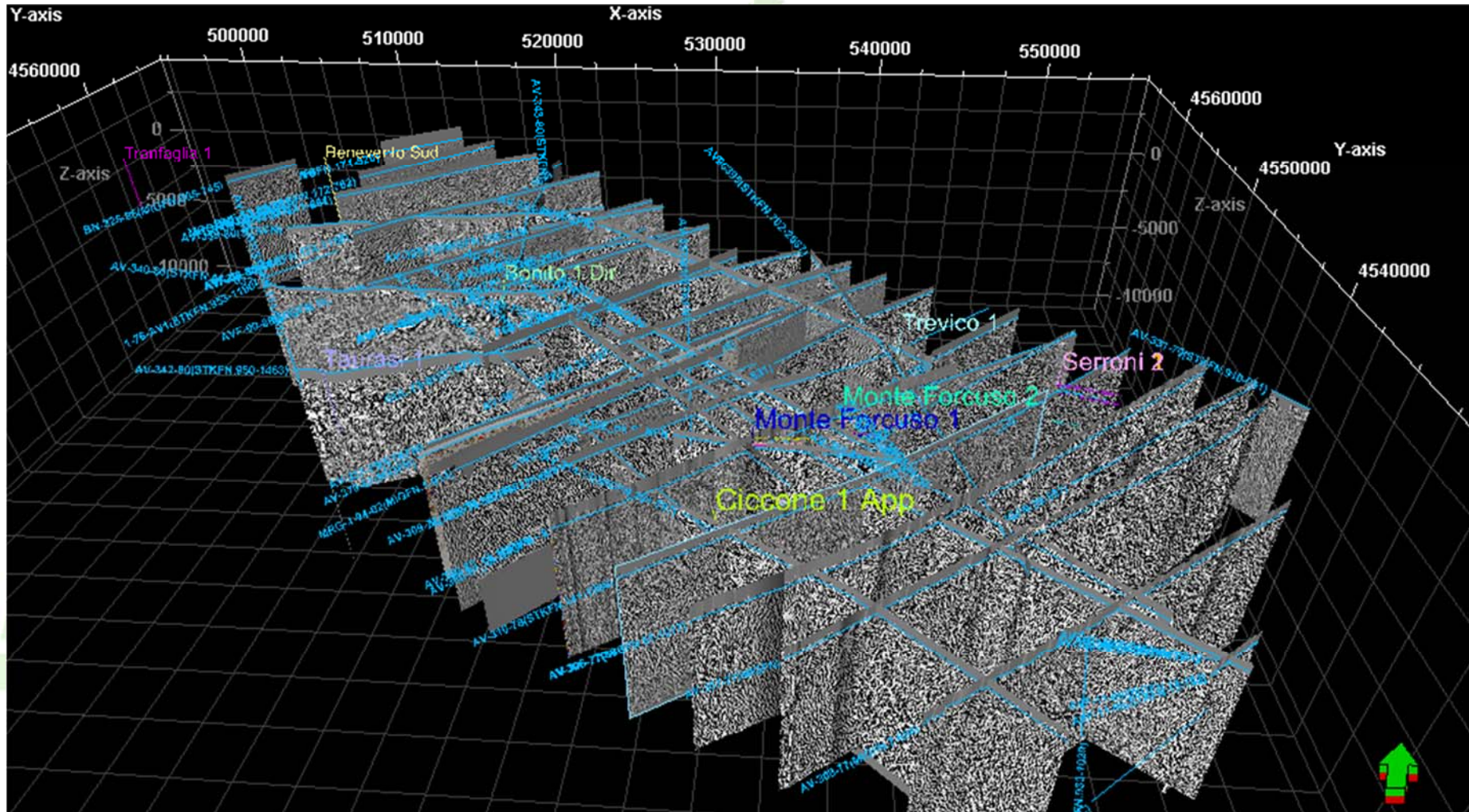


# Seismic Reflection Profiles: 1





# Seismic Reflection Profiles: 2

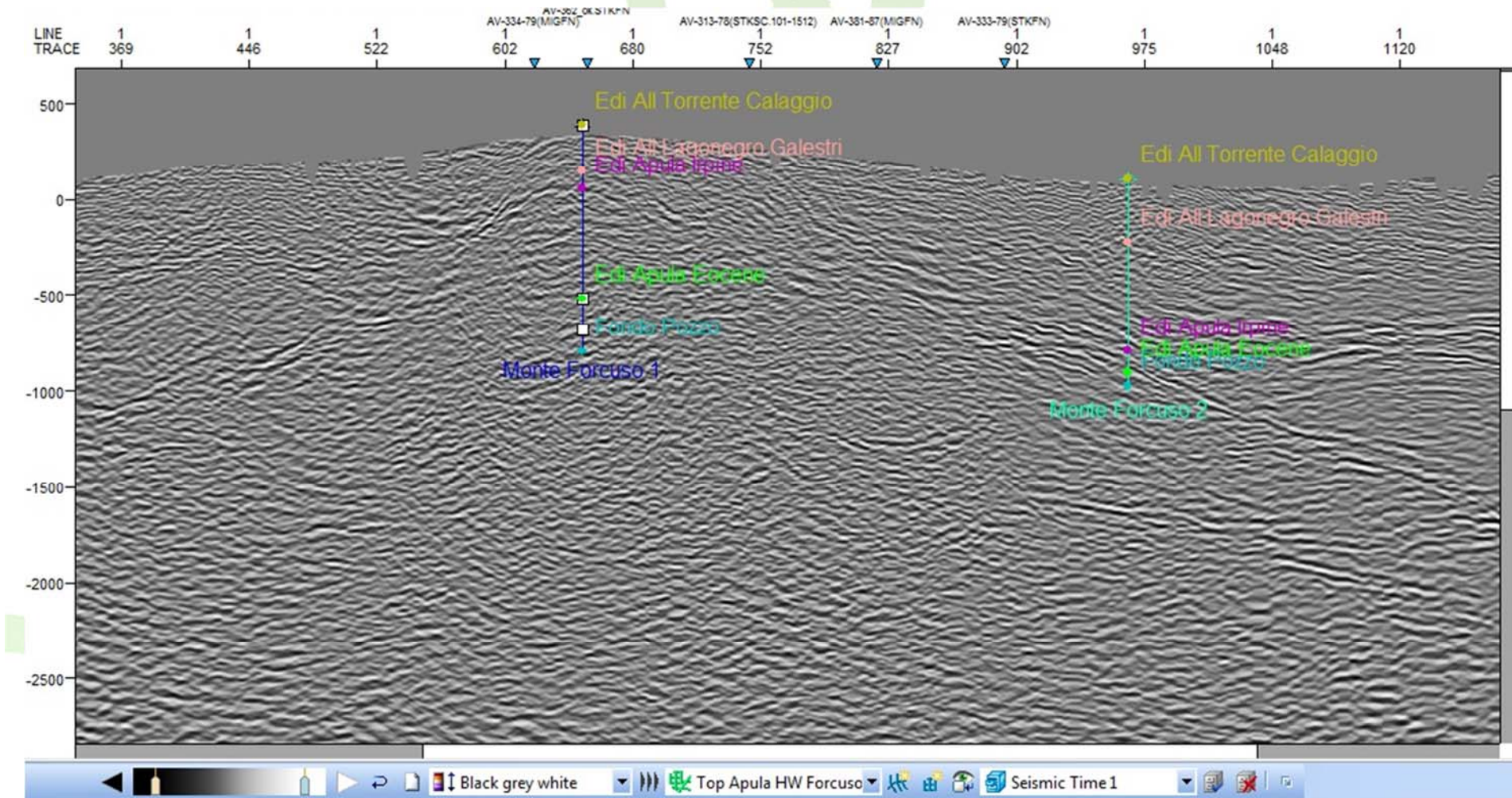






# Well Seismic Tie

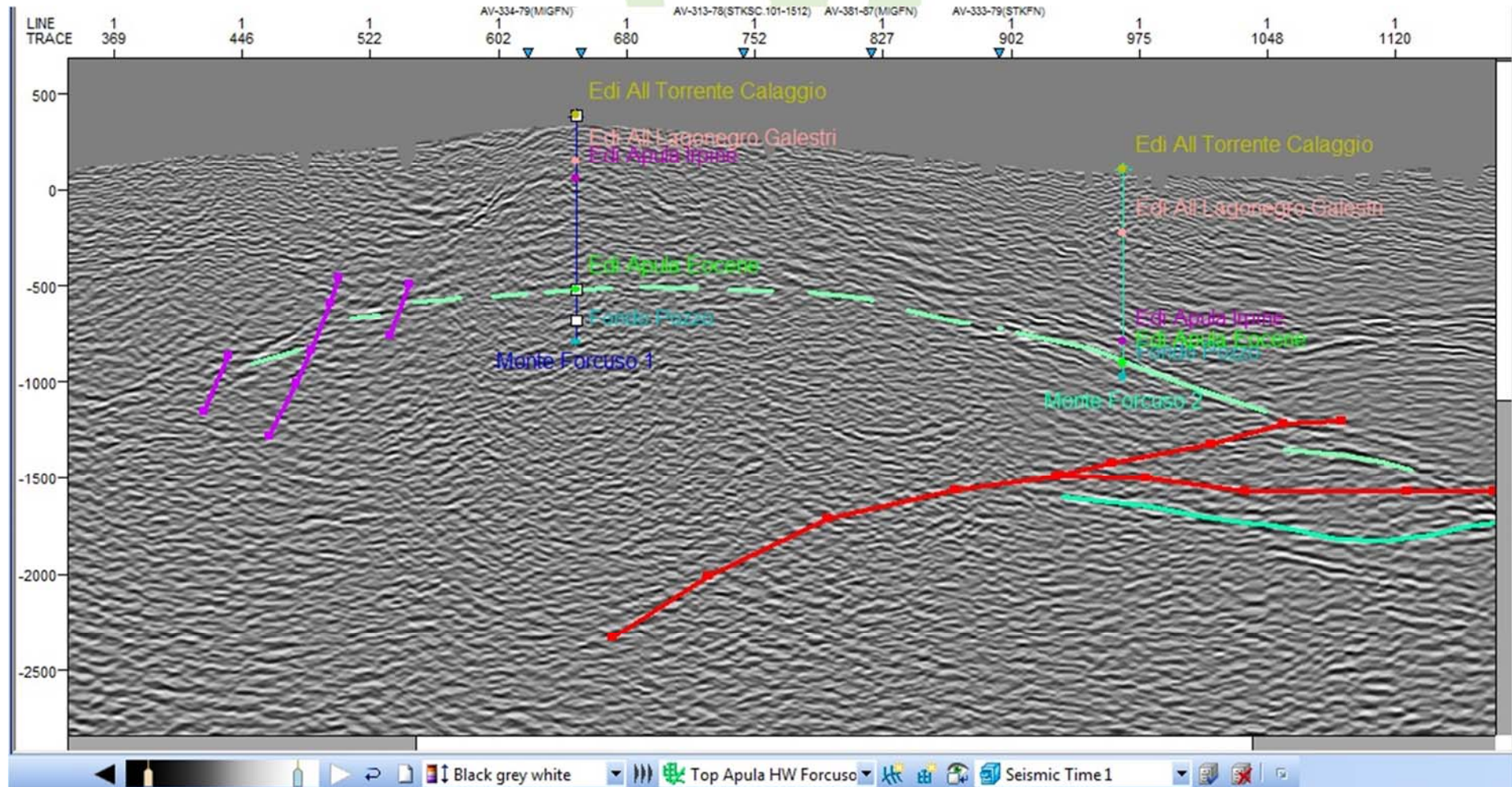
AV-380-87-MIG





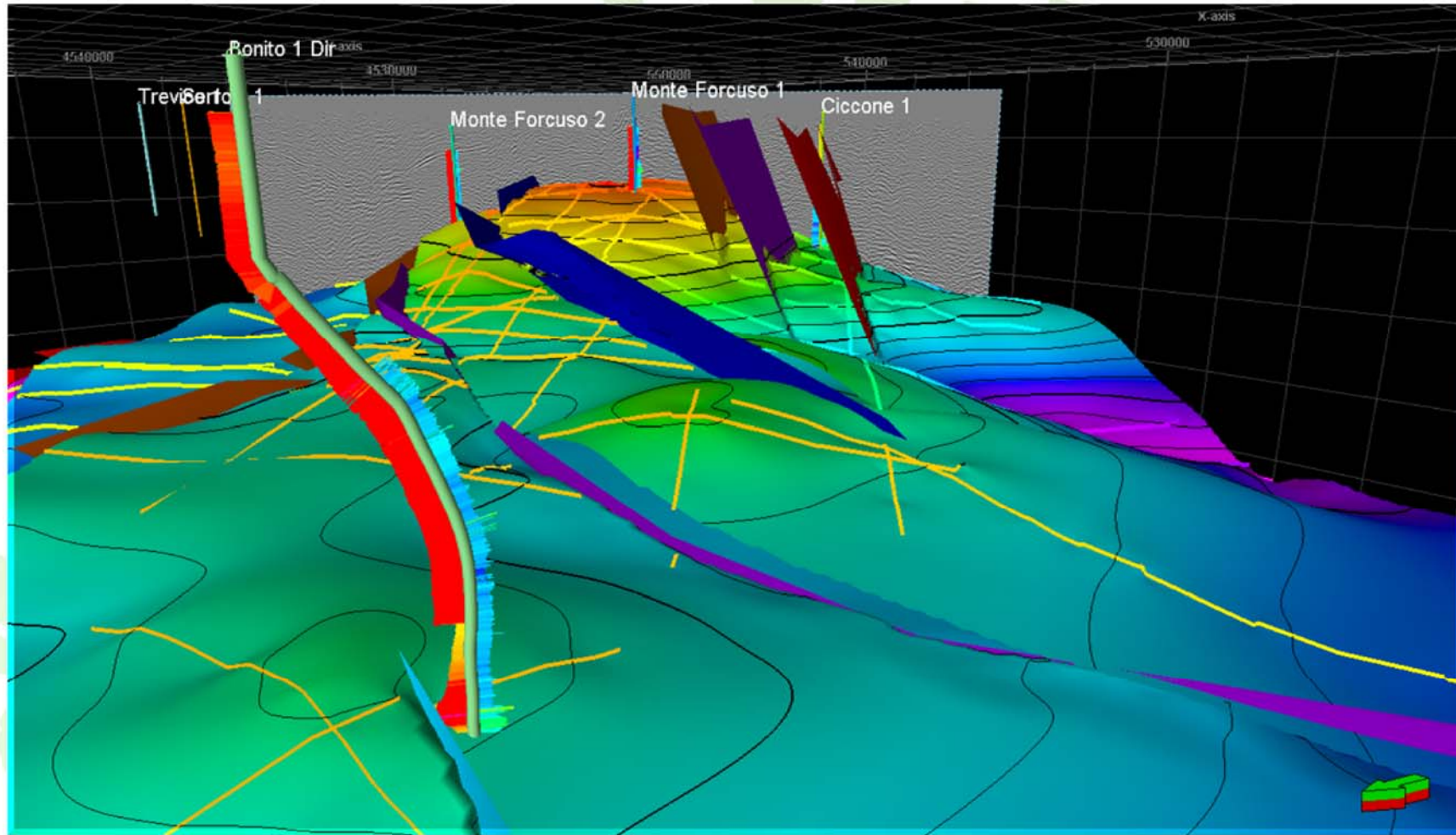
# Seismic Interpretation: an Example

AV-380-87-MIG





# 3D Geological Model



Consiglio Nazionale delle Ricerche  
Dipartimento Terra e Ambiente

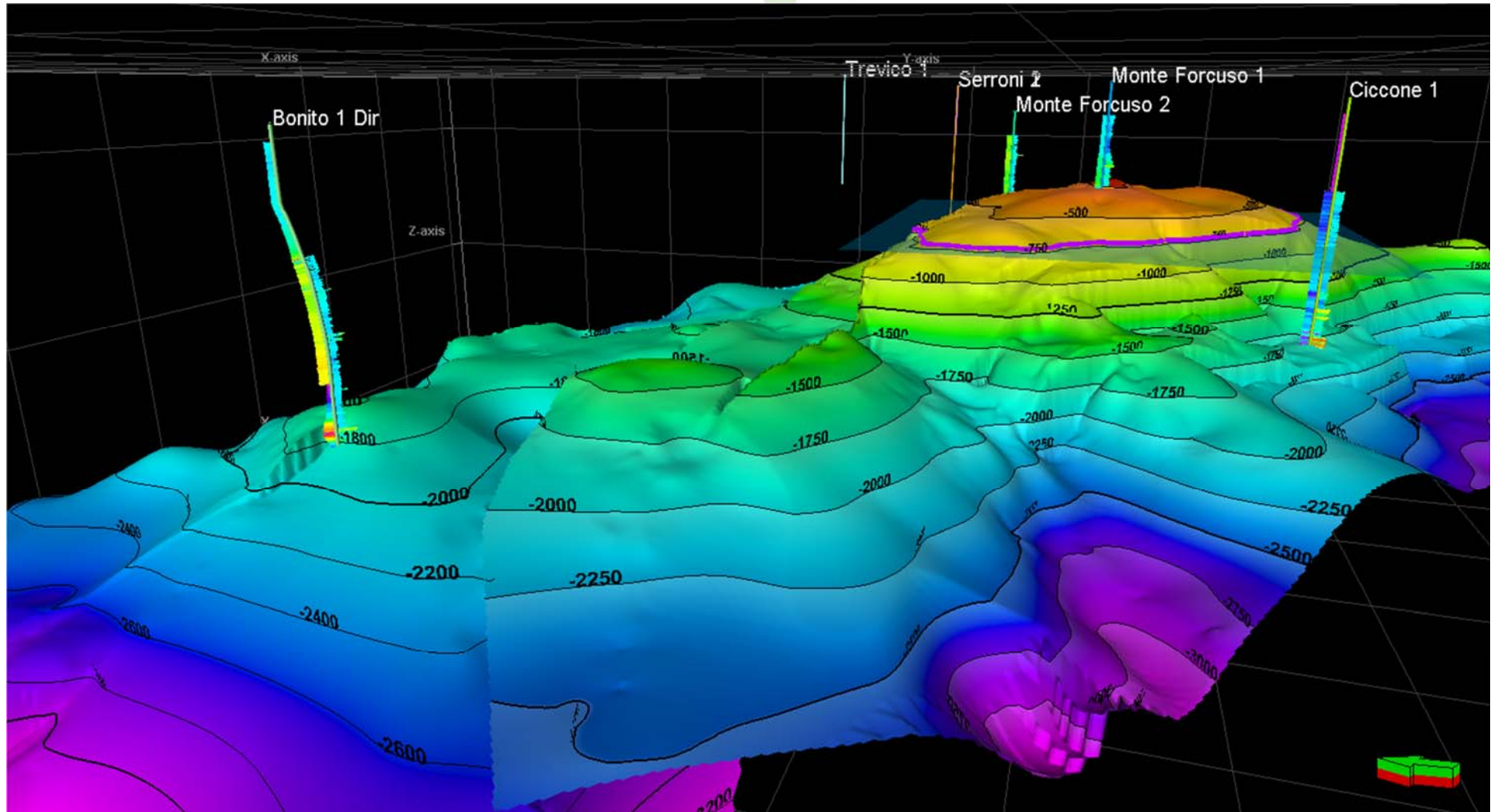
[www.vigor-geotermia.it](http://www.vigor-geotermia.it)



Programma Operativo Interregionale  
ENERGIE RINNOVABILI E  
RISPARMIO ENERGETICO  
2007-2013  
Una scelta illuminata

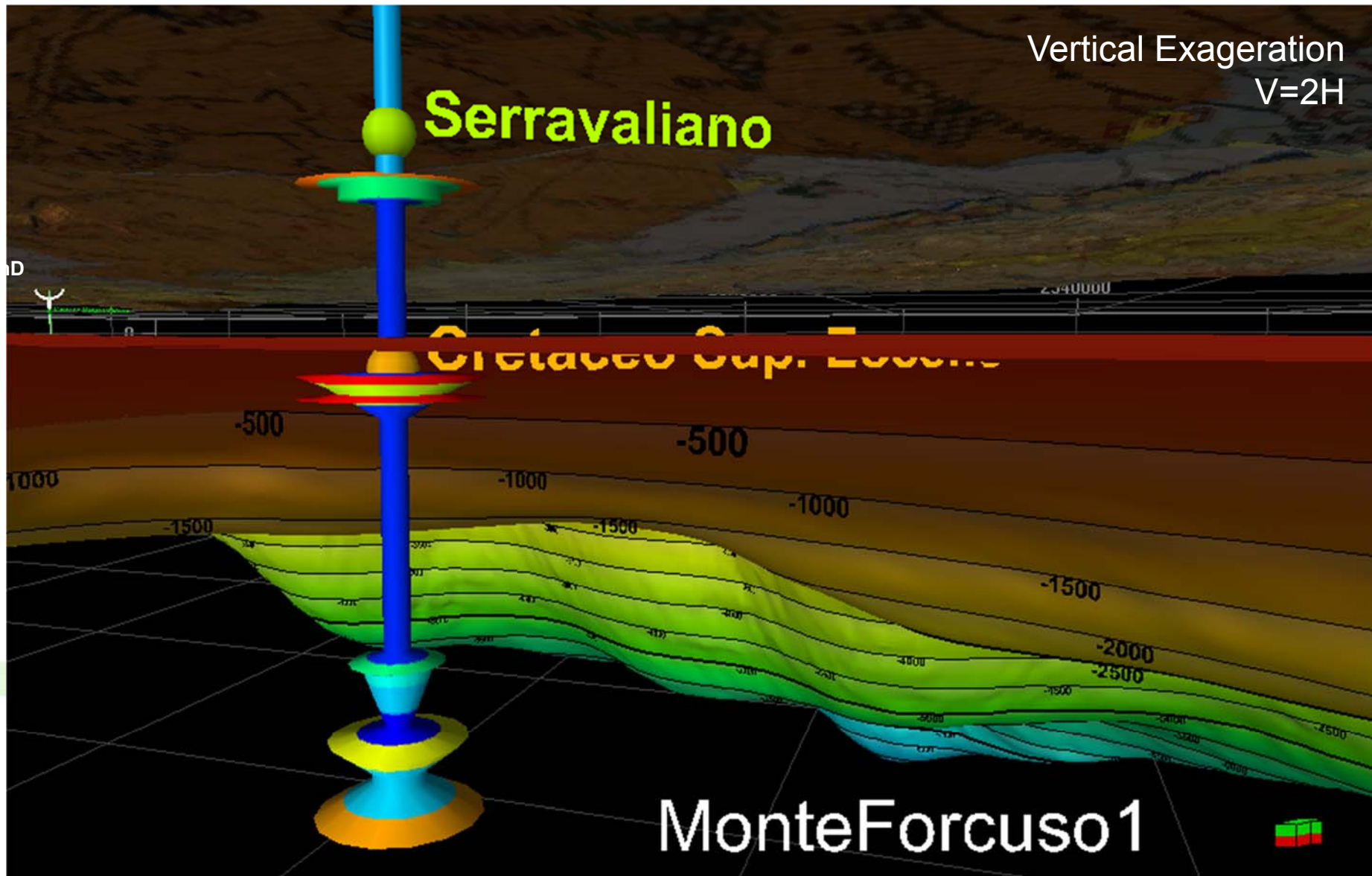


# 3D Model: Top Reservoir (m SSL)

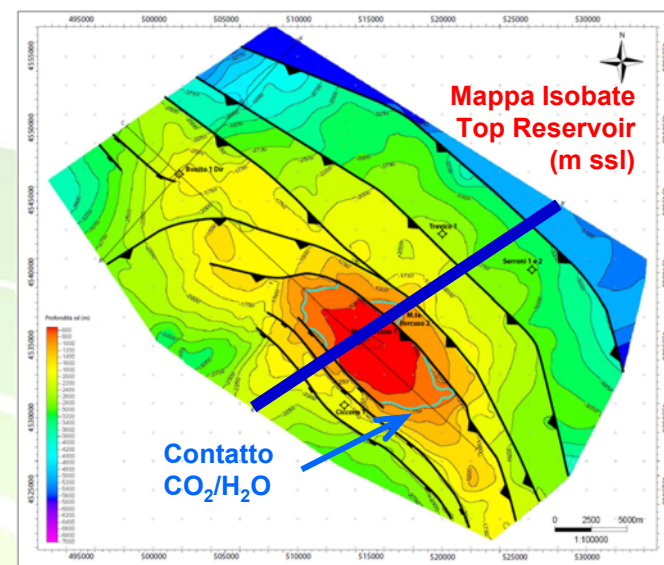
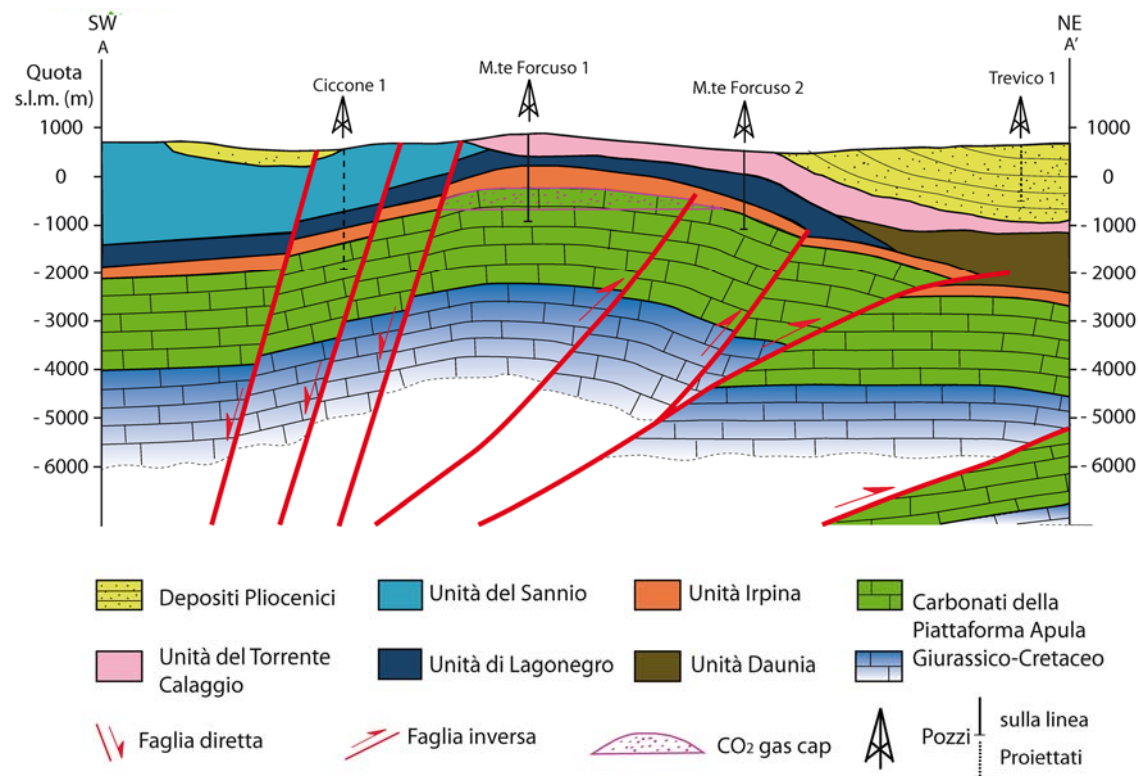




# Permeability Log



# Conceptual Model



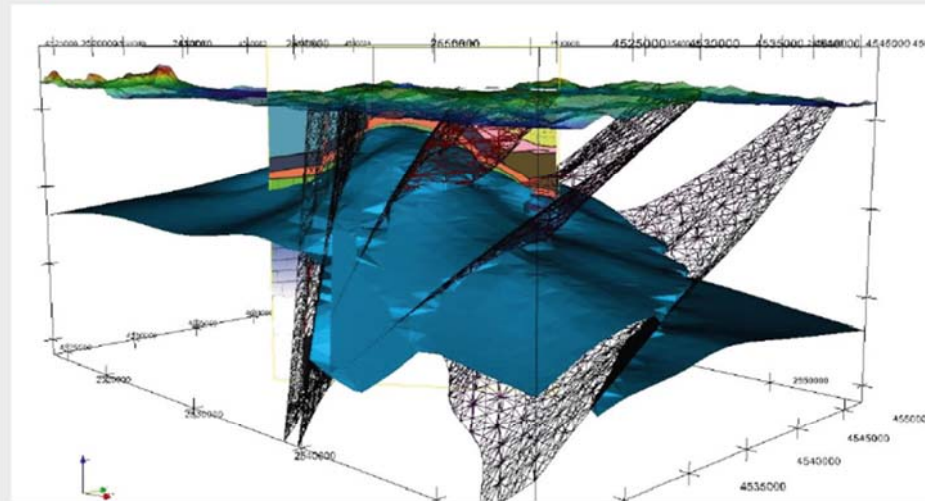
- Structural setting: buried thrust-related folds developed during the Apennine orogenesis in Pliocene times offset by extensional faults during Pleistocene times
- Main geothermal reservoir: shallow water, fractured, carbonates (Cretaceous-Eocene)
- Permeabilities: about 100-150 mD (fracture systems)
- Top reservoir depth: from about -250 m below the sea level (about -1125 m below the ground level) in Monte Forcuso 1 well to about -1750 m below the sea level (about -2315 m below the ground level) in Bonito 1 Dir well
- Temperature of about 120°C at depth of about -2000 m below sea level may be expected
- Reservoir fluids, in the central and upper part of the structural culmination (i.e., Monte Forcuso 1 well) mainly CO<sub>2</sub>, (gas cap about 470-500 thick) which rests above an accumulation of brackish water. Along the flanks of the buried anticline (e.g., Bonito 1 Dir, Ciccone 1 wells), the reservoir fluid do not show a free gas phase but only saline water
- Flow rates :variable from 10 l/m (Bonito 1dir) to 95 l/m (Ciccone 1) to a maximum of 205 l/m (Monte Forcuso 1)





# 3D MODELLING

## 2) Structural Model

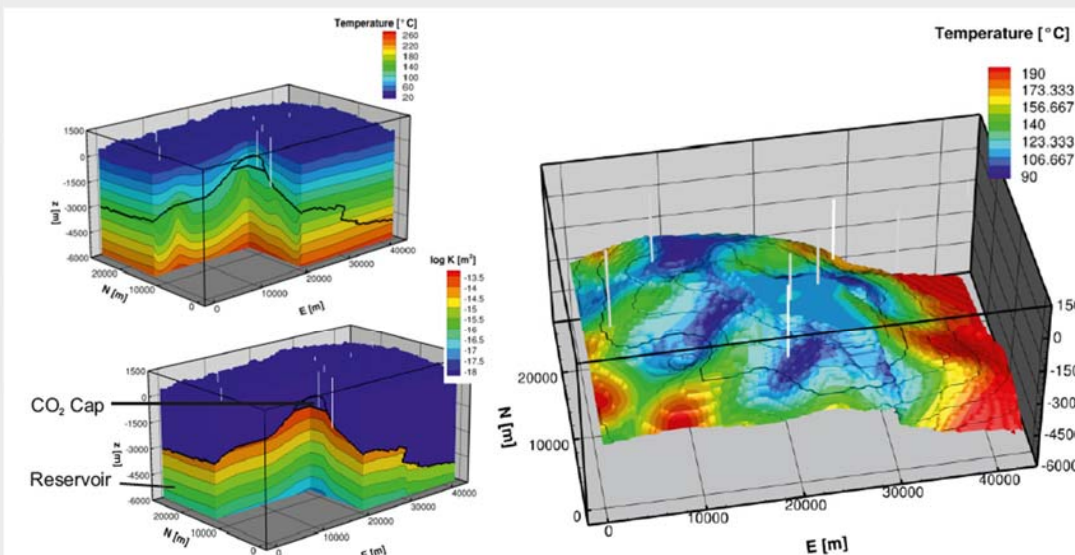


Based on Information from seismic profiles and composite well logs, we created a structural model comprising two major units:

- a) Reservoir Unit** which consists of Jurassic to Cretaceous shallow water carbonates, which were folded, faulted, and fractured during accretion of the southern Apennines.
- b) Sedimentary Cover** comprising mostly flysh-like and pelagic sediments with relatively low permeability.

## 3) Reservoir Model Simulation Results

Niederrau et al. (2015)



Permeability decreases as a function of depth and reservoir geometry, reflecting fracture closure with increasing overburden pressure. Transient hydrothermal simulations yield free convection in the carbonate reservoir unit. Distinct zones of upflow are controlled by the reservoir structure. A stable upflow region forms under the CO<sub>2</sub> cap, where the reservoir is thickest.

