

# The National Geothermal Resource Assessment of LEBANON

February 2014

## Copyright © UNDP/CEDRO 2014

Reproduction is authorized provided the source is acknowledged and provided the reproduction is not sold.

The United Nations Development Programme (UNDP) is the UN's global development network, advocating for change and connecting countries to knowledge, experience and resources to help people build a better life. We are on the ground in 166 countries, working with them on their own solutions to global and national development challenges. As they develop local capacity, they draw on the people of UNDP and our wide range of partners.

For more information:  
United Nations Development Programme  
[www.lb.undp.org.lb](http://www.lb.undp.org.lb)

CEDRO  
[www.cedro-undp.org](http://www.cedro-undp.org)

Note: The information contained within this document has been developed within a specific scope, and might be updated in the future.

## Acknowledgments

The United Nations Development Programme (UNDP) would like to thank both the Government of Spain for its generous donation that enabled the CE-DRO project to be realized, and the Lebanon Recovery Fund) LRF (through which this funding was approved and channeled. CEDRO would also like to thank all its partners including the Ministry of Energy and Water, the Ministry of Economy and Trade, the Council of Development and Reconstruction, the Lebanese Center for Energy Conservation (LCEC), and all other institutions that work closely with this project.

This report has been prepared by Geowatt AG Resources and Poyry for the UNDP-CEDRO Project

## Main Authors

**Dr. Vincent Badoux, Dr. Dieter Ollinger, Dr. Clément Baujard and  
Dr. Thom-as Mégel,**  
GEOWATT AG, Zürich, Switzerland

## Contributing Authors

**Mrs Roula Abou Chabke, Kobeissi & Frangié,**  
Attorney in Law, Beirut, Lebanon, for the legal aspects.

**MM. Arnaud Gilliéron, Dr. Robert Zwahlen and Dr. Fred Laufer,**  
POYRY Energy, Zürich, Switzerland, for the contribution to the Environmental,  
Power Plant technologies and financial aspects.

## Reviewers

**Mr. Karim Osseiran,**  
Power Generation Advisor, Ministry of Energy and Wa-ter

**Dr. Fadi Nader,**  
Geology Department; Geosciences Division, IFP Energies Nouvelles

**Mr. Ziad Khayat,**  
UNDP Project Manager, Water Center for Energy Management and Conservation

**Dr. Hassan Harajli,**  
UNDP-CEDRO Project Manager



## Report Contributors

**Mr. Richard Sarkis and Mr. Sassine Abou-Jaoude,**  
ENGICON Consulting, Beirut, Lebanon, for the local assistance as well as for the field temperature measurements;

**Dr. U. Schärli,**  
Geologie & Geophysik, Zürich, Switzerland, for the rock thermal conductivity measurements;

**Mr. Rachad Ghanem,**  
ELARD, Beirut, Lebanon, for the inspection visits of for temperature investigations in the deep O&G boreholes;

**Mrs. Chloé Asmar,**  
American University of Beirut, for the field rock samples and her colleagues;

**Mrs. Janine Somma,**  
Université St. Joseph, Beirut, Lebanon, for the field trip on the Mount Lebanon and the important discussions on karst development and groundwater vulnerability in Lebanon, and her team;

**Mrs. Roula Abou Chabke,**  
from the Cabinet Kobeissi & Frangié for the redaction of the legal aspects;

**MM. Arnaud Gilliéron, Dr. Robert Zwahlen and Dr. Fred Laufer and Peter Fischer,**  
from POYRY Energy, Zürich, Switzerland, for the contribution to the Environmental, Power Plant technologies and financial aspects;

**Mr. Abed F. Muriby,**  
WILDCAT Oilfields solutions, for his help for visiting the Summaquieh well in the Akkar region as well as for the advice in terms of deep borehole technologies;

**His Excellency Talal Baik Merehbi,**  
for the crucial documentation regarding the Summaquieh well in the Akkar region;

**Dr. Werner Leu,**  
Geoform Switzerland, for advices with deep boreholes investi-gations;

**Professor Mohamad Harajli,**  
for the fruitful information related to the seismic risk in Lebanon;

**Dr. Alexandre Sursock,**  
National Council for Scientific Research in Lebanon - Director of National Centre for Geophysics;

**Mr. Claudio Pajarola,**  
ESRI, Zürich, Switzerland, for the review of the GIS aspects of the project;

**Mr. Bassem el Hage,**  
for Arabic translation of the Executive Summary;

**Dr. Souad Sellami,**  
in Switzerland, for her support in Arabic translation.

# Foreword to the National Geothermal Atlas Resource Assessment Study - Ministry of Energy and Water

The challenges of the Lebanese Electricity sector are not limited to meet the Energy demand through the timely increase of the installed generation capacity but also to enhance a diversified mix of energy sources in which the sustainable Renewable Energies play a major role. In line with the 'Policy Paper for the Electricity Sector' approved by the Lebanese Council of Ministers in 2010, the Ministry of Energy and Water is investing all needed efforts to ensure that the 12% of the electricity production in 2020 is based on renewable energy sources.

In this regard, the Ministry of Energy and Water has investigated most types of renewable energy sources available in the country. With the support of the UNDP-CEDRO project, the national wind atlas for Lebanon was published in 2010. The efforts of the CEDRO project were also instrumental in the development of the national bioenergy strategy for Lebanon, as well as the potential for hydro power, solar energy & waste to energy from the waste water treatment plants sludge.

This current report has assessed a new untapped stream of renewable energy which is the Geothermal energy. In contrary to other renewable energy technologies, geothermal energy delivers constant and reliable power not subjected to variations of the meteorological conditions. Geothermal energy is also considered as unlimited and produces almost no CO<sub>2</sub> emissions. The geothermal resources have been assessed by collecting all the relevant geological, hydrogeological, structural and thermal information available for Lebanon and developing a 3D geological and geothermal model of Lebanon to calculate the temperature in the deep underground of Lebanon and the geothermal potential.

The results are presented in the form of maps that cover the whole territory and that are part of the Geothermal Atlas of Lebanon.

From this work, it can be concluded that the theoretical gross resource in Lebanon is of 1,000 Million GWh, the equivalent of around 70,000 times the yearly energy demand in Lebanon.

Even though only a very small part of the geothermal heat can be economically harvested considering the present state of the technology, the abundant nature of this resource and the fast development of the technology make it fundamental to initiate the process of exploiting it by laying the proper grounds for this process through this study.

A reasonable but challenging scenario for the Geothermal energy development in Lebanon, would be to have a total geothermal energy production of 6 GWh<sub>el</sub> by 2020 and 30 GWh<sub>el</sub> by 2025 which corresponds to an installed capacity of 1.3 MW by 2020 and 6.5 MW by 2025 and constitutes about 0.2% of the total energy demand at that time.

For this purpose, the current pilot study is an important milestone that has set the grounds for further investigations on the general geothermal potential for heat and power generation in Lebanon, with the present report, we hereby reconfirm the commitment of the Ministry of Energy and Water to pursue the search of every stream of renewable energy that can be identified in view of making Lebanon a better country for our future generations.

On behalf of the Ministry of Energy and Water, I would like to thank all those who contributed to the development of the report, hoping that its findings and recommendations will find their way to execution in the very near future.

**Arthur Nazarian**  
Minister of Energy and Water

# Foreword to the National Geothermal Atlas Resource Assessment Study - United Nations Development Programme

In recognition of its growing energy needs and the call for global action on climate change, Lebanon made an ambitious pledge at the Copenhagen Conference to meet at least 12% of its energy supply from renewable resources by 2020. The United Nations Development Programme has been supporting the Ministry of Energy and Water in elaborating a road map to help reach this target through a series of renewable energy assessments. Results of these efforts include a growing body of groundbreaking research, from the national Wind Atlas and the Bioenergy Strategy, to various assessments of hydro and micro-hydro power, concentrated solar power, photovoltaic farms and the potential for generating energy from waste.

On behalf of UNDP and the CEDRO Project, I am pleased now to present the National Geothermal Atlas, one of the first attempts in the region to assess and categorize a country's potential for renewable electricity and heat generation using natural heat sources found underground. With this latest report completing the circle of knowledge around the many renewable energy resources available to the country, Lebanon has gone far in better understanding the mix of renewable resources available to satisfy its development needs in a sustainable manner, in line with the United Nations Secretary General's call for increasing access to sustainable energy for all.

More specifically, the Geothermal Atlas delivers a preliminary appraisal of heat resources found underground through a series of heat maps at various depths. While uncertainties remain, given the challenge of deep-well temperature readings, we are confident that this study gives more than sufficient evidence to justify further investigation through a pilot demonstration project, possibly in the North of the country where the most favorable conditions have been found.

Despite the difficult situation that Lebanon and the region finds itself in, it is inspiring to see continued momentum in the renewable energy sector, contributing in important ways to political, environmental and economic resilience when most needed.

For this, I wish to take this opportunity to thank The Ministry of Energy and Water, in particular H.E. Minister Bassil, for his deep commitment both towards ensuring that national demands are met and in maximizing the use of renewable energy sources for our global good. I would also like to congratulate the UNDP-CEDRO project and its partners for the many important achievements recorded to date. Finally, I hope the Government of Lebanon and stakeholders at large will use the findings in this report to help the geothermal sector fulfill its potential in helping secure a sustainable future.

**Ross Mountain**  
UNDP Resident Representative

# Table of contents

List of Figures .....	i
List of Tables .....	v
List of Appendices .....	1
Executive summary .....	3
Table of Contents	
01. Introduction .....	24
02. Objectives and Methodology .....	26
2.1. Objectives .....	26
2.2. Methodology .....	27
03. General Framework .....	28
3.1. Introduction .....	28
3.2. Geography .....	28
3.3. Climate .....	28
3.4. Surface temperature .....	30
3.5. Landscape, patrimony and sites .....	33
04. Legal Framework .....	38
4.1. Introduction .....	38
4.1.1. Generalities .....	38
4.1.2. Lebanese legal system .....	38
4.1.3. Lebanese administrative system .....	38
4.1.4. Hierarchy of legislation .....	38
4.1.5. Applicable laws, regulations and guidelines .....	40
4.2. Supranational framework: Valid international conventions and documents .....	40
4.3. National Framework .....	41
4.3.1. Lebanese Constitution .....	41
4.3.2. Laws, decrees and decisions .....	41
4.3.2.1. Water Laws .....	42
4.3.2.2. Building law .....	43
4.3.2.3. Electricity law .....	43
4.3.2.4. Environmental laws .....	44
4.3.2.5. Labor laws .....	45
4.3.2.6. Real Estate Obligations .....	45
4.3.3. Regulations: financial governmental support .....	46
4.3.3.1. Lebanese Banking System & Investments Framework .....	46
4.3.3.2. BANKING LOANS .....	46
4.3.4. Policy framework .....	47
05. Geological, hydrogeological and geothermal context .....	48
5.1. Introduction .....	48
5.2. Geological context .....	49
5.2.1. Overview .....	49
5.2.2. Stratigraphy .....	54
5.2.2.1. Paleozoic to Late Triassic (620 Ma – 206 Ma) .....	54
5.2.2.2. Jurassic (206 Ma to 142 Ma) .....	55
5.2.2.3. Early Cretaceous (142 Ma to 97 Ma) .....	56
5.2.2.4. Late Cretaceous (97 Ma to 65 Ma) .....	57
5.2.2.5. Paleocene to Oligocene (Paleogene, 65 Ma to 24 Ma) .....	57
5.2.2.6. Miocene to Pliocene (Neogene, 24 Ma to 2 Ma) .....	58
5.2.3. Tectonic context and neo-tectonic .....	60

5.2.4.	Seismicity.....	62
5.2.5.	Volcanism.....	65
5.3.	Hydrogeological context.....	68
5.3.1.	Introduction .....	68
5.3.2.	General overview.....	69
5.3.3.	Groundwater wells and springs.....	71
5.3.3.1.	Shallow groundwater wells.....	71
5.3.3.2.	Springs.....	71
5.3.4.	Hydrostratigraphy of Lebanon .....	74
5.3.4.1.	The Quaternary .....	74
5.3.4.2.	The Miocene .....	74
5.3.4.3.	The Eocene .....	74
5.3.4.4.	The Sannine Formation.....	75
5.3.4.5.	The Chouf Formation .....	75
5.3.4.6.	The Bikfaya and Kesrouane Formations .....	75
5.3.5.	Karst in Lebanon.....	76
5.3.5.1.	Generalities .....	76
5.3.5.2.	Karst and temperature.....	77
5.3.5.3.	Karst in Lebanon .....	79
5.3.6.	Hydrodynamic properties .....	80
5.3.7.	Role of faults .....	82
5.4.	Heat flow and Temperature data .....	83
5.4.1.	Heat flow map .....	83
5.4.2.	Thermal conductivities.....	85
5.4.3.	Groundwater temperature.....	88
5.4.3.1.	Deep boreholes .....	88
5.4.3.2.	Shallow groundwater wells.....	89
5.4.3.3.	Temperature gradient measurements .....	89
5.4.3.4.	Thermal springs .....	93
5.4.4.	Groundwater temperature map .....	93
5.5.	Summary of geological, hydrogeological and geothermal features .....	96
06.	Geothermal potential of Lebanon.....	100
6.1.	Introduction .....	100
6.2.	Applied methodology .....	100
6.3.	3D geological model.....	101
6.3.1.	Approach.....	101
6.3.2.	Geological Data.....	101
6.3.3.	Model extent.....	102
6.3.4.	The stratigraphic pile and relationship (onlap/erode) .....	102
6.3.4.1.	Basement.....	102
6.3.4.2.	Series 1 (onlap).....	103
6.3.4.3.	Series 2 (erode).....	103
6.3.4.4.	Series 3 (onlap).....	103
6.3.4.5.	Series 4 (onlap) .....	103
6.3.5.	Faults .....	104
6.3.6.	Karst level.....	104
6.3.7.	Results .....	105
6.4.	3D temperature model.....	108
6.4.1.	Introduction .....	108
6.4.2.	Mesh generation and solver .....	108
6.4.2.1.	Extent of the model .....	108
6.4.2.2.	Considered layers.....	108
6.4.2.3.	Spatial discretization .....	109
6.4.3.	Model parameter and boundary conditions .....	109

6.4.3.1.	Model parameter .....	109
6.4.3.2.	Boundary conditions .....	110
6.4.4.	Results .....	110
6.5.	Geothermal potential estimation .....	111
6.5.1.	Introduction .....	111
6.5.2.	Depth of the potential target aquifers .....	112
6.5.3.	Temperature at depth of the target horizons .....	114
6.5.4.	Stored heat for the target zones .....	117
6.5.5.	Recoverable heat for the target zones .....	121
6.5.6.	Geothermal Power (Heat and Electricity) .....	124
6.6.	Conclusions .....	125
07.	State of the art of geothermal technologies .....	128
7.1.	Introduction .....	128
7.2.	Theoretical background .....	128
7.2.1.	Flow rate .....	128
7.2.2.	Temperature .....	129
7.2.3.	Stress field .....	129
7.2.4.	Secondary key factors .....	129
7.3.	Classification of geothermal systems .....	129
7.4.	Underground technologies .....	131
7.4.1.	Introduction .....	131
7.4.2.	Preliminary survey .....	131
7.4.3.	Exploration phase .....	131
7.4.3.1.	General considerations .....	131
7.4.3.2.	Seismic methods .....	132
7.4.3.2.1	2D seismic .....	132
7.4.3.2.2.	3D seismic .....	133
7.4.3.3.	Other geophysical methods .....	134
7.4.3.3.2.1.	Gravimetry .....	134
7.4.3.3.1.	Electrical and Electromagnetic methods .....	135
7.4.3.3.2.	Thermal gradient borehole .....	136
7.4.3.4.	Geochemical methods .....	137
7.4.3.5.	Surface geoscience studies .....	137
7.4.4.	Drilling phase .....	137
7.4.4.1.	General considerations .....	137
7.4.4.2.	Drilling of geothermal reservoir .....	137
7.4.4.3.	Well configuration .....	138
7.4.4.3.1.	Single well systems .....	138
7.4.4.3.2.	Coaxial well .....	139
7.4.4.3.3.	Multiple well systems (doublet, triplet) .....	139
7.4.4.3.4.	Horizontal wells .....	139
7.4.4.3.5.	Unconventional geothermal systems .....	139
7.4.5.	Well testing, tracer testing and logging phase .....	139
7.4.5.1.	General considerations .....	139
7.4.5.2.	Well testing .....	139
7.4.5.2.1.	Production testing scheme .....	140
7.4.5.2.2.	Injection testing scheme .....	140
7.4.5.2.3	Testing techniques .....	140
7.4.5.3.	Tracer testing .....	140
7.4.5.4.	Logging .....	141
7.4.5.4.1.	Temperature log .....	141
7.4.5.4.2.	Vertical seismic profile .....	141
7.4.5.4.3.	Borehole imaging and sonic log .....	141
7.4.5.4.4.	Gamma ray logs .....	141
7.4.5.4.5.	Resistivity log .....	141
7.4.5.4.6.	Stress determination .....	142
7.4.6.	Reservoir development phase .....	142
7.4.6.1.	Chemical stimulation .....	142
7.4.6.2.	Hydraulic stimulation .....	143

7.4.7.	Production phase.....	143
7.4.7.1.	Production and injection .....	143
7.4.7.1.1.	Production pump .....	143
7.4.7.1.2.	Injection pump .....	144
7.4.7.1.3.	Corrosion and scaling .....	144
7.4.7.2.	Reservoir management and monitoring .....	144
7.5.	Power plant technologies.....	145
7.5.1.	General.....	145
7.5.2.	Condensing power plants.....	146
7.5.3.	Binary cycle plants.....	147
7.5.4.	Heating applications .....	148
7.6.	Cost estimation Opex/Capex .....	148
7.6.1.	Introduction .....	148
7.6.2.	Investment Costs .....	149
7.6.2.1.	Well doublet .....	149
7.6.2.2.	Geothermal fluid loop .....	150
7.6.2.3.	Power plant unit .....	150
7.6.2.4.	Surface infrastructure.....	150
7.6.3.	CAPEX .....	150
7.6.4.	Operational and Maintenance Costs (OPEX).....	152
7.6.5.	Cost breakdown.....	152
7.6.6.	Economic feasibility .....	155
08.	Environmental aspects.....	158
8.1.	Introduction .....	158
8.2.	Phasing and EIA.....	158
8.3.	Type of impact.....	158
8.3.1.	CO2 emissions.....	158
8.3.2.	Microseismic activity .....	160
8.3.3.	Soil subsidence .....	162
8.3.4.	Noise .....	163
8.3.5.	Nature (Flora and Fauna).....	163
8.3.6.	Aesthetics .....	163
8.3.7.	Water quality (groundwater, surface water), soil protection, heat pollution.....	164
8.3.8.	Waste management (solids and fluids).....	165
8.3.9.	Land use.....	165
8.4.	Legal aspects related to the protection of environment .....	166
8.5.	Discussion.....	168
09.	Conclusions and recommendations.....	176
9.1.	Opportunities .....	176
9.2.	Barriers for geothermal development.....	176
9.2.1.	Physical barriers .....	177
9.2.2.	Technological barriers.....	178
9.2.3.	Legal barriers .....	179
9.2.4.	Economic, insurances and social barriers.....	181
9.3.	Overall potential of Lebanon .....	182
9.4.	Recommendations.....	183
010.	Bibliography.....	186
	Appendices.....	191

# List of Figures

Figure 3-1: Elevation model of Lebanon [meters a.s.l.].....	27
Figure 3-2: Seasonal evolution of the temperature with depth.....	28
Figure 3-3: Surface temperature for station Tripoli .....	29
Figure 3-4: Mean surface temperature values for the year 2007 versus topographic height... ..	29
Figure 3-5: Calculated average surface temperatures in Lebanon .....	30
Figure 3-6: Landscaping and Sites.....	32
Figure 3-7: Natural Domain of National interest.....	33
Figure 3-8: Protected natural reserves and grottos.....	34
Figure 5-1: Geological map of Lebanon.....	48
Figure 5-2: Typical NW-SE cross-sections of North Lebanon (top) and South Lebanon (Bottom). ....	49
Figure 5-3: Schematic petroleum system model for Lebanon, with possible Plays offshore, in the continental margin and onshore.....	49
Figure 5-4: Well correlation .....	49
Figure 5-5: Location of the 7 oil and gas exploration wells. Maximum depth below ground level reached by the wells is indicated in brackets.....	50
Figure 5-6: Detailed stratigraphic columns of North and South Lebanon.....	51
Figure 5-7: Isopach map of Triassic in Syria, as derived from well and seismic data.....	53
Figure 5-8: Overview (left) and outcrop (right) of the micritic Limestone of the Kesrouane Formation .....	54
Figure 5-9: Isopach map of Lower Cretaceous and Jurassic in Syria, as derived from well and seismic data.....	54
Figure 5-10: Outcrop of the light grey micritic limestone of the Sannine Formation overlying the brownish marls and limestones of the Hammama Formation .....	55
Figure 5-11: Simplified stratigraphic column for Lebanon .....	57
Figure 5-12: Structural maps of Lebanon .....	59
Figure 5-13: Seismicity of Lebanon, 2006-2009 with Magnitudes .....	61
Figure 5-14: Seismic Hazard Map of Lebanon .....	62
Figure 5-15: Miocene to Pliocene basaltic lava flow in North Lebanon.....	63
Figure 5-16: Distribution of basalts in Lebanon .....	65
Figure 5-17: Schematic representation of a karstic system .....	67
Figure 5-18: Schematic representation of the flow system in Lebanon, and distinction between the concepts of hydrogeological unit and the hydrostratigraphic unit.....	67
Figure 5-19: Reproduction of the hydrogeological map of Lebanon .....	68
Figure 5-20: Location of the groundwater wells examined in the framework of the groundwater well survey .....	70
Figure 5-21: Submarine spring in the Chekka region .....	71
Figure 5-22: Location of submarine springs in Lebanon by means of air borne infrared survey. ....	71
Figure 5-23: Block diagram of a karst aquifer .....	75
Figure 5-24: Depth and temperatures profiles (left) in the non karstic Simplon tunnel (Switzerland) and (right) in the karstic Gran Sasso tunnel (Italy).....	75
Figure 5-25: Rock temperature versus depth in the large alpine tunnels .....	76
Figure 5-26: Water level and discharge rate of the Jeita springs during water year 2010-2011.....	77
Figure 5-27: Extent of the rock formations regarding to the degree of karstification .....	78
Figure 5-28: Role of fault on groundwater circulation.....	80



Figure 5-29: Regional heat flow map .....	82
Figure 5-30: Location of the rock sample (Li-1 to Li-24) for thermal conductivity measurements and value of thermal conductivity (L).....	85
Figure 5-31: Thermal conductivities measured on rock sample in Lebanon .....	86
Figure 5-32: Map of the NIMO-T temperature logs .....	88
Figure 5-33: Temperature log performed in the well NMD019 .....	89
Figure 5-34: Temperature logs performed in the 7 shallow groundwater wells. The name of the well refers to the Water Establishment .....	90
Figure 5-35: Temperature distribution based on temperature groundwater measurement .....	92
Figure 5-36: Difference between the groundwater temperatures measured in shallow groundwater wells (TW) and the average surface temperature (TS) .....	93
Figure 6-1: Stratigraphic pile used for the geological model and correlation with the stratigraphy of Dubertret (1955)...	101
Figure 6-2: Faults considered and lateral extent of the geological model. ....	103
Figure 6-3: Comparison between the subsurface geology of Lebanon given by (left) the geological map of Dubertret (1955) and (right) the top view on the 3D geological model.....	104
Figure 6-4: 3D geological model of Lebanon: the basement and sea are shown in volume view, projections of the modeled geology on EW-sections and symbolized wells .....	104
Figure 6-5: Geological 3D-model for Lebanon, view from SW .....	105
Figure 6-6: Discretization of the numerical temperature model for Lebanon, view from SW .....	107
Figure 6-7: Depth of the Cretaceous aquifer [m. BGL.].....	110
Figure 6-8: Depth of the Jurassic aquifer [m. BGL.] .....	111
Figure 6-9: Temperature of the Cretaceous aquifer.....	112
Figure 6-10: Temperature of the Jurassic aquifer .....	113
Figure 6-11: Temperature at 4000 m depth (below ground level).....	114
Figure 6-12: Stored heat for the Cretaceous aquifer .....	116
Figure 6-13: Stored heat (HIP) for the Jurassic aquifer .....	117
Figure 6-14: Stored heat (HIP) for the depth interval 4,000-4,500 m .....	118
Figure 6-15: Recoverable heat for the Cretaceous aquifer .....	120
Figure 6-16: Recoverable heat for the Jurassic aquifer .....	121
Figure 6-17: Recoverable heat for the depth interval 4000-4500 m .....	125
Figure 6-18: Location of identified geothermal prospects in Lebanon .....	144
Figure 7-1: Schematic view of a condensing power plant (top) and of a binary cycle power plant (bottom).....	144
Figure 7-2: Flow chart of a single flash condensing geothermal power plant (top) and of a double flash condensing geothermal power plant (bottom) .....	145
Figure 8-1: Impact of drilling operations of the St. Gall Project in Switzerland (2013).....	162
Figure 8-2: Example of visual impact of the Riehen heat only installation (production borehole of 1500 m depth).....	162
Figure 8-3: Landuse during the preparation of the drilling site of the St.Gall project in Switzerland (2012) - 4500 m deep borehole.....	164
Figure 8-4: Land use of the Landau power plant in Germany (3MWe installed capacity) .....	164
Figure 8-5: Landscaping and Sites.....	170
Figure 8-6: Natural Domain of National interest.....	171
Figure 8-7: Protected natural reserves and grottos.....	172
Figure 8-8: Zones of water pollution risks .....	173
Figure 9-1: Typical risk profile for a geothermal project vs. time and project phases.....	180
Figure 9-2: Comparison between the energy demand and the energy that could be produced by mean of geothermal technologies by 2025.....	181

# List of Tables

Table 4-1: Laws and decrees entailed by the legal framework of the Lebanese Republic in regard to geothermal projects .....	39
Table 5-1: Specifications of the geothermal domains identified by Shaban (2010) .....	64
Table 5-2: Observed depth of the relevant hydrostratigraphic units in the deep O&G boreholes. ....	74
Table 5-3: Hydrodynamic properties (extracted from the hydrogeological map of Lebanon) .....	79
Table 5-4: Thermal conductivity measurements on rock samples from Lebanon .....	84
Table 5-5: Determination of thermal conductivity on crumbled rocks.....	86
Table 5-6: Groundwater wells suitable for NIMO-T temperature measurements .....	87
Table 5-7: Qualitative estimation of the transmissivity for the preliminary assessment of the geothermal resources.....	94
Table 5-8: Qualitative estimation of the temperature for the preliminary assessment of the geothermal resources.....	95
Table 5-9: Hydrostratigraphic units and preliminary qualitative geothermal potential of deep aquifers.....	96
Table 6-1: Model parameters for the numerical temperature model. Values, indicated with a star are based on measurements of local rock probes.....	108
Table 6-2: Parameter values for the calculation of the stored heat.....	115
Table 6-3: Parameters needed for the determination of the flow rate and optimal distance between the wells in the aquifer.....	122
Table 6-4: Geothermal power for a production temperature of 130°C.....	123
Table 6-5: Geothermal power for a production temperature of 180°C.....	123
Table 7-1: Life time for the different elements of a geothermal power plant .....	149
Table 7-2: Parameters and hypothesis for the estimation of the capital and operational costs of the geothermal plant ..	151
Table 7-3: Cost breakdown (in Million US\$) for power plant in four underground environments in Lebanon .....	152
Table 7-4: Summary of the CAPEX and OPEX for four Power Plant scenarios in Lebanon, and estimation of the net electricity production and the specific costs in US\$/kWh. ....	153
Table 7-5: Cost per kWh in US\$ for different hydraulic transmissivity and reservoir temperatures of the Jurassic aquifer in the Akkar region.....	155
Table 8-1: Comparison of CO <sub>2</sub> emissions between geothermal and conventional power plants .....	157
Table 8-2: Comparison of hydrochemical characteristics in the Summaqiyeh well (thermal water) with other water in the Akkar region. Comparison with the standards for groundwater .....	158
Table 8-3: Comparison between the modified Mercalli Scale that describes the intensity of an earthquake (damages, feelings...) and the Richter Magnitude Scale which described the quantity of energy released.....	159
Table 8-4: Maximum seism magnitude for some hydrothermal and EGS projects worldwide .....	160
Table 8-5: Zones of remarkable interest in terms of nature protection, landscape, urban planning and patrimony .....	168
Table 9-1: List of required permits for the construction of a geothermal power plant.....	178
Table 9-2: First cost estimates for the realization of the proposed exploration program .....	183



# List of Appendices

Appendix 1: Landscaping and sites .....	190
Appendix 2: Natural area of national interest.....	191
Appendix 3: Protected natural reserves and grottos .....	192
Appendix 4: Geological map of Lebanon.....	193
Appendix 5: Detailed stratigraphic column of Lebanon .....	194
Appendix 6: Seismicity of Lebanon, 2006-2009 with Magnitudes.....	195
Appendix 7: Seismic risk level in Lebanon.....	196
Appendix 8: Extent of the rock formations regarding to the degree of karstification .....	197
Appendix 9: Regional heat flow map .....	198
Appendix 10: Temperature distribution based on temperature groundwater measurement .....	199
Appendix 11: Difference between the groundwater temperatures measured in shallow groundwater wells (TW) and the average surface temperature (TS) .....	200
Appendix 12: Distribution of basalts in Lebanon .....	201
Appendix 13: Hydrogeological map of Lebanon .....	202
Appendix 14: Depth of the Cretaceous aquifer.....	203
Appendix 15: Depth of the Jurassic aquifer .....	204
Appendix 16: Temperature of the Cretaceous aquifer .....	205
Appendix 17: Temperature of the Jurassic aquifer.....	206
Appendix 18: Temperature in a depth of 4,000 m (BGL).....	207
Appendix 19: Temperature in a depth of 5,000 m (BGL).....	208
Appendix 20: Temperature in a depth of 6,000 m (BGL).....	209
Appendix 21: Temperature in a depth of 7,000 m (BGL).....	210
Appendix 22: Stored heat (HIP) for the Cretaceous aquifer.....	211
Appendix 23: Stored heat (HIP) for the Jurassic aquifer .....	212
Appendix 24: Stored heat (HIP) for the depth interval 4,000-4,500 m .....	213
Appendix 25: Stored heat (HIP) for the depth interval 5,000-5,500 m .....	214
Appendix 26: Stored heat (HIP) for the depth interval 6,000-6,500 m .....	215
Appendix 27: Stored heat (HIP) for the depth interval 7,000-7,500 m .....	216
Appendix 28: Recoverable heat (RH) for the Cretaceous aquifer .....	217
Appendix 29: Recoverable heat (RH) for the Jurassic aquifer .....	218
Appendix 30: Recoverable heat (RH) for the depth interval 4,000-4,500 m.....	219
Appendix 31: Recoverable heat (RH) for the depth interval 5,000-5,500 m.....	220
Appendix 32: Recoverable heat (RH) for the depth interval 6,000-6,500 m.....	221
Appendix 33: Recoverable heat (RH) for the depth interval 7,000-7,500 m.....	222
Appendix 34: Possible applications of the geothermal Atlas.....	223



# Executive summary

The UNDP-CEDRO project aims at supporting the greening of Lebanon's recovery, reform and reconstruction activities through the implementation and activation of end-use energy efficiency and renewable energy applications. To achieve this, the project works on three levels, including: the implementation of model end-use energy efficiency and renewable energy demonstration projects for public sector buildings and facilities; the setup of an enabling environment for the conversion of other public sector building and facilities into energy efficient modalities, and the development of a national sustainable energy strategy and action plan.

As part of the third level mentioned above, namely the development of a national sustainable energy strategy and action plan, a National Geothermal Resource Assessment for Lebanon has been initiated by UNDP-CEDRO Project in collaboration with the Ministry of Energy and Water. The study started in May 2012. It has been performed by the company GEOWATT AG in Zürich, Switzerland (UNDP Contract Ref: 12/42).

The objective of the National Geothermal Resource Assessment is to estimate the general geothermal potential for heat and power generation in Lebanon, based on presently available data and current knowledge. It shall be evaluated to which extent geothermal energy can contribute to the objective of the Lebanese government in covering 12% of the total energy needs of Lebanon from renewable energy sources by 2020 and beyond.

The geothermal resources have been assessed by collecting all the relevant geological, hydrogeological, structural and thermal information available for Lebanon. Small scale temperature measurements in abandoned groundwater wells and laboratory measurements of thermal conductivities on rock samples have also been carried out. Based on the collected information, a 3D geological and geothermal model of Lebanon has been developed and used to calculate the temperature in the deep underground of Lebanon and the geothermal potential. The results are presented in the form of maps that cover the whole territory and that are part of the Geothermal Atlas of Lebanon. The numerical model constitutes a very important milestone for future development of geothermal energy in Lebanon, as it will allow updating the assessment of the available resource and improving the accuracy of the estimates when more data will be available.

From this work, it can be concluded that the gross resource in Lebanon is of  $1.0 \times 10^9$  GWh, the equivalent of around 70,000 times the yearly energy demand in Lebanon. The gross resource is defined here as the total energy stored in the underground in Lebanon at a temperature high enough to produce electricity (higher than 100°C) and at a depth that could be reached with present drilling technologies (less than 7,000 meters below ground level). As there is no direct measurement of this resource, the level of confidence is considered as "low" and the resource are categorized as "inferred" (according to the international geothermal reporting code).

Only a very small part of the geothermal heat can be economically exploited considering the present state of the technology. An optimistic but not unrealistic scenario could consider the implementation of 1 pilot installation of 1.3 MW<sub>el</sub> by 2020. In case of success and positive results, 4 additional power plants could be installed until 2025. Considering this scenario, it is concluded that the total electricity production by 2020 by means of geothermal energy can reach 6 GWh<sub>el</sub>. By 2025, the total production could be increased to 30 GWh<sub>el</sub> which corresponds to about 0.2% of the total energy demand.

In contrary to other renewable energy technologies, geothermal energy delivers constant and reliable power not subjected to variations of the meteorological conditions. Geothermal energy is also considered as unlimited and produces almost no CO<sub>2</sub> emissions. It is a local energy that reinforces the independency from foreign energy suppliers.

The environmental and visual impact of a geothermal power plant is low. Therefore, the protection of patrimony, nature and

environment are rarely an unsolvable issue during the site selection process for a geothermal project.

This study identified two prospective areas suitable for the development of geothermal pilot projects. The most promising area is located in the Akkar region, where deep groundwater can be expected at a depth of 1,500 m and at a temperature up to 130°C. The second area is the Bekaa Valley, where the deep water can be estimated to be around 80-90°C and located at a depth of 2,800 m. Considering the degree of confidence of the available data, it cannot be excluded that water in the Bekaa Valley could be found at a temperature higher than 100°C, which would allow power generation as well. Other prospects have been identified in the Kaoukaba area and in the vicinity of Tyr, where evidences of thermal anomalies have been identified.

Considering this range of temperature, the conditions in Lebanon are suitable for low-enthalpy technologies using binary cycle power plant.

Despite of all the obvious advantages mentioned previously, the exploitation of a geothermal reservoir could have side-effects, such as induced seismicity, which must be addressed seriously. Induced seismic events are in fact of very low magnitude. Nevertheless strong risk mitigation measures and communication plans with local residents have to be implemented at the early stages of a project.

The most challenging issue during the development of a geothermal project is the strong dependency on local geological conditions. As for exploration in the O&G industry, geothermal energy presents a risk of non-discovery of the expected resource and therefore the consequent lack of production of the expected quantity of energy. Additionally, Lebanon does not have a long exploration history in Oil and Gas, and suffers consequently from the lack of appropriate data. Stringent procedures and relatively important costs are therefore required to determine the potential available.

This study suggests starting with an exploration program specifically dedicated to geothermal energy. The aim of the exploration program is to increase the level of confidence of the geothermal resource in the identified prospective areas, and to get them qualified as “indicated” or “measured” (according to the international geothermal reporting code). The proposed exploration program includes geophysical surface investigations and the drilling of one geothermal well, which is at the present state of technology, the only method to ascertain the presence of a geothermal resource. Investment costs for this exploration program are estimated to be around US\$ 5 million. The results could be achieved in a period of three years.

If the geothermal potential is confirmed, the completion of the first pilot installation could be achieved with another US\$ 20 million, by drilling a second well and by constructing a geothermal power plant until the start of electricity production. This stage could then be financed by private investors.

As a key factor, the development of geothermal technology in Lebanon will require strong government incentives and concise permitting and licensing procedures during the 10 first years of an initial development phase of geothermal energy in Lebanon.

## المُلخَص التنفيذي (صفحة ٢)

وخلالاً لتقنيات الطاقة البديلة الأخرى، توقّر الطاقة الحرارية الأرضية مصدر طاقة ثابتاً وموثوقاً به لا يتأثر بتقلّبات حالة الطقس. كما تُعتبر الطاقة الحرارية الأرضية لامحدودة وبكاد لا تنتج عنها أيّة انبعاثات من ثاني أكسيد الكربون، فهي طاقة محليّة تدعم الاستقلالية حيال مزوّد الطاقة الأجانب.

يُعتبر التأثير البيئي والمرئي لمحطّات توليد الطاقة الحرارية الأرضية متدنّياً. وبالتالي، نادراً ما تكون حماية الإرث والطبيعة والبيئة مسألة مستعصية خلال عملية اختيار موقع لإنشاء مشروع حراري أرضي.

حدّدت هذه الدراسة مجالين محتملين لتطوير مشاريع تجريبية في مجال الطاقة الحرارية الأرضية. تُعتبر عكّار من أهمّ المناطق الواعدة حيث يمكن العثور على المياه الجوفية العميقة على عمق ألف وخمسمئة متر ودرجة حرارة تصل إلى ١٣٠ درجة مئوية. أمّا المنطقة الثانية، فهي سهل البقاع حيث تقدّر درجة حرارة المياه بنحو ٨٠ إلى ٩٠ درجة مئوية على عمق ألفين وثمانمئة متر. إذا أخذنا في الاعتبار درجة الثقة بالبيانات المتوافرة، من غير المستبعد أن يتمّ العثور على مياه في سهل البقاع بدرجات حرارة تفوق ١٠٠ درجة مئوية، ما يسمح أيضاً بتوليد الطاقة. هذا وقد حدّدت إمكانات أخرى في منطقة كوكبا ومحيط مدينة صور حيث حدّدت الأدلّة على مواطن الشذوذ الحراري.

في إطار درجات الحرارة هذه، تُعتبر الظروف في لبنان مؤاتية للتقنيات ذات المحتوى الحراري المنخفض عبر استخدام محطة توليد طاقة ذات دورة ثنائية.

على الرغم من كلّ الفوائد المذكورة سابقاً، يمكن لاستثمار خزان طاقة حرارية أرضية أن تكون له تأثيرات جانبية، كالنسيب بالزلازلية، والتي تنبغي معالجتها بجدية. في الواقع، تكون النشاطات الزلزالية الناتجة من هذا الاستثمار خفيفة للغاية من دون أن ينفي ذلك الحاجة إلى اتّخاذ إجراءات صارمة للحدّ من المخاطر وخطط تواصل في المراحل الأولى للمشروع.

يُعتبر الاعتماد القوي على الظروف الجيولوجية المحليّة العنصر الأهمّ لدى تطوير مشروع طاقة حرارية. كما هي الحال في التنقيب عن النفط والغاز، تنطوي الطاقة الحرارية الأرضية على خطر عدم اكتشاف المورد المتوقّع، ما يؤدي إلى قصور في إنتاج الكمية المتوقّعة من الطاقة. كما أن تاريخ لبنان في مجال التنقيب عن النفط والغاز حديث، ما يعني أنّه يعاني من نقص في البيانات الملائمة ويفرض ضرورة اعتماد إجراءات صارمة وتكاليف مرتفعة نسبياً لتحديد الإمكانية المتوافرة.

تقترح هذه الدراسة البدء ببرنامج تنقيب مصمّم خصيصاً للطاقة الحرارية الأرضية بهدف تعزيز مستوى الثقة في المورد الحراري الأرضي في المناطق المحتملة المحدّدة وتصنيف هذه المناطق على أنّها "محدّدة" أو "مقاسة" (وفقاً للرمز الدولي لإعداد التقارير الحرارية الأرضية). يشمل برنامج التنقيب المقترح إجراء تحقيقات جيوفيزيائية سطحية وحفر بئر حرارية أرضية واحدة، علماً بأنّها الوسيلة الوحيدة المتوافرة نظراً للإمكانات التقنية الحالية للتأكّد من وجود مورد حراري أرضي. تُقدّر التكاليف الاستثمارية لبرنامج التنقيب هذا بنحو خمسة ملايين دولار أميركي على أن تصدر النتائج في غضون ثلاث سنوات.

وإذا تمّ التأكّد من الإمكانية الحرارية الأرضية، يمكن استكمال المنشآت التجريبية الأولى بكلفة إضافية تقدّر بعشرين مليون دولار أميركي عبر حفر بئر ثانية وبناء محطة لتوليد الطاقة الحرارية الأرضية إلى حين البدء بإنتاج الطاقة. ويمكن حينها أن يعمد مستثمرون من القطاع الخاص إلى تمويل هذه المرحلة.

سيطلب تطوير التقنية الحرارية الأرضية في لبنان أساساً محفّزات حكومية قوية وإجراءات موجزة لمنح الأذونات والتراخيص خلال السنوات العشر الأولى من مرحلة التطوير الأولى للطاقة الحرارية الأرضية في لبنان.



## الملخص التنفيذي (صفحة ١)

يهدف مشروع دعم تحسين كفاءة استهلاك الطاقة والطاقة المتجددة لهوض لبنان (CEDRO) التابع لبرنامج الأمم المتحدة الإنمائي إلى دعم اعتماد السياسات الخضراء في نشاطات نهوض لبنان وإصلاحه وإعادة إعمارهم عبر اعتماد تطبيقات كفاءة الطاقة لدى المستخدم النهائي والطاقة المتجددة وبدء العمل بها. يعمل المشروع لهذه الغاية على مستويات ثلاثة، ألا وهي تطبيق مشاريع نموذجية خاصة بكفاءة الطاقة لدى المستخدم النهائي والطاقة المتجددة في المباني والمنشآت التابعة للقطاع العام، وتوفير بيئة ممكنة لتحويل غيرها من المباني والمنشآت التابعة للقطاع العام إلى أشكال نمطية خاصة بكفاءة الطاقة، وتطوير استراتيجية وخطة عمل وطنية في مجال الطاقة المستدامة.

هكذا، أطلق مشروع دعم تحسين كفاءة استهلاك الطاقة والطاقة المتجددة لهوض لبنان (CEDRO) التابع لبرنامج الأمم المتحدة الإنمائي بالتعاون مع وزارة الطاقة والمياه مسحاً وطنياً للموارد الحرارية الأرضية في لبنان في إطار المستوى الثالث المذكور آنفاً، أي تطوير استراتيجية وخطة عمل وطنية في مجال الطاقة المستدامة. تولت الدراسة التي بدأت في أيار ٢٠١٢ شركة AG GEOWATT التي تتخذ من مدينة زوريخ السويسرية مقراً لها (مرجع العقد مع برنامج الأمم المتحدة الإنمائي: ٤٢/١٢)

يهدف المسح الوطني للموارد الحرارية الأرضية إلى تقدير الإمكانية الحرارية الأرضية لتوليد الحرارة والطاقة في لبنان بناءً على البيانات والمعلومات المتوفرة حالياً. ويقدر إلى أي مدى يمكن للطاقة الحرارية الأرضية أن تساهم في بلوغ هدف الحكومة اللبنانية بتغطية ١٢٪ من إجمالي احتياجات لبنان للطاقة من مصادر الطاقة المتجددة بحلول العام ٢٠٢٠ والسنوات التي تليه.

قُومت الموارد الحرارية الأرضية عبر جمع كل المعلومات الجيولوجية والهيدروجيولوجية والهيكلية والحرارية المتوفرة بشأن لبنان، إلى جانب إجراء قياسات حرارية على نطاق ضيق في آبار المياه الجوفية المهملة وقياسات مخبرية للتوصيلات الحرارية على العينات الصخرية. وبناءً على المعلومات المجموعة، طُوّر نموذج جيولوجي وحراري أرضي ثلاثي الأبعاد للبنان واستُخدم لاحتساب الحرارة الجوفية والإمكانية الحرارية الأرضية في لبنان. قُومت النتائج على شكل خرائط تغطي الأراضي اللبنانية كافة على أن تكون جزءاً من الأطلس الحراري الأرضي للبنان. يشكل هذا النموذج العددي محطة على درجة عالية من الأهمية بالنسبة للتطوير المستقبلي للطاقة الحرارية الأرضية في لبنان، إذ يسمح بتحديث تقويم الموارد المتوفرة وتحسين دقة التقديرات عند توافر المزيد من البيانات.

وعليه، يمكن الاستنتاج أنّ الموارد الإجمالية في لبنان تقدر بمليار جيجاواط/ساعة، أي ما يعادل نحو ٧٠ ألف ضعف من الطلب السنوي على الطاقة في لبنان. يُعرف المورد الإجمالي هنا على أنه الطاقة الإجمالية المخزنة تحت الأرض في لبنان على درجة حرارة تكفي لإنتاج الكهرباء (تفوق ١٠٠ درجة مئوية) وعمق يمكن لتقنيات الحفر الحالية أن تبلغه (أقل من ٧ آلاف متر تحت مستوى الأرض). وفي غياب أي قياس مباشر لهذا المورد، يعتبر مستوى الثقة "منخفضاً" ويصنّف هذا المورد على أنه "مخمن" (وفقاً للرمز الدولي لإعداد التقارير الحرارية الأرضية).

وحده جزء بسيط للغاية من الحرارة الأرضية يمكن استغلاله اقتصادياً نظراً للظروف التقنية الحالية. يسمح سيناريو متفائل وواقعي في آن واحد، بالتفكير في تركيب منشأة تجريبية بقدرة ١,٣ ميغاواط طاقة بحلول العام ٢٠٢٠. وفي حال كُملت هذه المحاولة بالنجاح والنتائج الإيجابية، يمكن بناء أربع محطات إضافية لتوليد الكهرباء بحلول العام ٢٠٢٠، ما يرفع إنتاج الطاقة الحرارية الأرضية إلى ٦ جيجاواط/ساعة من الطاقة. ويمكن رفع الإنتاج الإجمالي إلى ٣٠ جيجاواط/ساعة من الطاقة بحلول العام ٢٠٢٥، أي نحو ٠,٢٪ من إجمالي الطلب على الطاقة.

# 01. Introduction

The United Nations Development Programme, in partnership with the Ministry of Energy and Water, the Ministry of Economy and Trade, the Ministry of Finance and the Council for Development and Reconstruction, has initiated in October 2007 the implementation of the CEDRO project (Country Energy Efficiency and Renewable Energy Demonstration project for the recovery of Lebanon), which is funded through the Lebanon Recovery Fund by means of a grant from Spain.

The CEDRO project aims at supporting the greening of Lebanon's recovery, reform and reconstruction activities through the implementation and activation of end-use energy efficiency and renewable energy applications. To achieve the greening, reform and reconstruction, the project works on three levels: the implementation of model end-use energy efficiency and renewable energy demonstration projects for public sector buildings and facilities; the setup of an enabling environment for the conversion of other public sector building and facilities into energy efficient modalities, and the development of a national sustainable energy strategy and action plan.

Part of the third level mentioned above, namely the development of a national sustainable energy strategy and action plan, a National Geothermal Resource Assessment for Lebanon has been performed.

GEOWATT AG has been contracted by UNDP to provide services to conduct this study (UNDP Contract Ref: 12/42).

This report and the associated maps (see appendices) constitute the Geothermal Atlas of Lebanon. Each map is available in a GIS format on the attached CD.

Compared to other forms of renewable energy, geothermal energy presents the advantage of being a band energy that makes this source of energy very interesting as a component in any energy mix. However, the energy that can be recovered from geothermal energy is extremely dependent on geological conditions. It is thus necessary to correctly analyze and quantify the geothermal potential through using a site specific methodology.

In a first step, the study quantifies the total energy stored in form of geothermal energy in the underground of Lebanon, in order to assess the resources (identification, quantification). In a second step the quantity of energy that could be extracted by means of the current state-of-the art of geothermal energy is estimated in a quantitative way, considering both enhanced geothermal systems (EGS) and hydrothermal technologies. This recoverable energy represents only a small portion of the stored heat.

Based on this estimation, power plant scenarios are proposed and their economic feasibility is evaluated.

Barriers toward the development of geothermal technologies are reviewed, together with their environmental and social impacts.







# 02. Objectives and Methodology

## 2.1. Objectives

The objectives of the study are:

- To establish a Geothermal Atlas for Lebanon
- To estimate the current overall potential of geothermal heat and power generation in Lebanon. The focus is oriented toward power generation
- To estimate the ability of geothermal power to assist in meeting the objective of the Lebanese government in meeting 12% of its total energy needs from renewable energy sources by 2020 (and beyond), considering technological maturity, economic costs, environmental and social constraints, opportunities and considerations



## 2.2. Methodology

Geothermal potential aims at quantifying the quantity of energy that is stored underground and that could be extracted to be used in form of heat or electricity either for industrial or for domestic purposes. Geothermal potential is generally expressed in form of stored heat and recoverable heat.

Stored heat is a measure for the total thermal energy, which is stored in a specific target zone (e.g. deep aquifer or fractured rock). Recoverable heat is the fraction of the stored heat, which can be utilized by means of engineering techniques, given the current state of the art of the geothermal technologies.

If the stored heat provides the theoretical overall potential of geothermal energy in Lebanon, the recoverable heat is the entity that is relevant to estimate the ability of these technologies to assist in meeting the objectives of the government.

The methodology applied in this study precisely aims at estimating at best the recoverable heat in Lebanon, given the current state of the art of the geothermal technologies and given the current knowledge of the underground.

To reach this objective, the first step consists in gathering all the relevant information to develop a geothermal conceptual model of Lebanon. The conceptual model describes all the relevant processes and the relationship between them. The relevant information is mainly related to the deep underground (see Chapter 6) but also to the climatic and geographic conditions (see Chapter 4).

Once all the relevant information is gathered and the conceptual model established, the temperature in the underground could be estimated using a 3D-numerical model that simulates all the relevant thermal processes (see Chapter 7). The results of the 3D numerical model are then used to compute the geothermal potential (stored heat and the recoverable heat) as well as providing an estimation of a power plant production capacity (see Chapter 8).

Other relevant features for the development of the geothermal technology in Lebanon and in assisting the government in reaching its objectives are also treated in separate chapters and subsections:

- Chapter 4      Landscape, patrimony and site protection
- Chapter 5      Legal framework
- Chapter 8      Economical feasibility and capital cost breakdown
- Chapter 9      Environmental aspects



# 03. General Framework

## 3.1. Introduction

Although the key features of a geothermal project is the geothermal loop or heat exchanger, which are located in the underground, part of the installation consists of a power plant that is located on the surface. A geothermal project could therefore have some visual impacts that might have some importance in terms of landscape, patrimony and sites.

Moreover, the temperature in the underground depends first on the heat flux coming from the deep underground, and also on the average temperature on the surface. Daily variations of the surface temperature have an effect until a depth of a few meters maximum. Seasonal variations have an effect down to approximately 20 meters. Therefore, the relevant temperature is the yearly average surface temperature. The average surface temperature is determined in section 3.4.

All the relevant aspects related to the surface, such as climate, the landscape and surface temperature are described in this chapter. The next chapter will then focus on the key features located at depth, such as the geology, the groundwater and the heat flux, for instance.

## 3.2. Geography

Lebanon is located along the eastern coast of the Mediterranean Sea. The total area of Lebanon is 10,452 km<sup>2</sup> and the population in 2008 was estimated to be around 4.8 million inhabitants, whose great majority live along the coast line.

Topography is a key feature of Lebanon in terms of landscape, underground resources (water), distribution of the population, biodiversity and agriculture, for instance (Figure 3-1: Elevation model of Lebanon [meters a.s.l.]).

The general landscape consists of two mountainous chains, the Mount Lebanon to the West and the Anti-Lebanon Range to the East, which includes the Mount Hermon (2,814 m a.s.l.) at its southern end. Both mountain ranges trend NNE-SSW and are separated by a high plain, the Bekaa Valley. To the west, Mount Lebanon borders the Mediterranean Sea with relatively steep slopes except in its northern part (near Tripoli), where a stretch of coastal plain exists. This mountain chain has the highest altitude in its northern part. The Qornet el-Souda peak culminates at 3,088 [m. a.s.l.]. To the North, it plunges under the basalts and Quaternary deposits of the Tripoli-Homs depression, which separates it from the Jibal As-Sahilyeh in Syria.

## 3.3. Climate

Lebanon has a moderate Mediterranean climate. In coastal areas, winters are generally cool and rainy whilst summers are hot and humid. In more elevated areas, temperatures usually drop below freezing during the winter with heavy snow cover that remains until early summer on the higher mountaintops. Accumulation of snow in the elevated area is crucial in terms of water resources. Water is stored in winter in form of snow. During the spring, the melting snow could recharge the groundwater systems during several months, ensuring availability of groundwater for irrigation and domestic use during the dry periods.

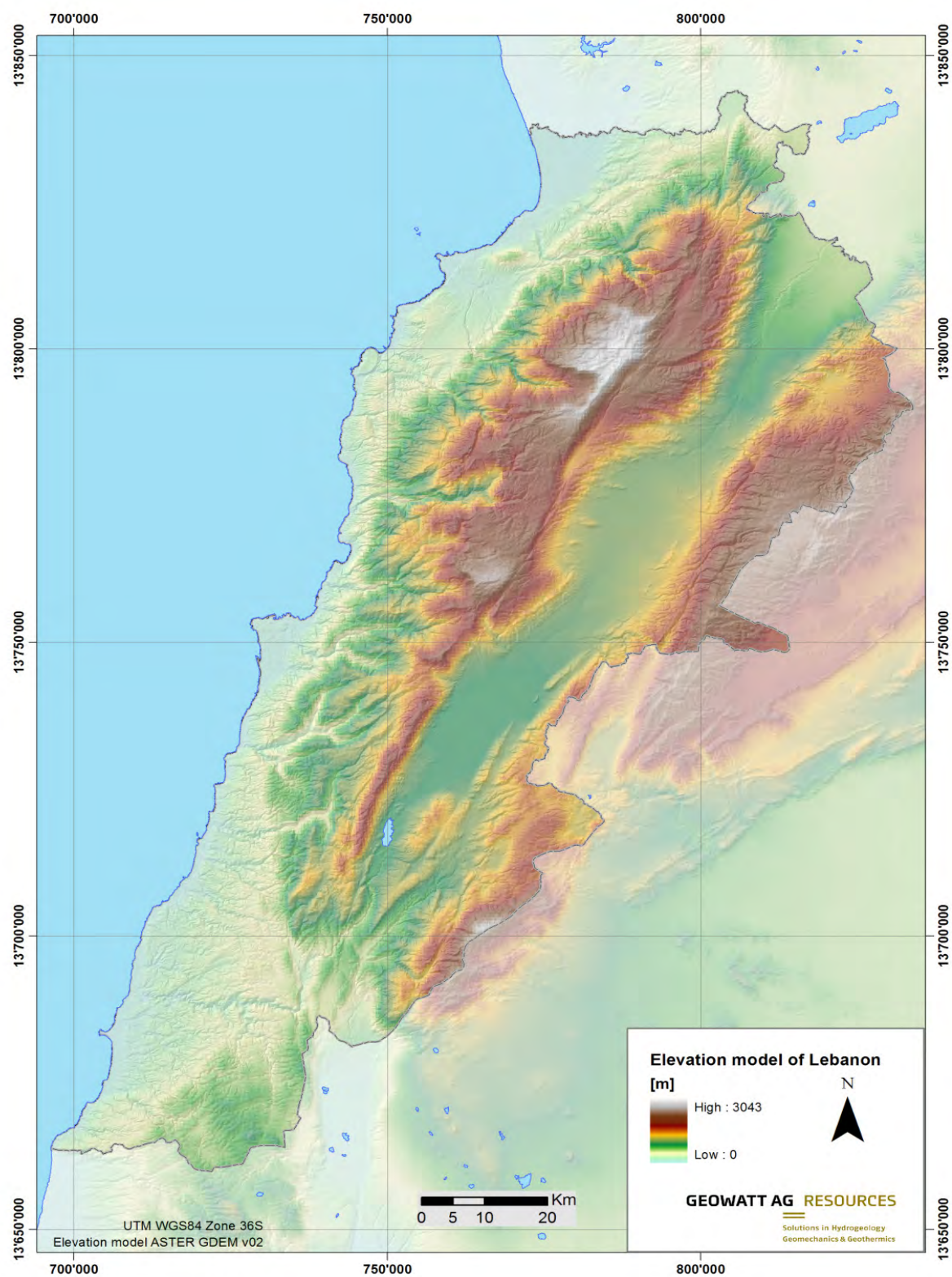


Figure 3-1: Elevation model of Lebanon [meters a.s.l.]



### 3.4. Surface temperature

Temperature distribution on the surface, as well as the temperature variation over the years or over the seasons are important features for the geothermal resources assessment of Lebanon, as they define the starting point for the increase of temperature in the subsurface (Figure 3-2: Seasonal evolution of the temperature with depth. The temperature at around 20 meter depth corresponds to the yearly average temperature on the surface). The temperature distribution on the surface is also used as boundary conditions for the thermal numerical model (see section 6.4). The average representative surface temperature has been calculated in the framework of this study. The data and methodology used are briefly described in the following paragraphs.

Since seasonal temperature variations decrease strongly with increasing depth, long time average temperatures are needed for the surface boundary condition. Additionally, short time average surface temperatures can be useful to compare measured groundwater temperatures with the actual surface temperatures.

A map of the temperature at surface has first been generated based on the available national and international databases, such as the MOD11C3 (Surface temperature measured by spacecraft) and the DS3505 (Temperature from land station measurements). A time series of the DS3505 database is available for the city of Tripoli (Figure 6-2). An extrapolation over the whole territory of Lebanon has then been calculated considering a linear trend between the elevation and the temperature decrease (Figure 3-4: Mean surface temperature values for the year 2007 versus topographic height. Surface temperatures have been determined by using spectroradiometer data (MODIS /MOD11C3 data) provided by USGS/Earth Resources Observation and Science (EROS) Center).

The calculated average surface temperature is presented in Figure 3-4: Mean surface temperature values for the year 2007 versus topographic height.

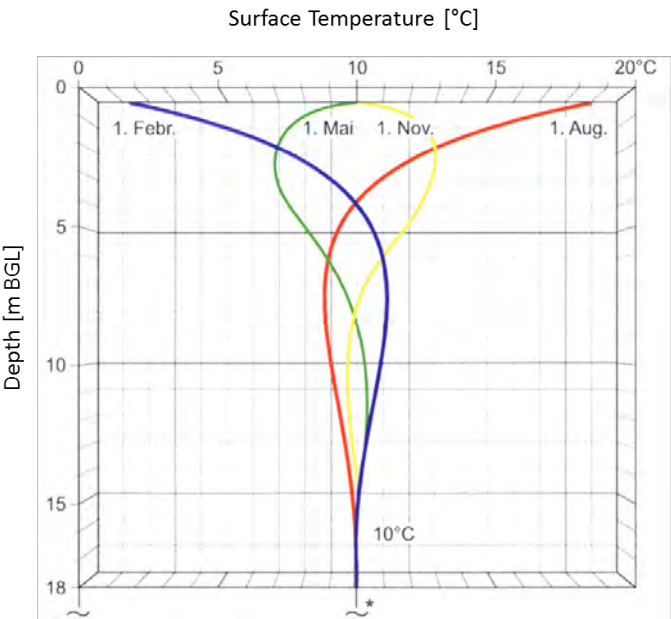


Figure 3-2: Seasonal evolution of the temperature with depth. The temperature at around 20 meter depth corresponds to the yearly average temperature on the surface



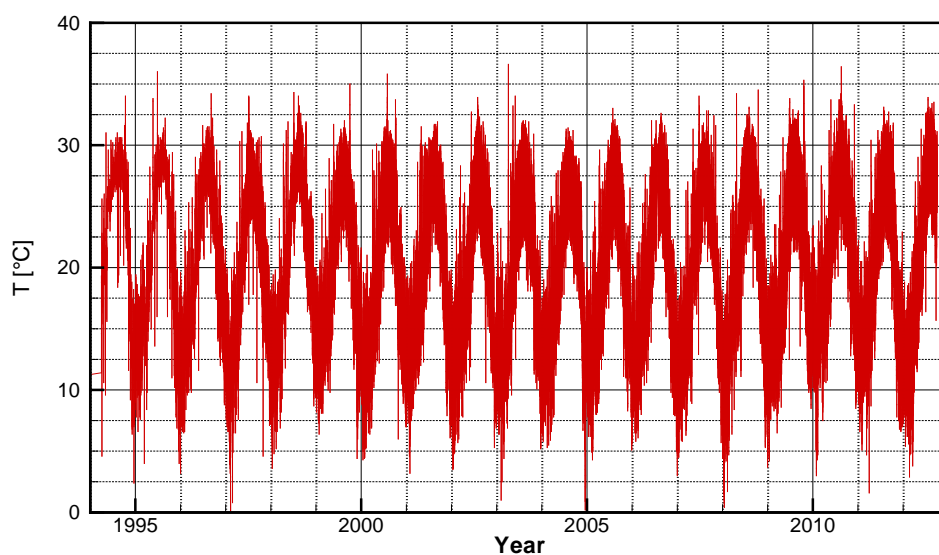


Figure 3-3: Surface temperature for station Tripoli (DS3505—ISH dataset provided by NOAA from their web page <http://gis.ncdc.noaa.gov/map/viewer/#>)

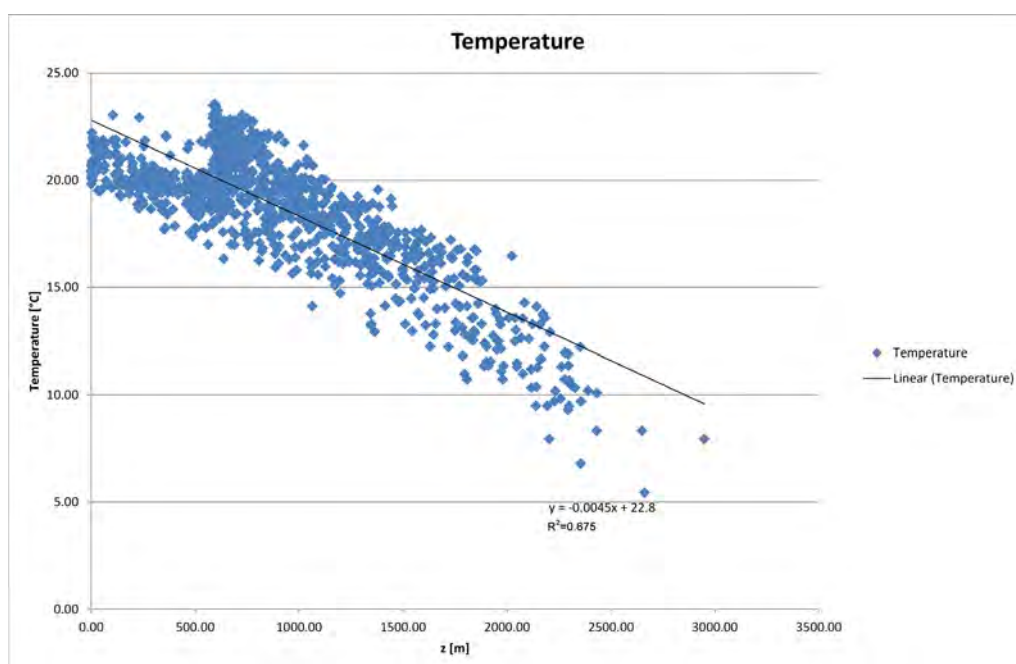


Figure 3-4: Mean surface temperature values for the year 2007 versus topographic height. Surface temperatures have been determined by using spectroradiometer data (MODIS /MOD11C3 data) provided by USGS/Earth Resources Observation and Science (EROS) Center

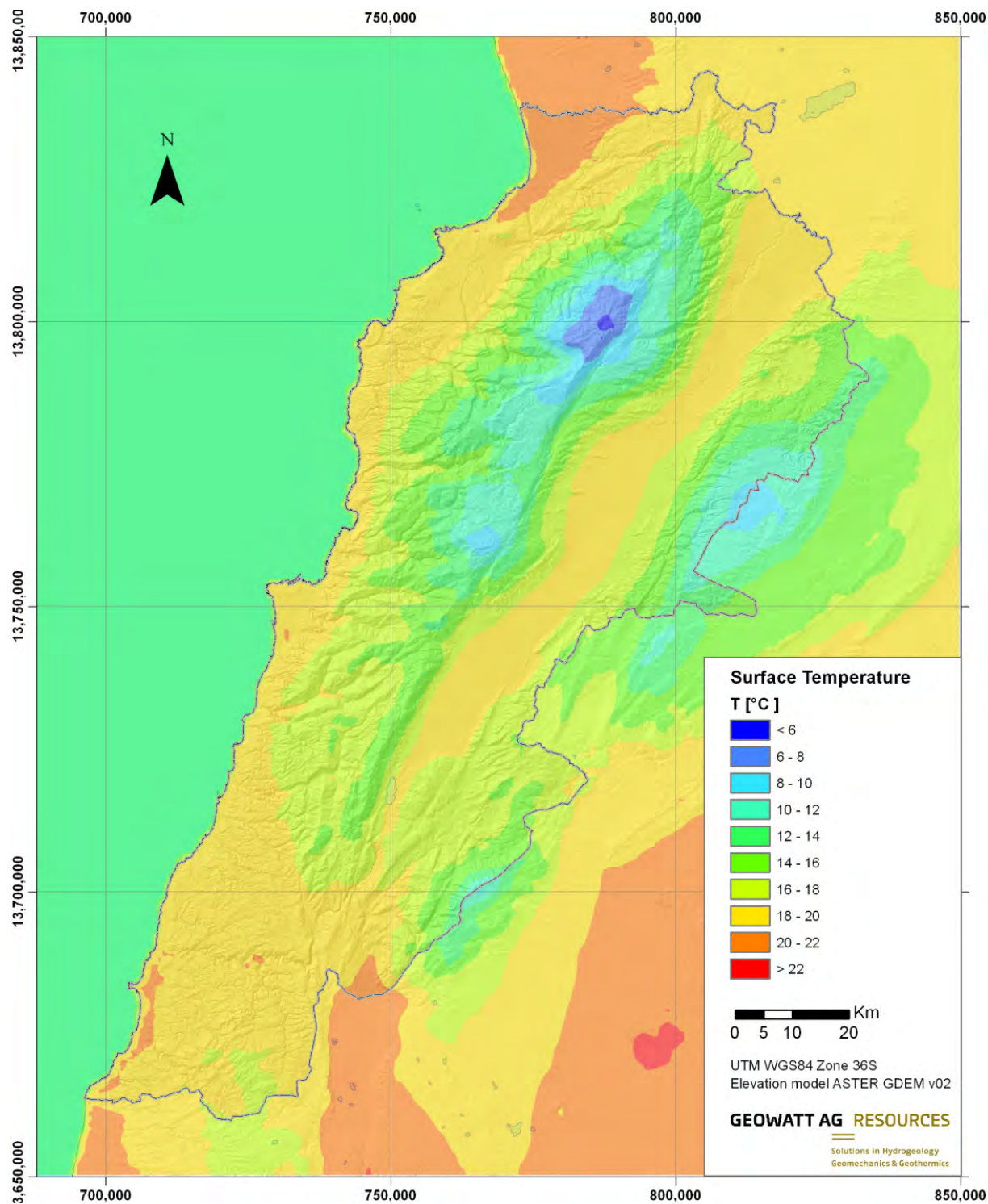


Figure 3-5: Calculated average surface temperatures in Lebanon

### 3.5. Landscape, patrimony and sites

Due to its geology, topography and climate, landscapes in Lebanon are diverse. Landscapes constitute part of the Lebanese identity and are a major factor for tourism attraction.

A list of the major landscapes in Lebanon is given in the National Physical Master Plan of the Lebanese Territory (DAR-IAURIF, 2005):

- Peaks (Qornet el-Saouda, Sannine, Barouk, Hermon)
- Agricultural large plains (Beqaa, Akkar, Koura, etc.)
- Great deep valleys (Abou Moussa, Qadisha, Ibrahim, Litani at Khardali, etc.)
- Picturesque valleys (Jaouz, el-Kalb, Beirut, Barouk – Bisri – Awali, Aassi, Hasbani, etc.)
- Important bays (Jounieh)
- Forests of the North and pine forests of the Cazas of Kesrwan, Baabda, Matn and Jezzine, hills of the South, Qaraoun Lake
- Outstanding coastal sites (Salinas of Enfeh, Ras ech-Shaqaa, Grotte aux Pigeons, Ramlet el Bayda, Damour plain, gorges and mouth of Litani, seashore of Sour, cliffs of Bayyada and Naqoura)
- Cedar forests (Sir, Jaje, Becharre, Tannourine, Laqlouq, Falougha, Barouk, Chouf)
- Smaller valleys and interior plains (Kfarhalda, Safa, Qammouaa, etc.).

Some of these landscapes have been turned into protected natural sites of national interest, which are protected by specific decrees (see legal aspects in section 4.3).

Sites and landscapes, natural domain of national interests and protected natural reserves and grottos are represented in Figure 3-6, Figure 3-7 and Figure 3-8, respectively.

Although the land use and the visual impact of a geothermal power plant is considered as relatively low in comparison to other technologies, the consideration of the landscapes, the patrimony and Sites is mandatory for the development of these technologies in Lebanon.

These aspects are already addressed by Lebanese legislation (see Chapter 4). It makes mandatory the achievement of Environmental Impact Assessments (EIA), which should include aspects related to the landscape, patrimony and sites. Regarding the environmental aspects, they will be further developed in Chapter 8.

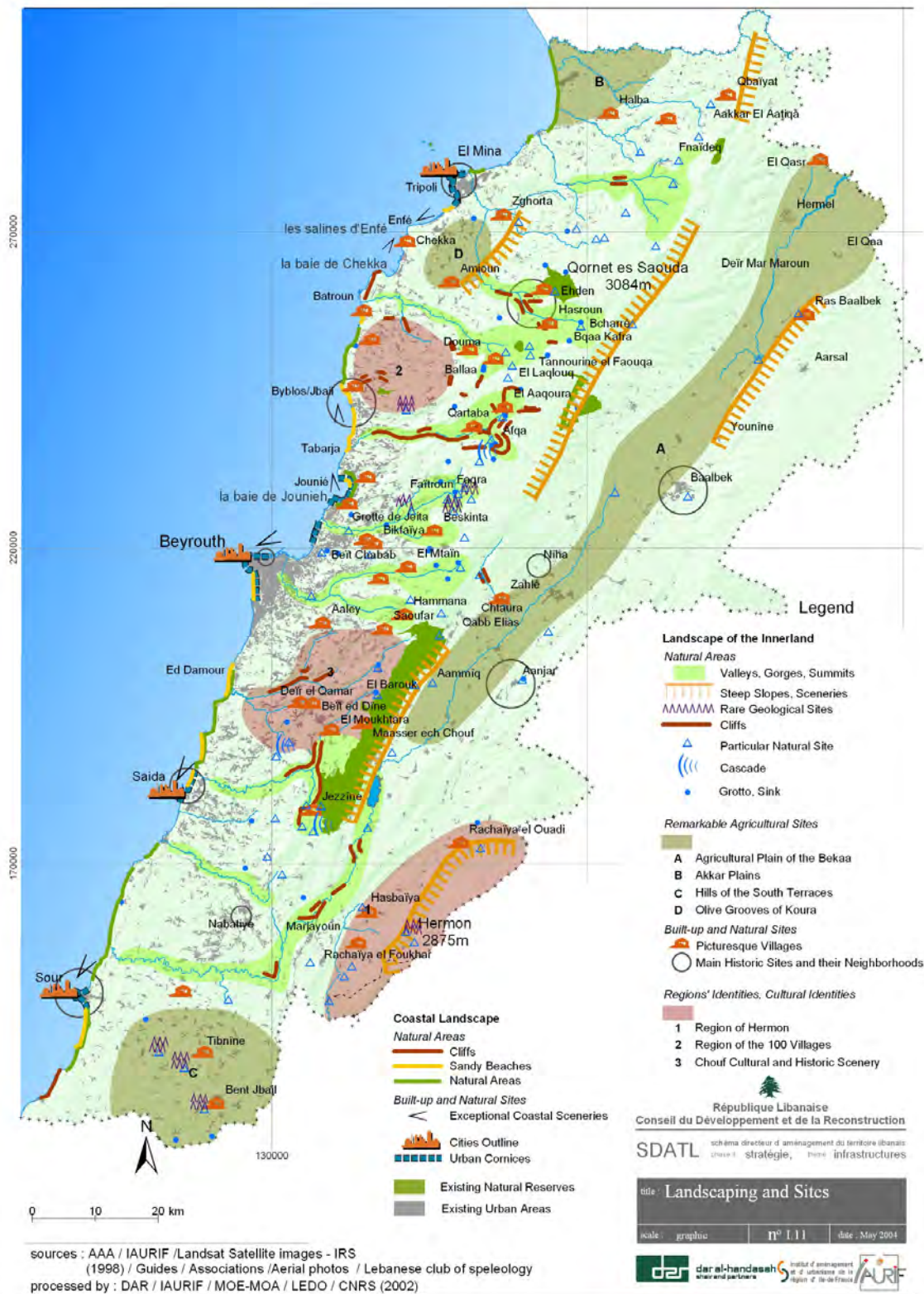


Figure 3-6: Landscaping and Sites (DAR-IAURIF, 2005)



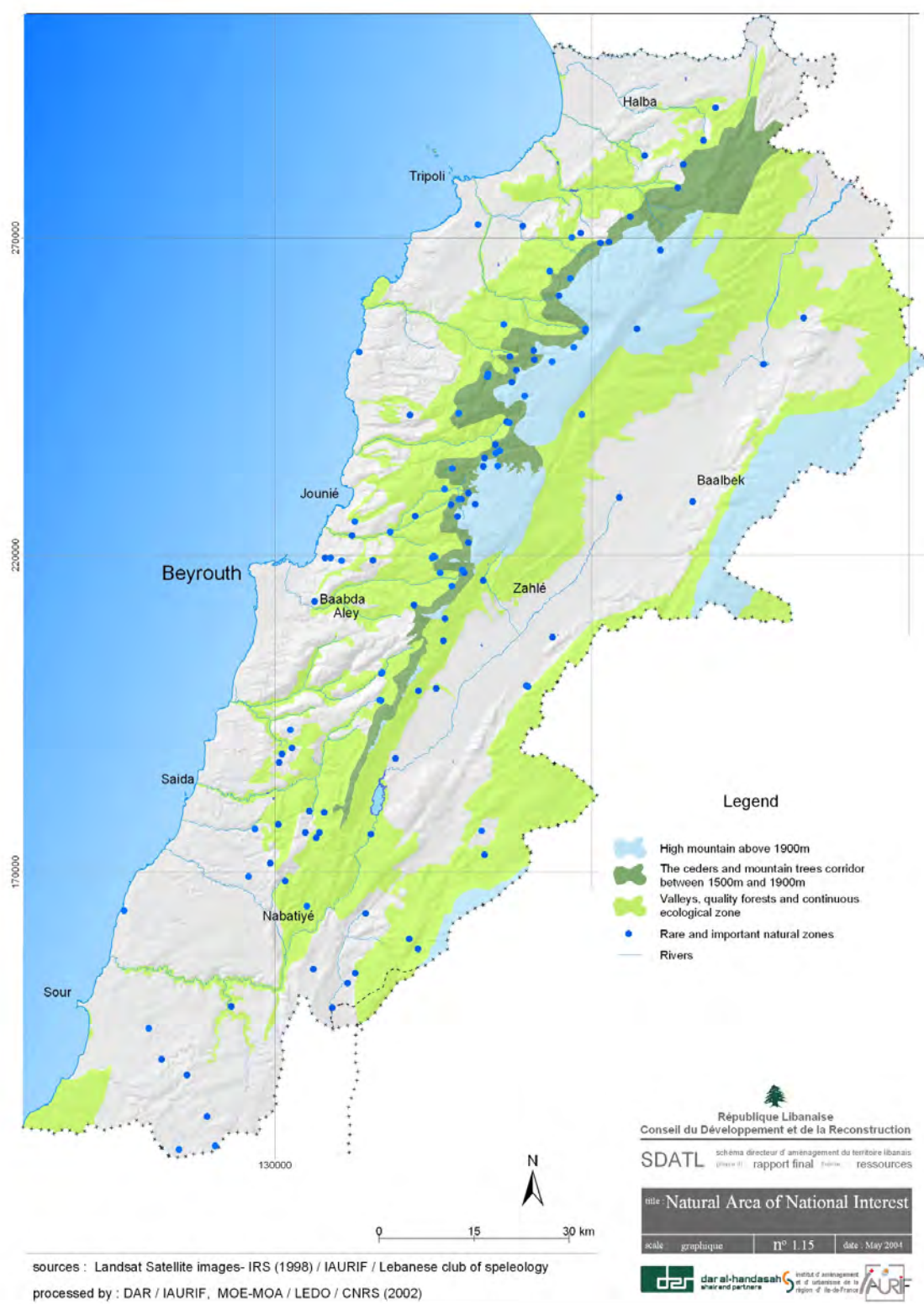


Figure 3-7: Natural Domain of National interest (DAR-IAURIF, 2005)

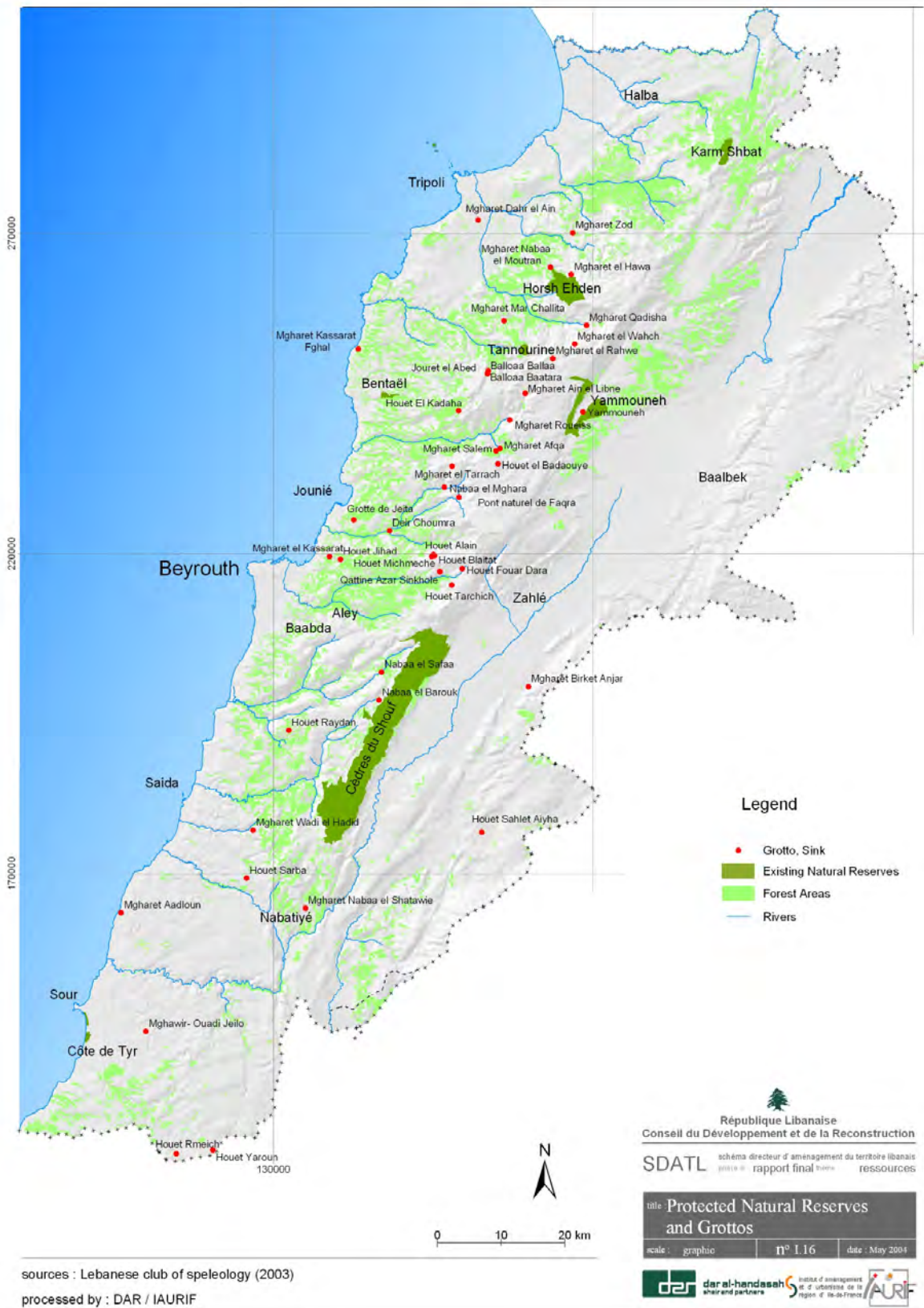


Figure 3-8: Protected natural reserves and grottos (DAR-IAURIF, 2005)





# 04. Legal Framework

## 4.1. Introduction

### 4.1.1. Generalities

Kobeissi & Frangié – Attorney and counselor in Law have been commissioned to conduct and analyze the legal framework for geothermal energy in Lebanon. A summary of the findings is reported in the following sections and paragraphs.

Although Lebanon is currently looking at its promising hydrocarbon reserves and is paving the way for potential oil exploration and production in its maritime waters, the UNDP-CEDRO project initiated in October 2007 and addressed the problem of climate change through supporting the reduction of the consumption of fossil fuels and the increase of the use of renewable energy sources such as geothermal heat and power generation in Lebanon.

The Lebanese government committed to launching, supporting and reinforcing all public, private and individual initiatives to adopt the utilization of renewable energies to reach 12% of electric and thermal supply by 2020.

The Ministry of Energy and Water (MEW) has introduced a policy paper setting forth an action plan of legislative and regulatory initiatives. This includes setting norms and standards and laws that reflect the international norms and standards in the energy efficiency, environmental and public safety domains and promoting safe, equitable and fair provision of electric services.

Lebanon's new draft law was prepared for this purpose and for all renewable energy projects but it has still not been adopted by the parliament.

Therefore this report shall address the existing legislation applicable to this new field.

### 4.1.2. Lebanese legal system

The Lebanese legal system is based on and inspired by the French legal system. Lebanon is considered to be a civil law country and possesses its own set of laws and codes. The most notable code is the "Code of Obligations and Contracts" promulgated in 1932. The COC is the equivalent of the French Civil Code except for matters related to personal status (heritage, marriage, divorce, etc.), which are governed by a separate set of laws designed for the different sectarian communities.

### 4.1.3. Lebanese administrative system

Lebanon is a centralized political system with limited level of delegation of powers to local authorities.

Lebanese municipalities are the only level of local government or decentralization and are granted certain prerogatives to provide services to citizens. Lebanon has around 710 municipalities.

Districts, or Mohafazat, and Caza don't have any political role and don't provide services to citizens, nor do they receive any financing. Lebanon is divided into 6 Mohafazat and 24 Cazas.

As for the decentralization of the services, it is relative to each sector.

Lebanon's electricity sector is dominated by the state-owned Électricité du Liban (EDL) which is responsible for the generation, transmission and distribution of electrical energy in Lebanon and leading to the centralization of Lebanon's power generation. Distribution of power and tariff collection has only just been privatized.



#### 4.1.4. Hierarchy of legislation

Before moving forward with the overview of Lebanese legislation governing this sector, and for a better understanding, it is essential to understand how legislation is created in Lebanon.

Legislative texts in Lebanon are issued in the form of decisions, decrees, or laws, with the Lebanese constitution being at the top. While decisions are issued by Ministers, decrees are issued by the Council of Ministers, and laws by the Parliament, after being proposed by the Council of Ministers or a Member of Parliament, and consultation with relevant parliamentary committees. Laws and decrees are published in the Official Gazette by the President of the Lebanese Republic.

In addition, Lebanon has adhered to many international conventions and treaties that take precedence over domestic law, as long as not in violation of the Lebanese Constitution. Article 2 of the Lebanese Civil Procedure Code affirms supremacy of treaties over other norms in conformity with the principle of the hierarchy of norms.

The current legal framework in Lebanon is addressed in section 4.3, in order to determine if, and the extent to which, the legal and policy frameworks in Lebanon encourage or present a barrier to energy investments, particularly investment in geothermal energy resources. Investment aspects are treated for several power plant scenarios in section 7.6. The barriers are summarized in the concluding chapter of this document, in section 9.2.

#### 4.1.5. Applicable laws, regulations and guidelines

There is currently no geothermal-specific legislative framework in Lebanon. The Lebanese law lacks an “umbrella” legislation setting forth general principles as well as implementation decrees and regulatory rules addressing specifically the geothermal energy sector which can be an alternative solution to generate electricity in Lebanon.

In this section, the existing laws and regulations are addressed, which can be applicable to the geothermal energy sector until final adoption of the project law awaited for the renewable energy sector in general.

## 4.2. Supranational framework: Valid international conventions and documents

Paragraph B of the preamble of the Lebanese constitution states that:

“Lebanon is also a founding and active member of the United Nations Organization and abides by its covenants and by the Universal Declaration of Human Rights. The Government shall embody these principles in all fields and without exception.”

Therefore the treaties and the values that embody them, ratified by Lebanon are not only binding upon its policies but are considered as an integral part of the block of constitutionality and take precedence over domestic law. Such is the case of the Kyoto Protocol.

This was confirmed by a decision of the Lebanese Constitutional Council which declared on the 18th of September 1995 that the Preamble of the Lebanese constitution had a constitutional value.

Valid international conventions and documents include the following:

- United Nations Conference on the Human Environment-UNCHE (June 5-16th, 1972).
- Lebanon attended the first earth summit and approved the Stockholm Declaration without any reservation.
- United Nations Conference on Environment and Development (UNCED) (Rio de Janeiro, June 3rd- 14th, 1992).
- The resulting document of the “Earth Summit”: Rio Declaration on Environment and Development, the Statement of Forest Principles, the United Nations Framework Convention on Climate Change and the United Nations Convention on Biological Diversity. Lebanon ratified the resulting document in 1994 and therefore committed itself to the principle of replacing the use of fossil fuels linked to global climate change by alternative sources of energy.
- Lebanon ratified the resulting document in 1994 and therefore committed itself to the principle of replacing the use of fossil fuels linked to global climate change by alternative sources of energy.
- Kyoto Protocol (December 11<sup>th</sup>, 1997).
- The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change. It was adopted in Kyoto, Japan, on 11<sup>th</sup> December 1997 and entered into force on 16<sup>th</sup> February 2005 and has been ratified by Lebanon on the 13<sup>th</sup> of November 2006. Therefore it is a binding treaty upon the Lebanese authorities. The treaty has become an integral part of the block of constitutionality, and the applicable law in this domain.
- In this regard, Lebanon committed itself “to set internationally binding emission reduction targets and to implement and/or further elaborate policies and measures in accordance with its national circumstances, such as research on, and promotion, development and increased use of, new and renewable forms of energy, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies”.
- Therefore, Lebanon recognizes the necessity of switching to alternative means particularly renewable energies as defined by the Protocol, among which we can mention geothermal energy in order to produce electricity and to reduce emissions of greenhouse gases.

## 4.3. National Framework

### 4.3.1. Lebanese Constitution

Under the Lebanese constitutional framework, Lebanon's geothermal resources are controlled by the state.

Article 89 of the Lebanese Constitution states that “No contract or concession for the exploitation of the natural resources of the country, or a public utility service, or a monopoly may be granted except by virtue of a law and only for a limited period of time.”

The exploration of underground water, drilling for geothermal energy and use of the water so as to generate electricity are exploitation of the natural resources and need therefore to be granted through a contract or a concession by virtue of a law and for a limited period of time.

### 4.3.2. Laws, decrees and decisions

The definition of geothermal energy is lacking in the Lebanese law. Geothermal energy in general, and geothermal resources in particular, are not defined in legal terms, and the regulation of their development and utilization is correspondingly diffuse and spread throughout the mining, energy, environmental, water, construction, labor, security sectors and in a non-coherent way. This implies that responsibilities are assigned to different Ministries.

**Table 4-1: Laws and decrees entailed by the legal framework of the Lebanese Republic in regard to geothermal projects**

1.	Law number /462/ on the organization of the regulation of the electricity sector (2 <sup>nd</sup> of September, 2002)
2.	Law number /221/ on the organization of the regulation of the Water Sector (25 <sup>th</sup> of May, 2000)
3.	Law number /444/ for the protection of environment (29 <sup>th</sup> of July 2002)
4.	Law number /8803/ the mining law (4 <sup>th</sup> of October, 2002)
5.	Law number /646/ for construction law (11 <sup>th</sup> of December, 2004)
6.	Decree number /2791/ for the building bylaws
7.	Law number /5243/ on the classification of industrial institutions
8.	Law number /591/ for joining the international labor conventions (air, noise and seismicity) (20 <sup>th</sup> of November, 2004)
9.	Law number /3339/ L.R. on the real-estate ownership of (12 <sup>th</sup> of November, 1930)
10.	Law of obligations and contracts (9 <sup>th</sup> of March, 1932)
11.	Law number /159/1992/ Rent Law
12.	Law related to traffic law (3 <sup>rd</sup> of July 2012)
13.	Law number /144/5/ on public properties (10 <sup>th</sup> of June , 1925)
14.	Law number /320/ for water preservation and usage (25 <sup>th</sup> Of May, 1926)
15.	Decree number /12/438/ for regulating water excavation and usage (2 <sup>nd</sup> of May, 1970)
16.	Decision number /118/50/ for water wells and drilling (13 <sup>th</sup> of September, 2010)
17.	Law number /102/ national defense law (16 <sup>th</sup> of September, 1983)
18.	Law number /17/ internal security forces (6 <sup>th</sup> of September, 1990)
19.	Law number /591/ allowing the Government to adhere to the international labor convention relating to the working environment (air pollution, noise and vibration)

### 4.3.2.1. Water laws

Law number /221/ on the organization of the regulation of the Water Sector issued on the 25<sup>th</sup> of May, 2000.

Article 1 considers the protection of the natural resources of water and its development falling in the category of the protection and preservation of the balance of environment, and thus considered a matter of public utility.

As per article 2, the Ministry of Energy and Water is entitled to grant licenses and permits for water exploration and for the use of the public waters and the riverside public properties.

Decision /144/ issued in 1925 by the French Mandate High Commissioner.

It is the first law that declared water resources as a public property.

We notice that “underground water” is considered as a public property by decision 144. Therefore in order to exploit the underground water, article 14 states that the project is considered a concession if it is made for a public utility purpose.

A concession must be granted by the Lebanese authorities in order to exploit and use the underground water.

On the other hand, article 17 states that temporary occupation license (1 year that can be renewed by tacit approval) must be requested from either the Municipality or the State authorities (depending on the nature of the property, if it is located within the municipality boundaries or not).

If the authorities decide to deliver the license, the amount of fees that shall be paid are fixed in the same decision and can be exceptionally symbolic if the purpose of this temporary occupation is thought to be a “public utility”.

Decision number /320/ for water preservation and usage issued on the 25<sup>th</sup> of May, 1926 by the French Mandate High Commissioner.

Article 1 states that it is prohibited to carry out the following works without a license within the specified condition of Decision 144/S:

“... Works related to exploration for ground water or surface water and controlling it ... in general any activity, either permanent or temporary, that could affect the quantity of public property water or its flow”

Article 4 mentions that the license shall be delivered by the President of the Republic or any other authority mandated by him if it involves any drilling or exploration project aimed at exploiting the underground water. The license is delivered for a period of time that cannot exceed 4 years.

On the other hand, article 12 mentions that if the drilling or exploration is for a public utility purpose then a concession must be requested from the Lebanese authorities and not a temporary occupation license.

The duration of the concession delivered upon request cannot exceed 75 years in this case.

### Decree number /14438/ of May 2, 1970 regulating the mechanism of water exploration and use dated 2<sup>nd</sup> of May, 1970

#### Drilling license

According to this decree, projects that involve drilling to reach and explore underground water cannot be done before requesting a Drilling License from the Ministry of Energy and Water.

The application must be presented to the Ministry of Energy and Water including the following:

- Name and address of the applicant;
- Type of works, its location and the purpose;
- To present the following documents:
  - Real estate certificate proving ownership of the land or any document which proves the applicant right to use the land;
  - Area map;
  - Detailed map of the types of the works.

The Minister of Energy and Water shall award the licenses based on the recommendation of the Directorate-General for Water and Electricity for a period of one year. In this decree the annual fee must be determined in addition to the following:

- Location, type and details of the works to be carried on;
- The drilling and the water disposal methods;
- Instructions or analyses required from the licensee to present to the authorities; and
- Assessment or inspection conditions.

### Water Use License

A Water Use License is required to authorize the taking and use of water from wells. This license is awarded by a decree based upon the Minister of Energy and Water proposition and for a period from (1) one year up to (4) four years.

The running underground water use and the water well use are subject to the Temporary Occupancy System for a maximum period of (4) four years.

## 4.3.2.2. Building law

### Law number /646/ for construction law issued on the 11<sup>th</sup> of December, 2004

The new building law encourages the thermal performance of building envelopes and stipulates expressly that the phases of construction, the occupancy and even the demolition of buildings is bound to be in compliance with the principles of the protection of the environment and of the sustainability of natural resources (water, air, land and living organisms) as defined in law number 444 dated 29<sup>th</sup> of July 2002.

Article 1 of the law imposes a compulsory license. Constructions of buildings of any type are subject to this prior authorization.

The request to obtain a construction permit must be signed by the engineer in charge and registered either at the engineer's syndicate of Beirut or the syndicate in Tripoli. Based on the technical disclosure of the relevant substantive department, the license is delivered either by the Head of the Executive Authority of the concerned municipality or the Kaemmakam if the concerned constructions are outside the municipal scale.

### Decree number /14293/ issued on the 11<sup>th</sup> of March 2005

This decree states the conditions for ensuring public safety in buildings, installations, elevators facilities and preventing fires and earthquakes.

In order to prevent risks or diminish their consequences, a certified technician to check if the design, facilities, materials and equipment used during the process of construction correspond to the technical specifications adopted does a technical scrutiny.

Technicians are requested by law to state their opinion with regard to measures that should be taken in order to prevent risks.

Article 5 provides that the technical scrutiny is mandatory. It should lead to verification of requirements that would ensure public safety in buildings and installations are fulfilled.

## 4.3.2.3. Electricity law

### Law number /462/ regulating the electricity sector issued on the 2<sup>nd</sup> of September, 2002

Reading the *travaux préparatoires* of the law reveals that this law mainly aims at realizing the corporatization and the privatization of the electricity sector. According to the corporatization of the sector, generation of electricity would be formed in one or more corporations, but the transmission would remain in hands of a public entity.

Law 462 recognizes Independent Power Producers ("IPP") to participate in electricity generation in Lebanon.

Article 1 of the law defines the term "production" as the production of electricity through thermal resources, water, renewable or other resources.

Article 3 states the principle of the independence of each of the activities of production, transport and distribution of electricity, a significant reform of the decree 16878 issued in 1964 which had established a monopoly in favor of a public institution, known as *Electricité du Liban* ("EDL"), regarding production, transport and distribution of electricity.

Moreover, article 7 provides the establishment of an Electricity Regulatory Authority (ERA) according to the capability that Law 462 grants to ERA, this entity is eligible to determine and classify the various types of electricity production in the country.

Such ability enables ERA to lead the industry toward more indigenous and environmental friendly technologies such as geothermal energy, but Law number 462 has yet to be implemented through decrees taken in the Lebanese Council of Ministers.

As soon as the ERA will see the light, a promising future will be waiting for the promotion of renewable energies as an alternative solution to produce electricity.

According to the law, the ERA has the ability to grant a license for limited companies. As soon as it is delivered, it will enable them to benefit of a concession that will last for no longer than 50 years. The concession involves the establishment processing, development, management or marketing of devices within the scope of public services used in the areas of production, transport and distribution of more than 10 MW or the right to use the devices listed in a form of leasing.

The ERA has the ability to issue licenses for a maximum of 50 years in accordance with the following:

- Tenders for production capabilities exceeding 25 MW;
- Call for bids for production capabilities of 25 MW and below.

#### Amendment to article 7 of Law number /462/ introduced by Law number /775/ issued on the 11<sup>th</sup> of November, 2006

This law provides that for a certain period of time not exceeding a (1) one year, and until the ERA is officially created and its members appointed, temporary licenses and permits to produce electricity are granted by a decision of the Council of Ministers based upon the proposal of the Minister of Energy and Water.

A similar law to Law number 775 could be a solution to overcome the obstacle of monopoly over the electricity sector in Lebanon and to grant the license to produce electricity for the geothermal power plants project.

#### Decree number /16878/ issued on the 10<sup>th</sup> of July, 1964

We strongly believe that the implementation of Law number /462/ through decrees taken by the Lebanese Council of Ministers would encourage the promotion of both renewable energies and Independent Power Producers who seek to produce electricity through alternative sources such as geothermal energy.

Until then, the Electricité du Liban (EDL) will de facto and de jure have a monopoly over the electricity sector and over activities such as the production, transport and distribution of electricity through Lebanese territories. The possibility to get access to the electrical grid is therefore difficult to achieve.

According to article 1 of the mentioned Decree the task of producing, transporting and distributing electricity in all Lebanese territories is legally and officially assigned to a single independent institution carrying the name of the “Electricité du Liban” (EDL). In practice, some service providers could operate the distribution of electricity.

Moreover article 4 states that no authorization, license or concessions shall be given to whosoever under any reason to produce, transport or distribute electricity after the issuance of the decree.

Therefore the activity that consists of producing or generating electric power is legally banned even if the electricity generated is to be sold to EDL.

### 4.3.2.4. Environmental laws

Environmental laws are treated separately in Chapter 8 “Environmental Aspects”.

#### 4.3.2.5. Labor laws

Law number /591/ allowing the Government to adhere to the international labor convention relating to the working environment (air pollution, noise and vibration)

According to article 3, legal definitions are given to the following:

<b>Air Pollution:</b>	Each air pollution material, whatever its physical nature, harmful to health or dangerous in other ways.
<b>Noise:</b>	Each sound can lead to hearing impairment or to be harmful to health or dangerous in other ways.
<b>Vibration:</b>	Each vibration is transmitted to the human body through solid objects and be harmful or dangerous in other ways.

#### 4.3.2.6. Real Estate Obligations

Law of Obligations and Contracts ("COC") issued on the 9<sup>th</sup> of March, 1932; and Leasing Law number /159/1999/:

There is no special law regulating the right of land use in case of renewable energy or geothermal energy. However, as per current laws listed above, and under the principle of the freedom of contracts, any person or moral entity can seek an arrangement for a particular lot of land and may set the conditions of such land use by virtue of an agreement with the owner of the property.

It is to be noted that, the relevant authorities such as the Ministry of Energy and Water may use its power of eminent domain "expropriation" to condemn a specific land for reasons of public interests.

The restrictions applying to the real property itself are as follows:

- Area/square footage restriction

Foreign individuals and legal entities may freely purchase a piece of real estate, whether built or just a land lot to be built, as long as the area of such real property does not exceed 3000 m<sup>2</sup>. For all acquisitions exceeding 3000 m<sup>2</sup>, foreigners must apply for a license before the Council of Ministers and such application must specify the purpose of the purchase<sup>1</sup>. In the event the Council of Ministers approves, it will issue a decree to that extent. In this context, the Council of Ministers has discretionary powers and its decision cannot be appealed. Moreover, once the decree is issued, the foreign purchaser must complete the planned project within five years, renewable for another five years, otherwise the license is revoked.

- Total territorial restriction

This restriction applies on the total area that the foreign purchaser may purchase in Lebanon:

- 3% of the total area of the Lebanese territories provided that:
  - It does not exceed 3% of the total area of each Caza; and
  - If in Beirut, it does not exceed 10% of the total square footage of the Beirut Mohafaza.

- Registration Fees

In order to promote foreign investment, the registration fees for real property purchased by foreigners have been dropped from 16% to 5% (which is the rate imposed on Lebanese nationals); thus upon registration, foreigners and Lebanese will be paying a total amount of fees equal to approximately 6% of the value of the acquired property, which includes a stamp fee of 0.3%, a notary public fee of 0.1%, and a municipality charge of 0.25%.

<sup>1</sup> The typical real property requirement for a geothermal power plant is around 10,000m<sup>2</sup>. Lower land use size could be achieved with special design, if required.

### 4.3.3. Regulations: financial governmental support

#### 4.3.3.1. Lebanese Banking System & Investments Framework

Given the liberal banking system that imposes no foreign exchange controls and no restrictions on the free flow of capital, Lebanon has become a major financial hub in the Middle-East. Thus, there are no restrictions concerning the repatriation of profits, income and capital nor are there any restrictions on the convertibility of currency. Residents can freely import and export national banknotes. They may own, deal in, export and import gold.

Residents may own foreign currencies and foreign securities, and may maintain bank accounts and balances abroad. Non-residents can also freely import and export national banknotes. They may maintain foreign currency accounts with banks in Lebanon and obtain loans and freely perform other banking transactions.

Further, Lebanon's bank secrecy law, adopted in 1956, has been a major pillar in the success of the Lebanese banking sector. The bank secrecy law imposes a duty of confidentiality on all bank personnel regarding all information on clients' accounts, whether it is identity of the clients, assets or other related facts. Such secrecy cannot be waived unless the client consents to the waiver or unless legal valid reasons exist, such as the bankruptcy of the client or a judicial request of waiver in the event of a legal claim against the client based in illicit accumulation of wealth. However, amongst themselves, banks are allowed to exclusively share information about clients' debt accounts for purposes of safeguarding their investments. In 2001, Lebanon adopted a comprehensive anti-money laundering law that upheld this bank secrecy while complying with new industry best practices and the need to combat financial terrorism. Under this new law, banks and financial institutions are required to have internal control measures to avoid any involvement in money laundering transactions such as reporting suspicious transactions, or maintaining record on clients' identification, and facilitating access to information for judicial authorities.

It is the Central Bank of Lebanon, known as Banque du Liban or BDL, and the Banking Control Commission, an administrative independent body closely cooperating with the Governor of the BDL that regulate the bank industry in Lebanon, and hold it in strict compliance. All of the above factors have rendered the Lebanese banking sector not only stable, but resilient and capable of attracting foreign investments despite all the internal and regional political turmoil. In addition an MOU was signed between the BDL, the UNDP, the European Union (EU), and the Lebanese Center for Energy Conservation (LCEC) to provide potential investors in green technology, specifically in energy saving and renewable energy technology, with low cost financing and medium to long term maturities. A detailed overview of these special loans will be observed later.

Moreover, and throughout the years, Lebanon has signed bilateral treaties with multiple countries aiming at the protection and promotion of reciprocal investments of the nationals of the signatory countries in Lebanon. Investment under such treaties encompasses real property rights and assets, shares, stocks, claims having economic values, intellectual property rights, and most important, business concessions including concessions to search for, extract and exploit natural resources. The protection afforded by such treaties includes protection of investments from expropriation, most favored nation treatment for investors, compensation for losses incurred under specific circumstances, free transfer of money and capital including but not limited to dividends, capital gains and royalties. Further, there are provisions for amicable settlement of disputes through negotiations, and possible recourse to arbitration, and these treaties remain valid regardless of the existence or non-existence of consular or diplomatic relations between the signatory countries.

Below is a comprehensive list of existing investment treaties, provided by the Ministry of Finance<sup>2</sup>.

#### 4.3.3.2. Banking loans

The NEEAP (National Energy Efficiency Action Plan), that has been approved by the Ministry of Energy and Water in December 2010, and the Council of Ministers in November 2011, provides financing mechanisms and incentives in order to promote the use of energy efficiency and renewable energy.

An MOU was signed by the BDL, UNDP and LCEC whose aims are:

- Develop a vehicle to finance Energy Efficiency and Renewable Energy, called NEEREA (National Energy Efficiency and Renewable Energy Action),
- Cooperate to involve International Donors and organizations (i.e. EU) to support NEEREA,
- Develop awareness and capacity building activities among Lebanese Commercial Banks and end consumers.

As a result of this collaboration as well as the involvement of the Ministry of Finance, Intermediary Circular number 236 relating to Reserve Requirements (for environmental projects) and Circular 313 relating to Financial Facilities from BDL to Banks and Financial Institutions issued by the Central Bank of Lebanon in January 14, 2013 focus on energy efficiency, certified green buildings, and renewable energy.

<sup>2</sup> Investment treaties could be found at: <http://www.finance.gov.lb/enUS/finance/InvestmentTaxAgreements/Pages/InvestmentProtectionAgreements.aspx>



As for the incentives it offers:

- Repayment period up to 10 years, beginning after the end of the grace period,
- Grace period ranging from 6 months to 4 years,
- if it's a non-subsidized loan in Lebanese pounds: 150% Exemption from RR Interest + Commissions  $\leq 3\%$  -50% (1Yr. TB. Yield),
- if it's a non-subsidized loan in foreign currency: 500% Exemption from Time Deposits subject to RR Interest + Commissions  $\leq$  Cost of Funds + 2% -50% (1Yr. TB. Yield).

#### 4.3.4. Policy framework

The Government of Lebanon had made a pledge in its Ministerial Declaration as to the following:

- “[...] The reduction in energy demand through the use of energy conservation measures and renewable energy applications”,
- “[...] The setup of a national road map built on environmental concepts to reach 12% of renewable energy by the year 2020”,

The result of this commitment was reflected in the issuance of various policies, regulations and assessments which accelerate renewable energy and geothermal development and encourage energy diversity in Lebanon.

##### Policy paper for the electricity energy sector in Lebanon issued in 2010 by the Ministry of Energy and Water:

This policy paper commits to “launching, supporting and reinforcing all initiatives to adopt the utilization of renewable energies to reach 12% of renewable energy”.

It encourages the private sector to adopt the technologies of “waste to energy” for power generation and investigate geothermal energy.

The main legal framework set in this paper is:

- Developing rules and laws that promote the largest penetration of “Green Buildings (GB)” and “Energy Efficiency (EE)”,
- Complying and respecting international norms and standards in the energy efficiency, environmental and public safety domains,
- Increasing the human resource capacity of EDL,
- Updating the legal due diligence needed to corporatize EDL as per the three functions of generation, transmission and distribution,
- Using Service Providers, independent power production, Operation & Maintenance (O&M) contracts,
- Initiating the process of revising Law 462 with concerned parties,
- Beginning with the current legal status of EDL governed by Decree 4517,
- Adopting a Law for the new power plants and encouraging all kinds of Public-Private Partnerships to facilitate the transition and ensure proper continuity between current and future legal status.

##### Lebanon’s Second National Communication (SNC) to the United Nations Framework Convention on Climate Change which was executed by the Ministry of Environment issued in February 2011:

The SNC contains a detailed overview of most sectors involved with the issue of Climate Change. It addresses the matter of emissions of different greenhouse gases (GHGs) in various sectors and issues recommendations to advance in respecting Lebanon’s international commitments in this field.

##### The Thermal Standard for Buildings in Lebanon issued in 2005:

This project was funded by the Global Environment Facility, managed by the United Nations Development Programme, and executed under the Lebanese General Directorate of Urban Planning, Ministry of Public Works and Transport.

This study sets thermal standards for buildings in Lebanon and provides capacity building and information dissemination for the implementation of these standards but unfortunately, these standards remain non-obligatory and non-binding unless they are incorporated into law and practice.

# 05. Geological, hydrogeological and geothermal context

## 5.1. Introduction

Geothermal energy basically consists in extracting the energy from the underground to generate heat or electricity. The energy that can be recovered from the underground strongly depends on the local geological conditions. A thorough understanding of the geological underground structures and their characteristics in terms of temperature, depth and permeability is therefore a prerequisite for assessing the geothermal potential in Lebanon.

The understanding of the geological framework in Lebanon allows first to determine the structure of the deep underground. Relevant characteristics of the underground structure are the depth and the geometry of specific geological layers. These layers could be a potential target for a geothermal reservoir. Secondly, geological investigations allow identifying and locating structural features such as faults and fractures that could locally increase the productivity of reservoirs. Moreover an analysis of the composition of the different geological units (lithological composition) allows determining if a specific geological layer is likely to contain water. Finally, the geology allows understanding the regional conditions in terms of geothermal activity, such as the presence of volcanoes or thermal anomalies. All these different geological features are summarized in Section 5.2.

The productivity of a geothermal reservoir will depend on one hand on the temperature, but on the other hand, also on the amount of water that could be extracted from the geothermal reservoir. The hydrogeology is a science that specifically aims at understanding the flow system in the deep underground (flow direction, velocity, depth) and to predict the amount of water that could be extracted from the reservoir. Hydrogeological investigations aim then at estimating the quantity of water that is contained in each of the geological units or that could be extracted from them, to help determining the target reservoirs.

Lebanon is mainly composed of carbonate rocks. These kinds of rock are strongly subjected to chemical dissolution processes by infiltration of meteoric water. This process is called karstification. Karstification has therefore an extreme influence on the hydrodynamical properties of a carbonate layer, and indirectly on the temperature. Karstification constitutes, therefore, an important process to be understood by hydrogeological investigations. The hydrogeological context is treated in Section 5.3.

Finally the productivity of a geothermal reservoir depends on its temperature. The estimation of the temperature at depth constitutes one of the main objectives of this study. The methodology used to estimate the temperature will be presented in Chapter 5, together with the main results. The basis for the applied methodology is presented within this chapter (geological and hydrogeological context). Geothermal processes, not directly related to the geological and hydrogeological context, such as direct temperature measurements, heat flow map, thermal conductivities, are treated separately in section 5.4.

## 5.2. Geological context

### 5.2.1. Overview

Lebanon is mainly composed of carbonate platform sedimentary rocks deposited since Paleozoic times at the northwestern margin of the Arabian plate (see section 5.2.2). The exposed Lebanese sedimentary sequence is made up predominantly of marine carbonate rocks ranging in age from Early Jurassic to Recent, with a total stratigraphic thickness in the order of 5,800 m (Nader & Swennen, 2004). Older sedimentary rocks (Paleozoic to Early Jurassic) are not exposed in Lebanon. They are believed to have a thickness ranging between 2,800 and 3,300 m (Nader & Swennen, 2004), based on paleogeographic considerations and facies correlation (Beydoun, 1977).

The sedimentary sequence has been deformed and fractured by several tectonic phases that occurred in the past. These tectonic elements are responsible for the present shape and geological structure of Lebanon (see section 5.2.3). They include the Palmyride Basin, the Levantine Margin, the Syrian Arc fold belt and the Levant Fault system. A description of these elements could be found in Nader (2011). Seismicity and volcanic activity are both related to tectonism. These topics are presented in sections 5.2.4 and 5.2.5, respectively.

Dubertret (1955) established the reference geological map of Lebanon as well as the stratigraphic nomenclature further used in this report, e.g. J1, C2... This nomenclature has been discussed later on in the literature review made by Walley (1997). The reference geological map is reproduced in Figure 5-1<sup>3</sup>. Typical NW-SE cross-sections of North Lebanon and South Lebanon are presented in Figure 5-2.

If the surface geology is extensively described in Lebanon, the older and deeper structures are much less known and are not well documented. A few exploration O&G boreholes have been drilled between the 1950's and the 1970's. These boreholes have failed to encounter oil and gas in commercial volumes. These boreholes are: *Terbol, El Qaa, Sohmar, Yohmor, Tell el Znoub, Adloun, Aabrine* (see location and depth in Figure 5-5)<sup>4</sup>. A well correlation plot is given in Figure 5-4. Detailed logging data can be found in the literature (Beydoun, 1977; Ukla, 1970). Some of these boreholes reached the top of the Jurassic rocks but unfortunately none of them have reached the base of the Jurassic. Moreover no extensive onshore seismic exploration is nowadays available or accessible in Lebanon. Finally, most of the Oil and Gas literature focuses on the off-shore geology and on the coastal Neogene deposits in North Lebanon (see example of Figure 5-3). For the deeper on-shore structures most of the information provided in this chapter is derived from studies performed in the surrounding countries.

The detailed stratigraphy from Jurassic to Quaternary is provided in the Lebanon Stratigraphic Columns of Figure 5-6.

<sup>3</sup> The geological map is available in high-resolution format in the accompanying CD.

<sup>4</sup> The state of these boreholes is unfortunately not well documented. Surface investigations have been performed in the framework of this study. They allowed determining that these boreholes are most likely to be closed and cemented.







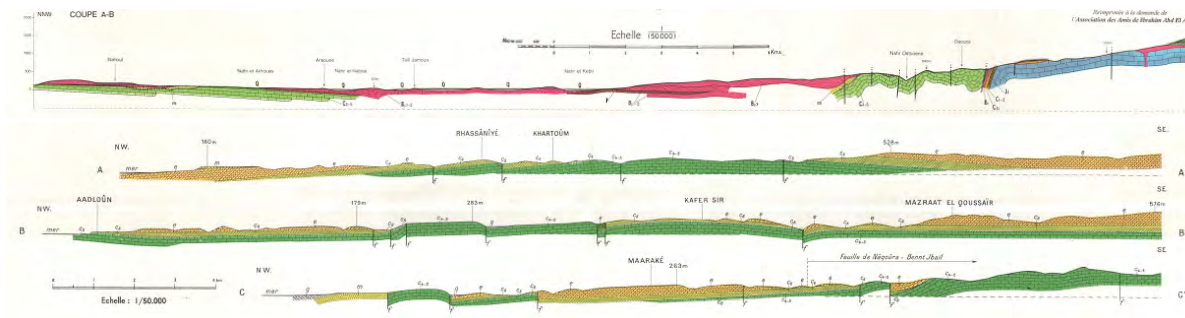


Figure 5-2: Typical NW-SE cross-sections of North Lebanon (top) and South Lebanon (Bottom). Source: (MEW)

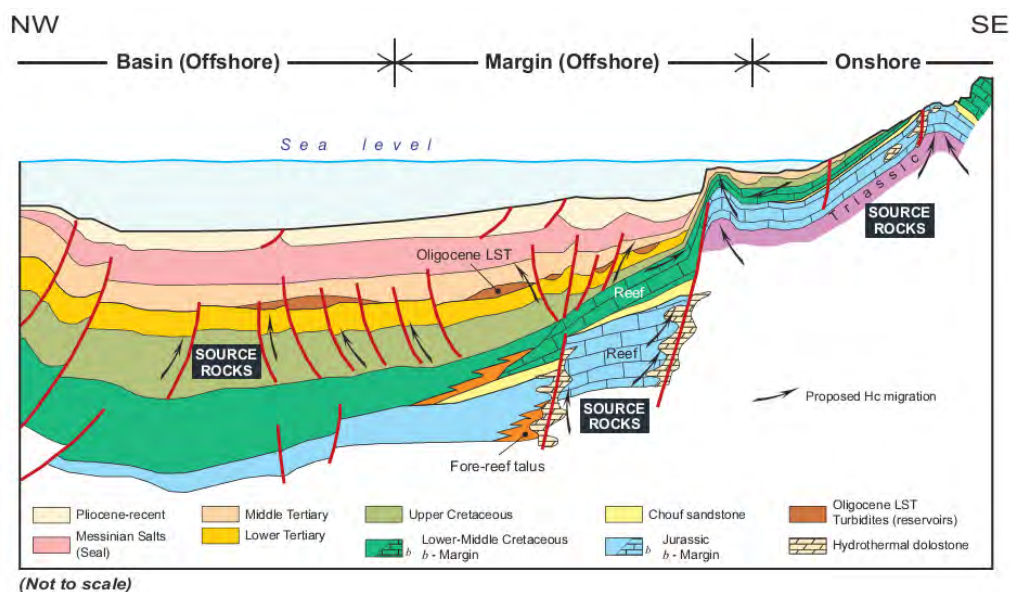


Figure 5-3: Schematic petroleum system model for Lebanon, with possible Plays offshore, in the continental margin and onshore. Potential source rocks (e.g. Upper Cretaceous strata, (pre-)Triassic rocks), reservoirs (e.g. Oligocene LST sandstones, Triassic dolostones) and seals (e.g. Cenozoic shales and evaporites) are indicated (Nader, 2011)

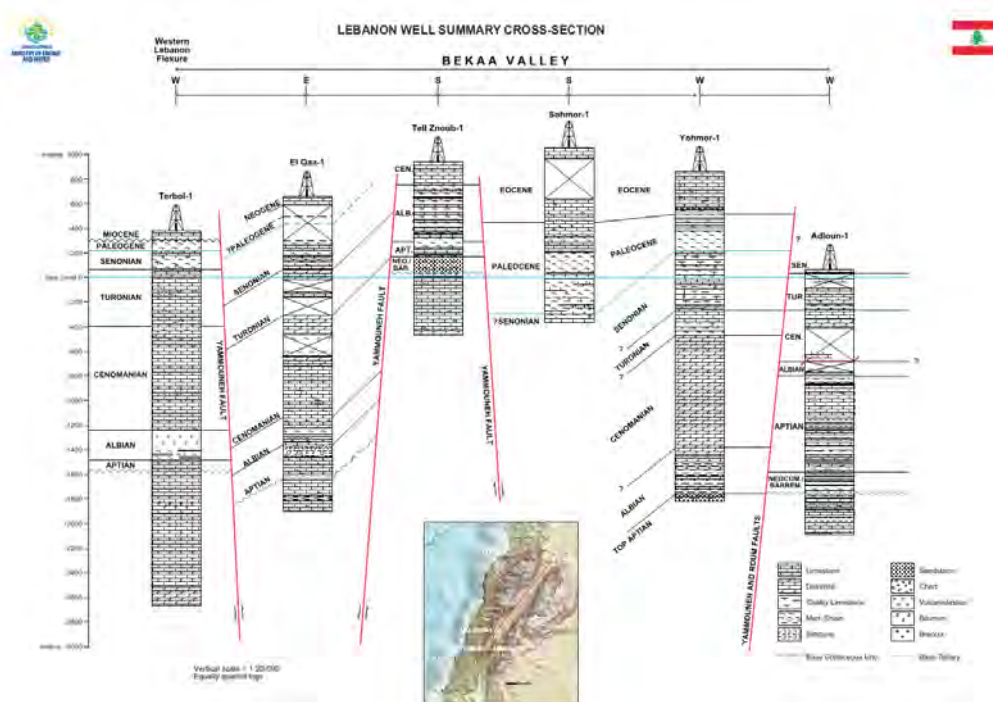


Figure 5-4: Well correlation (MEW)

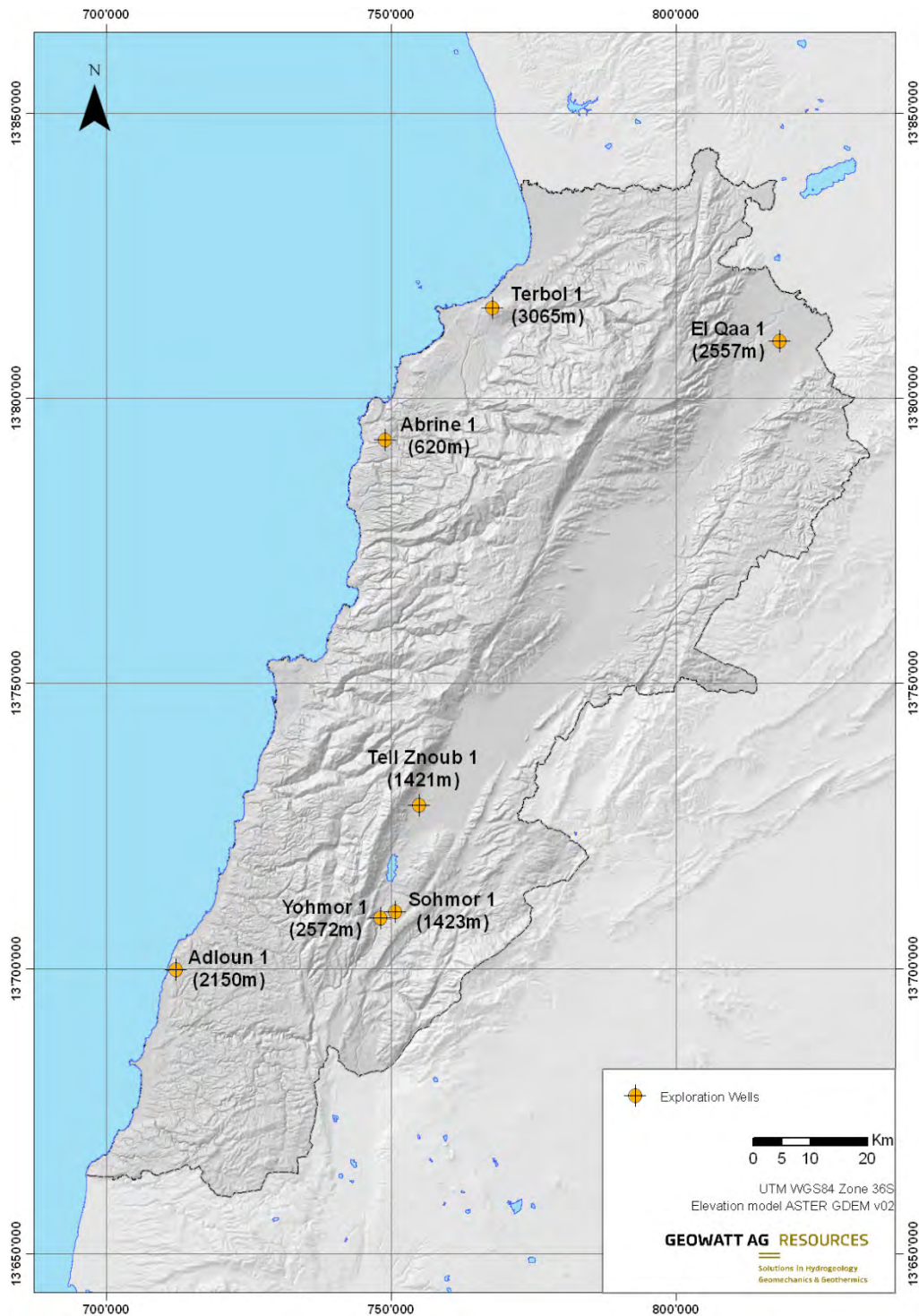


Figure 5-5: Location of the 7 oil and gas exploration wells. Maximum depth below ground level reached by the wells is indicated in brackets



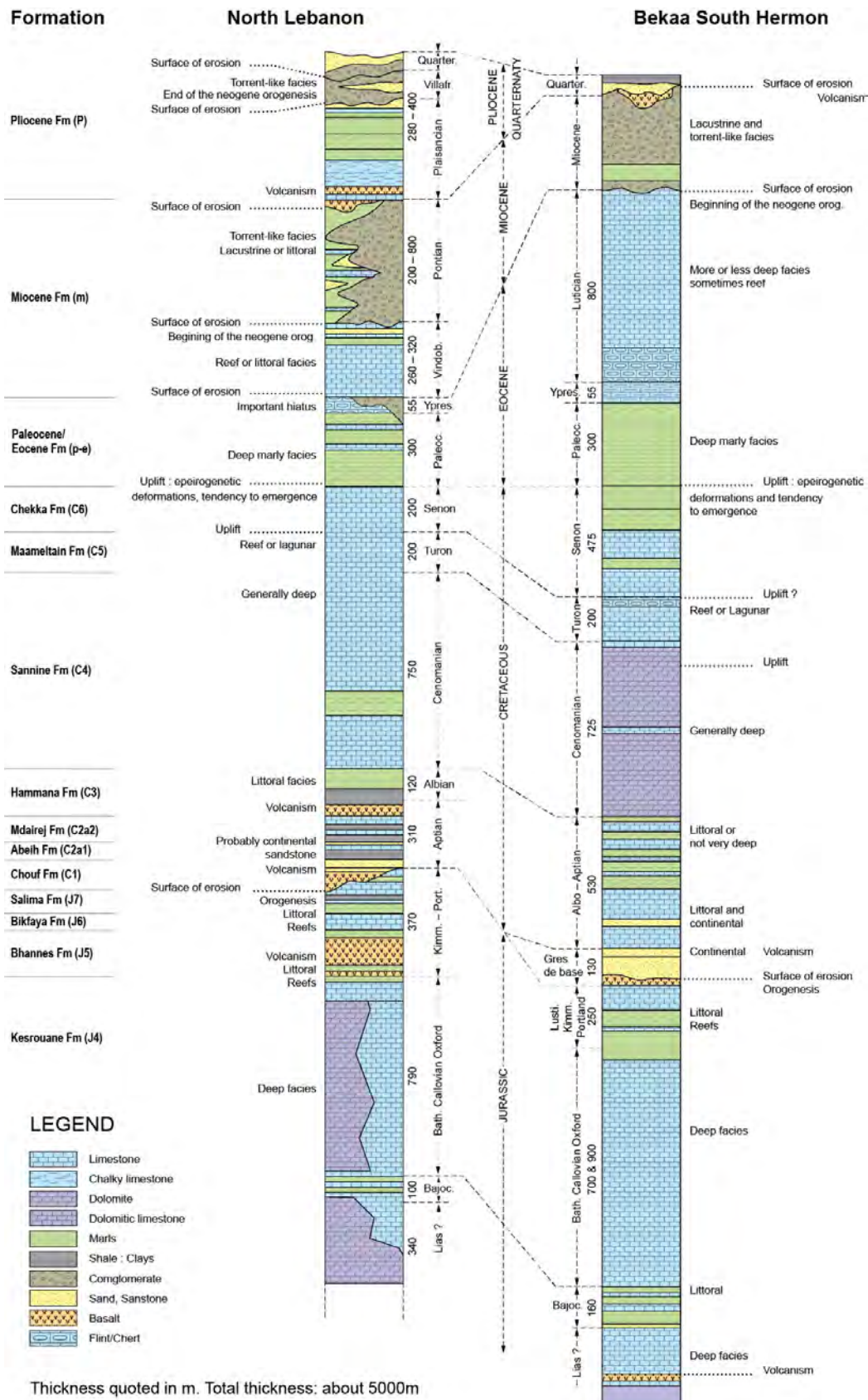


Figure 5-6: Detailed stratigraphic columns of North and South Lebanon (Modified after Renouard, 1955 and MEW)

## 5.2.2. Stratigraphy

### 5.2.2.1. Paleozoic to Late Triassic (620 Ma – 206 Ma)

Paleozoic to early Triassic rocks are only found at depth, below the Jurassic units. Therefore, these rocks are not outcropping in Lebanon. Moreover no information could be derived from the existing deep boreholes. Information is thus derived and extrapolated from geological studies performed in Syria (Brew et al., 2001). These units are briefly described in this section for the general understanding of the regional geology. The description mainly follows the review made by Brew et al. (2001) and Nader (2011).

During the Cambrian period, the erosion and the decomposition of the newly consolidated granitic basement resulted in the deposition of shallow marine clastic sediments in an interior sag near the northern edge of the Gondwana continent. Cambrian rocks are thus supposed to be composed in the South of arkosic sandstones together with some siltstone and shale (Brew, et al., 2001). Ordovician strata were deposited across a wide epicontinental shelf that was especially well developed on the northern and eastern margins of the Arabian Plate. The thickness of the Ordovician strata increases southeastwards from Aleppo to Rutbah and Jordan. The thickness could be comprised between 1.6 km and 3.5 km. Regarding the lithology, sandstones pass into siltstones and shales (Nader, 2011; Brew et al., 2001). In the Early Silurian period, most of Arabia was flooded due to the melting of glaciers. It resulted in the deposition of siltstones and shale of about 500 to 1,000 m thick. This shale constitutes one of the major sources of rocks for the oil and gas industry. Total thickness of the Silurian to Ordovician layer could reach a total thickness greater than 4500 meters. Late Silurian and Devonian rocks are generally absent in the region.

A strong change of the deposit environment happened in the Carboniferous period, with the formation of the extensive Palmyride Basin. With a total thickness exceeding 1,700 m, Carboniferous succession is composed of sandstones, and sandy shales, together with minor carbonates. Transgressive sedimentation dominates during Permian and persisted until early Triassic. The Lower Triassic Amanous Formation forms the basal unit. Permian to Early Triassic rocks are siliciclastic and could reach at total thickness exceeding 1,000 m.

By the end of the Early Triassic period, rifting in the Palmyrides had ceased (Brew et al., 2001). Middle to Late Triassic rocks are thus dominated by restricted-water dolomite interbedded in some locations with anhydrites. The content in evaporite<sup>5</sup> increases progressively in the upper section of the sequence. It forms the Kurrachine dolomite, which is overlaid by the Kurrachine Anhydrite.

The Late Triassic period is characterized by a return to limestone interbedded with anhydrites and dolomites. Late Triassic is restricted to the Palmyride Basin (Nader, 2011).

The Triassic rock has a total thickness ranging between 500 and 1,100 m (Nader, 2011).

<sup>5</sup> Evaporite describes sediments that are deposited from aqueous solution as a result of extensive or total evaporation. Examples include anhydrite, rock salt, and various nitrates and borates.



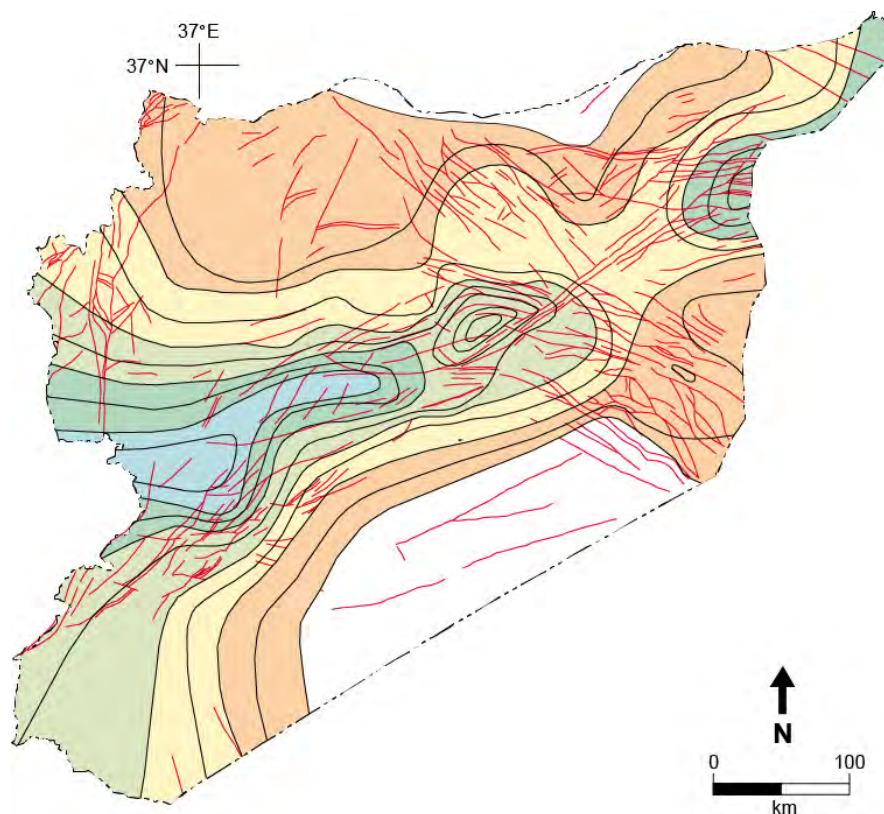


Figure 5-7: Isopach map of Triassic in Syria, as derived from well and seismic data. Contours at 250 m intervals; colored units 500 m thick (after Brew et al., 2001)

#### 5.2.2.2. Jurassic (206 Ma to 142 Ma)

Jurassic strata are the oldest rock surface exposed within the territory of Lebanon. In the absence of wells penetrating into the Triassic, estimates of the total thickness of Jurassic in Lebanon are somewhat very speculative (Walley, 1997). The marine transgression that had begun in the latest Triassic continued through Early Jurassic, covering most of Syria and probably all of Lebanon. Therefore the Liassic sedimentary rocks in the Levantine region have similar lithological characteristics to the underlying Triassic succession. It consists of grey, fine to medium crystalline dolostones, together with intervals of limestone and marls. The lagoonal-evaporitic depositional environment passed progressively into deeper marine conditions and resulting facies modification (mudstone, wackestone) (Nader, 2011). According to Ukla (1970), Liassic rocks are supposed to have a thickness of around 300 to 350 m.

The Middle Jurassic (Aalenian to Oxfordian, J2-J4, Dogger) succession is represented by undifferentiated dolomicrite over 1,000 m thick. Late Liassic to Kimmeridgian succession is made up of shallow marine carbonates, marls/shales with some interbedded volcanics. The total deposited sequence in the area of Mount Lebanon would be around 1,420 m thick. Due to erosion processes in Mount Lebanon or Anti-Lebanon, the thickness of the sequence is considerably reduced.

Part of this sequence is the Kesrouane Formation (J4), composed of massive bedded limestone and dolomite, Late Liassic to Oxfordian in age (Figure 5-8). Kesrouane Formation has been intensively fractured and karstified during the later emergence of the Mount Lebanon. This formation consists of the main water tower in Lebanon and is one of the target aquifers for geothermal exploration in Lebanon. The total thickness of the Kesrouane Formation is supposed to be between 700 to 1,000 m.

Above the Kesrouane Formation, the Jurassic strata have become more diverse. The first overlying unit is the Bhannes volcanic complex (J5) mainly composed of limestone and clays, locally in alternance basalts and tuffs. The thickness of the Bhannes volcanic could vary locally from 50 m to 150 m.

The Bhannes Volcanics are overlain by the Bikfaya Limestone Formation (J6), Late Kimmeridgian to Early Portlandian (Tithonian) in Age, representing the return of the sea in the area. It consists of a massive bedded carbonate rich in chert nodules. The thickness of this unit can vary very rapidly but is probably around 60-80 m (Walley, 1997).

The Bikfaya Formation is overlain by the Salima Limestone Formation (J7), Tithonian-Portlandian in age. It is a variable thin-bedded sequence of oolitic limestone in alternance with marls. Thickness vary enormously mainly due to pre-Chouf Formation erosion and ranges from 180 m to only a few meters (Walley, 1988).



Figure 5-8: Overview (left) and outcrop (right) of the micritic Limestone of the Kesrouane Formation (Photos Chloé Asmar)

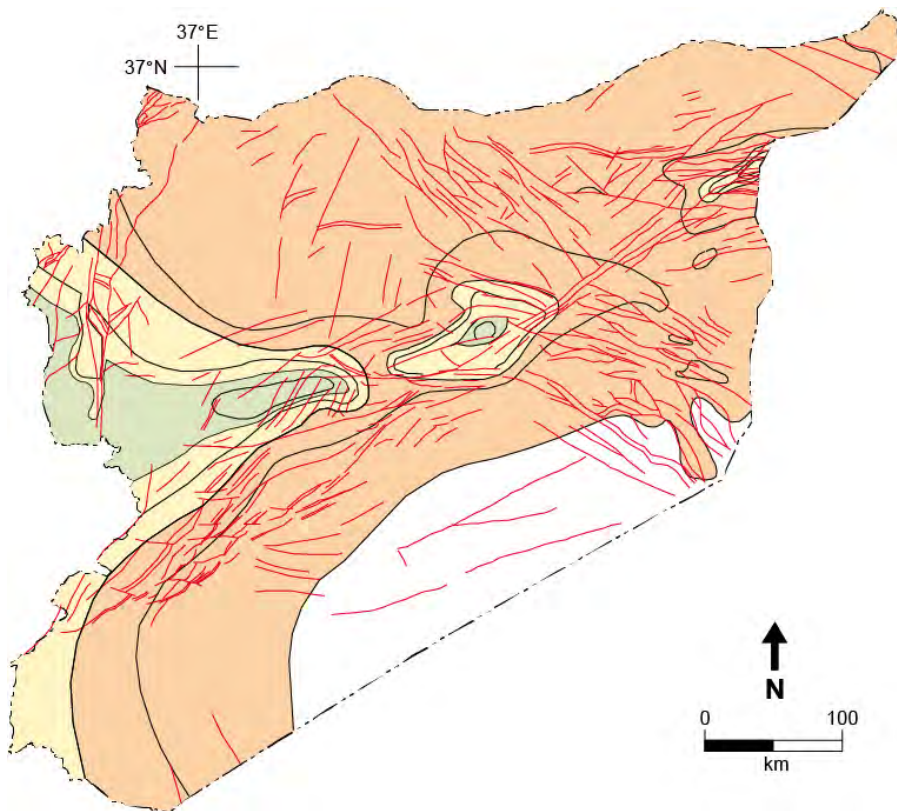


Figure 5-9: Isopach map of Lower Cretaceous and Jurassic in Syria, as derived from well and seismic data. Contours at 250 m intervals; colored units 500 m thick (after Brew et al., 2001)

### 5.2.2.3. Early Cretaceous (142 Ma to 97 Ma)

Due to volcanic activity together with associated uplift, emergence and erosion continued into the Early Cretaceous, resulting in a sedimentary hiatus lasting some 25 Ma (Nader, 2011).

In the Early Cretaceous (Upper Neocomian to Barremian) most of the areas of the northern Arabian platform was covered with hundreds of meters of fluviodeltaic to shallow-marine sands, which composed the Chouf Formation (C1).

The sandstones pass gradationally up into Late Barremian-Early Aptian nearshore carbonates. The facies could be oolitic

or sandy, such as for the Abeih Formation (C2,a1), 80 to 170 meters thick, and more reefal, such as the Mdairej Formation (C2a2), around 50 meters thick.

The surface-exposed Hammana Formation (C3), Albian in Age, indicates a short return to near-shore, supra-tidal conditions, during which clastics were deposited, before a sea-level rise in the Late Albian (Nader, 2011). The thickness of the Hammana Formation is estimated to be from 140 m to 400 m thick.

#### 5.2.2.4. Late Cretaceous (97 Ma to 65 Ma)

In general, slow subsidence and the stability of the relatively low sea-level resulted in the deposition of platform carbonates, Albian to Turonian in Age, across most of Syria and Lebanon.

The Sannine Formation (C4) is characterized by thin-bedded, chalky and cherty sediments in its coastal facies in the West and by supratidal-peritidal environment facies as well as reefal and lagoon settings in the East. The Sannine Formation is around 600 to 700 m thick. The Sannine Formation is of particular importance for this study as it is considered as an excellent aquifer and the second water tower of Lebanon.

In Lebanon, the Maameltain Formation (C5), Turonian in Age, has an average thickness of 200 to 400 m and was deposited during shallow marine conditions.

An unconformity marks the Turonian-Senonian boundary within the Palmyride Basin. A transgression occurs during Senonian resulting in the flooding and drowning of the Cenomano-Turonian platform carbonates and in the deposition of fine argillaceous limestone in the outer part of the platform. The total thickness of the Chekka Formation (C6) could reach 600 m in Lebanon.



Figure 5-10: Outcrop of the light grey micritic limestone of the Sannine Formation overlying the brownish marls and limestones of the Hammama Formation (Photos Chloé Asmar).

#### 5.2.2.5. Paleocene to Oligocene (Paleogene, 65 Ma to 24 Ma)

The early stages of the Cenozoic period witnessed stable conditions continuing from the Cretaceous period with marly limestone as major deposits reaching a thickness of up to 900 m. It continued until the late Eocene period in which the first stages of uplift of Lebanon occurred. The formations from Late Eocene to Mid Miocene are missing. Some deposition occurred however during the Mid Miocene (see section 5.2.3 about tectonism). The Paleogene (Paleocene to Oligocene) was largely a time of quiescence in the northern Arabian Platform and most of the platform remained under marine conditions (Brew et al., 2001; Nader, 2011).

Maastrichtian to Early Eocene strata are characterized by an increase in marly content, indicating greater water depths in a low-energy open-marine environment. The Paleocene consists of a monotonous succession of pelagic marly limestones (Brew et al., 2001). The Lower and Middle Eocene appear to occur in two facies; one is a chalky marly limestone often with chert concretion which occurs within basins. The other facies is a nummulitic limestone which is found on the basin margins on the South (Walley, 1997). This sequence reaches a total of at least 900 m in the southern Bekaa and about 450 m at Zahle. In Lebanon, marine deposition in isolated depocenters persisted until the Middle Eocene.



### 5.2.2.6. Miocene to Pliocene (Neogene, 24 Ma to 2 Ma)

In the Neogene, the opening of the Red Sea and activity on the Dead Sea Transform Fault and the Levant Fault System accentuated the uplift of the Mount Lebanon and resulted in the regional-scale present-day topographic structure (Nader, 2011). Sedimentation therefore only occurred in the coast and in the Bekaa basin. Miocene deposits have distinct facies. Coastal facies of the Nahr El Kalb Formation and of the Jebel Terbol Formation are composed of littoral limestone and conglomerates and beach rocks. The Miocene section in the coast has a thickness ranging between 200 to 300 m.

In the Bekaa basin, Miocene deposits are composed of alluvial fan and lacustrine clastics up to 1.5 km thick (Walley, 1997).

Further marine regressions occurred in Late Miocene times as evidenced by hiatuses and deposition of evaporites correlative with the Messinian crisis.

The Pliocene sequence shows a progression towards continental deposition with some volcanism (Brew et al., 2001; Nader, 2011). In Lebanon the basal Pliocene is marked by an important transgression. In the Akkar and Bekaa regions, Miocene rocks are overlain by fluvial and lacustrine sediments, Pliocene to Pleistocene in age. The thickness is variable and could reach 500 m.

Volcanism is represented by basaltic effusions and plumes (see section 5.2.5).

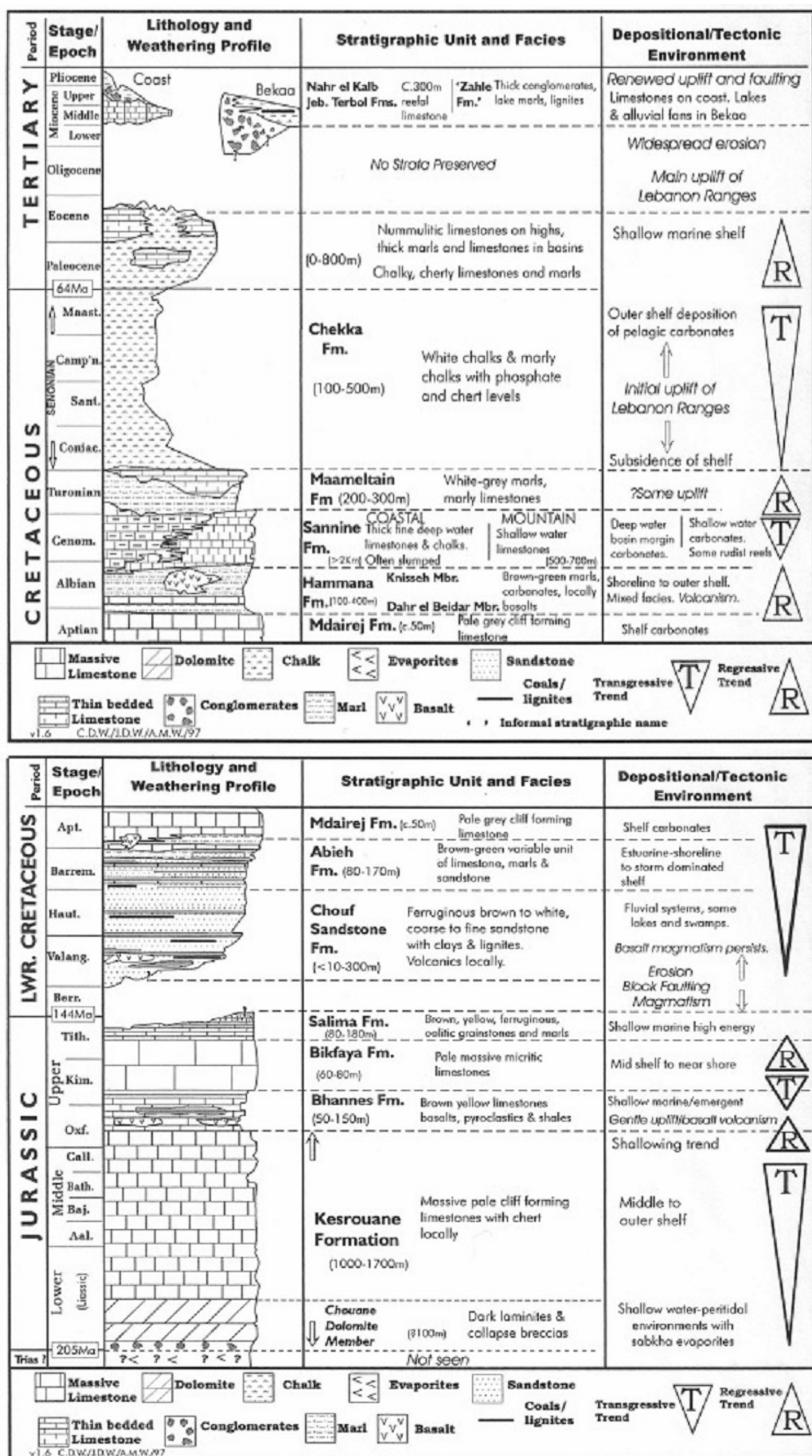


Figure 5-11: Simplified stratigraphic column for Lebanon (Walley, 1997)

### 5.2.3. Tectonic context and neo-tectonic

Lebanon lies along the 1,000 km long left-lateral or sinistral Dead Sea Transform Fault (DSTF) or Levant Fault System (LFS). The southern segment of the DSTF extends from the Gulf of Aqaba to the Hula depression in South Lebanon. This segment, also known as the Dead Sea Fault (DSF) or Jordan Valley Fault (JVF), has a fairly simple geometry and strikes in an approximate N-S direction. Upon entering Lebanon from the South however, it branches into a more complex system of braided faults (Walley, 1988) also known as the Lebanese Restraining Bend (LRB). When leaving Lebanon in the North, the DSTF resumes its N-S direction as the Ghab fault. In southern Turkey the DSTF meets the East Anatolian Fault system (EAF).

Figure 5-12 shows the main faults within Lebanon as well as many smaller and shallower faults that cover the country's surface. Until relatively recently the main active faults within the LRB were thought to be the Yammouneh, Rachaya, Serghaya and Roum faults.

A brief description of the main faults of Lebanon is indicated below (after Huijer, 2010):

- **Mount Lebanon Thrust:** the Mount Lebanon thrust is a newly identified 100-150 km long crustal thrust fault (reverse fault with small dip angle).
- **The Yammouneh fault:** the Yammouneh fault is the main link within the LRB between the Ghab fault and the Dead Sea fault. The fault is approximately 170 km in length, strikes NNE-SSW and is a primarily left-lateral strike-slip fault.
- **Rachaya-Serghaya Fault System:** Both fault traces run almost parallel to each other along the Anti-Lebanon mountain range. The Rachaya fault is approximately 45 km long and traces along the western flank of the Anti-Lebanon Range. The Serghaya fault is 100-150 km in length and traces from the south-eastern to the north-western flank of the Anti-Lebanon Range. In general, both faults strike approximately NNE-SSW and display left-lateral strike-slip movement.
- **Roum Fault:** The Roum fault branches from the Dead Sea fault in South Lebanon, runs along the south-western boundary of the Mount Lebanon range and is around 35 km in length. The fault is an oblique left-lateral thrust ramp, and strikes approximately NNW-SSE.
- **Zrariye-Chabriha fault:** a 26 km long reverse fault.
- **Niha thrust:** it is a 20 km long NW-dipping active thrust which goes from the Yammouneh fault to the NE.



Figure 5-12: Structural Maps of Lebanon (modified after Elias et al., 2007). Ar-Arqa; Ba-Batroun; By-Byblos; Ch-Chekka; Sa-Sarafand. AT – Aakkar Thrust; GhF – Ghab Fault; Mt. Lebanon Thrust; NT – Niha Thrust; RaF – Rachaya Fault; R-AF – Rankine Aabdeh Fault; RF – Roum Fault; SaF – Saida Fault; Serghaya Fault; TT – Tripoli Thrust; Yammouneh Fault; ZCF – Zrariye-Chabriha Fault; DSF – Dead Sea Fault



## 5.2.4. Seismicity

Seismicity is of major concern for geothermal projects as a change of the fluid pressure in the reservoir could result in inducing seismicity. As Lebanon is located in an active tectonic environment where the seismic hazard is considered to be moderate to high, the seismicity aspects have to be assessed with care.

A distinction is done between the natural seismicity and the induced seismicity. Natural seismicity describes seismic events or earthquakes that occur naturally in a specific area. Induced seismicity is related to events that are induced by an anthropogenic activity in the underground.

Seismicity has to be considered for two major purposes:

On the one side, active seismic areas are related to active fault systems. An active fault system is a good indicator of the presence of fluid circulation at depth. This constitutes one of the major site screening criteria for a geothermal project.

But on the other side, depending on the kind of geothermal installation, the development or the exploitation of the reservoir could induce seismicity. Depending on the stress conditions of the underground, a fault could be likely to be reactivated and to induce an earthquake.

This topic constitutes one of the most advanced research fields in the domain of geothermal activity (see GEISER project, for instance) and cannot be solved in the framework of this study.

The risk of inducing seismicity cannot be cancelled. However, a range of tools could be applied to reduce the risk of induced seismicity and to determine if the residual risk is acceptable or not. This point will be developed later on in this report, in Chapter 8, related specifically to the environmental aspects.

Earthquakes are monitored and analyzed through a network of seismological stations. These seismological stations are positioned all over Lebanon. Seismological stations located all over the world could also detect large magnitude earthquakes. Additional seismological stations are implemented temporarily or permanently for the specific needs of a project. The first tool to be applied to reduce the risk of induced seismicity is to design and implement a seismological network to monitor the natural seismicity within a given region. In Lebanon, the National Center for Geophysical Research of the National Council for Scientific Research (CNRS) is responsible for the monitoring of seismology. The natural seismicity of Lebanon is presented in Figure 5-13.

Based on the seismology data and taking into account the recent discovery of the offshore thrust fault system (Huijjer et al., 2011) concludes that the Yamouneh fault, the Mount Lebanon thrust as well as the Rachaya, Serghaya and Zrariye-Chabriha faults are assumed to be active faults. All major earthquakes are assigned to these faults. According to (Huijjer et al., 2011) all remaining earthquakes are assigned to the Lebanon region area source as background seismicity, which accounts for the seismic activity on the many other smaller faults.

The hazard map (established by Huijjer et al., 2011) is reproduced in Figure 5-14. indicates that the hazard is high in the central part of Lebanon and moderate to high in the rest of the territory, except the Tyr area, where the hazard is considered to be moderate.

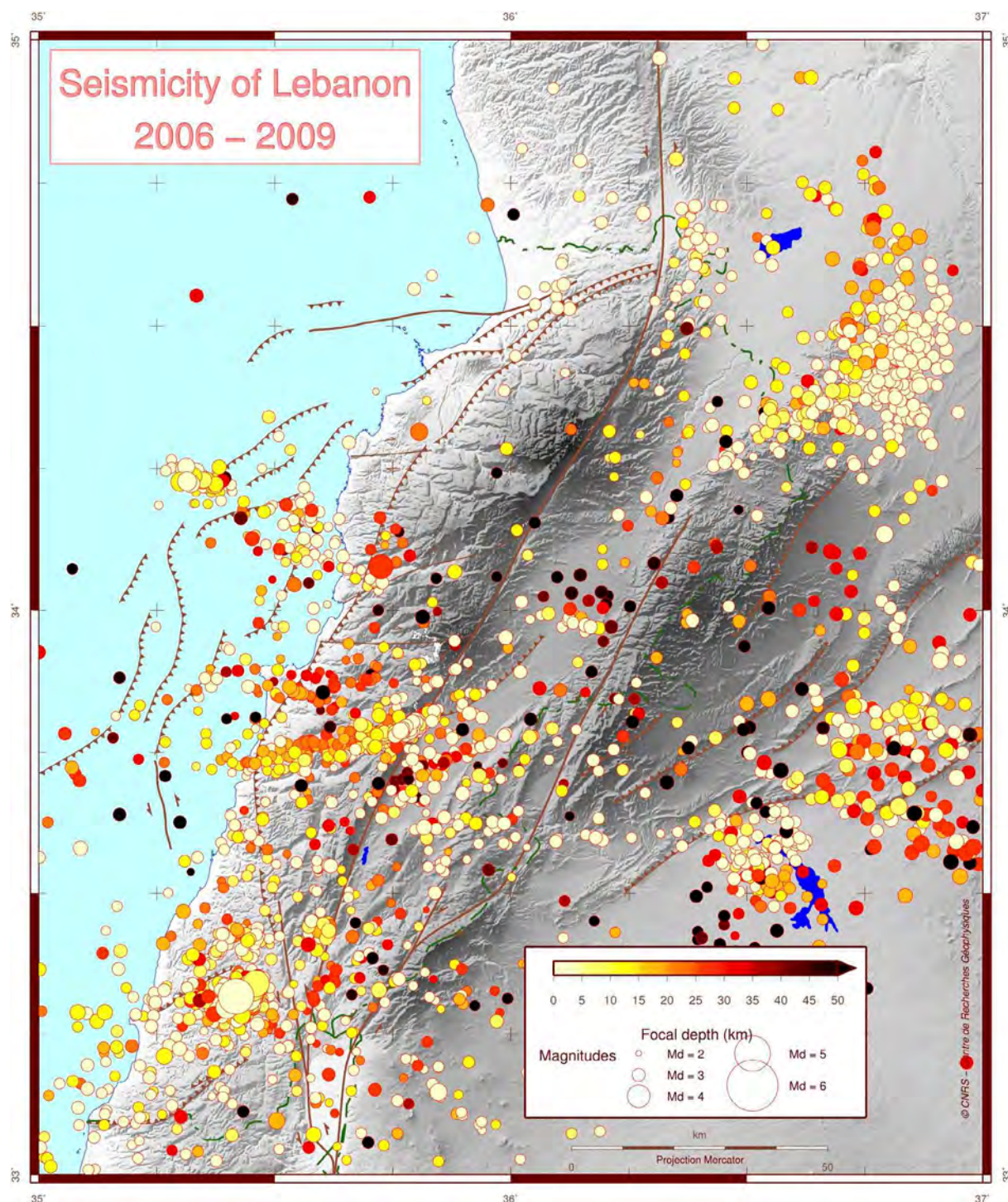


Figure 5-13: Seismicity of Lebanon, 2006-2009 with magnitudes (CNRS)

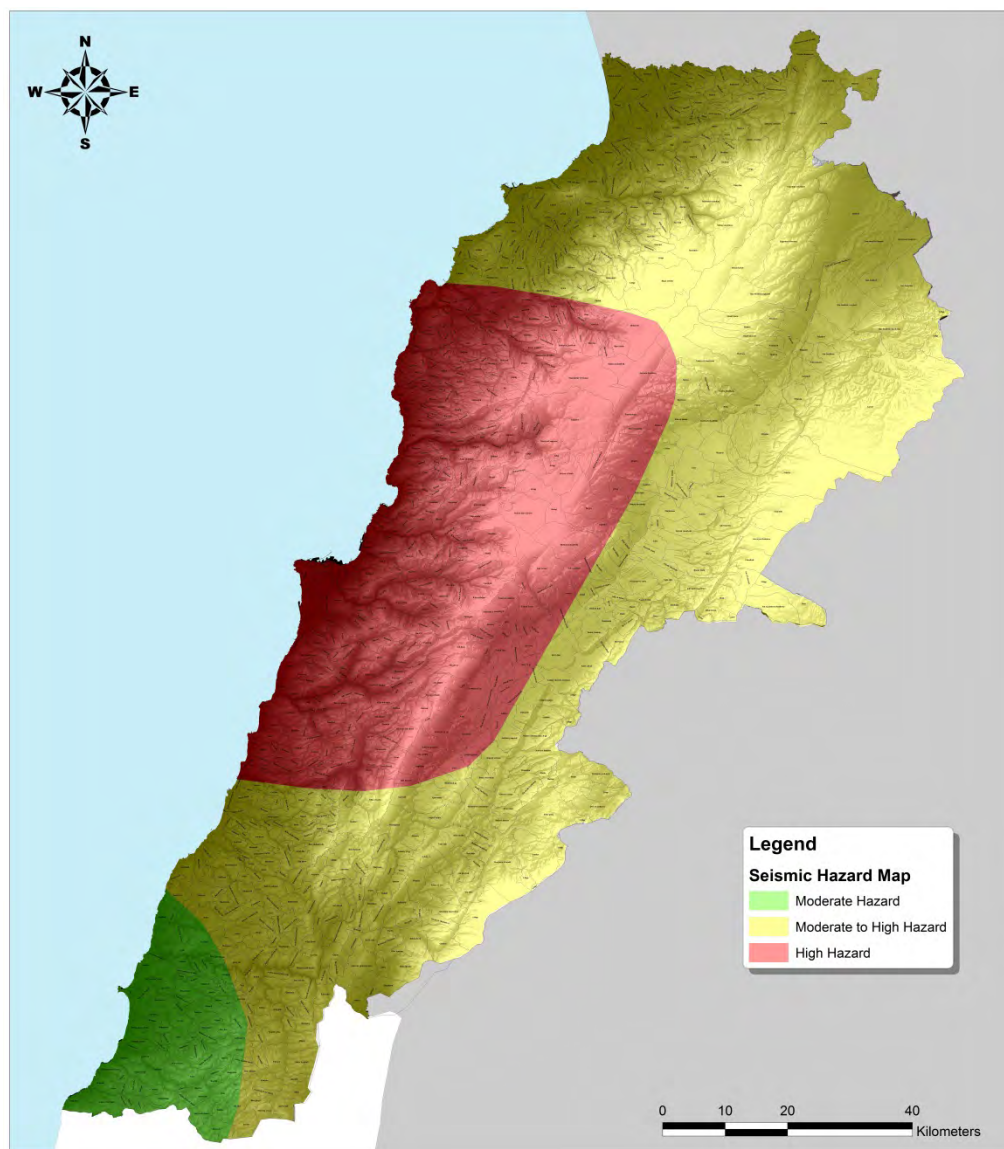


Figure 5-14: Seismic Hazard Map of Lebanon (Harajli, written communication, after (Huijjer et al., 2011))



### 5.2.5. Volcanism

There is no current volcanic activity within Lebanon. However volcanic activity had occurred during two main episodes in the past.

Continuous marine settings prevailed in Lebanon without interruption until the end of the Jurassic period when major tectonic movements started (Dubertret, 1955; Renouard, 1955; Walley, 2001). These movements were associated with hot spot volcanism leading to a local orogenic crisis affecting the Jurassic platform in northern Lebanon resulting in an uplift of northern Mount Lebanon during the Late Jurassic to Albian. During the first episode there was a widespread but temporary eruption of basalt lava and ashes from a number of vents. Lava flows, scories and tuffs of this episode are found in alternance with the marine carbonate layers. Due to their age (150-100 Million years), volcanic rocks of the first episode are now cold, and the related magmatic chambers are considered not active anymore. Therefore these volcanic episodes and associated rocks are not considered as relevant in terms of geothermal use.

More relevant in terms of geothermal use are the volcanic rocks that were deposited during a second episode that occurred within the last 50 million years, from Miocene, Pliocene and recent times (Quaternary). During that period, large-scale basaltic volcanism occurred in two main regions, the Akkar region in the North and in the Golan Plateau in the South. Mouty et al., (1992) have described the volcanic rocks.

In the North, the Homs Basalts mainly present in Syria extend into Lebanon in both the Akkar and the Hinayder regions. According to Dubertret (1955), the Homs Basalts are Pliocene in age (5.3 to 2.6 million years). The outcropping extent of the basalt in Lebanon is around 150 km<sup>2</sup> for the Akkar region and 20 km<sup>2</sup> for the Hinayder region. The real extent of the basalts is bigger as they certainly extend below the quaternary sediments that deposited on the top of the basalts. The exact extent of the basalt deposits is therefore unknown.



Figure 5-15: Miocene to Pliocene basaltic lava flow in North Lebanon (Photo: Chloe Asmar)

Basalts are also present in the extreme southeast of Lebanon where the Golan and Jebel Druze volcanics occur round Mount Hermon, in the Kaoukaba and Kel-Ghajar regions. The outcropping extent of the lava in both regions is around 15 km<sup>2</sup> and 35 km<sup>2</sup>, respectively. Again, the basalts might extend below more recent deposits present in the area. The Golan volcanism in particular seems to have died out very recently, probably within the last 10,000 years.

Shaban (2010) denominates these four regions as geothermal domains and provides a description of the basalt characteristics (see Table 5-1).

Although the basalt itself is considered as cold, the presence of a magmatic chamber in both areas with residual heat is most likely probable. In the Akkar region, thermal water at a temperature of 41°C has been measured on a 485 m depth well in the Summaqiyyeh Village. The reservoir is the Cenomanian karstic aquifer (see section 5.3.4.4). Karstic aquifers are usually characterized by a constant temperature corresponding to the temperature of the water that infiltrates in the aquifer, supposed to be around 15-20°C. The observed temperature of the Summaqiyyeh wells could only be explained by a strong thermal anomaly in this area. This point is further developed in Chapter 6.

The geographic distribution of basalt in Lebanon is represented in Figure 5-16.

Table 5-1: Specifications of the geothermal domains identified by Shaban (2010)

Geothermal Domain	Basalt Characteristics (according to Shaban, 2010)
Akkar	<ul style="list-style-type: none"> <li>- Massive basaltic plateau dominant with fracture systems</li> <li>- Syenite and tuff occur in different localities and at different levels</li> <li>- Fluid inclusions appear as internal and external vascular pits</li> <li>- Rose-basalt and calcite veins are common</li> </ul>
Hinayder	<ul style="list-style-type: none"> <li>- Basaltic, syenite and tuff occur at various levels</li> <li>- Surficial fluid inclusions are common</li> <li>- Laval flow is featuring in several sites</li> </ul>
Kaoukaba	<ul style="list-style-type: none"> <li>- Block basaltic lava with fumaroles</li> <li>- Fracture systems, mainly jointing is dominant</li> </ul>
El-Ghajar	<ul style="list-style-type: none"> <li>- Massive and boulder basalts,</li> <li>- Vertical joint and fracture systems are well developed</li> <li>- Calcite and iron veins exist</li> <li>- Empty vascular cylindrical veins</li> </ul>

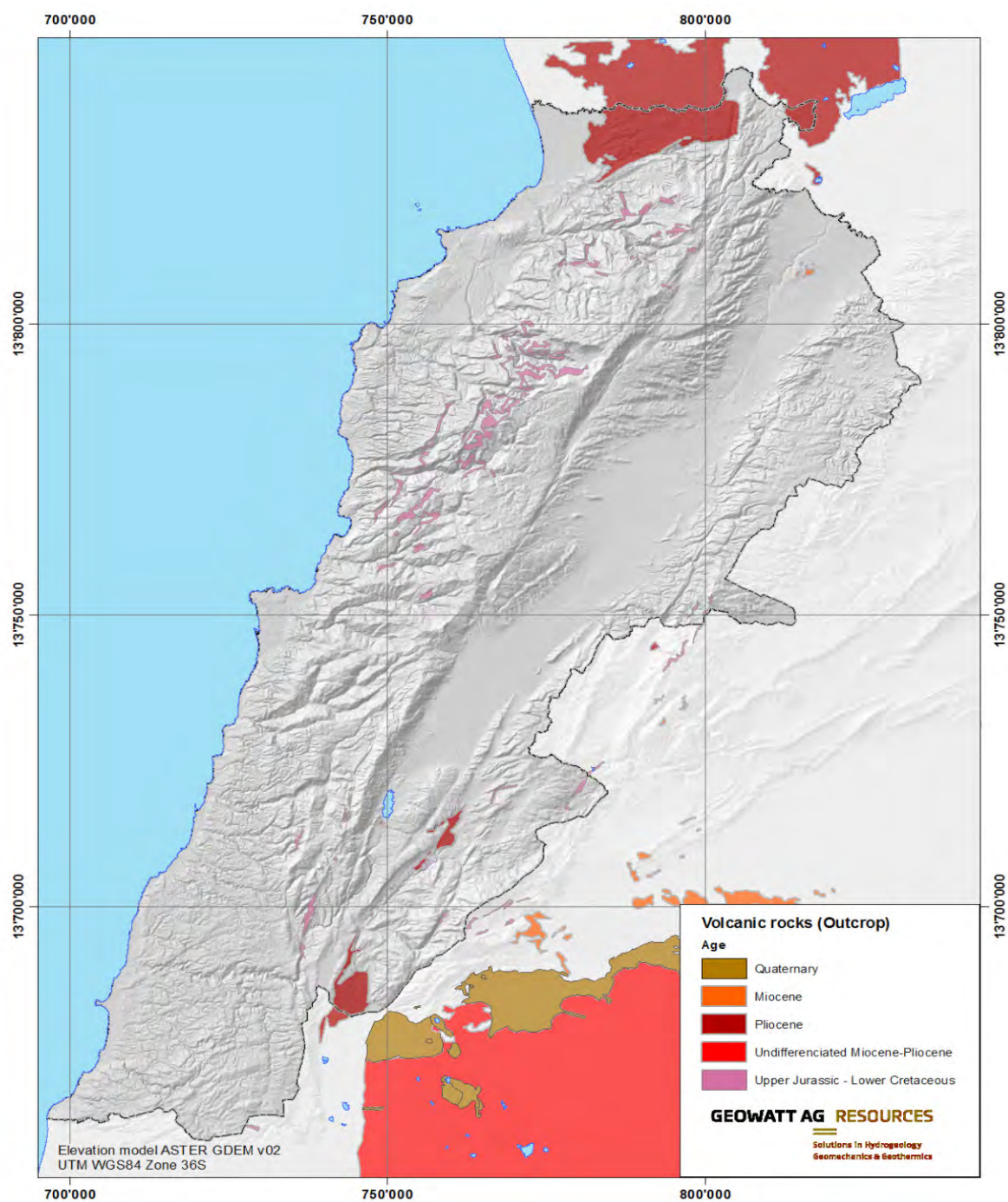


Figure 5-16: Distribution of basalts in Lebanon



## 5.3. Hydrogeological context

### 5.3.1. Introduction

The geological history in Lebanon consisted from the Paleozoic to the Miocene to a succession of transgressive and regressive phases of the sea resulting in the deposition of a succession of layers composed in alternance of massive limestones and of thin marly layers. Several active volcanic episodes occurred during the Jurassic and Cretaceous periods resulting in the deposition of basalts and tuffs, interbedded with the marine limestones and marls. The thickness of the sedimentary sequence is rather approximate but could reach around 9,000 m in total. The marine carbonate rocks ranging in age from Early Jurassic to Recent has a total stratigraphic thickness of 5,800 m (Nader and Swennen, 2004).

Lebanon is located in an active tectonic area. Tectonic activity results in the folding of the layers and an overall uplift, with its paroxysm in the Miocene. This uplift is responsible for the present day's regional topography, with the Mount Lebanon in the West and the Anti-Lebanon in the East. Both Mountain ranges are separated by a syncline, the Bekaa Valley. Precipitation of water is more important in the elevated areas. Therefore water infiltrates into the different rock formations and circulates towards the low elevation areas, by gravity effect. Springs are located in the low topographic areas. Therefore, the topographic relief is one of the key components to understand the groundwater flow systems in Lebanon.

The hydrogeology in Lebanon has been described in the late 60's in the framework of an extensive UNDP programme. A major result was the published hydrogeological map of Lebanon (UNDP, 1967) and the associated documentation (UNDP, 1970), which are the key references. The reference hydrogeological map is reproduced in Figure 5-19. The hydrogeological map summarizes all relevant information related to groundwater. The main component is the hydrogeological map itself, which presents the surface spatial distribution of the different groundwater bodies. The map also indicates the regional main flow direction within the different aquifers. Beside the map itself, the document presents some thematic figures, such as three small scales thematic maps (pluviometry, potential resources and water chemistry), three transversal geological cross sections and a hydrostratigraphic synthesis in the form of a table, with indication of hydrodynamic properties.

The main concern of the UNDP study was related to the use of groundwater for domestic usage and for irrigation. It is therefore focused on the shallow groundwater system. They divided the territory according to the extension of the different shallow flow systems, following the standards of UNESCO, International Association of Hydrogeologists) and IAHS (International Association of Hydrological Sciences (IAH). Each division has hydrogeological units (Figure 5-18). Unfortunately very little information is available about the deep groundwater systems, which is of interest for geothermal use. A more detailed overview of the groundwater flow systems in Lebanon is given in section 5.3.2.

Each of the geological layers could be classified according to their ability to conduct water. This classification leads to the definition of hydrostratigraphic units. The succession of hydrostratigraphic units is called hydrostratigraphy (Figure 5-18). By definition, an aquifer is a hydrostratigraphic unit that is saturated and sufficiently permeable to transmit economic quantities of water to wells or springs. Aquifers have good permeability or transmissivity <sup>6</sup>. An aquiclude is a hydrostratigraphic unit that can store water but has low permeability which limits the flow of water. Aquicludes have low permeability or transmissivity. Because the productivity of geothermal installation depends on the aquifer transmissivity, a hydrostratigraphy has been established for Lebanon. This hydrostratigraphy will then be used to identify target aquifers. The hydrostratigraphy is presented in more details in section 5.3.4.

The difference in altitude between Mount Lebanon and sea level, and the predominance of carbonate rocks in Lebanon offers ideal conditions for the intense development of karstic systems. Karstic aquifers constitute the main kind of aquifer in Lebanon. Karst systems are the result of the dissolution of carbonate rocks (limestone) by carbonic dioxide contained in meteoric water. It develops differentially according to the composition of the different geological layers, i.e. the carbonate content. The understanding of the karst flow systems and their interactions with the geothermal anomalies is one of the key elements of the present study. Karst in Lebanon is described more into details in section 5.3.5.

Finally, tectonism activity that occurred during Miocene is responsible for an intense faulting and fracturing all over Lebanon. Faults could considerably modify the groundwater flow systems and the hydrodynamic properties of aquifers themselves. The relationship between the faults and the aquifers needs to be clearly understood. Their role in terms of geothermal potential is discussed further on in section 5.3.7.

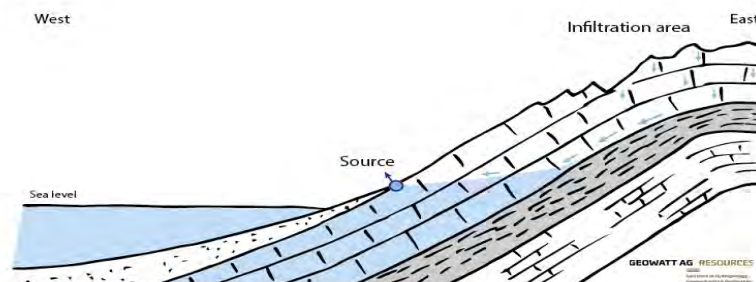


Figure 5-17: Schematic representation of a karstic system. Water infiltrates in the karstic structures in the high topographic area until it reaches an impermeable unit (here in grey)

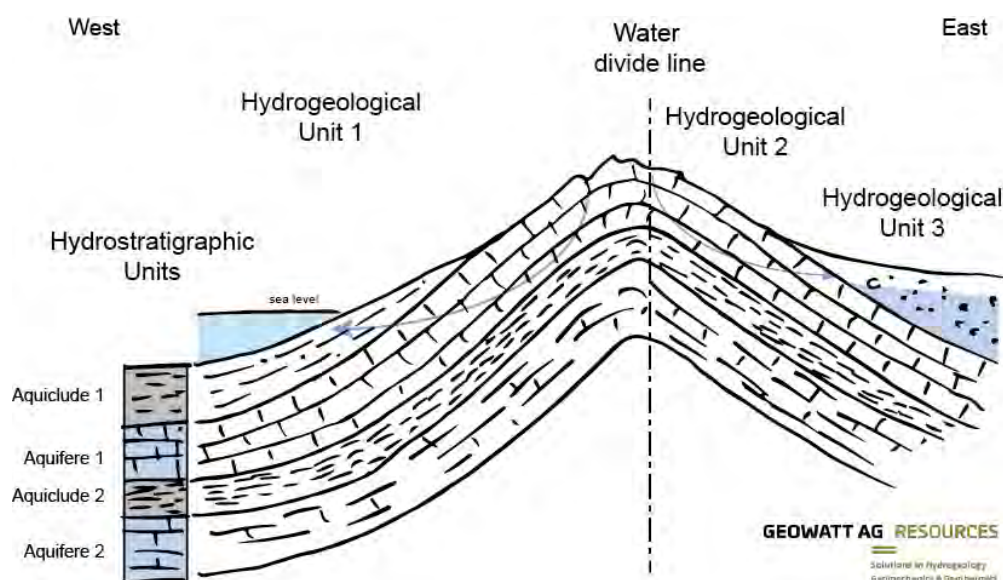


Figure 5-18: Schematic representation of the flow system in Lebanon, and distinction between the concepts of hydrogeological unit and the hydrostratigraphic unit

### 5.3.2. General overview

The UNDP hydrogeological study (UNDP, 1970) delineates two major groundwater flow systems: the Mediterranean Province and the Interior Province. It is indicated that the main groundwater divide border between these two Provinces follows the top of Mount Lebanon, the Jabal Barouk, the Jabal Niha and the Mount Galilee in Lebanon (UNDP, 1970).

These two Provinces are then subdivided into 30 shallow subsystems called hydrogeological units. For each of these units, the resource potential in terms of groundwater for domestic and agriculture usage has been estimated (UNDP, 1970). Results are compiled and presented in the hydrogeological map. This classification has been developed for domestic and irrigation usage and is not appropriated for deep geothermal energy usage. For the latter usage, classification in terms of hydrostratigraphic unit is preferred (Figure 5-18).

The Interior Province is a close water system delimited on the East and on the West by the water level divide lines of the Anti-Lebanon and of the Mount Lebanon mountain ranges, respectively. Outlet areas are then only present in the North and in the South of the Bekaa Valley.

East flank of the Mount Lebanon and the west flank of the Anti-Lebanon are both constituted of limestone, mostly from the Cretaceous. These areas are therefore preferential regions for rainwater to infiltrate and to circulate through the karstic

network. The water exfiltrates in the lower topographic areas of the Bekaa Valley, either in contact with the regional faults (such as the Yammouneh fault) or in contact with lower permeable units (see schematic representation of Figure 5-17). The presence of springs all along both flanks of the Bekaa Valley attests this evidence (see map of Figure 5-19).

In the Bekaa Valley, the uppermost filling material is generally composed of recent Neogene sediments with low permeability. The Eocene limestone that lies below the Neogene constitutes a good aquifer. The resources are widely exploited in the Bekaa Valley for groundwater or irrigation usage (UNDP, 1970).

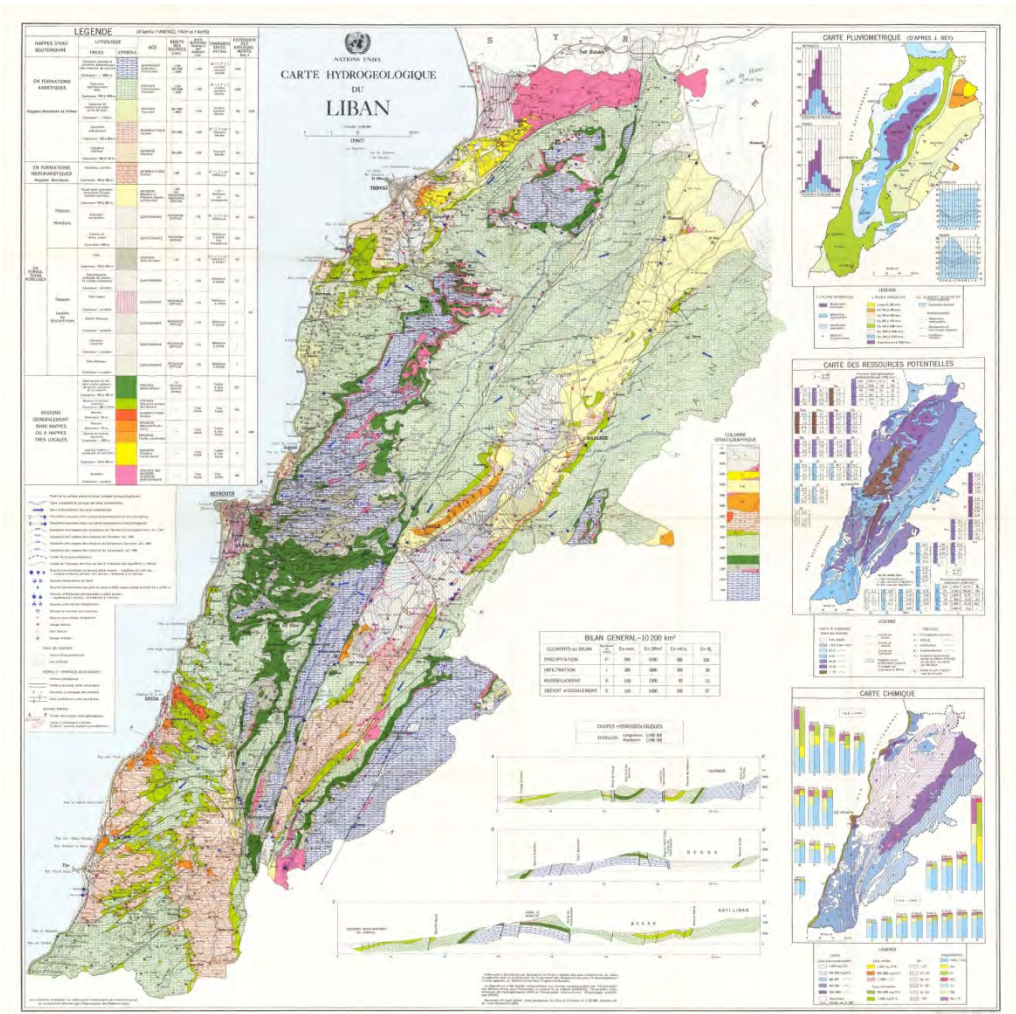


Figure 5-19: Reproduction of the hydrogeological map of Lebanon (UNDP, 1970)

The Mediterranean Province covers the coastal area of Lebanon, west from the main water divide line of Mount Lebanon. It could be separated into three distinguished units: (1) the Mount Lebanon including the Jurassic limestones, the Koura, the Akkar plain, and Beyrouth area; (2) the Barouk and (3) The Jabal Amel in the South. The various groundwater systems have been described in detail in the 1970 UNDP report (UNDP, 1970). Only the general concepts are summarized herein.

Average precipitation yearly rate in Lebanon is 950 mm (UNDP, 1970). On the highest elevated areas precipitation rate is more intense and could be higher than 1,500 mm in the Mount Lebanon, for instance. On average, around 30% of the rainwater directly infiltrates in the karstic structures of the carbonate layers. It could reach over 40% of Mount Lebanon. Infiltrated water then circulates at depth through the fractures and conduits of the rock massive until it reaches impermeable layers. Water then starts flowing along the top of the impermeable layers until it reaches the topographic surfaces, where it could exfiltrate in the form of springs. Depending on the location and on the geological configuration, springs could appear at quite elevated areas or along the coast. In the area where limestone rocks are in direct contact with the sea, springs are present below sea level, such as in the Chekaa region for instance (see Figure 5-21 and Figure 5-22).

Again the overall previous description and the UNDP report are mainly valid for shallow groundwater systems. Shallow groundwater systems describe aquifers generally located until a depth of around 500 m (exceptionally more) that could be exploited for domestic or agriculture usage.

Part of the infiltration water will also circulate more deeply in the rock massive and reach deeper aquifer units. These deep flow circulations are not well documented in Lebanon. Because the water is circulating at greater depth it is supposed to have higher temperatures. The understanding of the deep flow system is therefore important for the geothermal resource assessment.



### 5.3.3. Groundwater wells and springs

#### 5.3.3.1. Shallow groundwater wells

Groundwater constitutes a vital resource in Lebanon, and is therefore intensively exploited for domestic and irrigation use. It is estimated that around 705 million m<sup>3</sup> is pumped every year from the aquifer (Mudallal, 1989). The groundwater is pumped, on the one hand by wells belonging to the national water authorities and on the other hand, by private wells. MEW, in collaboration with the UNDP and the Lebanese Center for Water Management and Conservation (LCWMC), conducted a nationwide groundwater well survey (ELARD & BURGEAP-IGIP-RIBEKA, 2012). The water survey inventoried around 841 public groundwater wells spread over Lebanon. 729 wells are considered active. The remaining 112 wells are considered as abandoned (44) or not operational at the time of the survey (68) (Figure 5-20). The wells are classified according to the Water Establishments (Beirut & Mount Lebanon, North, South and Bekaa Water Establishments). For each Water Establishment, the wells are classified according to the different *cazas*.

The quantity of private wells in Lebanon is not known. In 1996, UNDP inventories indicated around 45,000 wells. In the current survey conducted under the UNDP national groundwater assessment and database study, the number of private licensed wells is approximately 21,000 and unlicensed wells have been estimated at approximately 60,000. The well survey performed in the framework of the present study confirmed that many wells supposed to be abandoned are presently equipped with a small pump for irrigation or domestic usages. The private wells are not represented in Figure 5-20.

Consequently, the overall quantity of water pumped for domestic and irrigation use is therefore not very accurate.

The depth of the wells could reach more than 400 m. For practical and evident reasons, these wells are drilled into the uppermost aquifer, which is the easiest reachable. Depending on the area, it could be the Jurassic aquifer, the Cretaceous aquifer, the Paleocene aquifer in the South and the porous aquifer in the Bekaa Valley. Very little information is therefore available for the deeper aquifers, which are of interest for geothermal energy use.

Three wells are of particular importance as temperature measurements indicate the presence of a thermal anomaly.

The first well is the Summaqiye well drilled in 1968 in the Akkar region near the Syrian border (Figure 5-20). The Summaqiye well provided the first evidence of the presence of thermal water in Lebanon. It was reported that the temperature was around 70°C at the beginning. The water is rich in sulfur and water erupted to a height of 30 m below ground. Nowadays, temperature is around 41°C at a depth of 485 m. Temperature does not vary during the seasons and is thus stable over the years. The Summaqiye well holds artesian characteristics. In the 1980's, a concession has been accorded to use this well for the operation of a health and touristic project.

According to Acra et al. (1982), the chemical characteristics of the Summaqiye<sup>7</sup> water differ from the normal chemical composition of the water in the surrounding wells. In particular Acra et al. (1982) are reporting a water rich in sulfur, chloride, calcium and silica. Sulfur is mainly found in form of Sulphate (SO<sub>4</sub>). The authors conclude that the water could have a magmatic origin.

The second thermal well is reported by Shaban (2010) in the Koukaba region in the South, with a measured temperature of around 35°C (Figure 5-20). The high total dissolved solids (TDS) of 16,000 [mg/kg] measured by Shaban (2010) could be a good indicator of the presence of deep geothermal fluids.

A third well has been identified in the framework of the nationwide groundwater survey (ELARD & BURGEAP-IGIP-RIBEKA, 2012) in Kfar Syr, where a temperature of 31°C has been measured. Although the temperature is not especially high, its difference with the surface temperature could indicate the presence of a thermal anomaly in the underground (see section 5.4.3).

In the framework of this study, temperature investigations have been performed in a selection of shallow groundwater wells. These wells are indicated in red in Figure 5-20. The applied methodology and the results of these temperature investigations are presented in details in section 5.4.3.

#### 5.3.3.2. Springs

Springs constitute the outlet area of a groundwater system. Spring water is therefore representative of the chemical and thermal conditions in the deep underground. Chemical and physical analysis of spring water could thus provide good evidence of thermal activity in a given area.

The exact amount of springs in Lebanon is not known. The UNDP study (1970) reported around 1,121 springs of importance that were monitored in the framework of the 1970's study. It is estimated that a total of around 1,145 million m<sup>3</sup> are outflowing from springs (UNDP, 1970). The geological conditions of Lebanon allow the presence of many offshore springs. El-Hajj (2008) estimates that a total of 54 springs are located along the coastline and only 14 of them are flowing directly into the sea. The total flow rate of the offshore springs is estimated to be 600-1,000 million m<sup>3</sup>.

7

The Summaqiye well was inspected on August 14, 2012. The well was closed. Therefore no temperature measurement has been done in the framework of this study.

Due to their importance in terms of groundwater resources, offshore springs have been subject to many studies during the last 50 years (see El-Hajj, 2008 and references therein).

Some of the springs are of particular interest for the present geothermal study, as their respective temperatures have been reported by local inhabitants or by studies, to be higher than the normal groundwater temperature. This thermal anomaly could be evidence for thermal activity in a given area.

Shaban (2010) mentioned that several observations for hot/warm water from springs or seepages have been reported in different localities of the Akkar region. The author mentions more specifically the Ain Esamak spring. Field tests reported by Shaban (2010) show that the temperature of this spring ranges between 50-65°C over various time periods. Flow rate is around 1 l/s. Higher temperature and lower discharges occur in the dry season.

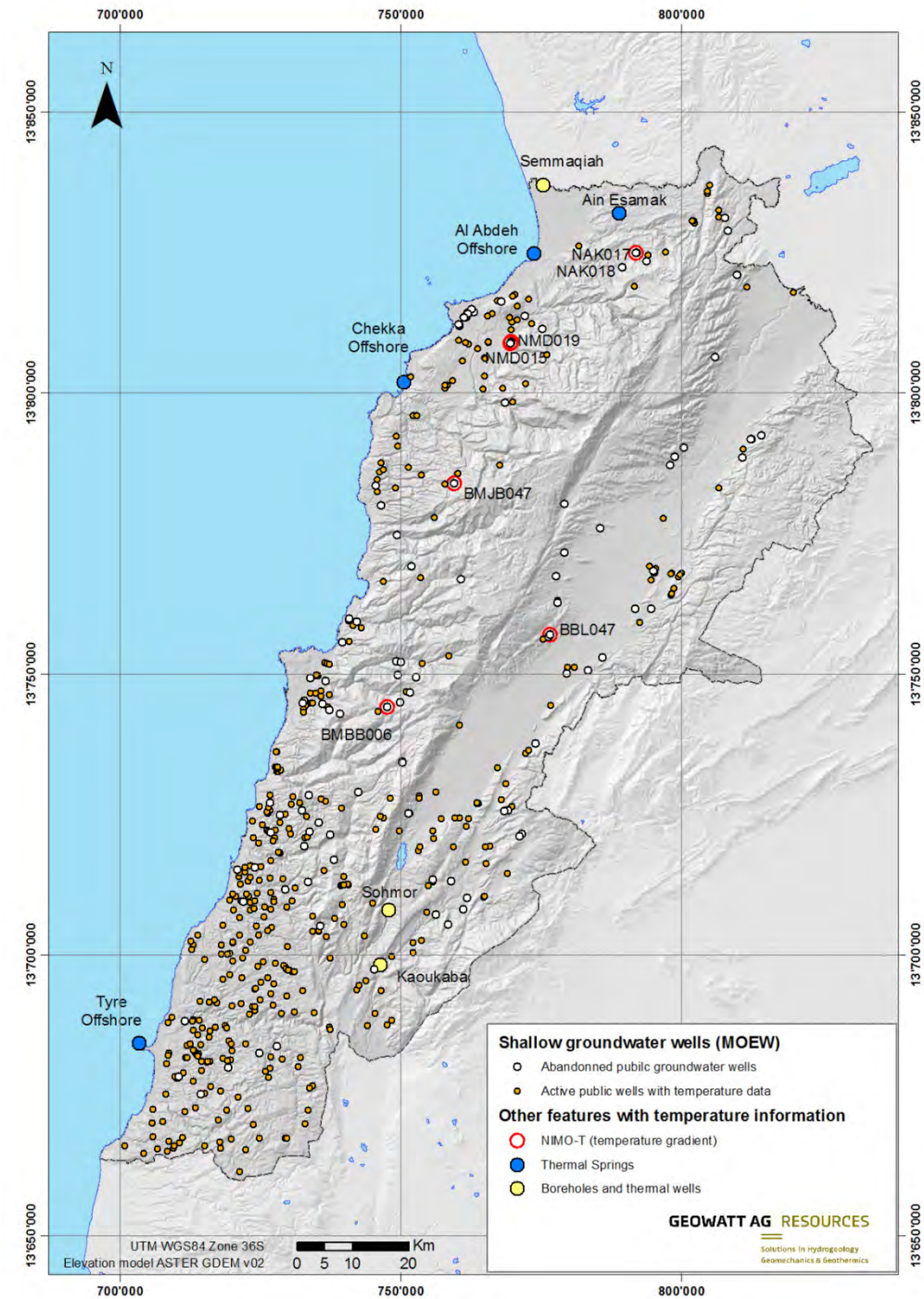


Figure 5-20: Location of the groundwater wells examined in the framework of the groundwater well survey. Other features in which temperature data is available are represented as well



Three off-shore hot springs have also been reported by Shaban (2010). These hot springs were identified by fishermen along the coastal zone. They were identified in three sites (Figure 5-20):

- Tyre area in the South (1 site): According to Shaban (2010) this spring occurs as thermal vents in the sea floor at a distance of about 300 m from the coast and at a depth of about 30 m. No temperature information is available.
- Chekka offshore springs: these springs were located by airborne infrared surveys. Temperatures of around 38°C were reported by (Shaban, 2010) for the Chekka spring while the surrounding temperature of sea water was about 26°C. This is, however, in contradiction with El-Hajj (2008) who measured that the temperature of the springs of the Chekka area is comprised between 17.6°C and 19.1 °C.
- Al-Abdeh offshore spring: a temperature of 38°C is reported for the Al-Abdeh spring (Shaban & Khalaf-Keyrouz, 2013), while the surrounding sea water is 22.5°C.



Figure 5-21: Submarine spring in the Chekka region (after El-Hajj, 2008)



Figure 5-22. Location of submarine springs in Lebanon by means of air borne infrared survey (Shaban, 1999)

### 5.3.4. Hydrostratigraphy of Lebanon

A hydrostratigraphy is established by the hydrogeological map of Lebanon. This classification is first based on the type of aquifer and secondly on the transmissivity of the different hydrostratigraphic units (see section 5.3.6). The hydrostratigraphic units are classified into three main categories:

- Karstic aquifers
- Porous aquifers
- Aquicludes or local aquifers

Karstic aquifers are mainly found in the Jurassic layers of the Kesrouane Formation (Bathonian-Portlandian), also called the first water tower of Lebanon and the Cretaceous layers of the Sannine Formation (Cenomanian-Turonian) called the second water tower of Lebanon. Karstic aquifers are also found in the Turonian, the Nummulitic and the Neogene limestones. In South Lebanon, the Nummulitic period is also classified by the UNDP study (1967) as a poorly karstified aquifer.<sup>8</sup> Porous aquifers are mainly found in the Neogene and Quaternary deposits. The hydrogeological map makes a distinction whether the aquifers are local or spread out. The porous formations are generally not considered as very good aquifers. Aquicludes include clayey or marly layers of the Cretaceous period, the marls of the Nummulitic period, the marls of the Neogene and the Basalts (Cretaceous, Miocene, Pliocene and Quaternary).

Following the UNDP studies (1967, 1970), the hydrostratigraphy of Lebanon is characterized by a number of excellent thick aquifers interbedded with relatively thinner aquicludes, with a high infiltration rate of precipitation (40%) in many lithological units, which consequently show a low to moderate runoff.

The hydrostratigraphic units are described in UNDP (1967, 1970) for all layers above the Jurassic Kesrouane Formation, which is the oldest Formation that outcrops in Lebanon. Indeed some layers that are not outcropping at the surface in Lebanon could be regarded as possibly very good geothermal reservoirs. For the assessment of the geothermal Atlas it is therefore necessary to describe the hydrostratigraphic units down to the basement.

The various hydrostratigraphic units are described in Table 5-2. The thickness and the different subdivisions could vary from one author to the other and from one area to the other. The most relevant hydrostratigraphic units in terms of geothermal potential are described in more detail, from the top to the bottom.

#### 5.3.4.1. The Quaternary

The Quaternary consists of coastal or alluvial deposits whose transmissivity is generally quite low, except in some local areas. The thickness of the Quaternary is variable and could reach a maximum of one hundred meters. Therefore Quaternary aquifers remain surface aquifers which are of no direct interest for geothermal use, if we exclude in our considerations heat pump utilizations.

#### 5.3.4.2. The Miocene

The marine Miocene succession is present only on the coast, south from Tripoli, in Jounié and between Saida and Tyr. It is constituted of massive limestones with a thickness of 200 to 250 m. The transmissivity is generally considered as high. Estimates of transmissivity for the Miocene in the Koura-Zgharta aquifer provides an average value of  $6.4 \cdot 10^{-4} \text{ m}^2/\text{s}$  (geometric average) and a range between  $5.8 \cdot 10^{-5}$  and  $6.4 \cdot 10^{-2} \text{ m}^2/\text{s}$  (Khayat, 2001). Like the quaternary aquifer, the Miocene rocks do not extend very deeply in Lebanon. Therefore they are not considered in more details in terms of a geothermal use.

#### 5.3.4.3. The Eocene

The Eocene limestone is outcropping in three areas:

- the South Bekaa
- the East Bekaa
- the West Bekaa

In the other areas of the Bekaa Valley the Eocene lays below the Neogene filling material. The thickness of the Eocene is around 200-300 m but could reach 800 m in the South Bekaa (Beydoun, 1977). The borehole "El Qaa" identified Eocene-Paleocene deposits in a depth of around 200 m. Sohmer borehole indicates a thickness of 600 m (Table 5-2). Some shallow boreholes in the South of the Bekaa Valley proved that the Eocene is also karstified below the Neogene deposits. The transmissivity estimation ranges from  $10^{-4}$  to  $10^{-2} \text{ m}^2/\text{s}$ , giving a potential production flowrate up to 100 l/s. In South Lebanon, the Eocene is considered as Merokarstic, e.g. as a poorly developed karst.

#### 5.3.4.4. The Sannine Formation

The first hydrostratigraphic unit that could have a transmissivity or a temperature high enough for an implementation of a hydrothermal power plant is the Sannine limestone "C4", Upper Albian to Cenomanian in age (Upper Cretaceous). This formation is called second-water tower of Lebanon. It consists of fractured, folded and karstified thin- and thick- bedded limestone with geodes and cherts bands at different levels. Main outcrops could be found in three areas:

- East flank of the Mount Lebanon, between Jdita in the South and the Homs basalts in the North
- The Anti-Lebanon
- North-West flank of the Hermon Mount, between Machghara and Tell ed Deir.

Between the Mount Lebanon and the Anti-Lebanon, the Sannine Formation plunges below the Paleogene and Neogene filling materials of the Bekaa Valley. In the borehole "El Qaa", the top of Cenomanian has been identified at around 1,000 m in depth. In the "Yohmor" borehole, the top of Cenomanian is identified at around 1,335 m depth.

Its thickness reaches up to 700 m. Due to its important thickness, it constitutes an aquifer with a high transmissivity. According to the UNDP the transmissivity of the aquifer is around  $10^{-2}$  to  $1.0 \text{ m}^2/\text{s}$ , which represents elevated values. They expect being able to exploit this aquifer with flowrates greater than 100 l/s.

#### 5.3.4.5. The Chouf Formation

The Chouf Formation forms the basis of Cretaceous and is constituted of fractured quartzitic, argillaceous, almost ferruginous sands, interbedded with tuff and basalt and with horizons of lignitic coal and sometimes with horizons of sandy limestone. It has been identified at a depth of 780 meters and 1,640 m in the boreholes "Tell Znoub" and "Adloun", respectively. Transmissivities have been estimated between  $10^{-5}$  and  $10^{-4} \text{ m}^2/\text{s}$ . The Chouf Formation is thus considered as a semi-aquifer.

Due to its depth, the Chouf Formation could still be considered as interesting for the geothermal use, primarily in intensively fractured areas, where the transmissivity could be several orders of magnitude higher.

#### 5.3.4.6. The Bikfaya and Kesrouane Formations

The Bikfaya Formation is a fractured, karstified, massive limestone with horizons of dolomitic limestone, thin marly limestone with frequent horizons of chert nodules. The Bikfaya Formation is differentiated from the underlying Kesrouane Limestone, in the area where the Bhannes Complex is present. Otherwise, it could be hardly differentiated. The top of Jurassic has been identified in boreholes "Tell Znoub", "Adloun" and "Terbol" at a depth between 1,000 and 2,000 m. The bottom of the Bikfaya Formation could not be distinguished from the underlying Kesrouane Limestone.

Although the permeability of this Formation could be high enough, its relative low thickness makes this Formation not so appealing to geothermal potential, except in the area where it is in direct contact with the Kesrouane Limestone.

Kesrouane Formation is composed of massive bedded limestone and dolomite and has been intensively fractured and karstified during the subsequent emergence of the Mount Lebanon. This formation consists of the main water tower in Lebanon. It is therefore one of the major target aquifers for geothermal exploration, considering hydrothermal technology.

The Bikfaya and Kesrouane are considered as Jurassic aquifers in the UNDP studies (UNDP, 1967, 1970).

The top of the Kesrouane Formation could not necessarily be distinguished from the basis of the overlying Bikfaya Formation, except in the area where the Bhannes Complex is present. The Kesrouane Formation has been identified in Tell Znoub, Adloun and Terbol boreholes, up to 3065 meters in depth. The basis of the Kesrouane Formation and thus of the Jurassic has not been reached by any boreholes in Lebanon. The total thickness of the Kesrouane Formation is supposed to be comprised between 700 to 1,000 m.

At the surface the Jurassic aquifer is outcropping in three areas of the Interior Province, the Barouk Niha, very locally in Jdita, and in the Hermon massif and mainly in three areas of the Mediterranean Province, from North to South, in Sir ed Danié-Aïn, in the massif of Kesrouane and in the Massif of Barouk.

The Kesrouane formation is considered as an excellent aquifer, with transmissivities comprised between  $10^{-2}$  and  $1.0 \text{ m}^2/\text{s}$ .

The transmissivity comes essentially from the secondary porosity due to the karstification. The comprehension of the karstification process is thus of prior importance for determining the depth at which the resources could be exploited.

Table 5-2: Observed depth of the relevant hydrostratigraphic units in the deep O&amp;G boreholes

Hydrostratigraphic Unit		El Qaa	Yohmor	Tell Znoub	Adloun	Sohmor	Terbe
Quaternary	Top	-	-	-	-	-	
	Bottom	-	-	-	-	-	
Miocene	Top	0	-	-	-	-	
	Bottom	175	-	-	-	-	
Eocene	Top	175 (2)	0	-	-	0	
	Bottom	240 (2)	350	-	-	615	
Sannine Fm.	Top	1000	1335	0	195	-	780
(Albian- Cenomanian)	Bottom	1900	2352	575	866	-	1625
Chouf Fm.	Top	n.l (1)	-	780	1640	-	n.l. (3)
	Bottom	n.l (1)	-	900	1810	-	n.l. (3)
Bikfaya Fm.	Top	-	-	1000	1971	-	1955
	Bottom	-	-	n.l (4)	2013	-	n.l. (4)
Kesrouane Fm.	Top	-	-	n.l (4)	-	-	n.l. (4)
	Bottom	-	-	>1425	-	-	>306
(1) Top Jurassic identified at 2290 meters depth. Chouf Fm not identified or not present							
(2) Identified here as Paleocene							
(3) Top Jurassic identified at 1954 meters depth. Chouf Fm. Not identified or not present							

### 5.3.5. Karst in Lebanon

#### 5.3.5.1. Generalities

The difference of altitude between Mount Lebanon and sea level, and the predominance of carbonate rocks offers ideal conditions for the intense development of karstic system. Karst systems are the result of the dissolution of carbonate rocks (limestone) by carbonic dioxide contained in meteoric water. Karst develops differentially according to the composition of the different geological layers, i.e. the carbonate content. Rock dissolution creates conduits that allow water to accumulate and circulate through them. Karst aquifers are thus excellent in terms of water resource. Groundwater wells are generally located above the karst conduits.

Karst flow systems could be summarized as follows:

Water from precipitation infiltrates in the high topographic area either through preferential infiltration points or more diffusively through the whole area. Water then circulates vertically through the epikarst and the unsaturated zone until it reaches the groundwater level. Water then circulates horizontally until the outlet area, characterized by the presence of springs. The very fast flow circulation between the infiltration area and the outlet area is a characteristic of karst systems.

The location of the groundwater level and of the springs will strongly depend on the regional and local geology. The springs could be located below sea level.

What remains unclear today is the total depth of the karstic system development. Of course, it is demonstrated at different places within the Mediterranean basin that the salinity crisis that occurred during Messinian allowed the development of karst systems at a much higher depth than the present sea level.

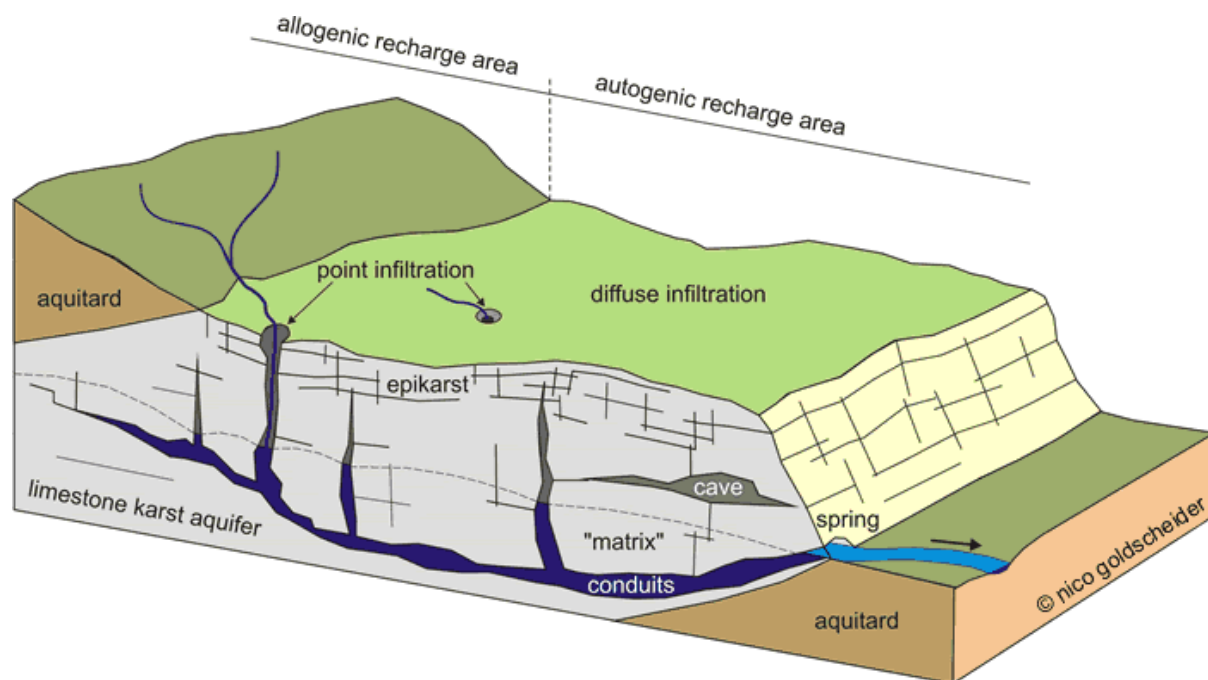


Figure 5-23: Block diagram of a karst aquifer (Goldscheider & Drew, 2007)

### 5.3.5.2. Karst and temperature

Specific behavior of a karst groundwater system has a strong influence on the groundwater temperature. In a normal rock massif, flow circulation is normally very low and limited to the surface. The overall temperature in the massif is therefore controlled by the geothermal gradient. Badino (2005) proceeded to a compilation of temperature data measured in the deep alpine tunnels and made a comparison between karstic mountains and non karstic mountains. Temperature measurements in non-karstic massifs, such as the Simplon tunnel in Switzerland, show a good correlation between the temperature and the depth below the surface (Figure 5-24, left). Temperature increases in the central part of the massif where the depth below the surface is higher. In contrary, measurements done in a tunnel located in a karstic massif, such as the Grand Sasso tunnel in Central Italy, show constant temperature or even a slow decrease all along the tunnel profile, because the deep it is, the colder the incoming waters are (Figure 5-24, right). Figure 5-25 presents the temperature with respect to the depth for 5 tunnels. In red and blue are tunnels located in karstic massifs. Figure 5-25 indicates that there is almost no temperature difference at depth and at the surface.

The karst conduits allow cold water to circulate very fast in the deep underground, cooling the whole massif into a temperature level slightly higher than the temperature in the infiltration area. Therefore the whole Mount Lebanon and Anti Lebanon ranges are considered as cold. This effect influences the temperature until the basis of the active flow area. At greater depths, the temperature is supposed to follow the normal temperature gradient.

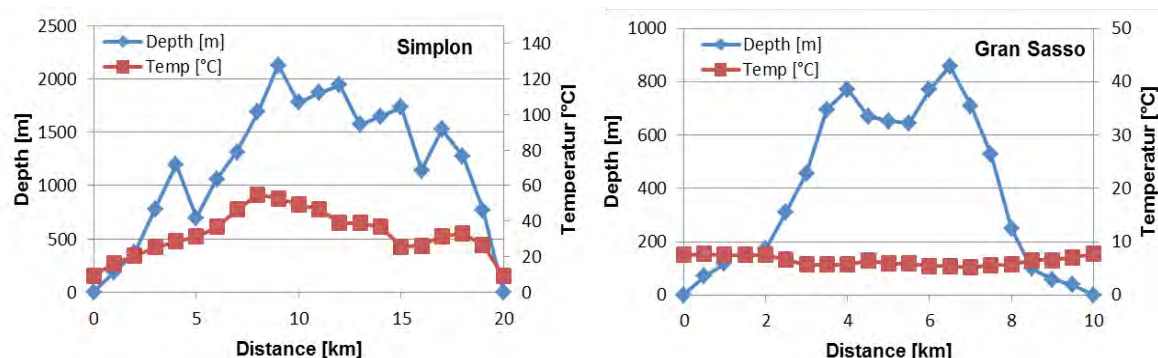
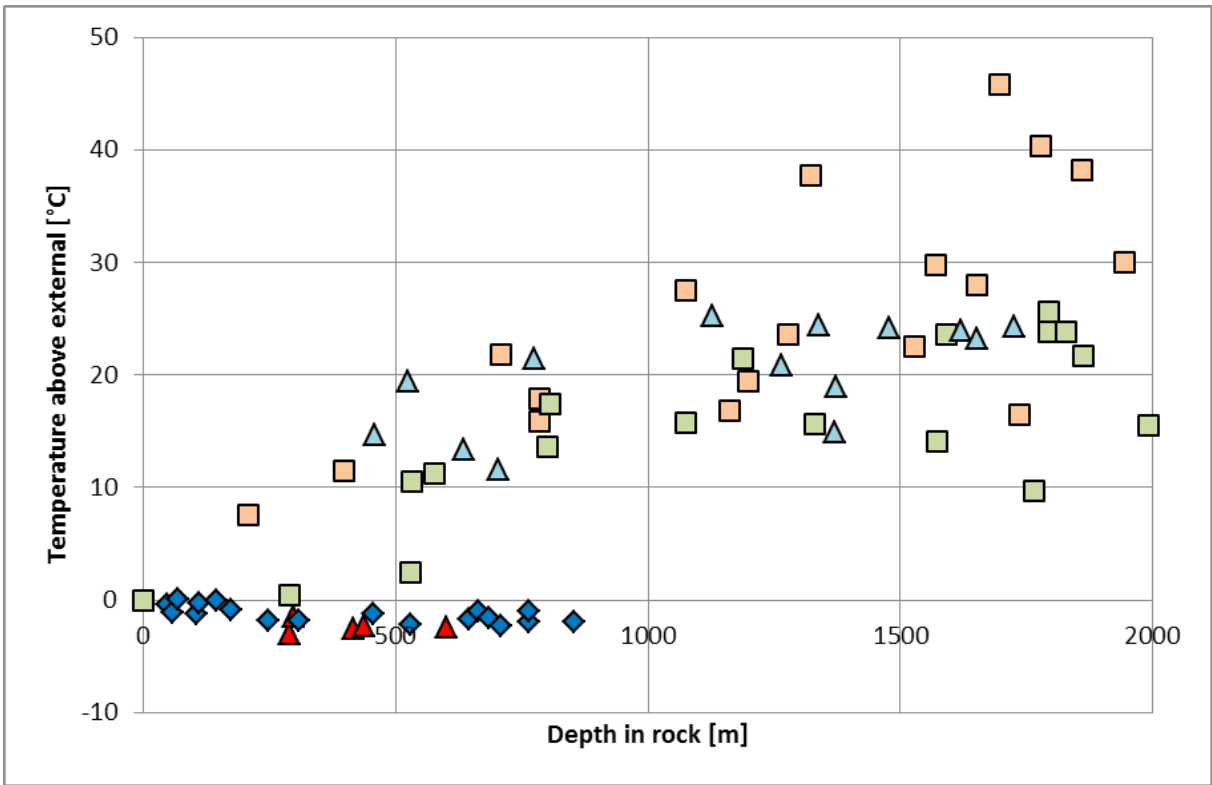


Figure 5-24. Depth and temperatures profiles (left) in the non karstic Simplon tunnel (Switzerland) and (right) in the karstic Gran Sasso tunnel (Italy) (Badino, 2005)





### 5.3.5.3. Karst in Lebanon

The outcropping rocks in Lebanon are mainly composed of the carbonate limestone of the Jurassic, the Cretaceous and the Eocene, as well as some Miocene limestone in the coastal area. The Jurassic, Cretaceous and Tertiary limestone cover a total area of around 6,900 km<sup>2</sup> which represents around 66% of the total area of the Lebanese territory (10,450 km<sup>2</sup>). The extent of the Jurassic and Cretaceous carbonates are around 1,300 km<sup>2</sup> and 4,400 km<sup>2</sup>, respectively.

The presence of relief in Lebanon allows an intensive karst development over the whole territory, with a predominance in the areas where the difference of altitude is important (such as in Mount Lebanon). The main evidence of this is the Jeita Cave located 18 km north of Beirut in the Nahr al-Kalb valley. The Jeita Cave is located in the Jurassic Kesrouane formation. The karstic network was explored by speleologists over a distance covering about 10,000 m. The water level and the discharge rate are given for the water year 2010-2011 in Figure 5-26. Base average discharge rate is around 2 m<sup>3</sup>/s with a maximum of around 25 m<sup>3</sup>/s during the high water level time in spring (Margane & Stoeckl, 2013).

The hydrogeological map distinguished karstic rocks with very high permeability, karstic rock with high permeability and other kinds of rocks (see section 5.3.4). The extent of the three groups is represented in Figure 5-27.

The intensive development of karst formation in Lebanon and the possible deep karstic structures have positive and negative aspects with respect to the development of geothermal energy.

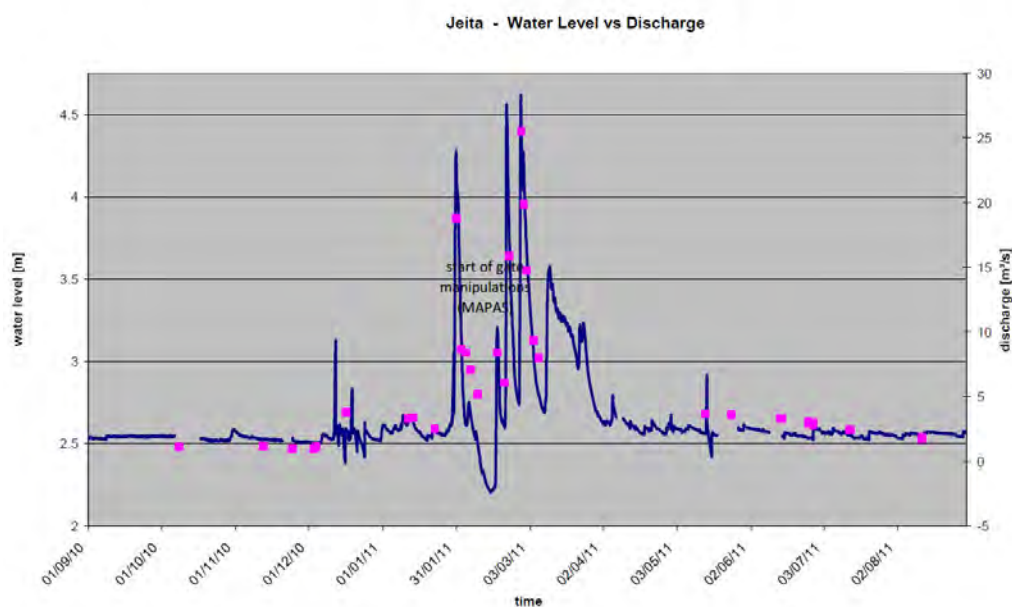


Figure 5-26: Water level and discharge rate of the Jeita springs during water year 2010-2011 (Margane & Stoeckl, 2013)

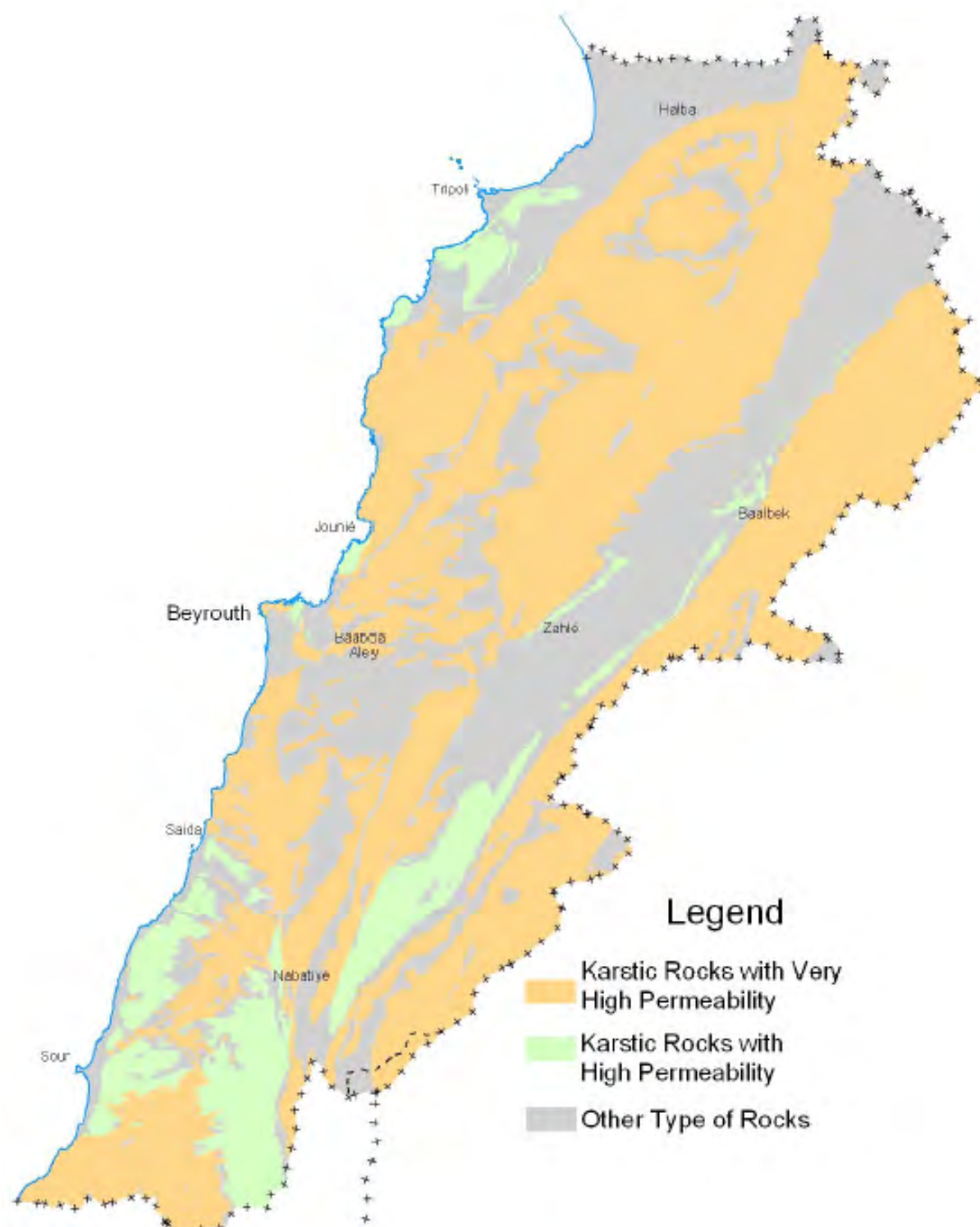


Figure 5-27: Extent of the rock formations regarding the degree of karstification (very high permeability, high permeability and other type of Rocks) (DAR-IAURIF, 2005)

### 5.3.6. Hydrodynamic properties

The most important parameter in terms of geothermal power production is the transmissivity of the aquifer. The transmissivity is the product of the hydraulic conductivity and the thickness of the aquifer. This property describes the ability of the aquifer to provide water. The productivity of the reservoir is directly proportional to the transmissivity.

Transmissivities of the main hydrostratigraphic units are summarized in the following table:

Table 5-3: Hydrodynamic properties (extracted from the hydrogeological map of Lebanon (UNDP, 1967))

Classification	Age/Description	Spring flowrate [l/s]	Well flowrate [l/s]	Transmissivity [m <sup>2</sup> /s]	Outcropping area [Km <sup>2</sup> ]
Vast and productive karstic formations	Limestone of the Kesrouane Formation	<100 100-1000 >1000	>100	$10^{-2} \leq T \leq 1$	1290
	Limestone of the Sannine Formation	<100 100-1000 >1000	>100	$10^{-2} \leq T \leq 1$	4290
	Turonian limestone	100-1000 >1000	>100	Mostly high	100
	Nummulitic limestone	100-1000	<100	$10^{-4} \leq T \leq 10^{-2}$	317
	Neogene limestone	100-1000	<100	usually high	103
Large but less productive karstic formations	Nummulitic marls	<100	<50	$10^{-4} \leq T \leq 10^{-3}$ Limited	536
Important porous formations	Neogene (continental facies)	<100	<30	$<10^{-3}$ Limited and variable	746
	Old quaternary alluvions	Diffuse	<30	$10^{-4} \leq T \leq 10^{-3}$	68
	Quaternary limons and "terra rossa"	Diffuse	<10	Limited to poor	830
Local or discontinuous	Cretaceous sandstone	<10	<10	$10^{-5} \leq T \leq 10^{-4}$ Limited to poor	275
	Quaternary deposits	Diffuse	<10	Limited to poor	156
Areas without productive aquifers or very local	Cretaceous Aptian-Albian	<5	<10	Poor to very poor	552
	Cretaceous Senonian and basis Eocene	-	Very poor	very poor	416
	Nummulitic	-	Very poor	very poor	
	Neogene marine	-	Very poor	Poor to very poor	73
	Neogene continental	-	Very poor	Poor to very poor	
	Basalts	-	Very poor	Very poor	365

### 5.3.7. Role of faults

Due to the intense tectonic activity that occurred in Lebanon, it is intensively faulted. Main faults are presented in the structural map of Figure 5-12. The role of faults on the hydrogeological behavior of the reservoir strongly depends on the regional geological setting. Main features could be summarized as follows:

- Due to the fault displacement, a fault could connect to aquifers that are normally separated by an impermeable geological layer (see Figure 5-28-A).
- The fault itself presents different hydrodynamic characteristics than the intact host rock. Depending on the stress regime, the fault could be either more permeable or on the contrary less permeable (see Figure 5-28-C).
- In case of permeable faults, the latter could connect two aquifers at different depths, allowing the fluid to flow through an impermeable unit. This process is very often responsible for geothermal anomalies (see Figure 5-28-B).
- Faults could connect deep aquifers directly with the surface (see Figure 5-28-D).
- Springs are often located along faults (see Figure 5-28-D).

Moreover, faults could be tectonically active or not. Tectonically active faults could present an increased risk of inducing seismicity while reservoir testing.

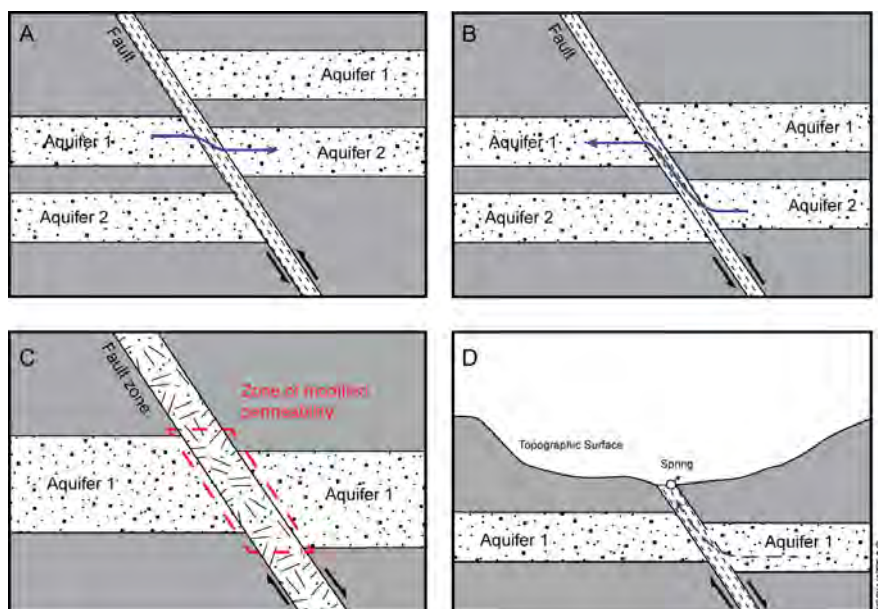


Figure 5-28: Role of fault in groundwater circulation.



## 5.4. Heat flow and temperature data

### 5.4.1. Heat flow map

Heat flow data from the International Heat Flow Commission (<http://www.iaspei.org/commissions/IHFC.html>) have been collected for the Near-East Region.

A regional heat flow map for Lebanon was derived using 2D interpolation (inverse distance weighted) of the data. The interpolated map is presented in Figure 5-29.

The heat flow map first indicates relative low values of heat flow density. The heat flow is comprised between 35 to 70 mW/m<sup>2</sup>. This range is relatively low in comparison to the world mean heat flow of around 75 mW/m<sup>2</sup>.

The heat flow map also indicates that the heat flow density is higher in the Southern part (showing classical values of 50-70 mW/m<sup>2</sup>) of Lebanon as in its Northern part (values of 35-50 mW/m<sup>2</sup>).

It must be pointed out the map of Figure 5-29 is only a rough indicator of the heat flow in Lebanon, as no data in the heat flow commission database is located directly in Lebanon and no direct measurement of the heat flow was obtained from the temperature logging carried out in the framework of this study.

As indicated by Figure 5-28, flow circulation from deep aquifers towards the surface through fault zones could create a local thermal anomaly.

The data available from the Heat Flow Commission are too sparse to allow an identification of such local features.

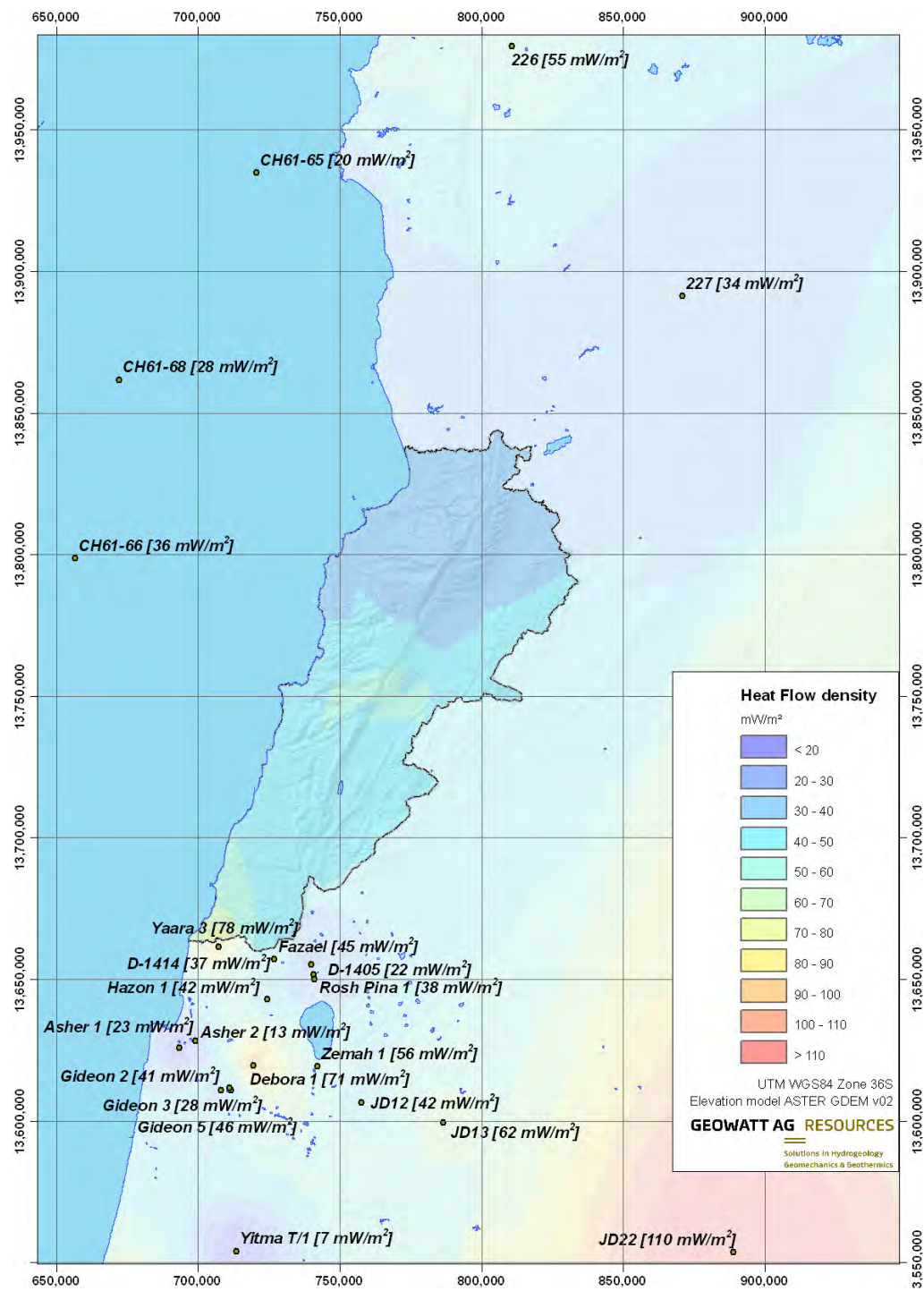


Figure 5-29: Regional heat flow map (using data of the international heat flow commission)

## 5.4.2. Thermal conductivities

Thermal conductivity of the principal rock types of Lebanon is an important parameter to estimate the temperature in the deep underground. Indeed, geothermal heat flow, which is to be estimated using the temperature logs, can only be determined if the thermal conductivity of the surrounding rocks is known.

The relation between the thermal heat flow and the temperature gradient in the well is the Fourier law, and can be written as:

$$q = \lambda \cdot \frac{\Delta T}{\Delta z}, \text{ with}$$

- $q$  [W/m<sup>2</sup>] being the heat flow (see section 5.4.1)
- $\lambda$  [W/m/K] being the thermal conductivity of the rocks (this section)
- $\frac{\Delta T}{\Delta z}$  [K/m] being the vertical temperature gradient (increase of temperature with depth)

25 rock samples of the representative geological formations have been collected in Lebanon (see location in Figure 5-30). The selection of the sample location is mainly based on the availability and the quality of the outcrop zones. Indeed fresh rock samples are preferred to avoid influence of surface alteration and to obtain a valuable representative of rocks at depth.

Thermal conductivity of the rock samples was measured in a specialized laboratory in Switzerland. The method used is the transient line source method by the Tk04 apparatus. The measuring probe consists of a line heat source and a temperature sensor attached to a flat, smooth surface of thermal insulating material. The temperature sensor is placed under high pressure on a sample with a flat, smooth surface and the heat source is energized by a constant voltage. The probe temperature increases with time at a rate related to the thermal conductivity  $\lambda$  of the rock sample.

The results of the thermal conductivity measurements are shown in Table 5-4 and Table 5-5 as well as in Figure 5-31.

The measured values of thermal conductivity on compact rock range between 1.0 and 3.0 [W/mK]. The measurements on crumbled sandstone and on the crumbled tuff show a matrix thermal conductivity of more than 6 [W/mK] and 3.9 [W/mK], respectively. The in-situ thermal conductivity of these samples can be estimated with an assumption on the water content. If the pore filling consists also of air or oil, the methodology has to be modified accordingly.

The limestone samples show thermal conductivities between 2.1 and 3.0 [W/mK]. The volcanic rock samples show lower values.

The deviation of the measurements of one sample is mostly less than 5%.

Table 5-4: Thermal conductivity measurements on rock samples from Lebanon

Prtbz	Latitude m.u.T.	Longitude	Geologic-Formation	sample description	samples, water saturated			Cuttings, grains< 2 mm		
					$\lambda_f$ W/m.K	$s\lambda_f$ W/m.K	Nf	$\lambda_m$ W/m.K	$\Delta\lambda_m$ W/m.K	N $\lambda$
Li-1	N 34° 34.858'	E 036 16.151'	Pliocene Volcanics		1.89	0.02	8			
Li-2	N 34° 35.915'	E 036° 09.110'	Pliocene Volcanics	Vesicular	1.07	0.02	7			
Li-3	N 33° 57.206'	E 035° 36.246'	Nahr El Kalb Fm.	Reefal Limestone	2.34	0.04	8			
Li-4	N 33° 59.041'	E 035° 42.414'	Keserouane Fm.	Micritic Lst	2.94	0.08	7			
Li-5	N 34° 01.223'	E 035° 45.840'	Chouf Fm.	Sandstone				6.46	0.19	6
Li-6	N 34° 01.226'	E 035° 45.845'	Bhannes Fm.	Volcanic Boulder	1.70	0.04	10			
Li-7	N 34° 10.216'	E 035° 52.677'	Bikfaya Fm.	Micritic Lst	2.82	0.07	8			
Li-8	N 34° 09.465'	E 035° 52.156'	Abeih Fm.	Sandy Lst	2.65	0.04	8			
Li-9	N 34° 08.826'	E 035° 53.493'	Sannine Fm.	Micritic Lst	2.87	0.03	8			
Li-10	N 34° 09.498'	E 035° 54.335'	Mdeirij Fm.	Micritic Lst	2.64	0.03	8			
Li-11	N 34° 05.180'	E 035° 40.424'	Sannine Fm.	Chalky Lst	2.40	0.09	8			
Li-12	N 34° 17.365'	E 035° 42.317'	Chekkafm.	Chalky Lst	2.10	0.05	8			
Li-13	N 34° 10.776'	E 035° 38.147'	Sannine Fm.	Micritic Lst	2.45	0.07	8			
Li-14	N 33° 41.024'	E 035° 35.279'	Hammana Fm.	Limestone unit of Hammana Fm.	2.50	0.07	8			
Li-15	N 33° 33.257'	E 035° 35.433'	Mdeirij Fm.	Micritic Lst	2.69	0.04	8			
Li-16	N 33° 33.520'	E 035° 35.446'	Abeih Fm.	Sandy Limestone	2.55	0.07	8			
Li-17	N 33° 33.525'	E 035° 35.174'	Chouf Fm.	Volcanic Tuff				3.91	0.12	6
Li-18	N 33° 33.647'	E 035° 34.426'	Chouf Fm.	Sandstone				6.25	0.11	6
Li-19	N 33° 33.212	E 035° 31.239'	Sannine Fm.	Micritic Lst	2.75	0.06	8			
Li-20	N 33° 52.100'	E 035° 55.304'	Zahle Fm.	Conglomerates	2.45	0.09	10			
Li-21	N 33° 48.774'	E 035° 45.327'	Hammana Fm.	Limestone unit of Hammana Fm.	2.46	0.11	8			
Li-22	N 34° 0.611'	E 035° 39.015'	Maameltain Fm.	Chalky Lst	2.61	0.07	8			
Li-23	N 33° 56.635'	E 035° 38.377'	Keserouane Fm.	Micritic Lst	2.97	0.16	8			
Li-24	N 33° 56.715'	E 035° 38.300'	Salima Fm.	Sandy Lst	2.63	0.05	8			

Legend: Prtbz = sample identification

$\lambda_s$  = thermal conductivity, f = water saturated,  $s\lambda_f$  = deviation from mean

$\lambda_m$  = matrix thermal conductivity

N = number of measurements



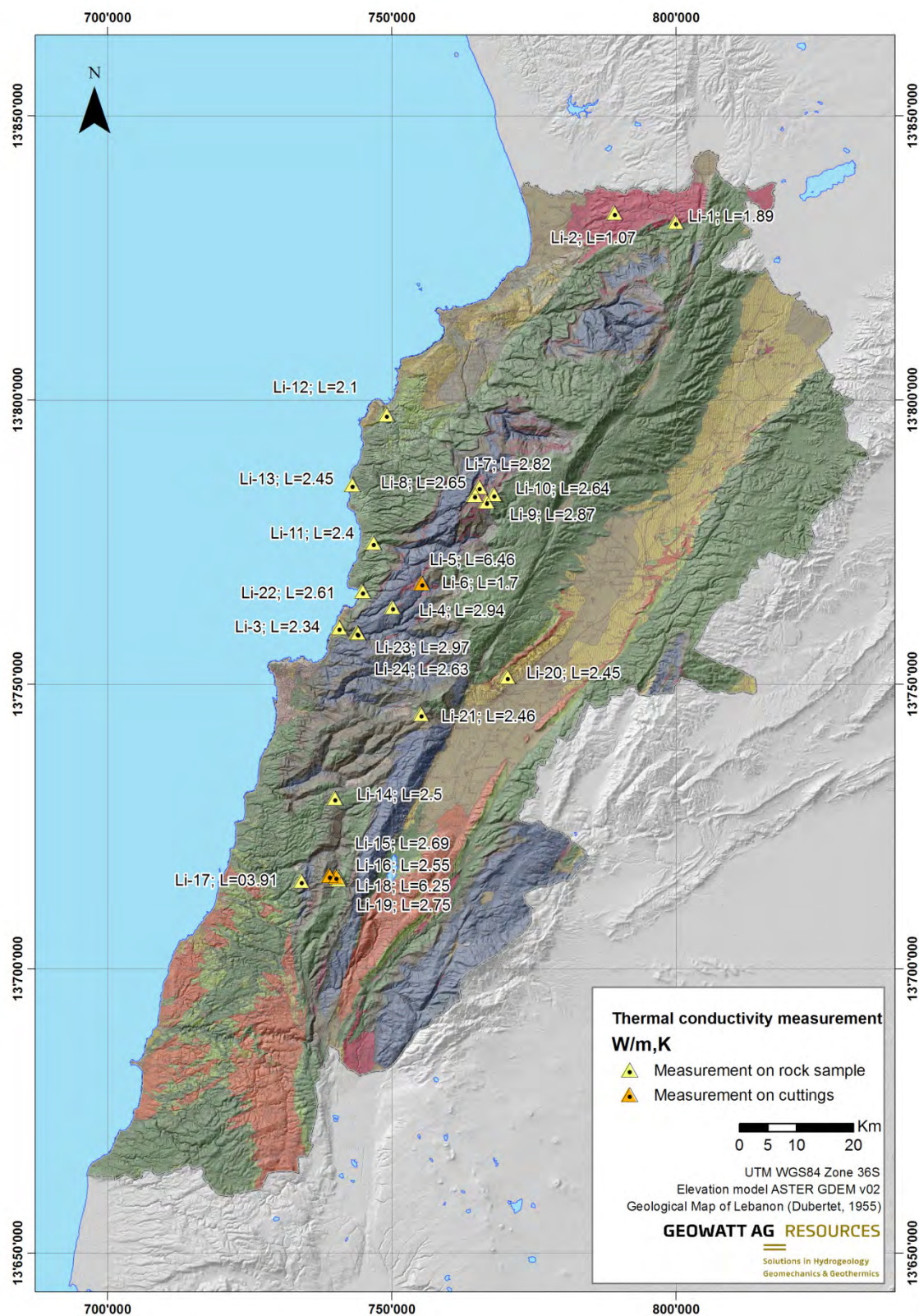


Figure 5-30: Location of the rock sample (Li-1 to Li-24) for thermal conductivity measurements and values of thermal conductivity (L)



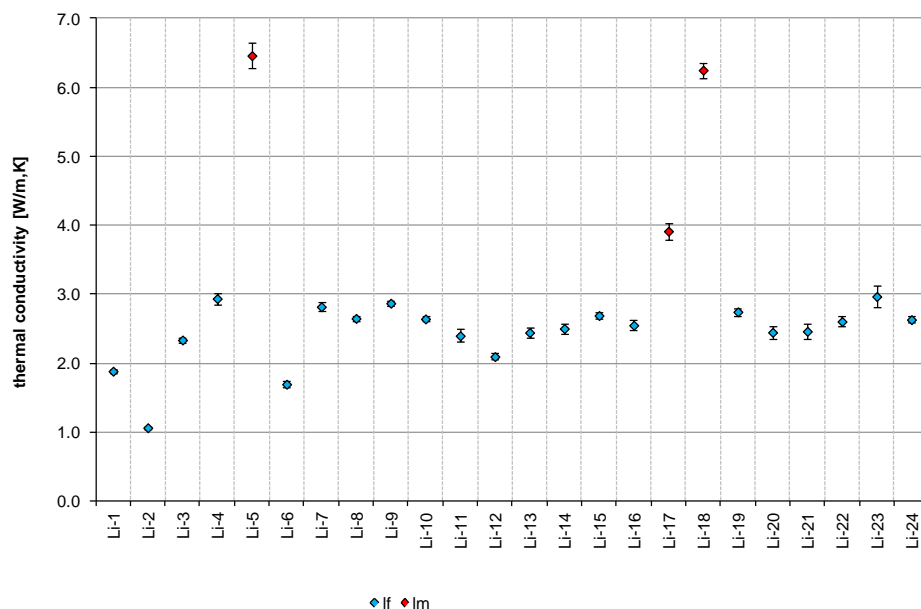


Figure 5-31: Thermal conductivities measured on rock samples in Lebanon (If measurements are performed on the rock samples directly), Im measurement are made on crumbled rocks (see detailed methodology in Appendix III).

Table 5-5: Determination of thermal conductivity on crumbled rocks

Probe	Geology	Lithology	$\lambda_{gem}$	$\lambda_{gem}$	$N_{gem}$	$\lambda_w$
			[W/m K]	[W/m K]		[W/m K]
Li-5	Chouf Fm.	Sandstone	2.63	0.05	6	0.62
Li-17	Chouf Fm.	Volcanic Tuff	1.91	0.04	6	0.62
Li-18	Chouf Fm.	Sandstone	2.74	0.04	6	0.62

Probe	$m_m$	$m_w$	$r_w$	$r_m$	$\lambda_m$	$D\lambda_m$	$f$	$Df$	$\lambda_{eff}$	$D\lambda_{eff}$
	[g]	[g]	[g/cm <sup>3</sup> ]	[g/cm <sup>3</sup> ]	[W/m K]	[W/m K]	[%]	[%]	[W/m K]	[W/m K]
Li-5	174.52	41.34	1	2.63	6.46	0.19	10.00	1.00	5.11	0.12
Li-17	172.85	44.71	1	2.47	3.91	0.12	25.00	1.00	2.47	0.08
Li-18	210.56	44.29	1	2.64	6.25	0.11	10.00	1.00	4.96	0.12

Legend:

- $\lambda_{gem}$  thermal conductivity of the grain-water mixture
- $\lambda_w$  thermal conductivity of water (0.62 W/m.K)
- $\lambda_m$  matrix-thermal conductivity
- $m_w$  weight of water in the 'grain-water' mixture
- $m_m$  weight of rock matrix (grains)
- $\rho_w$  density of water
- $\rho_m$  density of rock matrix
- $N$  number of measurements of a sample
- $\Delta$  error of measuring

### 5.4.3. Groundwater temperature

#### 5.4.3.1. Deep boreholes

The only available data in the deep oil and gas exploration boreholes are Bottom Hole Temperature measurements (BHT) in the Yohmor borehole. BHT indicates the following temperatures:

- 43°C at 1530 mBGL (meter below ground level)
- 43°C at 1830 mBGL
- 43°C at 2060 mBGL
- 51°C at 2620 mBGL

BHT measurements are generally used directly after the drilling. The temperature conditions might not be representative of the undisturbed conditions. This value is therefore questionable and has a limited accuracy.

#### 5.4.3.2. Shallow groundwater wells

Temperature measurement has been performed in the framework of the nationwide groundwater survey (ELARD & BURGEAP-IGIP-RIBEKA, 2012). 472 single water temperature measurements are now available. The measurements were done in wells with active pumping. The temperatures are thus not representative of the undisturbed underground temperatures. The measured temperature is represented at the well location in Figure 5-35.

A water temperature of 41°C has been recorded at a 550 m depth in the Summaqiyyeh well in the Akkar region (Acra, et al., 1982).

The second thermal well is reported by Shaban (2010) in the Kaoukaba region in the South, with a recorded temperature of around 35°C.

A third well has been identified in Kfar Syr, where a temperature of 31°C was recorded in the framework of the nationwide groundwater survey (ELARD & BURGEAP-IGIP-RIBEKA, 2012). This well also presents abnormal differences between the surface temperature and the groundwater temperature.

#### 5.4.3.3. Temperature gradient measurements

Temperature gradient profiles in shallow public wells (down to 300 m) give valuable information on the evolution of temperature with depth. This information can then be used to derive a local geothermal gradient (rate of temperature increase with depth), which is the base for a prediction of the temperature at a higher depth or for the delineation of a regional heat flow map. Temperature gradient measurements have been performed in the field in the framework of this study using the NIMO-T instrumentation toolkit developed by GEOWATT AG. The applied methodology consisted in selecting suitable groundwater wells. To be considered as suitable, a well should first be accessible for the instrumentation toolkit. Secondly, the temperature in the well should be representative of the natural undisturbed conditions. In an active well, the water is flowing either naturally (Artesian) or by pumping. Water circulation modifies the temperature of the rock in the vicinity of the well. Therefore an active well is not considered suitable for temperature measurements.

The selection has been done on the list of the abandoned wells provided by MEW (ELARD & BURGEAP-IGIP-RIBEKA, 2012). Seven wells have been found to be suitable (Table 5-6 and Figure 5-32). Temperature gradient measurements have thus been done on the seven selected wells. The temperature logs are provided in Figure 5-34. Detailed temperature logs are given as examples for the well NMB019 in Figure 5-33.

**Table 5-6: Groundwater wells suitable for NIMO-T temperature measurements (status February 2013)**

Well number	Sector number	Water Establishment and Caza	Date of Temp. measurement
NAK 017	1	Aakar Caza (NAK)	21/08/2012
NAK 018	1	Aakar Caza (NAK)	12/08/2012
BMJB 019	3	Jbeil Caza (BMJB)	30/08/2012
BMBB 006	7	Baabda Caza (BMBB)	29/08/2012
BBL 047	8	Baalbak Caza (BBL)	28/08/2012
NMD 015	10	El Minie - El Donnie Caza (NMD)	22/08/2012
NMD 019	10	El Minie - El Donnie Caza (NMD)	22/08/2012

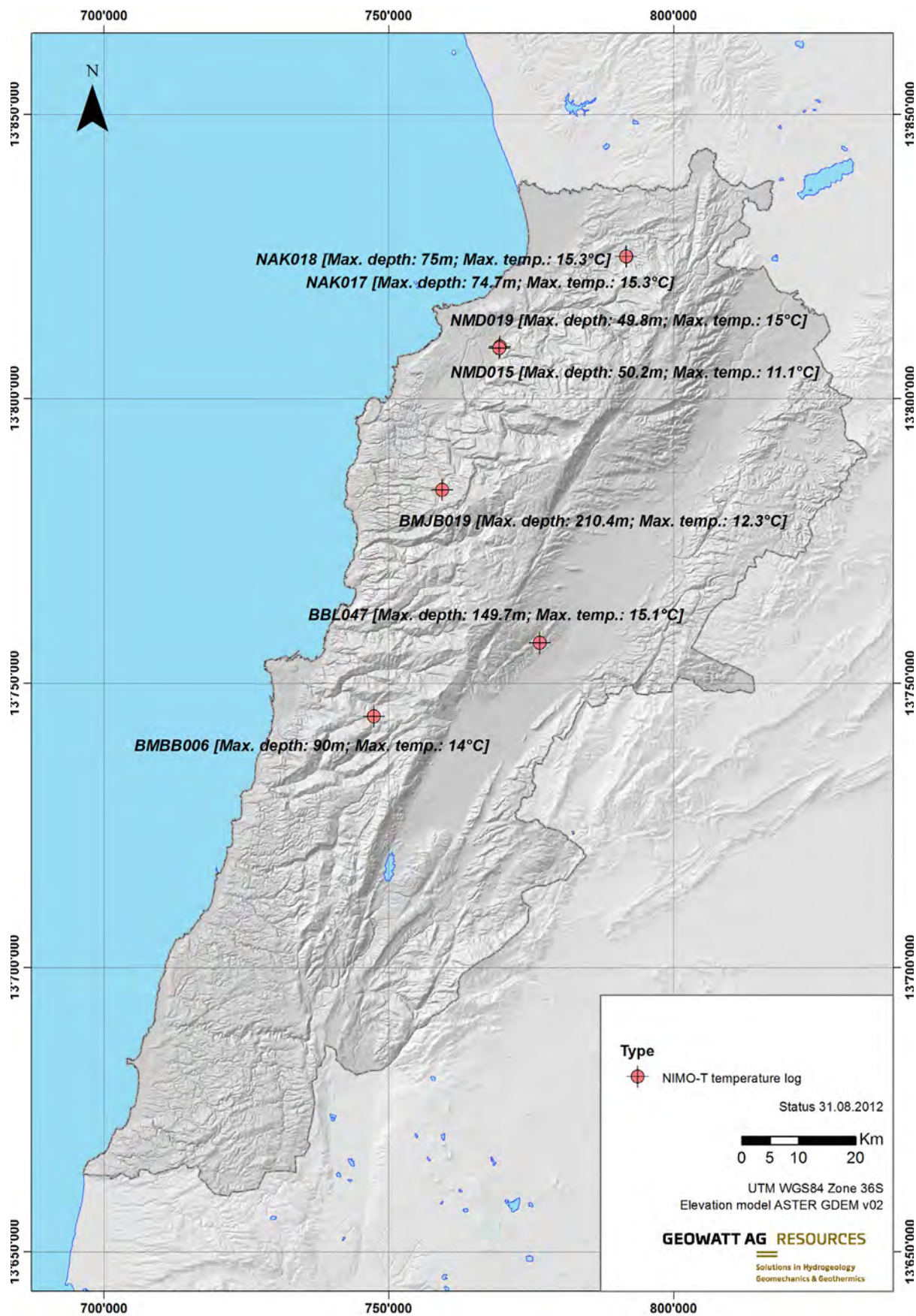


Figure 5-32: Map of the NIMO-T temperature logs

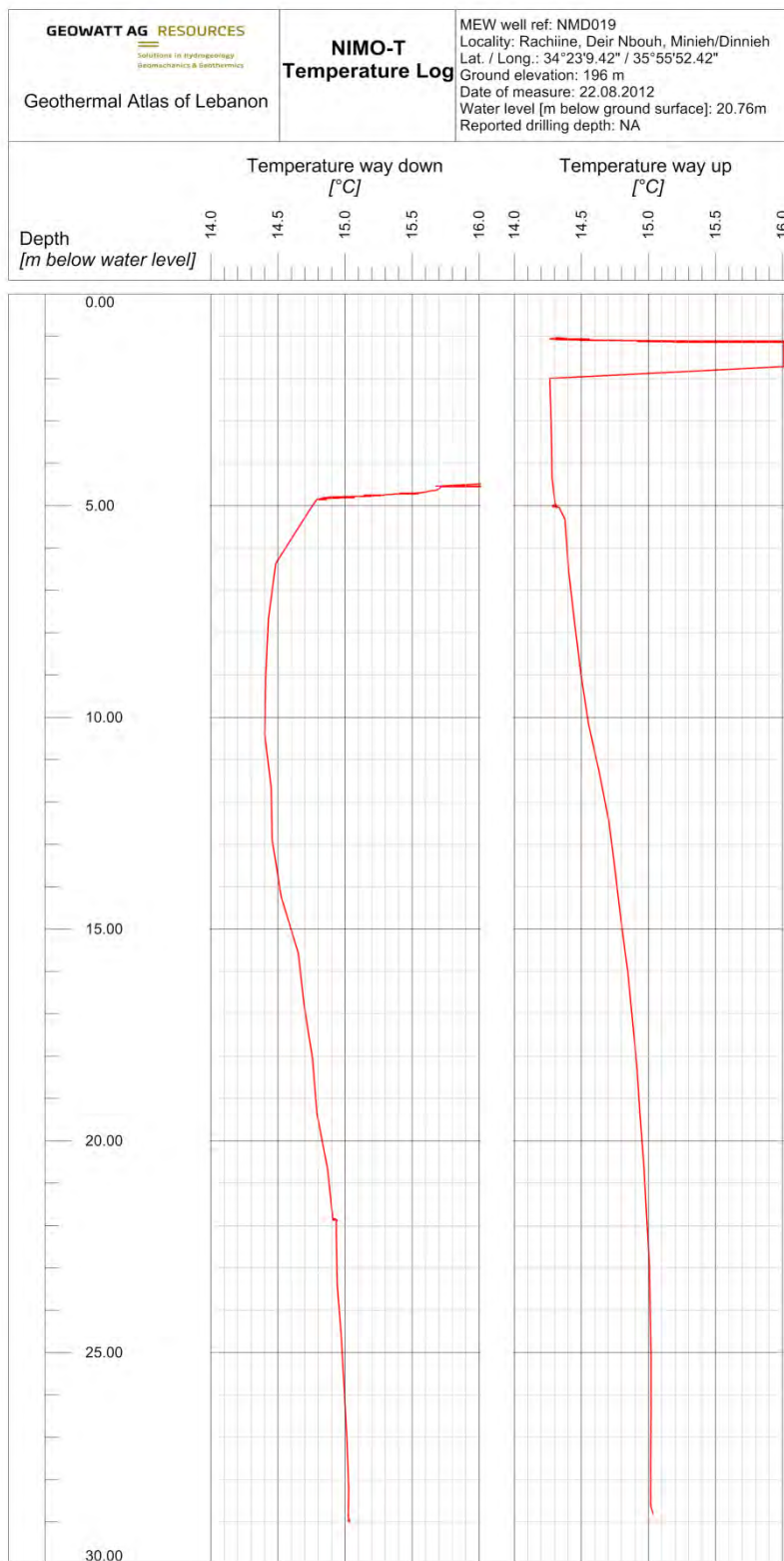


Figure 5-33: Temperature log performed in the well NMD019 (North Water Establishment, Caza El Mini-EI Donnie)



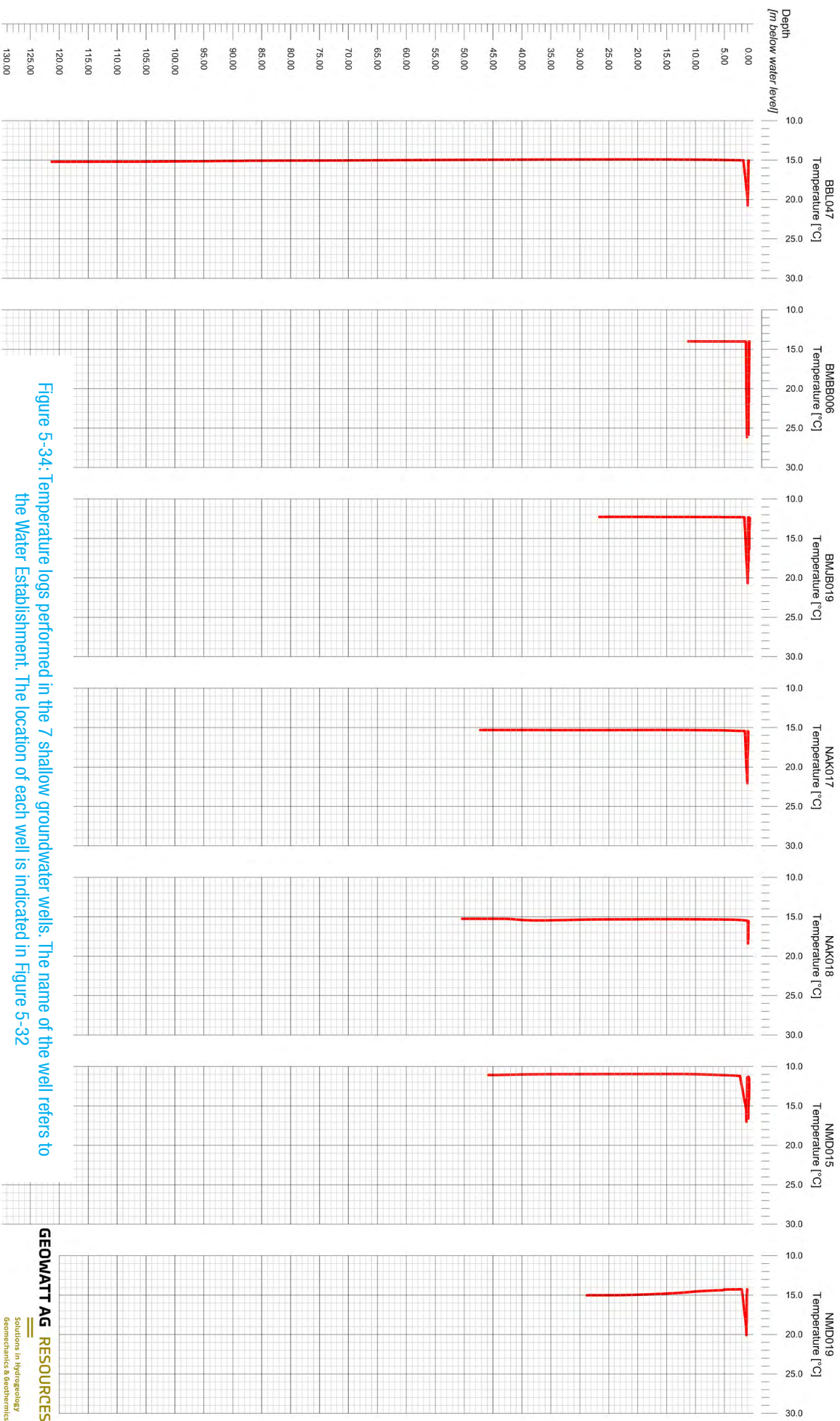


Figure 5-34: Temperature logs performed in the 7 shallow groundwater wells. The name of the well refers to the Water Establishment. The location of each well is indicated in Figure 5-32



#### 5.4.3.4. Thermal springs

Three sources presenting a thermal anomaly have been identified and located (Figure 5-35):

- Ain Esamak spring in the Akkar region with temperatures ranging between 50-65 °C (Shaban, 2010)
- Chekka offshore springs with temperatures of around 38 °C (Shaban, 2010). However, El-Hajj (2008) mentions temperatures comprised between 17.6 °C and 19.1 °C
- Al-Abdeh offshore spring with a temperature of 38 °C (Shaban & Khalaf-Keyrouz, 2013)

#### 5.4.4. Groundwater temperature map

Temperature data obtained by MEW and from the literature are compiled together with the temperature gradient measurements performed in the framework of this study to produce a groundwater temperature map (Figure 5-35).

Shallow circulation of cold water in the karst network has to mask an eventual thermal anomaly located at depth. If the deep circulation of warm water is important enough, it should still be possible to observe thermal anomalies by comparing the groundwater temperature with the average surface temperatures, to check if this method could be used to identify possible thermal anomalies in Lebanon (Figure 5-36).

A North-South trend of temperature exists with increasing temperatures toward the South, showing a good correlation with the surface temperature, the latter being, on average, higher in the South, simply due its geographic location but also due to the overall lower elevation in the South.

The groundwater temperature is higher on the coastline than in the mountain, which is also representative of natural conditions of the groundwater flow systems. This difference in temperature is due to the following process:

Cold water infiltrates in the high elevation area and circulates at depth until the low elevation area, i.e. the coastline. During the transit path, the water is warmed by the geothermal flux, resulting in a temperature difference between the inlet and the outlet of around +4-5 °C. Such a temperature difference is typical of karstic groundwater systems with normal geothermal flux (Badino, 2005). Although mixing processes with deep water of higher temperature could not be excluded, it is considered here to be of lower importance.

As shown by Figure 5-36, three areas present a positive difference between the groundwater temperature and the topographic surface. This means that the temperature of the groundwater is higher than the surface temperature.

- The first and main area is located in the South. In this area the difference could reach +11 K, in the Kfar Syr well. Otherwise, the average difference is around +3-4 K. This behavior is actually representative of the normal thermal conditions of an area where the influence of karst is less important, or simply in non-karstic areas, which is consistent with the hydrogeological map.
- The second and third areas are located in the suburbs of Tripoli and Beirut; the higher observed temperatures are explained by a thermal influence of the cities.
- Single temperature measurements with positive anomalies are present in the North, in Tripoli's suburb and at the very south. These areas should require further investigation as well.

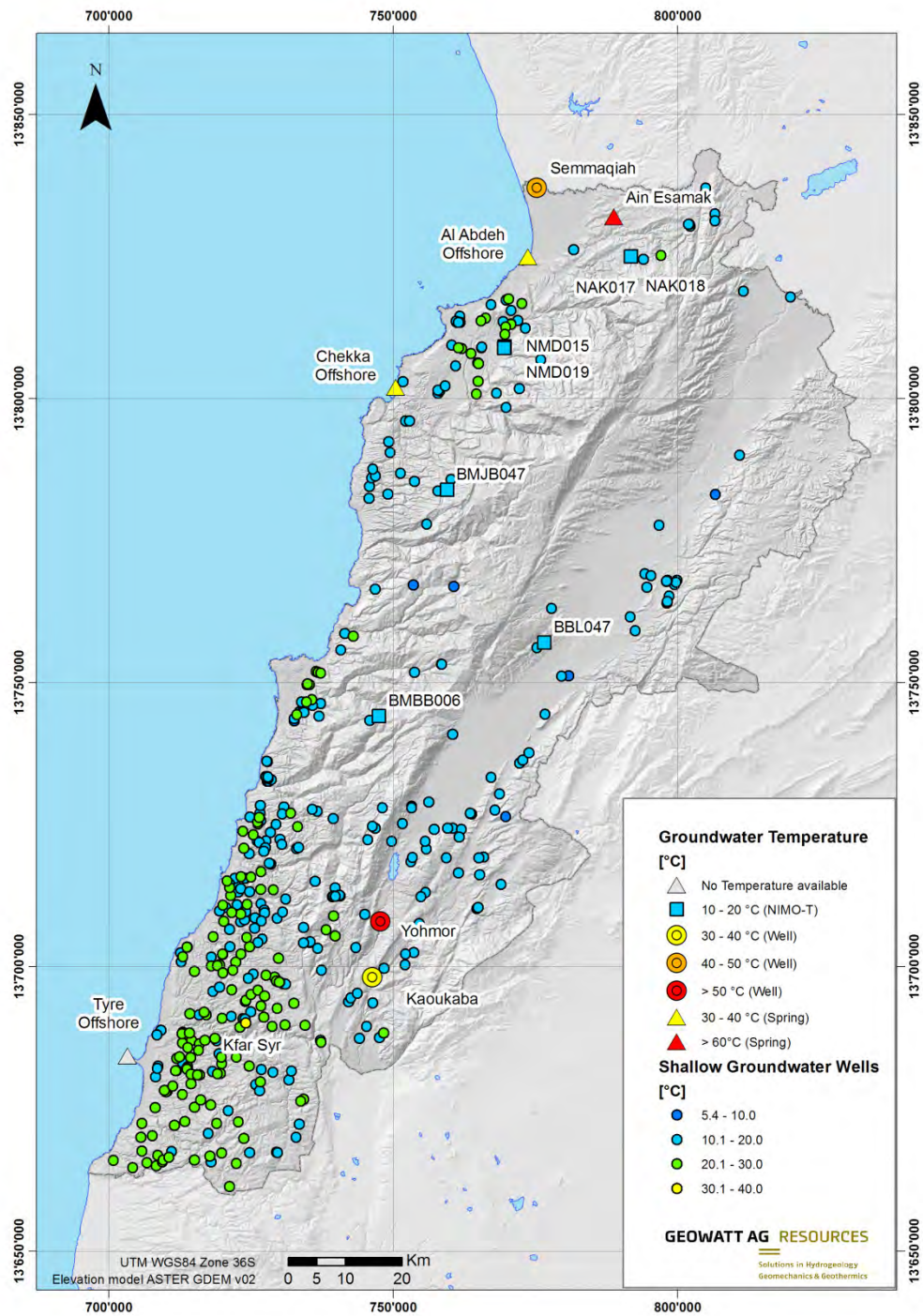


Figure 5-35: Temperature distribution based on temperature groundwater measurement

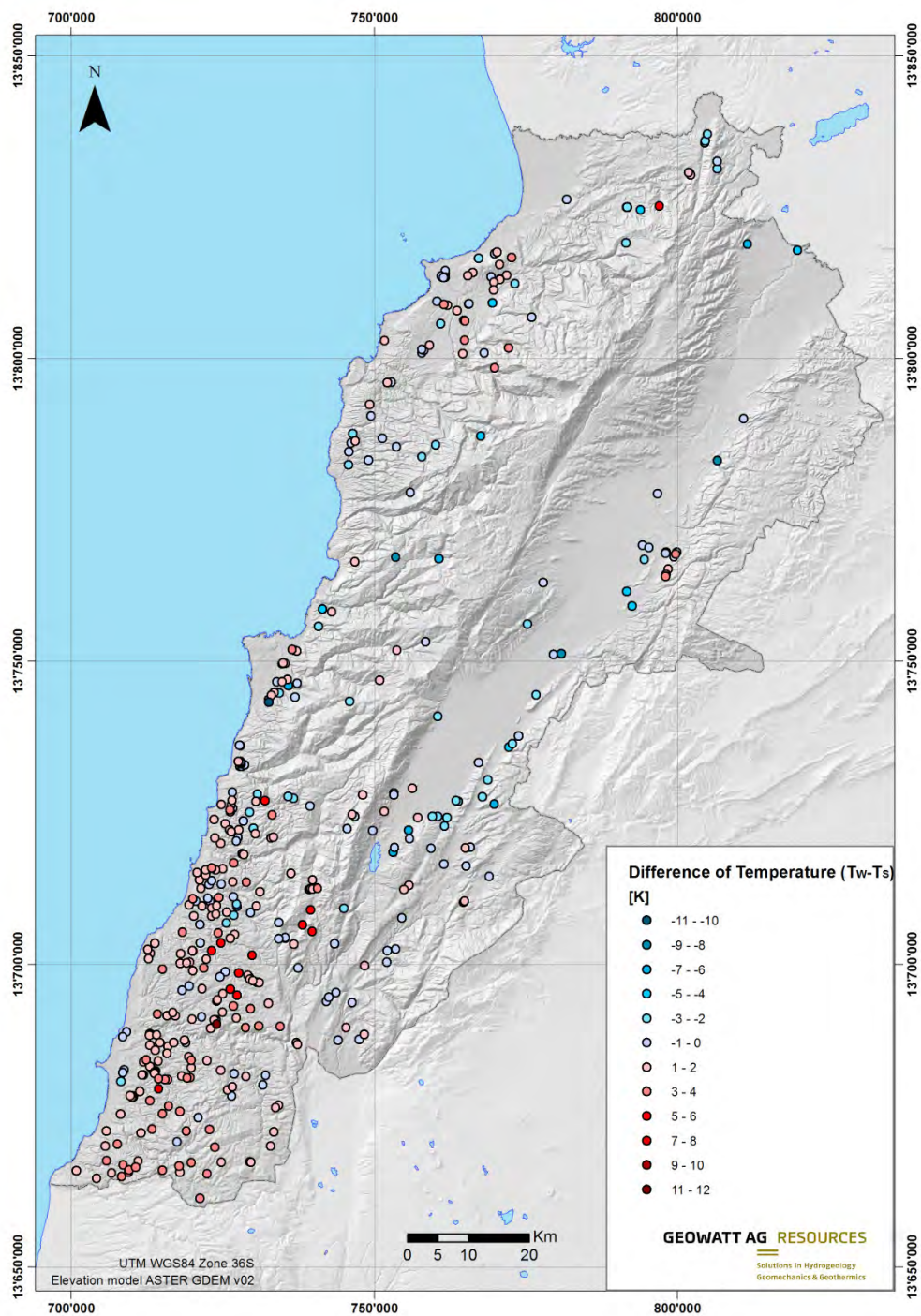


Figure 5-36: Difference between the groundwater temperatures measured in shallow groundwater wells (TW) and the average surface temperature (TS)

## 5.5. Summary of geological, hydrogeological and geothermal features

### *Lack of data and relative high uncertainty*

The main barrier is related to the amount of available data and to its related uncertainty. This barrier revolves around the following aspects:

- The depth of the relevant aquifers in the Bekaa valley is uncertain, as very few boreholes have reached the bottom of the Jurassic limestone and as there are no onshore seismic lines available. Although this aspect has no influence on the thermal gradient, it has an effect on the prediction of the temperature in the aquifers.
- The heat flux is derived and interpolated from a worldwide database. However, no interpolation point is available within the territory of Lebanon. No point is available in both volcanic regions of Akkar in the North.
- No information about the geothermal gradient is available. Temperature gradient measurements performed in the framework of this study have shown a constant evolution of temperature with depth, confirming the strong influence of the karst system in Central and North Lebanon. Karst systems are less influent in South Lebanon.

### *Preliminary qualitative geothermal resource assessment*

The information and data collected in the framework of this study allows establishing a preliminary qualitative geothermal resource assessment (see Table 5-9). As a first step, this preliminary assessment is used to identify target aquifers that could be exploited for geothermal energy production. A quantitative assessment could be established as a second step (see Chapter 6).

The preliminary qualitative geothermal resource assessment is presented in Table 5-9. It first describes the main stratigraphic units, providing the name of the geological formation, the age and a short description of the lithology. The stratigraphic units are then subdivided in hydrostratigraphic units according to an estimation of their transmissivity. The classification is based on Khair et al., 1992; Abbud & Aker, 1986 and UNDP, 1970. The qualitative evaluation of the transmissivity is provided according to Table 5-7.

Table 5-9 then provides, for each hydrostratigraphic unit, a preliminary assessment of the temperature. Quaternary deposits for instance are never located deep enough to provide a temperature level that could be used for geothermal power. The evaluation of the temperature quality is based on an approximation of the depth on a regional scale (Table 5-8).

Based on these two qualitative regional evaluations, a preliminary geothermal resource assessment is given in Table 5-9.

- A hydrostratigraphic that has either a low transmissivity or a low temperature is considered to have a low geothermal potential.
- A hydrostratigraphic that has an average transmissivity and an average temperature are estimated to have a medium geothermal potential.
- A hydrostratigraphic unit that has both a good transmissivity and a good temperature are considered to have a good geothermal potential.

Table 5-7: Qualitative estimation of the transmissivity for the preliminary assessment of the geothermal resources

Description	Transmissivity	Preliminary assessment
Aquiclude	Very low	-
Semi-Aquifer	Low	+/-
Aquifer	Average	+
Good Aquifer	Good	++
Excellent Aquifer	Very good	+++



Table 5-8: Qualitative estimation of the temperature for the preliminary assessment of the geothermal resources

Description	Approximate depth	Temperature	Preliminary assessment
Superficial and shallow deposits	<1,000 m	Low	-
Intermediate depth	>1,000	Average	+
Great depth	>2,000 m	Good	++
Very great depth	>3,000 m	Very good	+++

### *Karstification*

Karstification in Lebanon constitutes a major element for the assessment of the geothermal potential. Karstification has positive and negative effects:

- The main positive effect of karst is related to the strong increase of permeability of the carbonate layers, leading to higher potential in terms of productivity. Karst is the process responsible of the high permeability of the two main target aquifers, which are the Sannine and Kesrouane Formations.
- The main drawback of karst is the overall cooling of all the massif of Lebanon, by the circulation of cold water. This cooling effect annihilates the geothermal influence in the underground until the basis of the karst active zone. Due to its importance, karst also covers any thermal anomalies that could occur in the underground.
- The bigger uncertainty related to the karst system is related to the depth of influence. Although, nowadays, it is known that karst develops below sea level, the depth at which the system is considered active is still unknown.

### *Target aquifers*

The succession of carbonate and marly layers together with the tectonism and related karstification provided ideal conditions for the development of two aquifers with very good transmissivity (permeability and thickness). These target aquifers are the Sannine Formation (called the Cretaceous aquifer) and the Kesrouane Formation (called the Jurassic aquifer) (see Table 5-9).

The hydrostratigraphy allowed identifying other potential aquifers at a greater depth, such as the Triassic, for instance. The lack of data about the transmissivity does not allow us to make any assessment in terms of geothermal productivity (Table 5-9). These deeper aquifers have not been considered for the quantitative estimation of the geothermal potential.

### *Volcanism*

Presence of volcanism activity in the North and in the South during previous geological periods constitutes the main positive aspect for the development of geothermal technologies in Lebanon. It must be pointed out that this volcanic activity in Lebanon is dated back to the Miocene (23 to 5.3 million years) and Pliocene (5.3 to 2.6 million years). No recent volcanic activity is present in Lebanon. Most recent activity is found in the surrounding countries in the North and in the South. However, the evidence of thermal water in the Akkar region in close contact with the Miocene Lavas indicates that some residual heat from an old magmatic chamber could still be present. The local heat flux could thus be locally strongly increased.

The low thermal conductivity of the lava flow creates a thermal cap. For this thermal cap to take effect, it has to increase the geothermal gradient through the volcanic lavas. The temperature at depth is thus higher than normal.

### *Faults and tectonism*

Lebanon is located in a tectonic active area, which constitutes a chance and a drawback for the development of geothermal projects. Indeed faults and tectonism are closely related. The abundance of faults all over Lebanon is an important feature in terms of geothermal productivity. Faults could locally strongly increase the transmissivity of an aquifer. Fault areas within an aquifer could constitute a target zone for a geothermal project.

Moreover, fault zones could create preferential pathways for deep, hot water to flow towards the surface, and to create a local thermal anomaly. This could be an explanation for the thermal anomaly supposed in the Kaoukaba and Kfar Syr wells. Further investigations are required to confirm these anomalies.



Table 5-9: Hydrostratigraphic units and preliminary qualitative geothermal potential of deep aquifers (hydrostratigraphy based on Khair, et al. (1992); Abbud & Aker (1986) and UNDP, (1970))

Period			Formation (Age)	Lithology	Hydrogeological Classification	Thickness [m]	Transmissivity	Temp.	Preliminary Geothermal Potential
Quaternary			Quaternary	Coastal or alluvial loose deposits	Semi-aquifer	0 - 100	-/+	-	Low
Tertiary	Neogene	p	Pliocene succession	Marl, conglomerate, basalt	Aquiclude, locally semi-aquifer	0 - 500	-	-	Low
		m	Miocene succession	Conglomeratic limestone, sand-silty marls, followed by a thick sequence of fractured limestones.	Aquifer	200-300	+	-	Low
		mcg	m = marine mcg = continental	Lacustrine conglomerates and sandy-silty marl dep.	Aquiclude, but aquiferous under favorable conditions	0 - 1500	-	-/+	Low
	Paleogene	e2	Lower (plus Paleocene) and Middle Eocene successions	Fractured, sometimes folded beds (Majdel Anjar, Marjayoun & Dubbieh synclines) or chalky markedly limestone and hard limestone, chertified and sometimes with chert concretions	Aquifer	100 - 800	+/++	-/+	Low/Medium
		e1		Chalky marl and marly limestone;	Aquiclude	0 - 1200	-	-/+	Low
		p							
Cretaceous	SENONIAN	C6	Chekka Fm.	Chalky marl and chalky marly limestone with nodules and bands of chert	Aquiclude	0 - 600	-	-/+	Low
	CENOMANIAN-TURONIAN	(C4)-C5	Maameltein Fm.	Massive to thin-bedded limestone and marl	Semi-aquiferous or aquiferous depending on locally prevailing lithology	200 - 400	-/+	-/+	Low
	Up. ALBIAN-CENOMANIAN	(C3)-C4	Sannine Fm.	Fractured, folded and karstified thin- and thick-bedded limestone with geods and cherts bands at different levels	Excellent aquifer "second water tower" of Lebanon	700	+++	+	Low/Medium
	Up. ALBIAN-Mid. ALBIAN	(C2b)-C3	Hammana Fm.	Marl and fractured limestones beds which grade toward the top into dolomitized limestone with geods and chert bands	Aquiclude	200 - 400	-	+	Low
	L.-Up. APTIAN	C2a2	Mdairej Fm.	Fractured massive limestone followed (overlain) by a sequence of limestone, marl, sand limestone, sandstone, and/or local volcanic rocks	Limestone member is aquiferous	50	-	+	Low
	L. APTIAN	C2a1	Abeih Fm.	Argillaceous sandstone, sandy argillaceous limestone, claystone, argillaceous limestone, marls and shales	Aquiclude	80 - 170	-	++	Low
JURASSIC	Up. PORTLANDIAN	J7	Salima Fm.	Oolitic limestone, marls and shales	Aquiclude	>180	-	++	Low
	Up. PORTLANDIAN	J6	Bikfaya Fm.	Fractured, karstified, massive limestone with horizons of dolomitic limestone, thin marly limestone with freq. horizons of chert nodules	Excellent aquifer	50	++	+++	Medium/High
	KIMMERIDJIAN - Up. PORTLANDIAN	J5	Bhannes volcanic complex	Basalt and volcanic tuff. Volcanism was accompanied by simultaneous deposition of detrital & oolitic limestone, marls, and shales assigned as Bhannes volcanic complex equivalent	Aquiclude	40 - 150	-	+++	Low
	KIMMERIDJIAN OXFORDIAN	J4	Kesrouane Fm.	Fractured, karstified massive dolomite, dolomitic limestone, and massive to bedded limestone with some marl intercalations. This formation is characterized by a series of fault lines and fault valleys	Excellent aquifer "First water tower of Lebanon"	700 - 1000	+++	+++	High
	CALLOVIAN BATHONIAN BAJOCIAN AALENIAN	J2, J3							
	LIAS	J1		Green marls and black dolomites	Aquiclude	350	-	+++	Low
Triassic	Middle to Late Triassic	Tr		Presumed very shallow lagoon disposition in evaporate environment, marked with regressive cycles (Nader, 2011 -> J.P.Geology)	Aquifer (supposed to have very high salinity content)	800 - 1500	+	+++	Low/Medium
	Early Triassic			Transgressive siliciclastic sequence	Aquiclude		-	+++	Low
	PERMO-CARBONIFEROUS			Not outcropping		> 1700	-	+++	Low
	SILURIAN ORDOVICIAN CAMBRIAN			Arkosic sandstones together with siltstone and shales. Beydoun (1977)		> 4000	-	+++	Low

# 06. Geothermal potential of Lebanon

## 6.1. Introduction

Geothermal potential is an estimation of the quantity of energy that is present in the underground of a given region or country. The geothermal potential could be expressed in terms of stored heat and recoverable heat.

The stored heat, also called heat in place (HIP), is a measure of the total thermal energy, which is stored in a given volume. The stored heat is usually estimated for a geothermal target reservoir, such as a deep aquifer or a fractured rock mass.

Recoverable heat is the fraction of the stored heat, which can be effectively extracted or recovered from the geothermal reservoir, by means of engineering techniques.

The ratio between the recoverable heat and the stored heat is called the recovery factor. The recovery factor depends on the one side on the kind of technique used to extract the heat from the reservoir, and on the other side on the transmissivity of the target reservoir. The transmissivity is the product of the hydraulic permeability and the thickness of the reservoir.

As the stored heat mainly depends on the temperature and the thickness of the target reservoir, and the recoverable heat mainly depends on the hydraulic conductivity, it can be stated that the geothermal potential of a target reservoir depends on the three following main factors:

- The temperature of the target reservoir,
- The thickness of the target reservoir,
- The hydraulic conductivity of the target reservoir.

In order to assess the geothermal potential of a given region, the identification of target reservoirs is required as a first step. As a second step, the above mentioned properties have to be estimated quantitatively for each of the identified targets. The methodology applied in the present study precisely aims at providing the best estimates of these three parameters, given the quantity and quality of data available.

The assessment of geothermal potential in Lebanon and the determination of the relevant properties are based on a methodology developed by GEOWATT AG and applied for several geothermal projects. It corresponds very closely to the methodology described by the best practices report of the International Geothermal Association (IGA) (Geothermex Inc., 2013).

This chapter is structured as follows:

Section 6.2 provides the overall overview of the applied methodology. The main steps are then described in individual sections. The first step consists in gathering all the relevant geological information and to construct a 3D geological model of Lebanon (section 6.3). The 3D geological model then provides the geometry of the geological horizons and thus the basic structure for the numeric model used for the thermal calculations (section 6.4). The results are then used to assess the geothermal potential of Lebanon, by calculating the heat in place and recoverable heat of the geothermal target reservoirs as well as an estimation of a power plant capacity (section 6.5).

## 6.2. Applied methodology

The assessment of geothermal potential in Lebanon follows a specific methodology, which could be summarized as follows:

- STEP 1: Development of a conceptual model,
- STEP 2: Creation of a geological model,
- STEP 3: Creation of a numerical temperature model,
- STEP 4: Extraction of the temperature at depth of the target aquifers,
- STEP 5: Calculation of the heat in place and recoverable energy,
- STEP 6: Creation of maps for the geothermal atlas.

This methodology aims at obtaining the best estimate of geothermal potential within a given area, given data availability and quality.

The first step towards the estimation of the geothermal potential consists in the creation of the conceptual model. The conceptual model integrates all the various data sets and information found in literature or collected by the developer. The description of the conceptual model is the aim of Chapter 5.

This conceptual model is then used as a basis for the development of the 3D geological model. Since the depth and thickness of the geological layers and potential target reservoirs could only be measured in the exact location of boreholes who have reached the target reservoir, the spatial distribution of the depth and thickness of the geological layers over the whole territory of Lebanon needs to be extrapolated. The extrapolation can be achieved at best using a 3D geological model, which integrates all the available relevant geological information about the structure of the deep underground. The geological model is described in section 6.3.

As there is also very little information available for the temperature in the deep underground, the temperatures have to be estimated by indirect methods. The most suitable method for the estimation of the underground temperatures is the use of a 3D-numerical model, which simulates all the relevant thermal processes in the underground. Such a 3D-numerical model provides the best estimate for the underground temperature, which is achievable given the available data. The structure of the 3D-numerical model is obtained from the geological model. The parameters of the model and the boundary conditions are derived from the geothermal conceptual model. The thermal properties of the rocks have been measured in the laboratory. The 3D-numerical model, the parameters and the boundary conditions are described in section 6.4.

The next steps consist of processing the temperatures obtained by the 3D-numerical model to compute the stored heat and the recoverable energy for the target aquifers or at specific depth intervals (see section 6.5).

The very last step consists in map production for assessing the geothermal resources in Lebanon.

## 6.3. 3D geological model

### 6.3.1. Approach

The geological model constitutes the basis for the development of the numerical model. The geological model gathers all relevant geological data and aims at defining the geometry (depth, orientation and extent) of the deep geological structures.

The degree of detail and precision in the geological model needs to be adapted to its purpose and to the quality and amount of available geological datasets. Therefore, the number of geological units considered in the model is very restricted. They will be described later in this chapter in section 6.3.4.

The 3D geological model was created with the software 3D GeoModeller from the company Intrepid Geophysics in Australia.<sup>9</sup>

The approach of 3D GeoModeller differs from other geological modeling software. Most of the geological modeling software uses a CAD approach where the geological layers are literally drawn or designed in 3D. In 3D GeoModeller, the layers are generated or simulated using mathematical cokriging interpolation algorithms, called the potential field method. This method is constrained by geological observation or hard data, such as contact points between geological formations, orientation of a bedding plan, borehole data or interpreted geophysical cross-sections. Basically the software finds “by itself” a surface that fits at best with the geological observations. In other terms, the geological model is basically constructed by simulation. More detailed information could be found in the documentation of 3D GeoModeller.

The geological data used for the construction of the 3D geological model are described briefly in section 6.3.2. The next step consists then in defining the model extent in horizontal and vertical directions (section 6.3.3). The different geological units that composed the geological model (stratigraphic pile) and the relationship between the different units are described in section 6.3.4. More specific features such as the integration of faults and the integration of the karstic layers are described in sections 6.3.5 and 6.3.6, respectively.

### 6.3.2. Geological Data

The main sources of geological information to construct the 3D geological model are the geological maps (surface geology), the deep geological boreholes and interpreted geological cross-sections. All these data are described in details in chapter 5 of this report.

- Two geological maps have been used to define the surface geology: the geological map of Lebanon of Dubertret (1955) and a simplified geological map from Nader (2011).

---

<sup>9</sup> <http://www.intrepid-geophysics.com/ig/index.php?menu=products-3dweg>

- Information on major faults has been taken from the simplified geological map of Nader (2011).
- In addition to the geological map, the information from geological logs of seven deep exploration O&G boreholes has been integrated into the model.
- The well logs have been integrated into the geological model to locate the base of the relevant geological units. Different data sources have been used (Ukla, 1970; Nader, 2011 and Haddad, 2006).

### 6.3.3. Model extent

The model perimeter is of rectangular shape. It covers the whole territory of Lebanon (onshore and offshore) including some areas of the surrounding countries. The model perimeter is defined by the SW and NE coordinates <688,000/13,650,000> and <850,000/13,850,000>, respectively (in meters based on the projection UTM WGS84 Zone 36S).

The top of the geological model is composed in the onshore area by the topographic surface. The dataset used is the ASTER Global Digital Elevation Model V002. The data originates from METI/NASA and is published by NASA LP DAAC. The release date is 2011. The resolution of the raster surface is 30x30 m, which is suitable for the scale of the geological model.

In the offshore area, the top of the geological model is composed by the ground of the Mediterranean Sea. The dataset, which has been used to define the submarine ground in the geological model, is the GEBCO\_08 Grid data set (IOC, 2003). The bathymetrical data originates from GEBCO (General Bathymetric Chart of the Oceans).

The bottom of the geological model is defined at a depth of 10,000 m below sea level.

### 6.3.4. The stratigraphic pile and relationship (onlap/erode)

In the geological model, the term formation is used to designate a geological unit or group of geological units, which is explicitly represented in the geological model. It consists of the basis unit of the geological model.<sup>10</sup> Formations that deposited successively during the same sedimentary sequence are called a series. Stratigraphic discontinuities due to erosion processes, a cease of sedimentation or tectonic folding are modeled using different series. The relationship between each series must be specified. 3D GeoModeller allows defining two kinds of relationships. "Onlap" is used when the newer series is deposited on the older one during a transgressive event. "Erode" is used when the newer series is deposited after an erosive period. The newer series then cross-cuts the older series. Each series has its own potential field, and must thus be defined by a specific set of attributes and geological constraints (contact point and orientation data). The different series and their formations compose the stratigraphic pile.

Five main series were required to construct a geological model for Lebanon that integrates the relevant stratigraphic discontinuities in the model area (see Figure 6-1):

- Basement
- Paleozoic / Triassic / Jurassic
- Cretaceous
- Tertiary / Quaternary
- Basalts

In order to account for the complexity of the geological structure and history in Lebanon, the Basalts series has been divided into four subseries (4a-c), and the Tertiary & Quaternary series has been divided into seven subseries (7a-g). The introduction of subseries was required for construction reasons. This can also be justified from a geological point of view, as Basalts and Tertiary & Quaternary units appear in quite isolated and independent areas of the model. Each of these areas needs to be modeled by a separate potential field.

The stratigraphic pile of the 3D geological model of Lebanon and the relation to the stratigraphy of Dubertret (1955) is shown in Figure 6-1.

This stratigraphy is described in more detail in the following sections. The relationship with the underlying series is indicated in brackets.

#### 6.3.4.1. Basement

The basement series is used to model the rock below the sedimentary sequence. This series has no substructure and therefore consists in one formation only.

<sup>10</sup> This term should not be confused with the fundamental lithostratigraphic unit, called Formation. The latter is generally written with capital "F".



### 6.3.4.2. Series 1 (onlap)

Series 1 is composed by the undifferentiated Paleozoic and the Triassic to Jurassic sedimentary units. Series 1 is considered having been deposited without interruption. It directly overlies the basement and is therefore attributed with an “onlap” relationship.

From Figure 6-1, it can be seen that the Jurassic aquifer of the Kesrouane Fm has not been explicitly modeled by a specific formation. The top and bottom horizons of the Jurassic Aquifer have instead been determined by assuming a constant thickness of the aquifer of 700 m and a constant thickness of the Lias of 350 m.

### 6.3.4.3. Series 2 (erode)

Series 2 is composed by the units of the Early Cretaceous and Late Cretaceous. In order to use the information provided by the geological map, the Cenomanian-Turonian / Senonian has been differentiated from the Late Cretaceous and simulated as an independent formation (labeled Turonian). The formations of series 2 are then as follows:

- Early Cretaceous
- Late Cretaceous
- Turonian

Cretaceous was deposited during a transgressive sequence following an uplift phase of the Mount Lebanon. To account for the angular discordance between both series, they have then been modeled using an “erode” relationship.

### 6.3.4.4. Series 3 (onlap)

Tertiary and Quaternary (except Miocene and Pliocene Basalts) have been modeled using seven sub series (3a-g) in order to simulate the different geographic areas where Tertiary and Quaternary deposited, e.g. the North and South coast areas, and the Bekaa Valley.

Due to their place in the uppermost part of the stratigraphic sequence, Tertiary and Quaternary sedimentary units are of secondary importance for the geothermal atlas of Lebanon. They are thus simulated using one single formation.

### 6.3.4.5. Series 4 (onlap)

Miocene and Pliocene basaltic units are defined by three additional independent series. Series 4a/b are used to model the basalt of the Akkar area (on the north, east and west of the Yammounneh fault). Series 4c is used to model the basalt of the Golan Plateau in the South.

GeoModeller		Dubertret	
Series	Formation	Key	Formation
4(a-c)	Basaltes	<i>b</i>	<i>Basaltes</i>
3(a-g)	Tertiary & Quaternary	<i>a</i>	<i>Quaternary</i>
2	Turonian (& Senonian)	<i>p, m, mca</i>	<i>Neogene</i>
	Late Cretaceous	<i>e2, e1, p</i>	<i>Paleogene</i>
	Early Cretaceous	<i>C6</i>	<i>Senonian</i>
1	Jurassic	<i>(C4)-C5</i>	<i>Cenomanian-Turonian</i>
		<i>(C3)-C4</i>	<i>Up. Albian-Cenomanian</i>
		<i>(C2b)-C3</i>	<i>Up. Albian-Mid. Albian</i>
		<i>C2a2</i>	<i>L.-Up. Aptian</i>
	Triassic	<i>C2a1</i>	<i>L. Aptian</i>
		<i>C1</i>	<i>Up. Neocomian-Barremian</i>
		<i>J7, J6</i>	<i>Portlandian</i>
Basement	Basement	<i>J5</i>	<i>Kimmeridian – Up. Portlandian</i>
		<i>J2, J3, J4</i>	<i>Kimmeridian, Oxfordian, Callovian Bathonian, Bajocian, Aalenian</i>
		<i>J1</i>	<i>Lias</i>
		<i>Tr</i>	<i>Triassic</i>

Figure 6-1: Stratigraphic pile used for the geological model and correlation with the stratigraphy of Dubertret (1955). The two target potential aquifers are marked with a blue background color

### 6.3.5. Faults

The geology of Lebanon is characterized by a high density and complex fault network resulting from the regional scale tectonic movements. A summary of the geological setting could be found in Nader (2011) and references therein.

The 3D geological model integrates the most important and representative faults (see Figure 6-2). Minor faults are not considered by the 3D geological model. To simplify matters, all the faults are considered vertical.

### 6.3.6. Karst level

Karst is found in almost the whole territory of Lebanon. It acts as an aquifer in which rainwater can easily pass through. This hydraulic behavior plays an important role for the temperature distribution in the underground. It then has to be considered for the definition of the boundary conditions of the numerical temperature model. For this reason, karst has been integrated in the geological model. In the absence of adequate data about the depth of the karst level, its integration in the geological model is based on strong assumptions:

- The upper limestone units are karstified from the surface down to the groundwater table
- The groundwater table on the coast of Lebanon and in the Bekaa Valley corresponds to the topographic level
- The elevation of the groundwater level in the mountainous regions is supposed to correspond to 1/3 of the topographic level

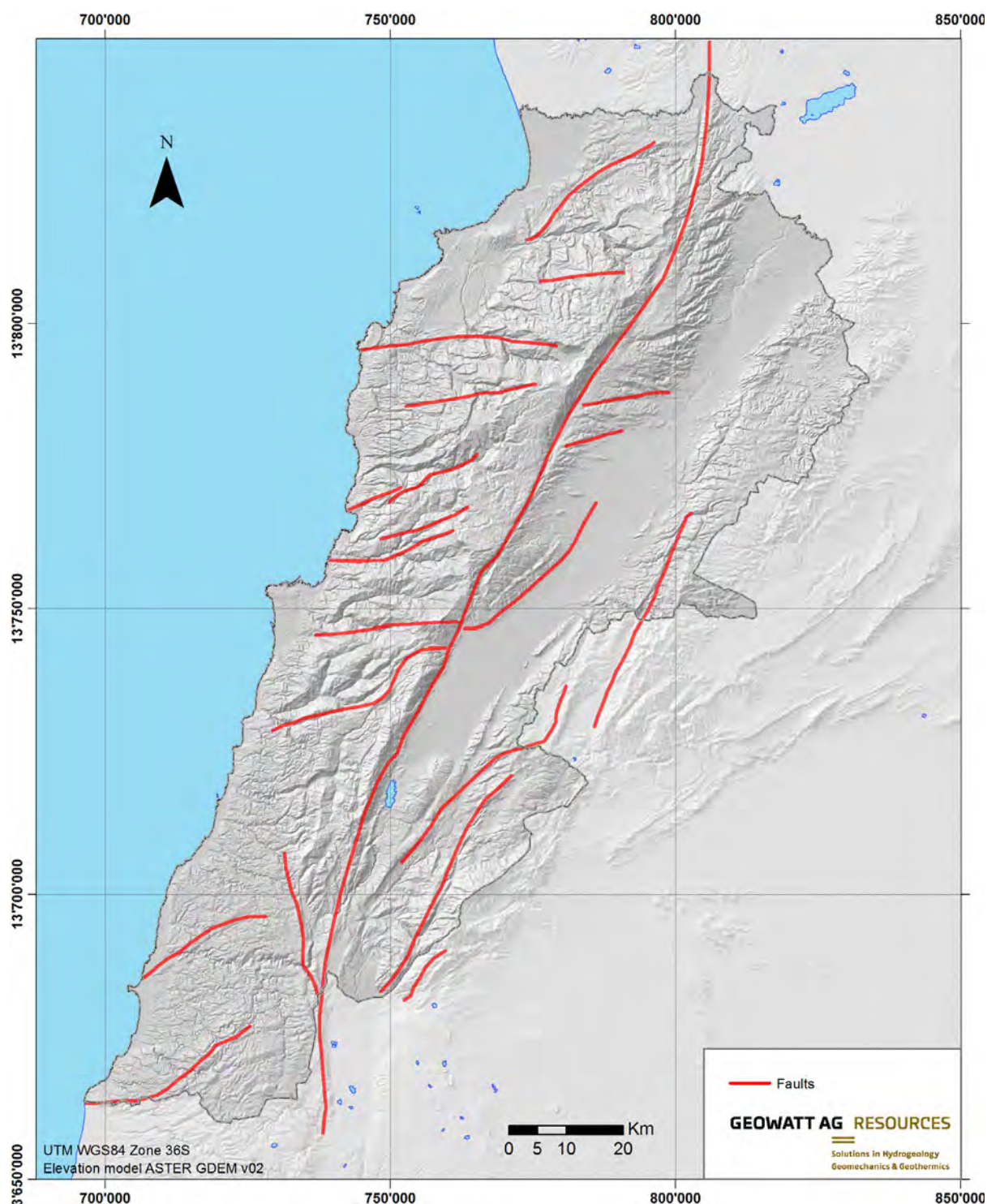


Figure 6-2: Faults considered and lateral extent of the geological model

### 6.3.7. Results

The 3D geological model of Lebanon is presented in Figure 6-3 to Figure 6-5. The comparison between the geological model and the surface geology (Figure 6-3) confirms that the general trend of the geology in Lebanon is correctly reproduced by the geological model.

For illustration purposes, the basement and some E-W sections of the model are shown in Figure 6-4 and a 3D view of the model is given in Figure 6-5.

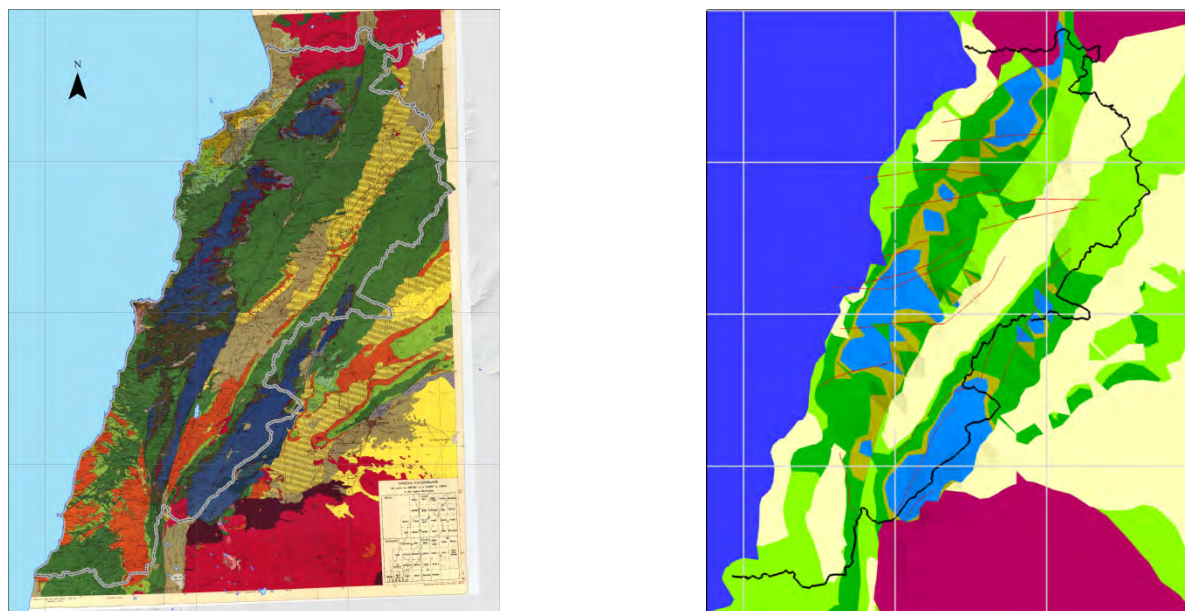


Figure 6-3: Comparison between the subsurface geology of Lebanon given by (left) the geological map of Dubertret (1955) and (right) the top view on the 3D geological model

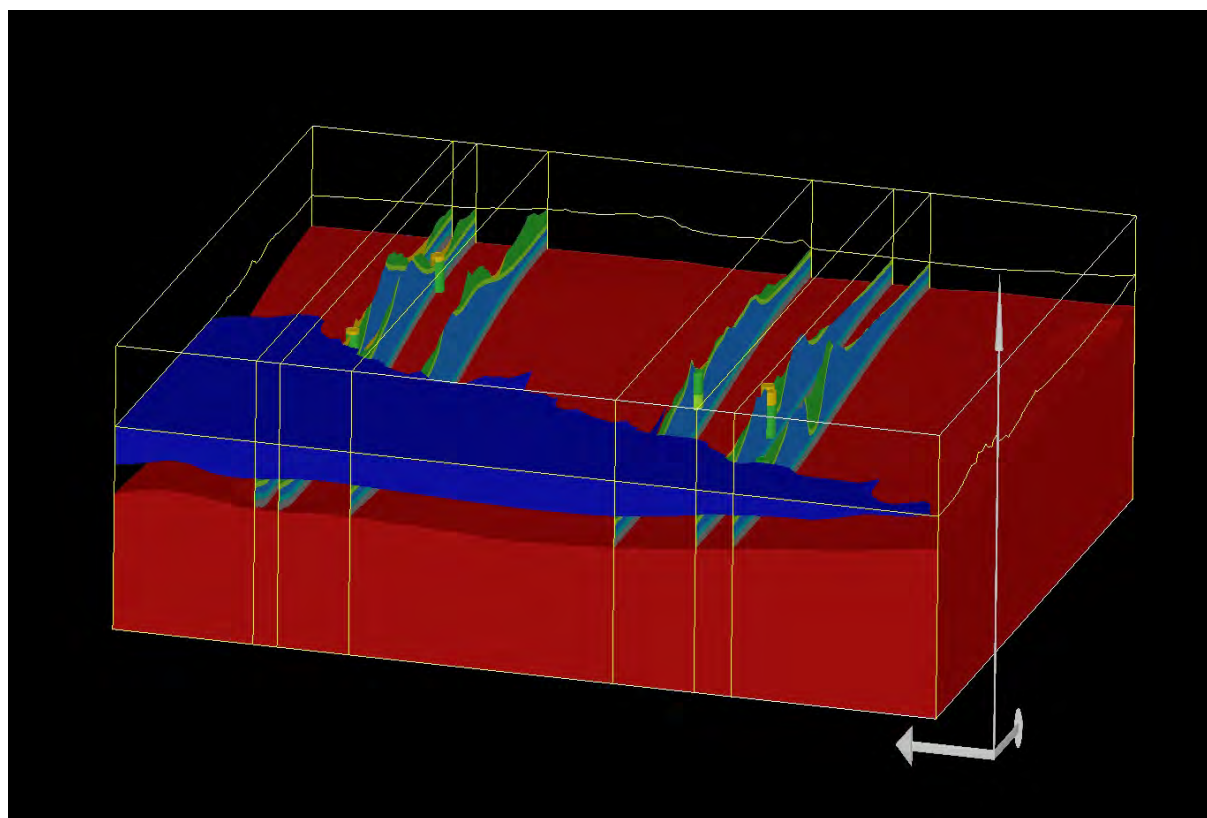


Figure 6-4: 3D geological model of Lebanon: the basement and sea are shown in volume view, projections of the modeled geology on EW-sections and symbolized wells



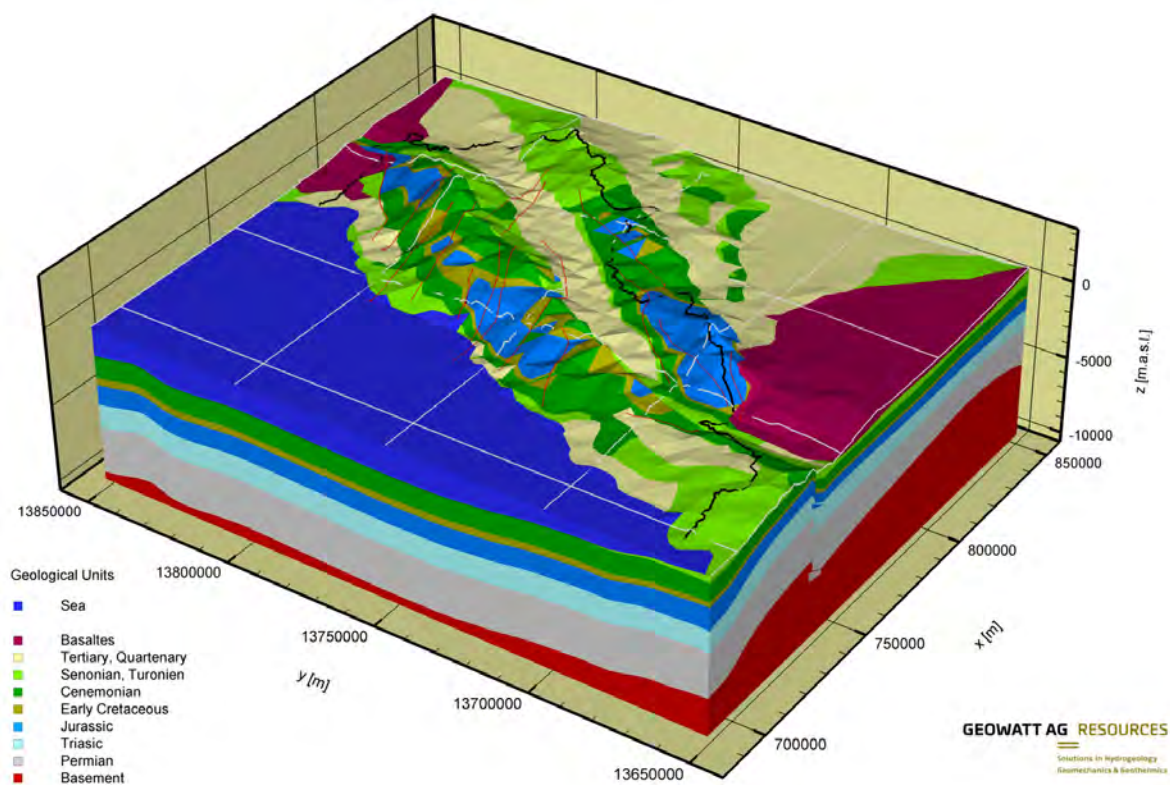


Figure 6-5: Geological 3D-model for Lebanon, view from SW



## 6.4. 3D temperature model

### 6.4.1. Introduction

The underground temperature is one of the most important factors for the estimation of geothermal potential. As very little information is available for the deep underground temperature in Lebanon, a 3D numerical temperature model has been developed with the aim to determine the best prediction of the underground temperature, which can be achieved on the basis of the available data (surface temperature, heat flux, thermal conductivities, etc...)

The structure of the 3D-numerical model is given by the geological model. The parameters of the model and the boundary conditions are derived from the geothermal conceptual model and the thermal properties of the rocks, respectively.

Thermal processes are generally divided in a diffusive and an advective component. Advection describes the transport of heat by the fluid movement. Diffusion or conduction is transport of heat due to a temperature gradient. Conduction involves no mass or fluid movement.

$$\mathbf{F} = \underbrace{\rho c_L \mathbf{q} T}_{\text{advection}} - \underbrace{\Lambda \nabla T}_{\text{dispersion-diffusion}}$$

Whether advection has to be considered or neglected in the temperature model depends on the hydrogeological conditions in the model area. In the absence of comprehensive database about the hydrodynamic properties of the deep underground, advective processes were not considered.

As a first approach, the underground temperature is thus calculated by a diffusive model only.

### 6.4.2. Mesh generation and solver

The simulation of the thermal processes and the calculation of the underground temperature is performed by the code FRACTure developed by GEOWATT AG (Kohl & Hopkirk, 1995), based on the finite element method. This method consists in subdividing or discretizing the whole model volume into small elements that are used to solve the differential equations. All the elements form the 3D mesh.

The numeric mesh for the temperature model of Lebanon is constructed from the geological model. The geological horizons are used for the vertical discretization of the 3D mesh.

#### 6.4.2.1. Extent of the model

The lateral extent of the numerical model, as well as the upper and lower boundaries, correspond according to the boundaries of the geological model:

- X-coordinates (UTM 36S): 688,000 – 850,000 m
- Y-coordinates (UTM 36S): 13,650,000 – 13,850,000 m
- Upper boundary: topographic surface
- Lower boundary: 10,000 m below sea level

#### 6.4.2.2. Considered layers

The layers, which have been considered in the numerical model, correspond directly to the formations of the geological model. The following layers have been used to build the numerical model:

- Sea (for construction only)
- Basalts
- Tertiary, Quaternary
- Karstified limestone
- Senonian, Turonian
- Cenomanian

- Early Cretaceous
- Jurassic
- Dogger
- Lias
- Triassic
- Permian
- Basement

### 6.4.2.3. Spatial discretization

The size of the mesh elements is 1 km x 1 km in both x and y directions. The size is constant all over the domain.

The vertical size of the elements is given by the thickness of the geological layers. The vertical size, therefore, differs from one location to another. Depending on the thickness of the individual layers, the layers have been refined vertically. The vertical size of the elements ranges from 20 m to more than 400 m.

The resulting mesh is then composed of 532,512 nodes and 507,904 elements (see Figure 6-6).

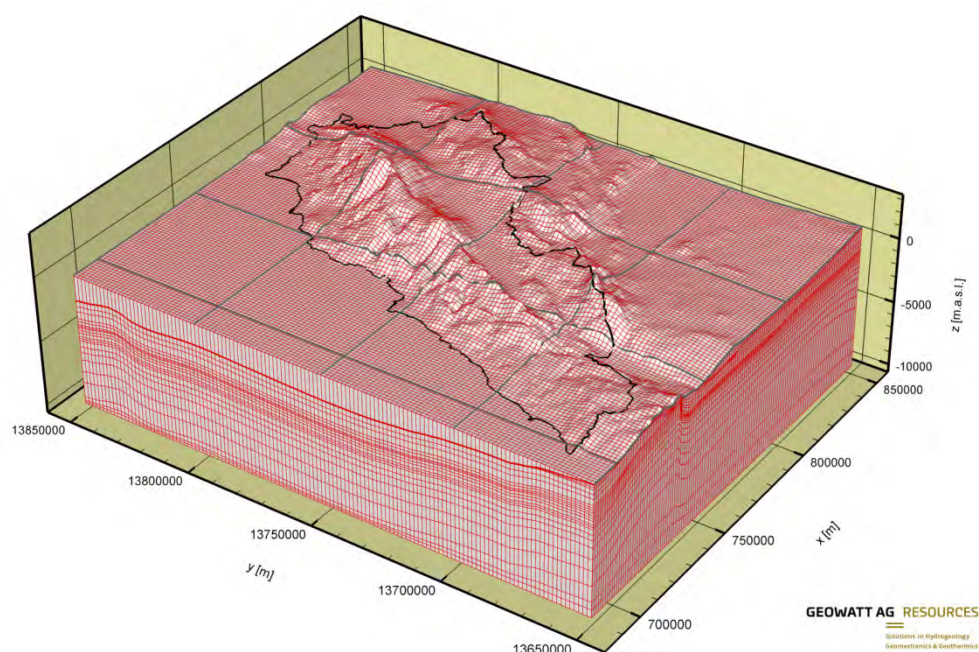


Figure 6-6: Discretization of the numerical temperature model for Lebanon, view from SW

### 6.4.3. Model parameter and boundary conditions

#### 6.4.3.1. Model parameter

Model parameters are the petrophysical properties, such as the thermal conductivity and heat production for each considered geological layer. The values, which have been used for the temperature calculations are listed in Table 6-1. Values, marked with a star, are based on measurement values for local rock samples (see section 5.4.2). These rock samples belong to different lithological units. As the values, which are needed for the numerical model, are related to the geological units, which were considered in this numerical model, the rock samples had to be assigned to the respective layer of this model first. As a second step, a weighted average value was calculated from the measurement values.

Values, not marked with a star, are average values for the corresponding geological units originating from literature and geothermal studies.

The heat conductivities of the sea and the Karst have been set to very high values to achieve the high temperature gradient, which can be expected in the sea<sup>11</sup> and in the karstified limestone units<sup>12</sup>.

**Table 6-1: Model parameters for the numerical temperature model. Values, indicated with a star are based on measurements of local rock probes (see section 5.4.2).**

Material	Layer	Heat conductivity [W·m <sup>-1</sup> ·K <sup>-1</sup> ]	Heat production [μW·m <sup>-3</sup> ]
1	Sea	100.0	0.0
2	Basalts*	1.5	0.5
3	Quaternary -Tertiary*	2.4	0.5
4	Karst	10.0	0.5
5	Senonian, Turonien*	2.3	0.5
6	Cenemonian*	2.6	0.5
7	Early Cretaceous*	2.6	0.5
8	Jurassic*	2.6	0.5
9	Dogger	2.6	0.5
10	Lias	2.6	0.5
11	Triassic	2.5	0.5
12	Paleozoic	2.5	0.5
13	Basement	4.0	2.5

#### 6.4.3.2. Boundary conditions

Boundary conditions have to be defined for all model boundaries if the heat equation has to be solved in a limited volume. Two types of boundary conditions can be distinguished:

- the Dirichlet boundary condition defines a temperature along a specific boundary;
- the Neumann boundary condition defines a heat flux at the specified boundary.

The boundary conditions for the lateral model boundaries have been defined as Neumann boundary conditions with a zero heat flux. At the bottom of the model, at a depth of 10 km below sea level, the boundary condition is defined by the basal heat flux (see section 5.4.1).

The Dirichlet boundary condition for the upper model boundary is defined by the mean surface temperature. The determination of the mean surface temperatures is displayed in Figure 3-5: Calculated average surface temperatures in Lebanon in section 3.4.

<sup>11</sup> The average temperature of the whole sea is more or less constant over the years and there is only a negligible temperature gradient between the surface and the bottom of the sea.

<sup>12</sup> See section 5.3.5

It should be noted, that the temperature, which can be found at the base of the karstified units is expected to correlate strongly with the surface values.

According the discussion in section 5.3.5, the karst conduits allow cold water to circulate very quickly in the deep underground, cooling the whole massif to a temperature level slightly higher than the temperature in the infiltration area.

The described advective processes cannot be simulated with the diffusive model, which is used for the temperature calculation. Instead, the thermal effect of this process has been considered indirectly by assuming a high thermal conductivity of the karstified limestone units. The high thermal conductivity of these karstified units insures that the temperature at the bottom of the karst is only slightly higher than the surface temperature.

#### 6.4.4. Results

The result of the 3D numerical model consists in a 3D distribution of the temperature in the underground over the whole model area, i.e. covering the whole Lebanese territory. These results provide the basis for the determination of the temperature of the target resources and the geothermal potential of Lebanon.

### 6.5. Geothermal potential estimation

#### 6.5.1. Introduction

There are four main factors, which could be used to characterize the geothermal potential of a specific target in a broader sense:

- depth
- temperature
- stored heat
- recoverable heat

The depth of the target is an important factor in terms of accessibility and in terms of economics (drilling costs etc.). Temperature is an important factor, as minimum temperatures are required as well for heating purposes and for the production of electricity. In case of the production of electricity a minimum temperature of 100 °C is required.

In a more strict sense geothermal potential is often used as a measure of either the total thermal energy (stored heat) of the target reservoir, or as the recoverable heat, defined as the fraction of the stored heat, which can be utilized by technical means.

The geothermal potential has been estimated for the following target reservoirs:

- Jurassic aquifer
- Cretaceous aquifer
- Depth horizon at 4,000 m below sea level
- Depth horizon at 5,000 m below sea level
- Depth horizon at 6,000 m below sea level
- Depth horizon at 7,000 m below sea level

Cartographic representation of the four factors is made for the six target horizons (see figures here after and Appendices 10 to 33).

The temperature maps of both Jurassic and Cretaceous aquifers clearly indicate that the most suitable area is in the Akkar region in the North (due to the local thermal anomaly) and eventually in the Bekaa Valley which corresponds to a low syncline structure.

The Akkar region and the Bekaa valley are therefore two potential target areas.

6.5.2. Depth of the potential target aquifers

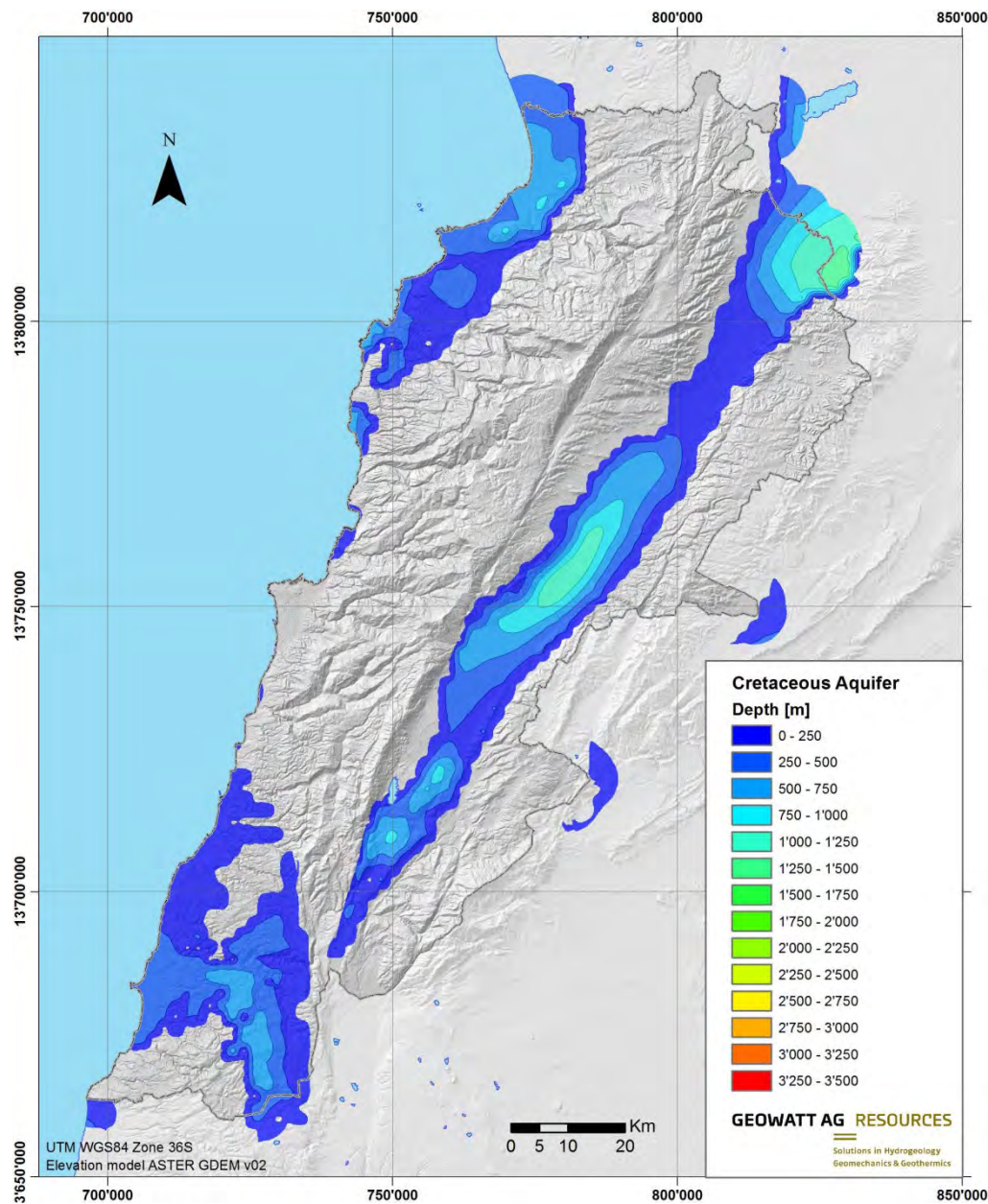


Figure 6-7: Depth of the Cretaceous aquifer [m. BGL.]



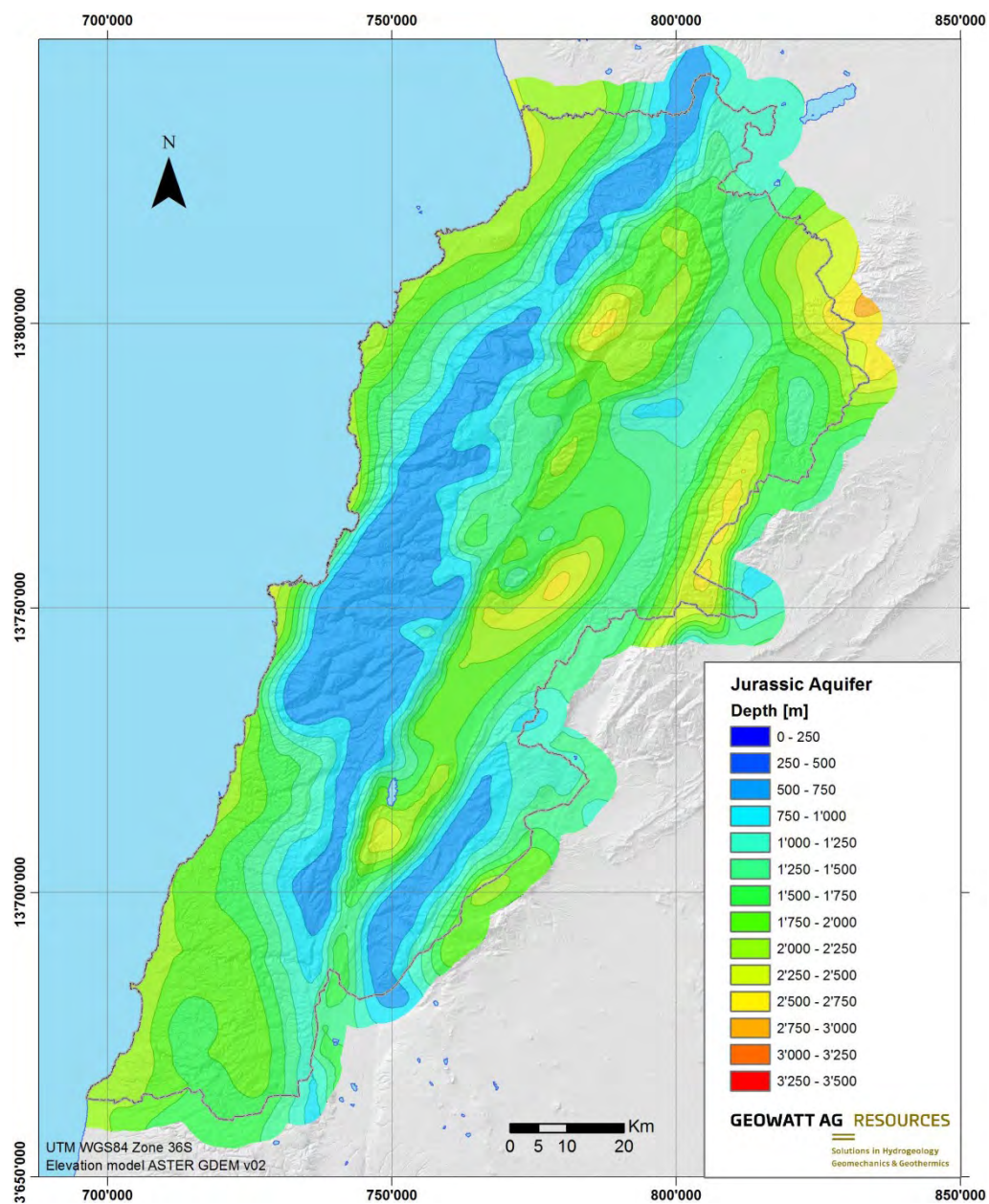


Figure 6-8: Depth of the Jurassic aquifer [m. BGL.]

6.5.3. Temperature at depth of the target horizons

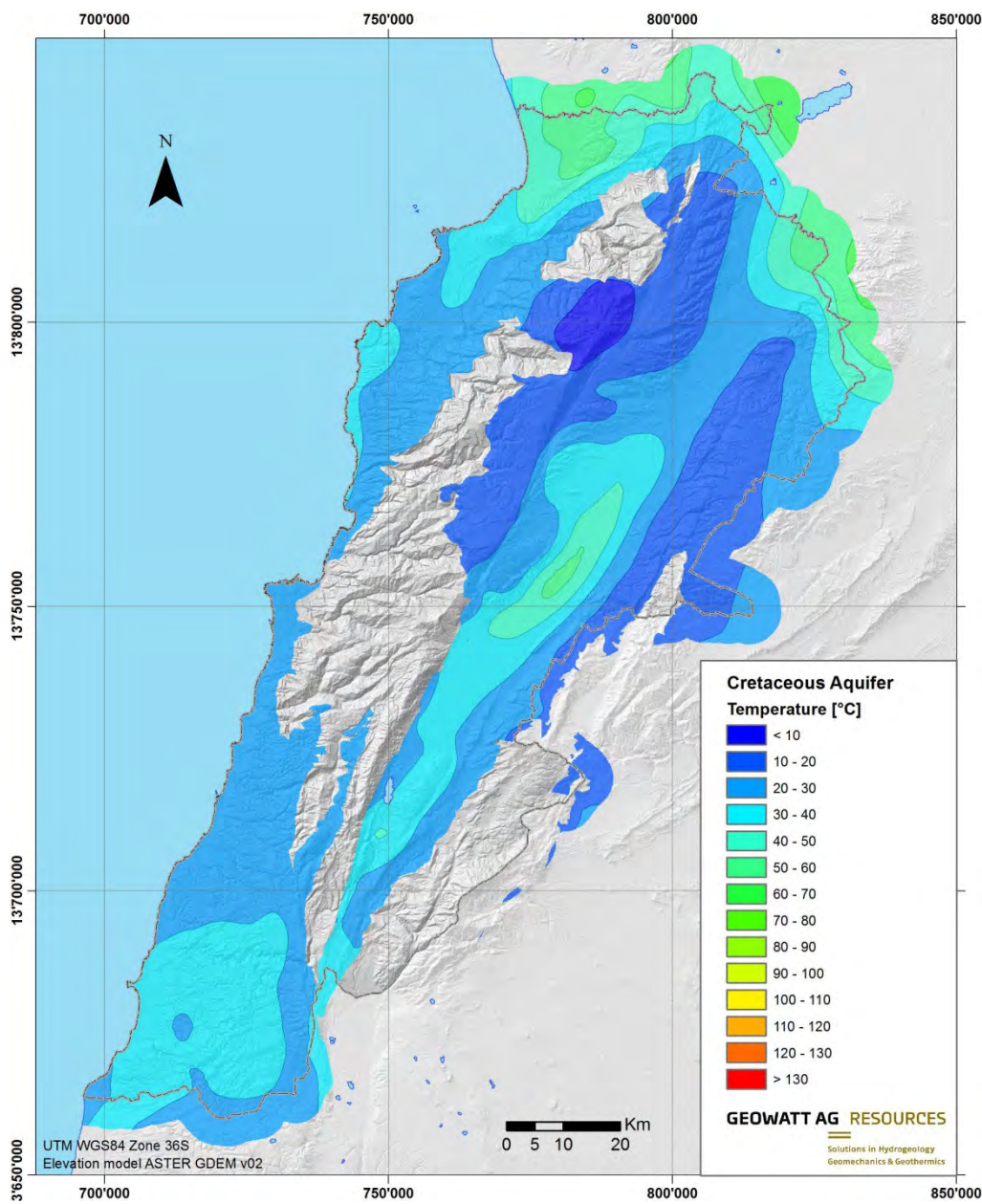


Figure 6-9: Temperature of the Cretaceous aquifer

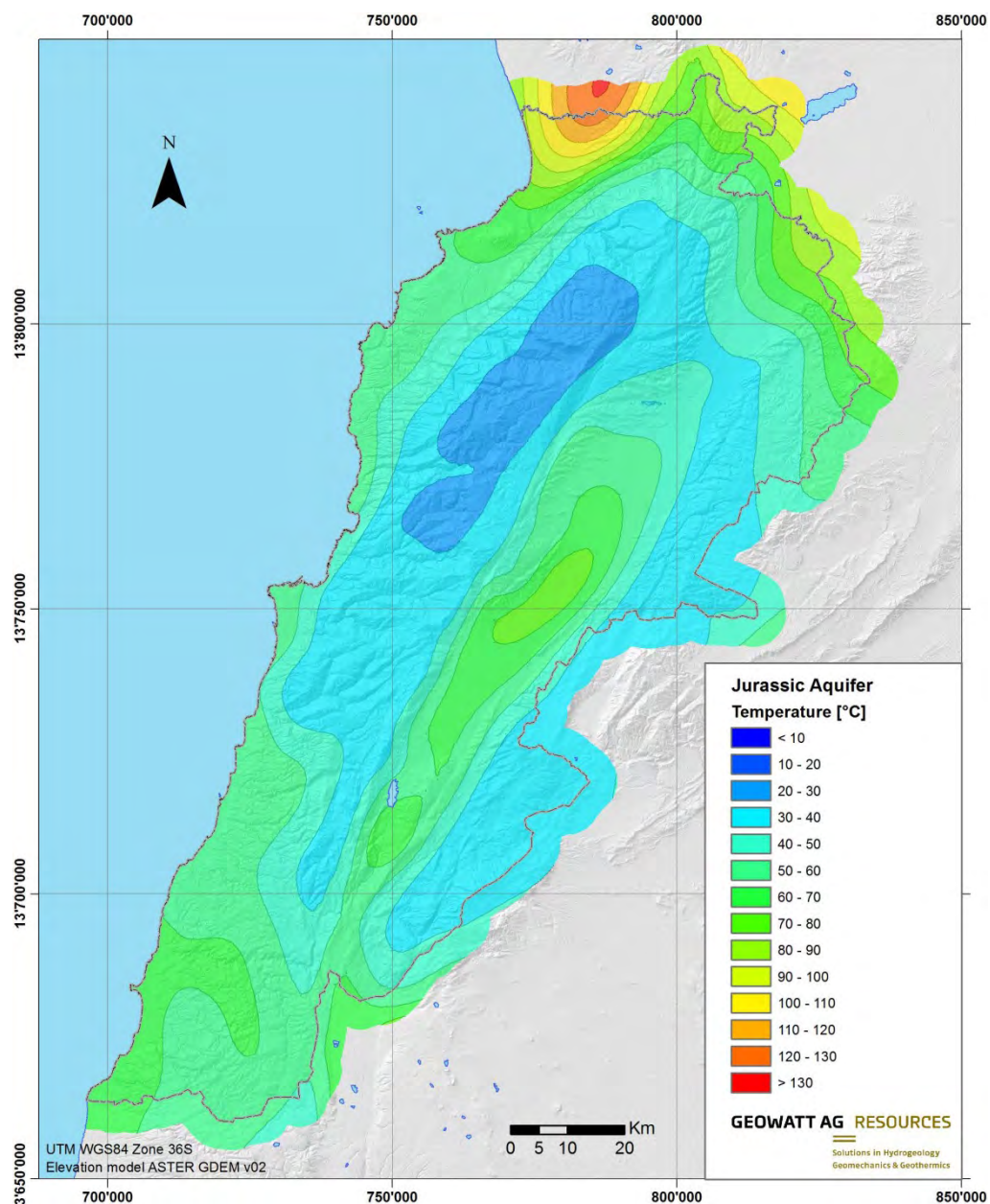


Figure 6-10: Temperature of the Jurassic aquifer



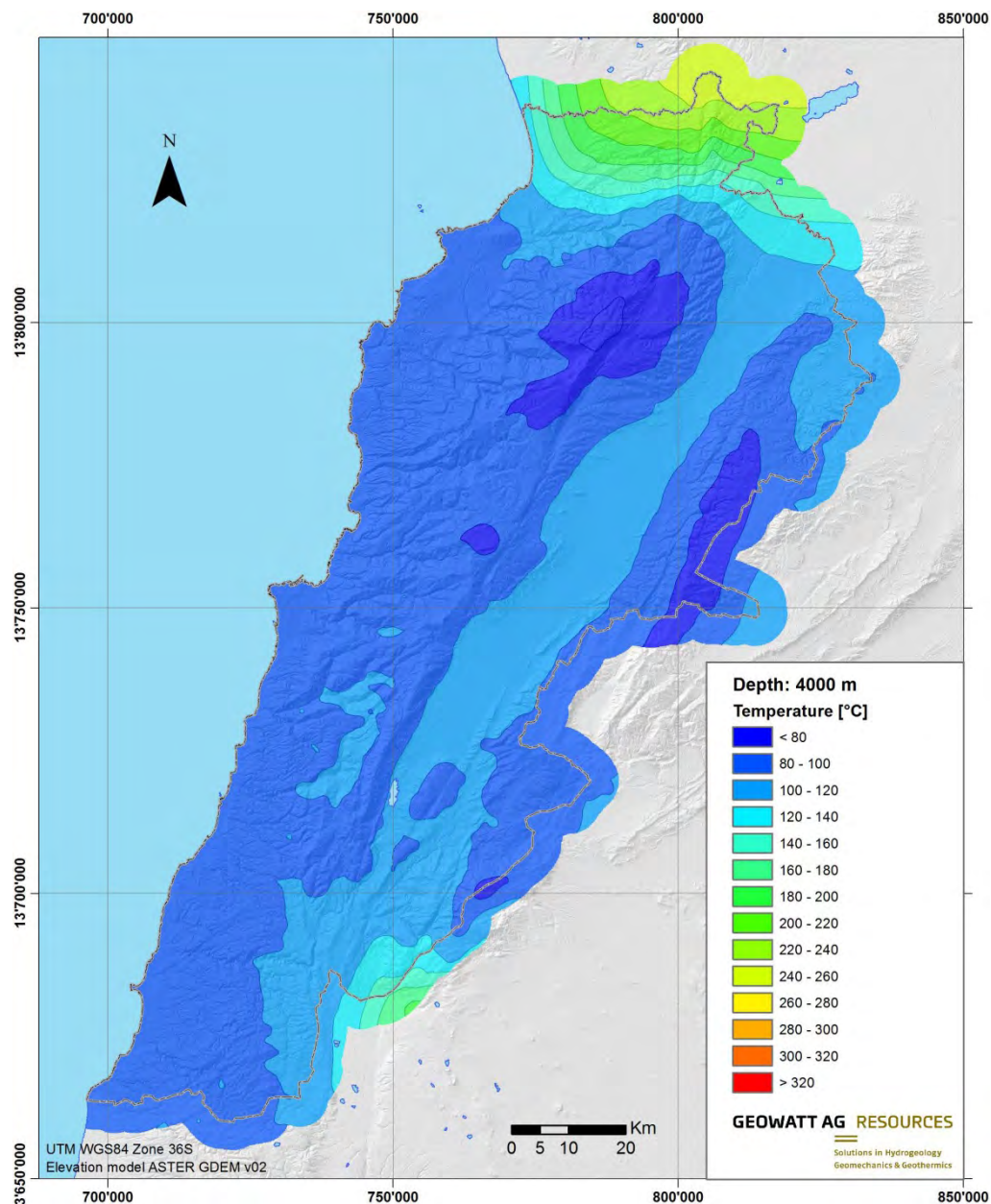


Figure 6-11: Temperature at 4,000 m depth (below ground level)

### 6.5.4. Stored heat for the target zones

Stored heat or heat in place (HIP) depends on the temperature and the thickness of the target reservoirs, the heat capacity of the rocks and the reinjection temperature. The reinjection temperature is a key element as it defines the lower boundary for geothermal utilization. It is defined by the outlet temperature at the surface installation.

Stored heat is calculated as follows:

$$E_{HIP} = \rho C_p \cdot V \cdot (T_{prod} - T_{reinj})$$

with  $\rho C_p$ , heat capacity of the rock [ $J m^{-3} K^{-1}$ ],  $V$ , volume of the target [ $m^3$ ],  $T_{prod}$ , mean temperature of the target zone before heat production [K] and  $T_{reinj}$ , temperature to which the target is cooled [K].

The following figures show the results for the area-specific stored heat for each potential target zone. The parameters that were used for the calculation of the different targets are listed in Table 6-2.

Parameter	Value	Unit
heat capacity of the rocks	$2.2 \cdot 10^6$	[ $J \cdot m^{-3}$ ]
thickness of the reservoir		
Cretaceous & Jurassic aquifers	700	[m]
Constant depth layers	500	[m]
re-injection temperature	50	[°C]

Table 6-2: Parameter values for the calculation of the stored heat

Stored heat is represented in the form of maps in Figures 6-12 to 6-17.

Due to the reinjection temperature limit, stored heat is available only in the areas where the temperature of the reservoir is higher than the reinjection temperature. It makes the Cretaceous Aquifer unsuitable for geothermal power generation.

Logically, stored heat increases with depth. For the Jurassic aquifer, stored heat is at its maximum in the syncline structure of the Bekaa Valley and in the Akkar region, due to the local thermal anomaly.

In the South, stored heat also seems to be interesting at a depth of 4,000 m, due to a presumed thermal anomaly, responsible for the volcanic activities south from Lebanon. The Jurassic aquifer is, however, not deep enough in this area to present an interesting potential in terms of geothermal exploitation. Deeper aquifers, if present, could provide more interesting potential.



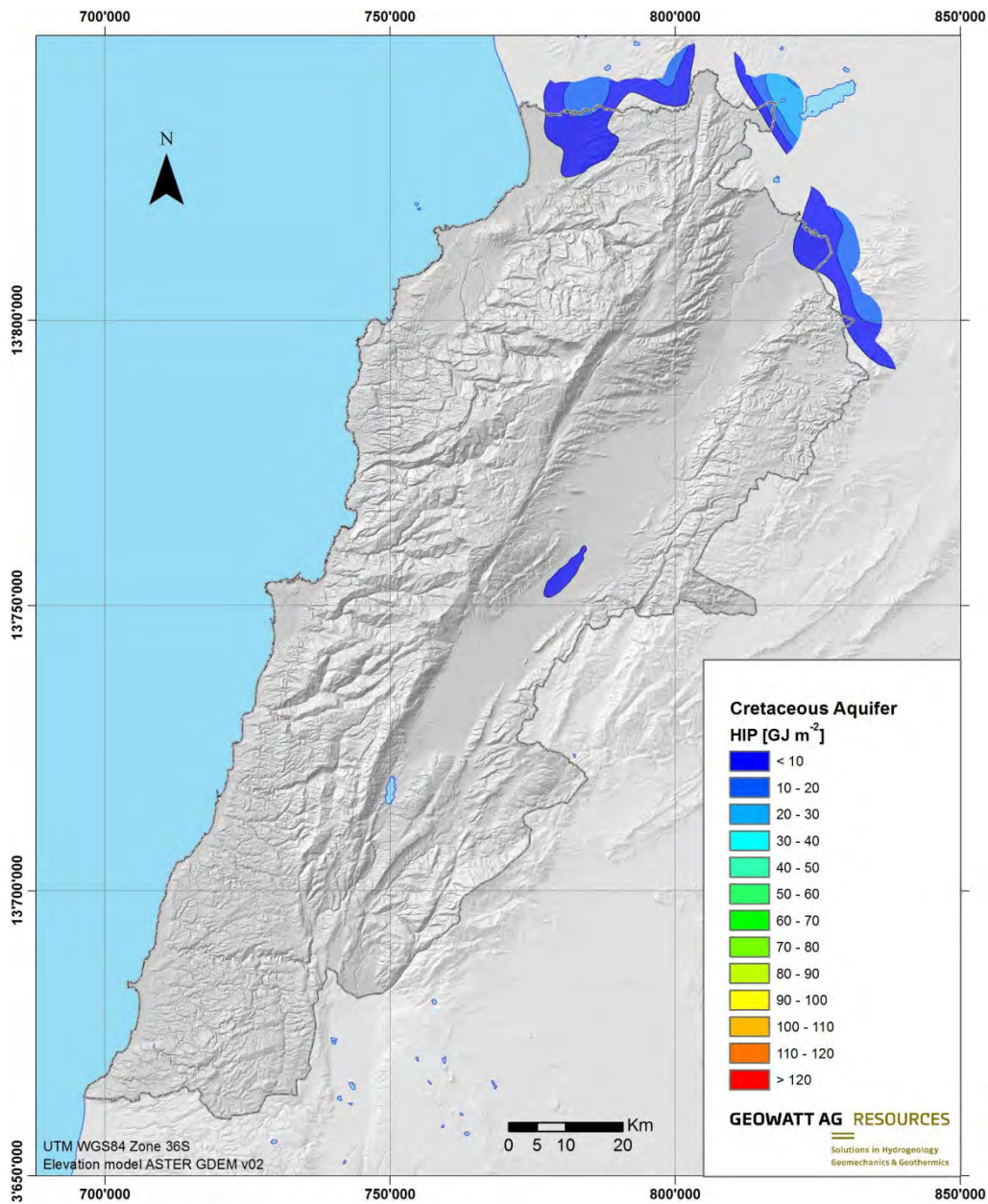


Figure 6-12: Stored heat for the Cretaceous aquifer

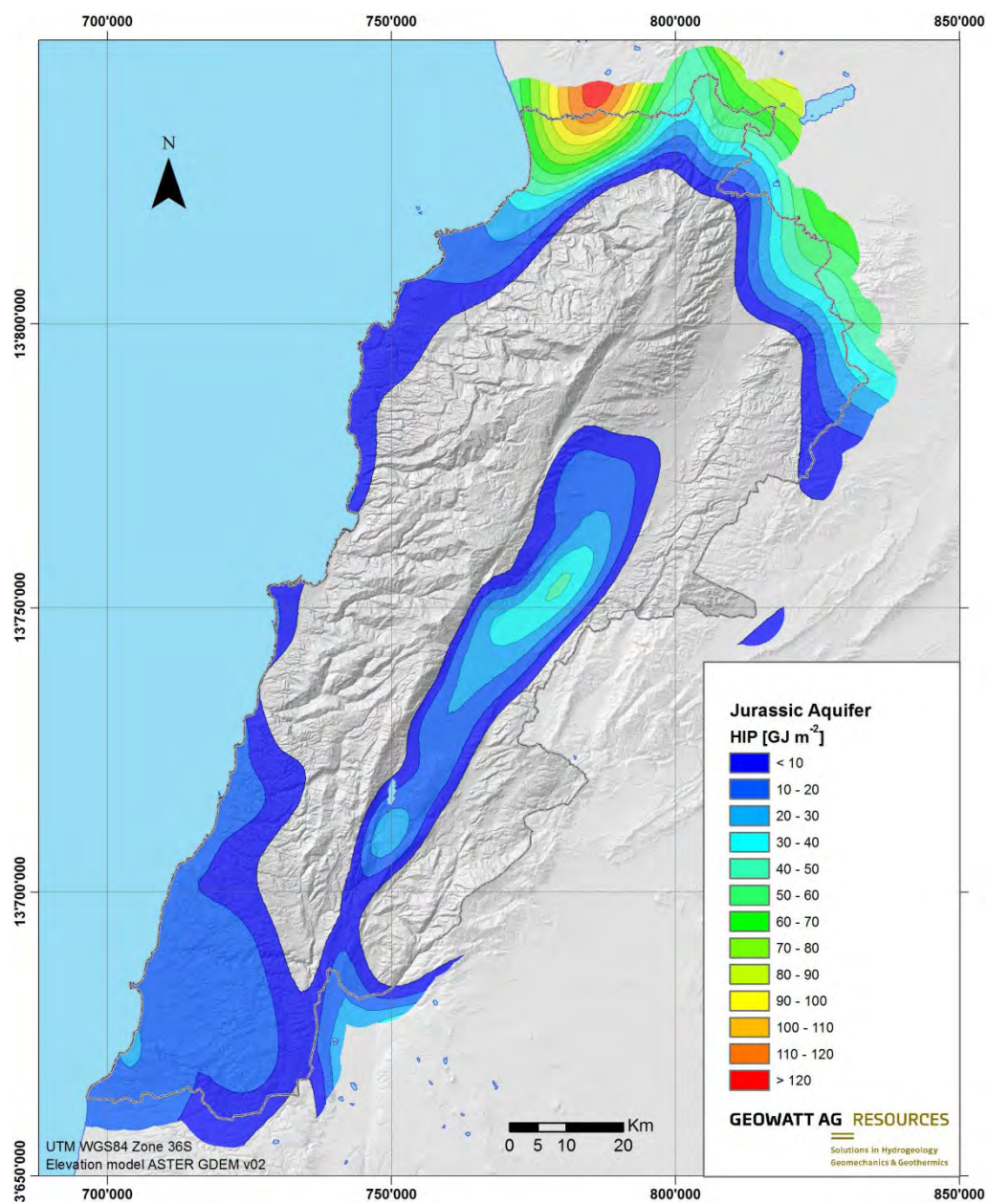


Figure 6-13: Stored heat (HIP) for the Jurassic aquifer

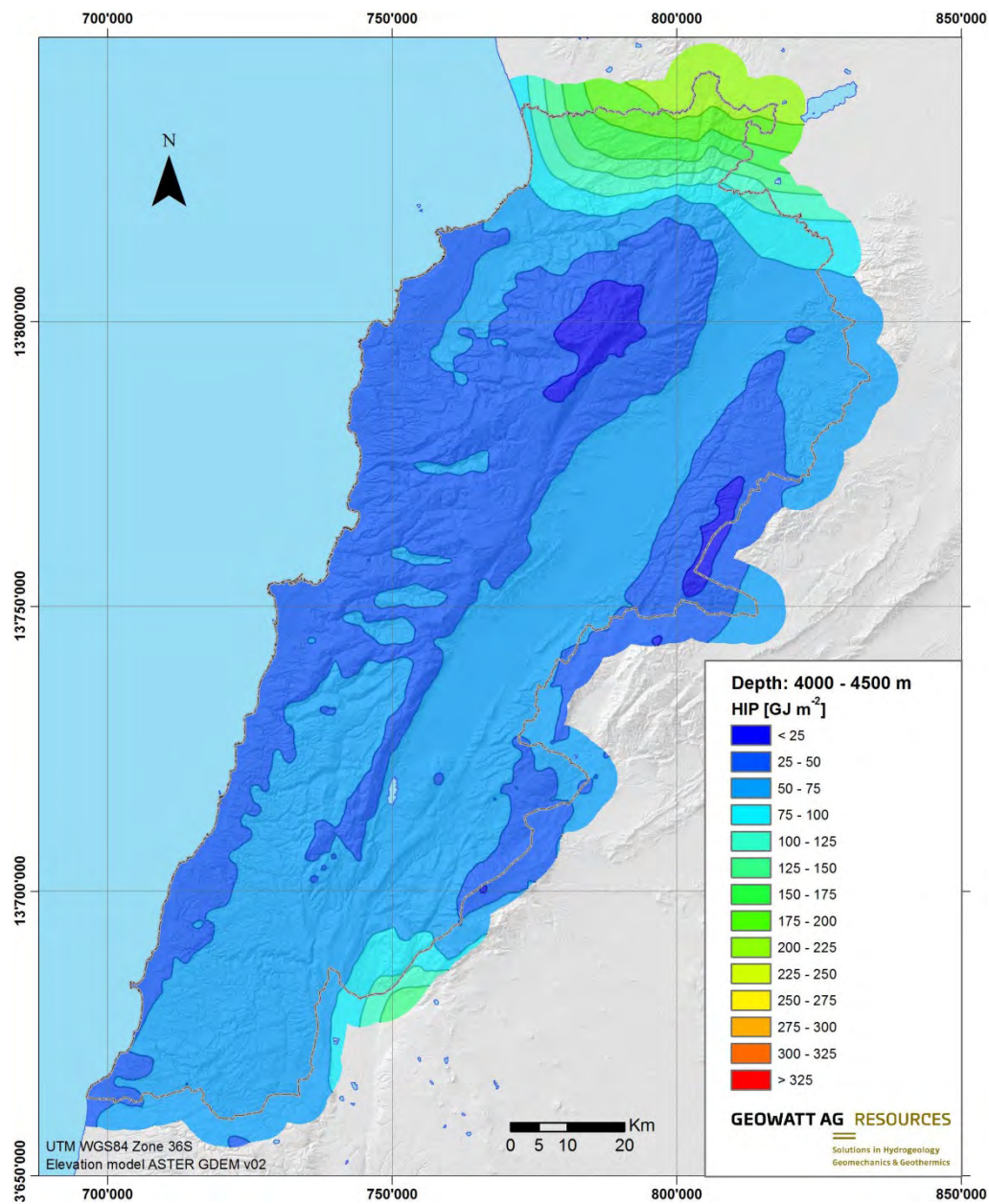


Figure 6-14: Stored heat (HIP) for the depth interval 4,000-4,500 m

### 6.5.5. Recoverable heat for the target zones

Only a fraction of the stored heat can be utilized by a geothermal system. This fraction is called Recoverable Heat (RH). The ratio of recoverable heat to stored heat is called recovery factor  $f_R$ . This factor mainly depends on the hydraulic transmissivity of the target aquifer, which is already included in the estimation of the recovery factor.

Typical values of the recovery factor  $f_R$  range from 5% to 20%. The recoverable heat can be calculated by

$$E_{RH} = f_R \cdot E_{HIP} ,$$

with  $E_{RH}$  the recoverable heat,  $f_R$ , recovery factor and  $E_{HIP}$ , the stored heat.

Hydraulic transmissivity is discussed in section 5.3.6. Values for the transmissivity are only available for near surface regions. Due to the high uncertainty concerning the transmissivity of the potential target zones, a recovery factor of 10% has been chosen as a first guess. This estimate takes into account that the outcropping limestone units have a rather high permeability and that a relatively good permeability can be expected for the deep aquifers in the Jurassic and the Cretaceous formations. The following maps for the area-specific recoverable heat of the target zones are thus based on a recovery factor of 10%, which is quite optimistic. This value is standard in similar projects.

Faults present different hydraulic characteristics than the intact host rock. Depending on the stress regime and the general state of the fault, the fault could be more permeable than the surrounding host rock, or on the contrary less permeable as the surrounding host rock.

In a fault zone, the hydraulic conductivity may be increased by a multiplication factor ranging from 1.5 to 2.0<sup>13</sup>. In this case, it is possible to utilize a higher fraction of the stored heat. Therefore, the recoverable heat in fault zones is most likely to be higher than in undisturbed layers.

A rather high fault density can be found in the different parts of Lebanon (see geological map of Figure 5-1: Geological map of Lebanon (Dubertret, 1955) and tectonic map of Figure 5-12). If the location of the fault is well known at the surface, their location at the depth of the reservoir cannot be estimated precisely.

In the following maps of the recoverable heat in the target zones, the trace at the surface of the main fault zones are represented. They indicate areas where a higher recoverable heat can be expected, of a factor 1.5 to 2 higher than the value indicated by the map.

<sup>13</sup> Depending on the lithology, multiplication factors of 5 have been reported in the literature. This value is not applicable in our case, as our estimation of a recovery factor of 10% is already optimistic.



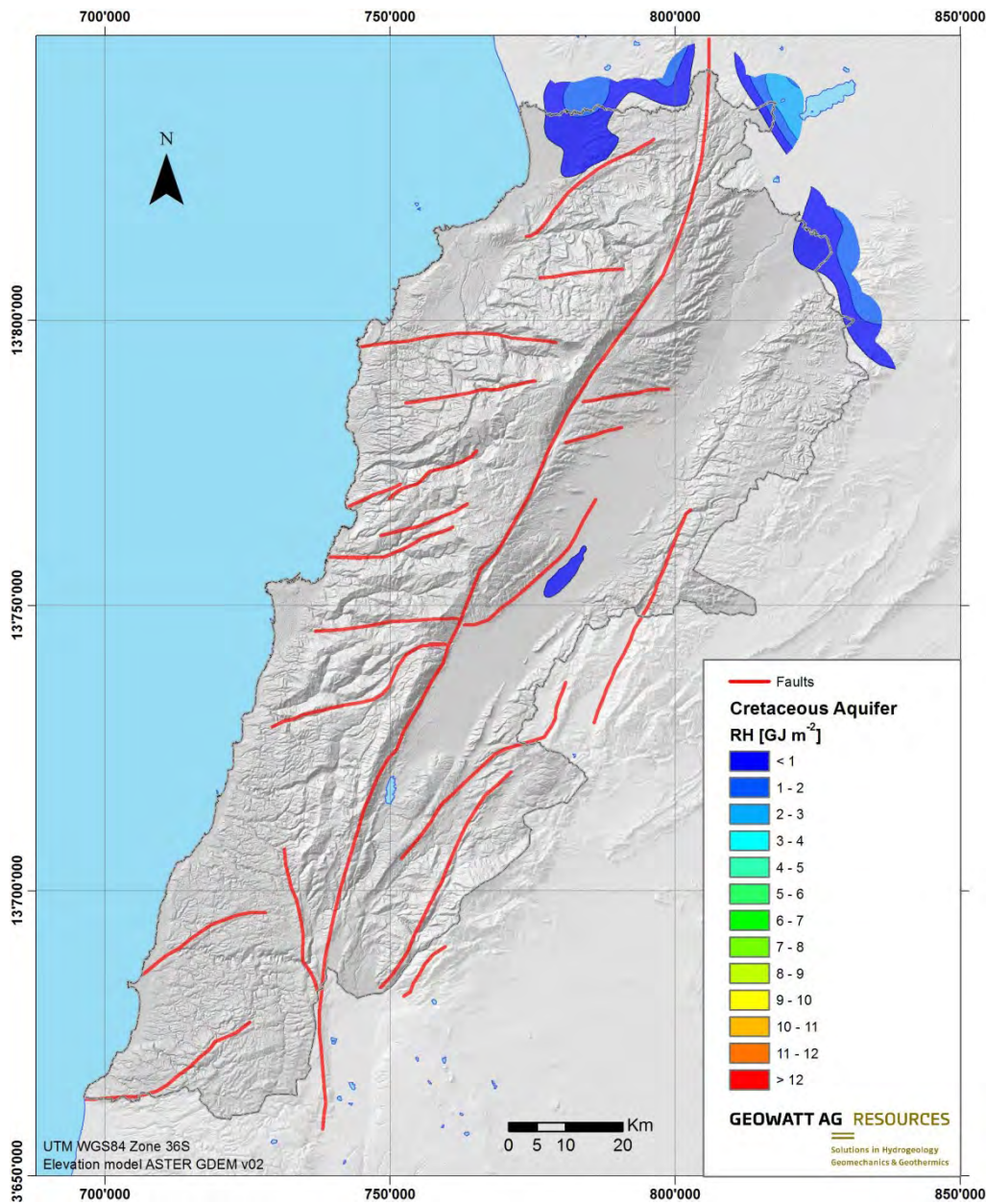


Figure 6-15: Recoverable heat for the Cretaceous aquifer



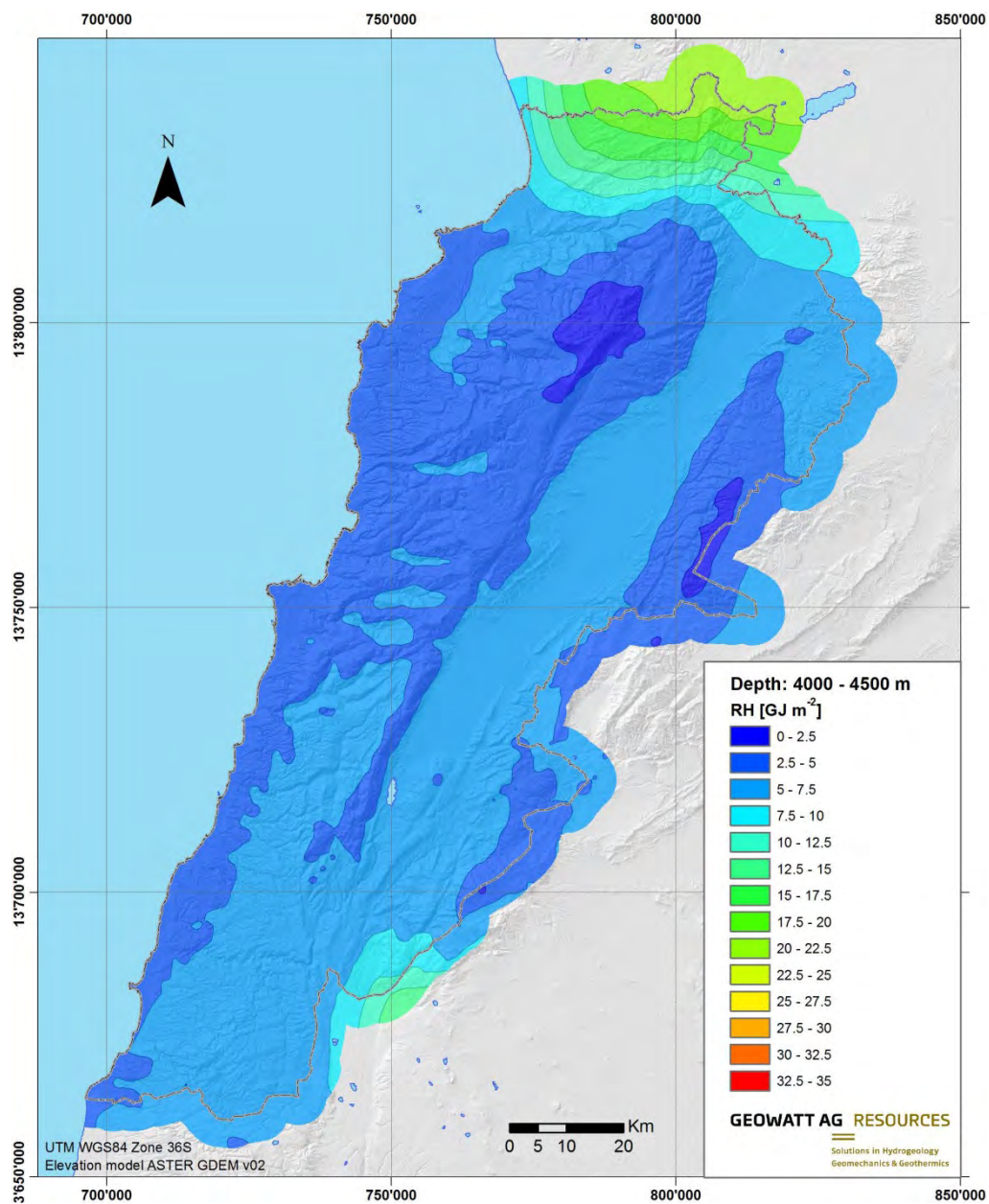


Figure 6-17: Recoverable heat for the depth interval 4,000-4,500 m

6.5.6. Geothermal Power (Heat and Electricity)

The amount of geothermal power in terms of heat production [MW<sub>th</sub>] and power generation [MW<sub>e</sub>], which can be produced by a geothermal system, depend on several factors which depend, on the one hand, on the property of the reservoir (temperature, transmissivity) and, on the other hand, on the kind of utilization.

The transmissivity of the reservoir provides the maximum flow rate that could circulate through the geothermal loop. Secondly, it depends on the temperature of the reservoir, but more specifically on the difference between the production temperature and the reinjection temperature. The reinjection temperature is defined by the kind of utilization (power only: 70°C; cogeneration: 50°C). For power generation [MW<sub>e</sub>], a conversion factor has to be considered additionally, which takes into account the energy losses due to the conversion of heat to electricity.

The kind of installation used to take the heat out from the reservoir (Geothermal doublet).

The maximum flow rate is estimated together with the optimum distance between the production well and the injection well in the reservoir after Gringarten (1978). The set of parameters used for the Gringarten methodology is listed in Table 6-3.

The life expectancy is given here as the time of the thermal front to migrate from the injection well to the production well. This time is called the breakthrough time. Starting from this time, the capacity of the power plant starts decreasing.

As almost no data for the transmissivity of the target reservoir exists for the deep underground of Lebanon, the geothermal power is estimated on a scenario basis, considering three values of transmissivity and two values of reservoir temperatures. The calculations are based on a geothermal doublet system.

Table 6-3: Parameters needed for the determination of the flow rate and optimal distance between the wells in the aquifer

Parameter	Value	Unit
Radius of the well	0.1	m
Maximum pressure drawdown	200	m
Heat capacity of the aquifer	2.2×10 <sup>6</sup>	J/ m <sup>3</sup> K
Heat capacity of the fluid	4.2×10 <sup>6</sup>	J/ m <sup>3</sup> K
Life expectancy of the installation	30	Years
Re-injection temperature	70	°C

If the flow rate is known, the thermal power of a doublet system can be calculated with

$$P_{th} = \rho_w c_w \cdot Q \cdot (T_{prod} - T_{reinj})$$

where:

- P<sub>th</sub> = thermal power [W]
- ρ<sub>w</sub> = fluid density [kg/m<sup>3</sup>]
- c<sub>w</sub> = heat capacity fluid [J/ m<sup>3</sup> K]
- Q = flow rate [m<sup>3</sup>/s]
- T<sub>prod</sub> = temperature of produced fluids [K]
- T<sub>reinj</sub> = temperature of re-injected fluid [K]

The electricity power is calculated from the heat by using a conversion factor  $c$ . Depending on the power plant technology and the temperature level, the conversion factor could be comprised between 5% to 15%.

$$P_e = c \times P_h$$

Based on the relations above, the thermal power and the geothermal power have been calculated for two different reservoir temperatures (130°C and 180°C) and for three values of hydraulic transmissivity. The heat produced by a standard geothermal installation and the generated power are listed for the different scenarios in Table 6-4 and Table 6-5.

Table 6-4: Geothermal power for a production temperature of 130°C

Parameter	Transmissivity Variants			Unit
	low	medium	high	
transmissivity	$5.0 \cdot 10^{-5}$	$2.5 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$	m <sup>2</sup> /s
thickness	700	700	700	M
flow rate	13	57	110	l/s
thermal power	4	19	37	MW <sub>th</sub>
electrical power	0.3	1.4	2.8	MW <sub>el</sub>

Table 6-5: Geothermal power for a production temperature of 180 °C

Parameter	Transmissivity Variants			Unit
	low	medium	high	
transmissivity	$5.0 \cdot 10^{-5}$	$2.5 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$	m <sup>2</sup> /s
thickness	700	700	700	M
flow rate	13	57	110	l/s
thermal power	7	31	60	MW <sub>th</sub>
electrical power	0.6	2.6	5.1	MW <sub>el</sub>

## 6.6. Conclusions

The methodology applied in the framework of this study allows estimating the geothermal potential of Lebanon. This potential is expressed by the stored heat or heat in place and by the recoverable heat. These two parameters are represented cartographically for different target horizons.

Due to its interesting permeability, the Cretaceous aquifer was initially considered as a potentially good target horizon for the use of geothermal energy. The estimation of the geothermal potential has shown that temperatures are not high enough to allow power generation.

However, the Jurassic aquifer (Kesrouane Formation) could be found at a depth deep enough to allow power generation.

Four areas seem to be interesting (see location in Figure 6-18). The first area is located in the Akkar region, where a thermal anomaly is assumed. This local thermal anomaly creates a very good gradient that brings temperature high enough to make use of geothermal technologies. The main uncertainty is related to the transmissivity of the Jurassic aquifer in this region. Capex and Opex estimation will be performed using different value of transmissivities.

The second area is the Bekaa Valley, where the Jurassic aquifer is deep enough to reach suitable temperatures. The estimations provided by this study show temperatures of around 80-90°C. Due to the uncertainty of the heat flux and of

the depth of the Jurassic aquifer in this area, we cannot exclude that temperatures are higher than 100°C and that this aquifer could be used for power generation. Again the capacity will mainly depend on the transmissivity which remains very speculative.

Evidences of thermal water have also been reported in the Kaoukaba area and in the area of Tyr in South Lebanon (Kfar Syr well). No confirmation of such thermal anomaly could have been found in the framework of this study. Further investigations are required to ascertain the presence of a thermal anomaly in these areas.

Temperatures higher than 100 °C are found in a depth of around 6,000 meters in Lebanon. The reason is the apparent very low regional heat flux. This makes the development of EGS technologies very difficult in Lebanon, mainly due to the costs associated with the drilling.

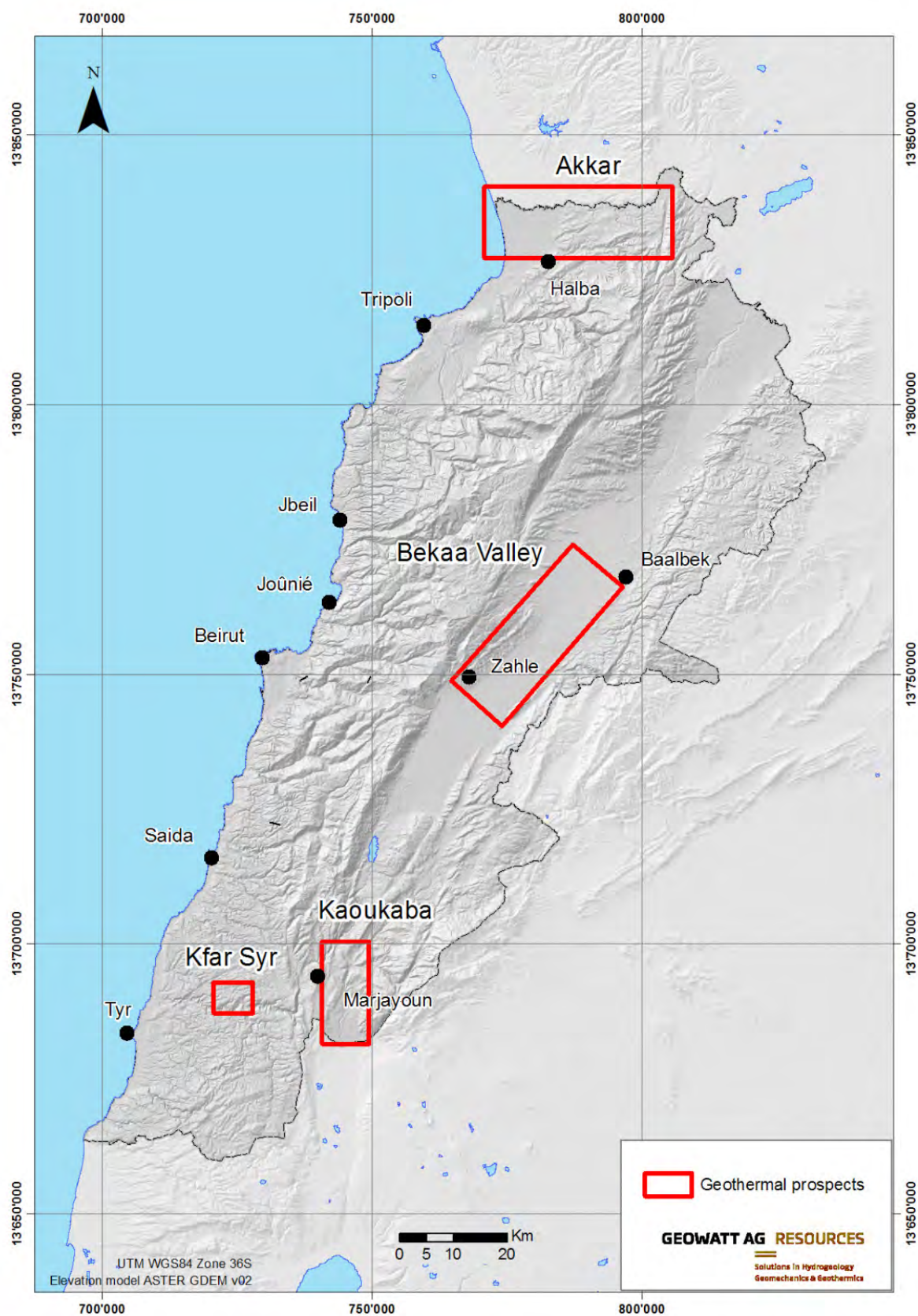


Figure 6-18: Location of identified geothermal prospects in Lebanon



# 07 . State of the art of geothermal technologies

## 7.1. Introduction

Lebanon's geothermal potential was estimated in the previous chapter. Among others, the geothermal potential provides the temperature of the fluid that could be extracted from the underground as well as the depth at which the geothermal brines are found. The temperature is a determinant factor for the selection of the appropriate power plant technology. The depth is one of the main criteria for the economic feasibility of a geothermal project and for the design of the borehole.

In this chapter, a review of the state of the art geothermal technologies is presented. Section 7.2 provides a summary of the theoretical background as well as a short discussion on the relevance of the key parameters, such as the temperature and the flow rate. A classification of the different geothermal technologies is then proposed in section 7.3. The description of the geothermal technologies themselves is made in two different sections: underground technologies are described in section 7.4, following the classical phases of project development, starting from the preliminary survey until the drilling phase and the reservoir development phase. Above ground technologies or power plant technologies are described in section 7.5.

In section 7.6 a cost breakdown analysis is proposed for three scenarios of a power plant in Lebanon. The first scenario considers a power plant in the Akkar region, where the highest potential is expected. The second scenario considers a power plant in the Bekaa Valley where deep aquifers have been identified, with temperatures potentially high enough to be used for power generation. The third scenario considers a power plant on the coast line, typically for the city of Beirut. As the temperature of the deep aquifer below Beirut is expected to be too low for a conventional hydrothermal installation, the capital cost breakdown for this scenario considers a reservoir located at a 6,000 m depth, exploited by the EGS technology (see section 7.3).

## 7.2. Theoretical background

Geothermal energy consists in extracting the heat that is found in the deep underground to produce heat and/or electricity. In order to bring this heat to the surface for power generation, a number of wells are drilled until they reach the reservoir. Production wells are used to pump the water to the surface. Reinjection wells are used to bring the water back to the reservoir. The geothermal brine has a role of carrier to transport the heat from the deep underground to the surface.

The most common technology used in low to medium enthalpy geothermal environment is the geothermal doublet system, which consists of one production well and one re-injection well. The re-injection well is optional and is used to maintain a pressure into the reservoir to guarantee long-term exploitation.

More complex systems could be implemented with more than two wells, such as the triplet system as implemented in Soultz-sous-Forêt (France). Multiple-wells allow an overall optimization of the exploitation system in terms of energy and economics. Examples of this system are the installations of Larderello, Travale, and Mt. Amiata (Italy). The current high drilling costs prevent the wide use of multiple well systems.

The high financial investment for well drilling goes along with a high risk of identifying a non-productive reservoir in which production flow rates and temperatures obtained are not economically viable.

### 7.2.1. Flow rate

In a specific geo-environment with a given reservoir temperature, the productivity of a geothermal system is increased by higher flow rates. The dominant factor is the subsurface permeability that can vary broadly from  $10^{-18} \text{ m}^2$  up to  $10^{-12} \text{ m}^2$ . Large reservoir permeability commonly yields natural convection patterns that influence the heat distribution in the subsurface. Permeability can be controlled by fractures or by matrix porosity. Generally, the natural permeability can be increased by various stimulation techniques. In geothermal systems, typical operation flow rates can vary between 10 kg/s and  $> 100 \text{ kg/s}$ .

From an economic perspective, reasonable flow rates greater than 50 kg/s have to be targeted for. Besides technical constraints, high flow rates will dramatically increase the power required for pumping in low permeable reservoirs. Prospection for potential geothermal systems should therefore focus preferentially on areas with high natural permeability, such as deep aquifers or fractured rock.

### 7.2.2. Temperature

The thermal field can become a critical factor for economic viable geothermal systems, since it determines the necessary drilling depth for a given target temperature. In view of the fact that drilling costs increase non-linearly with depth, shallower geothermal systems tend to be more lucrative. The target production temperature needs to reflect the present state of conversion technology in the Organic Rankine Cycle (ORC) (lower limit around 70 °C) and of Kalina technology (lower limit around 100 °C).

### 7.2.3. Stress field

The stress field is generally defined by the value of three stress components (one vertical and two horizontal ones) and by orientation of the maximal horizontal stress. The stress regime is defined by the relative magnitudes of vertical and horizontal components of the stress tensor:

- $\sigma_v < \sigma_h < \sigma_H$ : compressional regime (reverse faulting)
- $\sigma_h < \sigma_v < \sigma_H$ : transcurrent regime (strike-slip faulting)
- $\sigma_h < \sigma_H < \sigma_v$ : extensional regime (normal faulting)

$\sigma_v$ ,  $\sigma_h$  and  $\sigma_H$  being, respectively, the vertical, minimum and maximum horizontal stress components.

Shearing is favored by a large difference between minimum and maximum stresses. The direction of  $\sigma_{\max}$  defines the orientation of the main fractures. Stress regime variation patterns can be identified from a continental to a very local scale. Indeed, stress field evaluation and importance will be treated in several sections of this handbook. On a reservoir scale, the stress regime defines the failure conditions of the rock mass. This, in turn, defines for the creation of flow paths, a very important factor for reservoir exploitation. The local stress can also be linked with the mean orientation of fractures within and near the reservoir; the well orientation (in the case of drilling a deviated well) should be defined according to local stress, in order to maximize the probability of crossing important fractures, allowing large water inflows.

### 7.2.4. Secondary key factors

There are several other crucial factors that determine the longevity of a geothermal system. If the system cools down too rapidly, existing flow paths may be clogged by chemical precipitation or scaling in the geothermal loop, thus destroying the technical infrastructure. Therefore, beginning with the investigation phase, possibilities of reservoir extension or fluid chemistry should be included in the preparatory assessments. Economic sustainability of geothermal production depends strongly on the reservoir characteristics and the selected drilling operations.

## 7.3. Classification of geothermal systems

Depending on the point of view, several classifications of the geothermal systems are possible:

- Reservoir exploitation technology:
  - Hydrothermal corresponds to geothermal power systems where geothermal resources are naturally occurring in sufficient amounts (heat, water and rock permeability) to allow energy extraction in an economically feasible way. Examples of current geothermal projects based on hydrothermal technologies are found in Bayern (Germany) and St.Gall (Switzerland).
  - Petrothermal project or enhanced geothermal systems “EGS”, previously also called Hot Dry Rock, is a type of geothermal power technology that does not require natural convection of hot brines. Permeability is then created or enhanced by means of stimulation technologies, such as chemical stimulation or hydraulic stimulation. The only EGS project currently producing electricity is the pilot power plant of Soultz-sous-Forêt in France, funded by the research program of the European Union.
- Geothermal fluid type:
  - Saturated or Dry steam
  - Wet steam
  - Liquid
  - Supercritical ( $T > 250\text{ °C}$ )
- Geo-environments
  - Volcanic (Iceland, Guadeloupe, ...)
  - Crystalline (Rosemanowe (UK), Soultz (FR), Toscana (IT), Basel (CH))
  - Sedimentary environment (St.Gall (CH), Lebanon)
- Temperature
  - Low enthalpy ( $< 140\text{--}150\text{ °C}$ )
  - Medium enthalpy ( $150\text{--}200\text{ °C}$ )
  - High enthalpy ( $> 200\text{ °C}$ )

## 7.4. Underground technologies

### 7.4.1. Introduction

A deep geothermal project is classically executed in a phased process. The main execution phases related to the underground are as follows:

- Preliminary survey
- Exploration Phase
- Test drilling phase
- Well testing and logging phase
- Reservoir development phase
- Production and reservoir monitoring phase

In this section, the state of the art of the various underground technologies is presented for each of these phases.

### 7.4.2. Preliminary survey

The first phase towards the development of a geothermal power plant consists in the realization of a preliminary survey. The preliminary survey aims to assess the economic and technical feasibility of a project and to identify potential barriers for the development of a geothermal power plant. A preliminary survey is usually based on already available information. This information should already provide any evidence of geothermal potential within an area of investigation. The area of investigation could be considered on a local, regional, national or international scale.

The present study corresponds, in fact, to a preliminary survey on a national scale. The technologies that need to be applied for the preliminary survey are exactly the ones used for the realization of this study (data compilation, development of a conceptual model, realization of a geological model, estimation of the geothermal potential...). The description of the work to be done during the preliminary survey is found in the different chapters of this report. They will therefore not be described furthermore in this section.

A national preliminary survey provides regional information to allow a first screening of the most suitable regions to develop a geothermal project. The information provided by the national survey is valid on a regional scale only. Complementary surveys on a regional or local scale are required before the start of a project.

### 7.4.3. Exploration phase

#### 7.4.3.1. General considerations

The exploration phase ideally aims to better characterize the structure and the properties of the deep subsurface. The main objective is to identify and target the geothermal reservoir before proceeding with the first drilling. The first phase of drilling, commonly called exploration drilling, can be considered as part of the exploration phase. However, other less costly and complex investigation is needed prior to drilling to limit the risks of abortive drilling costs. Therefore, drilling is considered as a separate phase (see section 7.4.4).

During the exploration phase, most of the methods that could be used to investigate the deep structure and their petrophysical characteristics are applied from the ground surface, i.e. surface based geophysical methods. Such investigation techniques result in an indirect image of the subsurface. This image needs careful interpretation to obtain the relevant characteristics of the subsurface together with an understanding of the uncertainty in the technique used. Once there is sufficient confidence in the interpretation, the investigation moves to the more costly and technically complex drilling phase to validate the model interpretation.

Most common exploration methods are geophysical methods that include seismic methods (see section 7.4.3.2 here below) and more recent methods such as gravimetric, electric and electromagnetic methods, and thermal gradient boreholes (see section below). Non-geophysical methods such as geochemistry and other geoscience surveys are described in Sections 7.4.3.4 and 7.4.3.5 respectively.

### 7.4.3.2. Seismic methods

#### 7.4.3.2.1. 2D seismic

2D seismic is the most classical method for oil and gas exploration, but also for geothermal exploration.

As the method is based on seismic velocity contrast, the application of this method in crystalline or basement areas is of limited efficiency.

Very often, 2D seismic data already exists for a given region. These data should be utilized where possible. Due to the rapid advances in improvement of seismic data post-treatment methods, reprocessing and reinterpretation of already existing seismic data are highly recommended. However, because the target investigation depth defines the frequency of the seismic source, an old seismic campaign that is aimed at oil and gas prospection, would not necessarily give information precise enough for deep rocks underlying oil and gas reservoirs and therefore more targeted seismic investigation might be required to target geothermal reservoirs.

Benefits	Limitation
Data often already available (for reinterpretation/reprocessing);	A limited efficiency in granite or basement rocks, as seismic velocity remains relatively homogeneous in such rocks;
Low cost compared with other investigation methods	Inability to see vertical faults;
Standard method and deep investigation depth penetration.	Inability to derive fault directions in 3D;
	Limited information about the hydrodynamic properties; and
	Not relevant for the thermal properties.

Costs:

- US\$ 300,000,- for new 2D profile acquisition
- US\$ 80,000,- for data reprocessing and reinterpretation



#### 7.4.3.2.2. 3D seismic

3D seismic campaigns are recently more frequently used in the geothermal industry. 3D seismic allows a much better characterization of the geothermal reservoir than 2D seismic, but the associated costs are much higher.

The area covered by 3D seismic campaigns is usually larger than a single target reservoir. Results of a 3D seismic campaign could then be used for the implementation of several geothermal power plants. For example, such campaigns were carried out for geothermal exploration in the following geothermal areas in Europe:

- Rhine Graben (Germany)
- Lardarello geothermal site, Toscana (Italy)
- St. Gallen area (Switzerland)
- South German molassic basin, Bavaria (Germany)

Still, 3D seismic campaigns may lead to limited results in granite or basement rocks, due to the low seismic velocity contrasts of the deep structures.

It should be noted that some private insurance companies, insuring non discovery risk for geothermal wells, require the execution of a 3D seismic campaign during the exploration phase, in order to define at best the target zone and to assess at best the risk of non-discovery.

Some successful projects across Europe would have failed without the use of 3D seismic.

The characterization of the geothermal reservoir can be increased by the computation of the seismic attributes of 3D seismic. Seismic attributes are measurements derived from the seismic data, like amplitude, shape and position of the seismic waveform. They can provide additional information on the geological facies and on fracture patterns.

Benefits	Limitation
A high resolution of the underground structures	Higher costs than 2D
The ability to derive fault directions in 3D.	Difficult to deploy in an urban environment.

Costs:

- Several millions of US Dollars.

### 7.4.3.3. Other geophysical methods

#### 7.4.3.3.2.1. Gravimetry

Gravity data provide information about the geological structure at depth and on a local scale, when correlated with other kinds of data, such as 3D geological models. They are used to better characterize subsurface geological structures.

By attributing reasonable densities to the lower crust, to the upper mantle and to the major rock types in the area, the density distribution in the upper crust can be defined through a modeling approach. Because density is temperature dependent, the geothermal gradient within the area of investigation should be considered as well. Density values could then be attributed to the various formations and elements of the geothermal systems, e.g. intrusions, faults and reservoirs.

The comparison between the simulated distribution of gravimetric anomalies based on the geological model and the measured gravimetric anomaly distribution can be used to eliminate, constrain or select hypotheses on the subsurface structures.

Gravity data are particularly effective for determining location and depth of vertical and sub-vertical geological structures with density contrasts. These density contrasts can be, for example, limits of sedimentary basins, vertical or sub-vertical faults (steps) and boundaries of bodies with different porosities. These data also allow the determination of the shape of sedimentary basins where the density contrast is strong enough ( $> 50 \text{ kg}\cdot\text{m}^{-3}$ ).

Benefits	Limitation
Lower cost than other investigation techniques	Only effective for structures with good density contrast
Delineation of vertical or sub vertical structures.	Would ideally require a 3D geological model for comparison between modeled and measured anomaly distribution.

Costs:

- US\$ 80,000 - to US\$ 200,000 -

#### 7.4.3.3.1. Electrical and Electromagnetic methods

Geothermal resources are ideal targets for electromagnetic (EM) methods since the liquid phase produces strong variations of electrical resistivity in the subsurface. Electrical resistivity is affected by properties such as temperature, porosity, permeability, fluid salinity, partial melt fraction and viscosity. Many of these parameters may take an important role in defining a geothermal system. Therefore, the interpretation of EM signals could provide good indication of these properties and thus of the understanding of the geothermal systems.

Since rheology is profoundly affected by temperature and the presence of fluids, low electrical resistivity may be an indication of rheologically weak zones in the lithosphere within which deformation is most likely to occur. Moreover, active deformation greatly influences fluid interconnectivity, so that low resistivity may also represent the state of the deformation itself. Electrical resistivity models may offer an image of fluid generation during active crustal thickening and of its transport towards the surface in major zones of crustal weakness (Wannamaker, et al., 2002).

In addition to rheological investigation, resistivity distribution at various depths may show the location of possibly enhanced fluid concentration and the presence of intrusions that are still molten. On the other hand, resistivity should always be considered with care. Experience has shown that the correlation between low resistivity and fluid concentration is not always correct since mineral alterations produce comparable and often a greater reduction in resistivity. Moreover, although water-dominated geothermal systems have an associated low resistivity signature, the opposite is not true, and the analysis requires the inclusion of geological and possibly other geophysical data in order to limit the uncertainties.

Among EM methods only magnetotelluric (MT) may provide the suitable investigation depth for regional characterization. Disadvantages of the MT method are its low geometrical resolution (though lateral resolution may be improved when using short site spacing) and noise (both geological and industrial) sensitivity.

Benefits	Limitation
Lower cost than other investigation techniques	Low geometrical resolution at higher depth
Identification of rheologically weak zones.	Non-unique explanation for low-resistivity zones.

Costs:

- US\$ 80,000 - to US\$ 200,000 -

7.4.3.3.2. Thermal gradient borehole

One of the basic methods to outline prospective areas for geothermal research is the analysis of terrestrial heat flow density (or terrestrial heat flow), which defines the amount of heat flowing across a unit surface area during a time unit. It is expressed as the product of the thermal conductivity of rocks and the temperature gradient. The temperature gradient is the rate of increase of temperature with depth. Assuming that the heat is only transported by conduction, the temperature at any depth (relevant for exploration) can be calculated using the temperature gradient (Haenel et al., 1988). Accordingly, areas characterized by high heat flow and low thermal conductivities resulting in a large temperature increase with depth should be the most favorable sites for geothermal research.

However, heat flow is influenced by numerous phenomena and processes such as the spatial variation of thermal conductivity and heat production due to different rock types, sedimentation and erosion, groundwater flow, volcanism, etc. In such cases the heat flow and the temperature gradient vary with depth and the prediction of temperature at great depth is carried out by numerical modeling. Most of these processes act on a local scale (e.g. groundwater flow) and less on a regional scale (e.g. erosion). On continental and regional scales the assumption of conductive heat transport is a good approximation. Therefore, the average heat flow describes well the underground temperature conditions.

Benefits	Limitation
Lower cost than other investigation techniques Identification of geothermal active area.	Only suitable where geothermal anomalies occur

Costs:

- US\$ 200,000 - to US\$ 300,000 -

#### 7.4.3.4. Geochemical methods

Geochemistry encompasses a wide range of methods, each one fulfilling a different objective. Geothermometers for instance, are based on isotopic ratio. They aim to estimate the fluid temperature at a depth to provide better understanding of the flow systems (depth of the circulation, groundwater transit time, mixing processes etc). Electrical conductivity measurements are performed on rock samples in the laboratory to characterize the thermal characteristics of the different rock type. This parameter is mandatory for a better prediction of the temperature at depth. Other classical hydro-chemical fluid parameters such as pH, Eh, Cation and Anion concentrations, etc. provide relevant information for the understanding of deep flow systems. Information about the chemistry of the fluid itself also provides important information for the design of some components of the well and of the power plant. Gas content (Radon, CO<sub>2</sub>...) at the surface or in natural springs or water wells may give important information on subsurface structures. For example, it is well known that the detection of Radon anomalies in surface waters can reveal the presence of moving groundwater at depth (Durrance, 1986).

#### 7.4.3.5. Surface geoscience studies

Many kinds of surface geoscience studies, such as geological mapping or surface facies characterization, could be applied during the exploration phase to contribute to the site selection process or in identifying and locating a geothermal reservoir.

### 7.4.4. Drilling phase

#### 7.4.4.1. General considerations

Drilling operations are performed in order to open up geothermal reservoirs for energy exploitation. The drilling phase is probably the most important phase of the overall project, as it represents more than half of the overall budget. Therefore a detailed and comprehensive planning of the drilling is required.

The choice of an appropriate drilling rig is one of the most important decisions in well planning. The rig should have a sufficient safety margin. Its technical specifications (hook load, rig horse power, etc.) should fit to the specifics of the planned well. In order to avoid unnecessary costs, standard bit sizes and casing diameters should be used wherever possible.

During the drilling process, the drilling rig has to fulfill the following functions:

- Rotation of the drilling bit, either by rotating the whole drill string or by delivering the hydraulic energy to drive the down-hole motor, in order to achieve penetration into the drilled formations;
- Ensure circulation of the drilling mud, so that the drill cuttings can be transported up the well bore; and
- Provide traction power for the drill string to be pulled out of the well and to control the weight on the drill bit during drilling.

The design of geothermal wells present important differences from the design of hydrocarbon wells. For example, due to the high production rate in geothermal wells, the well diameter and corresponding diameters of injection and production strings have to be larger.

With only very few exceptions, a drilling mud will circulate within the well bore during the drilling operations. The drilling mud has to fulfill various main functions within the drilling process:

- Transportation of the cutting material away from the drill bit, up the well bore;
- Stabilization of the well bore by means of balancing the pressures at the borehole wall; and
- Cooling of the drilling equipment.

In order to enable a continuous operation, a sufficient supply of drilling mud has to be ensured. Mud pumps have to be dimensioned in such a way that they are capable of providing drilling mud at adequate rates. Mud cleaning facilities have to be installed and, if necessary, mud cooling services as well.

#### 7.4.4.2. Drilling of geothermal reservoir

The drilling techniques applied for geothermal reservoir exploitation do not fundamentally differ from those applied in drilling O&G wells. Drilling techniques are to be found in standard textbooks like Nguyen (1996) or Jackson (2000). Particular attention must be paid to the large diameter of geothermal wells, to directional drilling and to techniques targeted at avoiding formation damage.

In order to obtain flow rates in geothermal wells, which are high enough to sustain an economically viable operation of a



geothermal power plant, the borehole and casing diameters have to be large enough. Diameters of geothermal wells are therefore generally larger than the diameters of corresponding hydrocarbon wells of comparable depth. This has implications not only for drilling costs, but also for issues related to borehole stability. Taking into account the strength parameter of a given formation and a given stress field with its associated anisotropy, the potential for borehole failure at the level of the given formation increases with the borehole diameter. This becomes even more important for directional drilling. It is therefore necessary to carefully investigate the in-situ stress field and borehole stability ahead of well planning, such that the well path (particularly its direction in relation to the stress field), the mud weight and the casing program can be chosen accordingly.

In order to hit the subsurface target zone with a sufficient degree of accuracy, it is generally necessary to proceed with directional drilling. Directional drilling is accomplished through the use of proper Bottom Hole Assembly (BHA) configurations, 3D well bore path measurement instrumentation, data linking instrumentation to communicate down-hole measurements to the surface, mud motors and special BHA components and drill bits. Drilling parameters like Weight On Bit (WOB) and rotary speed (rpm) are also sometimes used to deflect the bit away from the axis of the existing well bore. The orientation of the bit in the desired direction is done through the use of a bend in a down-hole steerable mud motor assembly.

The drilling bit generally has to be chosen according to the geological formation to be drilled. In sedimentary environments this will in most cases be a roller-cone bit, which either has steel teeth or may have hard metal inserts made from Tungsten Carbide (TCI-bits). Polycrystalline Diamond Compacts (PDC) bits have been used successfully when drilling uniform sections of carbonates and evaporates that are not broken up with shale stringers (Bourgoyne Jr, et al., 1986). Although successful use of these bits has also been reported from sandstone, siltstone and shale formations, PDC bits cannot be generally recommended in these formations. Although a high drilling speed (ROP = Rate Of Penetration) is generally desirable in order to keep drilling costs low, for technical reasons it is not always recommended. While drilling ductile formations like clay or claystone for example, it may be appropriate to reduce drilling speed and, if necessary, also the WOB in order to keep the bit in a cutting mode, and not turn into a pressing mode.

In order to achieve the highest flow rates possible from the geothermal well formation damage, for example due to mud invasion, has to be avoided. When drilling in sandstone dominated formations it is desirable to avoid mobilization of clay minerals and therefore in such conditions it is recommended to drill under balanced or near balanced. Special drilling mud should be used which will reduce clay mineral mobilization. A marble-flour might be added to the drilling mud which will help to build up a thin mud cake, which protects the reservoir formation. If necessary, this thin mud cake might later easily be removed through acidization.

Thermally induced stress on the casing during hot water production has to be considered. Casing damage in general has to be prevented. This commonly requires a complete cementing of the casing along the whole well profile. Alternatively the uncemented part of the casing string has to be pulled in tension in order to compensate the thermally induced elongation.

In order to prevent fluid circulation behind the casing within the overburden, cementation up to the surface is essential. The bond between tubing, cement and the rock has to withstand the thermal tensions and the pressure changes during the entire life span of the well. Blast furnace cement has turned out to be very suitable for this purpose. The process of cementation up to the surface represents a high pressure load for the unlocked formations. The cement slurry density can be adapted to these conditions by specific additives.

Usually cementing of a well will be performed from the base to the top, but in case this is not successful then other techniques can be used such as a squeeze cementation performed from the top of the well to the former cement infiltration zone. It is generally recommended to verify the successful placement of the cement. This can either be achieved by means of conventional cased-hole logging (Cement Bond Log, CBL) operations or by thermal logging.

Attention has to be paid when drilling through gas bearing formations. The choice of mud weight has to be great enough to avoid the gas entering the drilling mud. Potentially gas bearing formations also have to be considered when planning the casing program for the well.

### 7.4.4.3. Well configuration

#### 7.4.4.3.1. Single well systems

A single well system is a borehole from which water is pumped up from the aquifer, and discharged at the surface, for example into a river or lake. Due to high salinity and temperatures that could be encountered in deep geothermal systems and associated environmental concerns the discharge to surface without treatment is unlikely to be a viable option. These aspects are usually regulated on a national level, in the framework of the environmental protection regulations.

Not re-injecting the fluid in the reservoir could also lead to a reservoir depletion issue, such as in the Geysers geothermal field in the USA. Comprehensive reservoir modeling should be performed first to evaluate the technical feasibility of not re-injecting the fluid in the reservoir.

#### 7.4.4.3.2. Coaxial well

Coaxial well consists in a single well that is used simultaneously for the production and the reinjection. The design consists in two coaxial tubing of different diameters. The internal tube is used for the production. The external tube is used for the reinjection.

#### 7.4.4.3.3. Multiple well systems (doublet, triplet)

A doublet is a system composed of one production well and one injection well. The injection well is used to maintain the pressure in the reservoir to avoid depletion. It is also used to limit the environmental impact by flushing the geothermal brine in the rivers or lakes.

To optimize the reservoir production, additional wells could be drilled, leading to a triplet configuration. These wells could be used either as a production well or as a reinjection well, depending on the reservoir properties.

Usually the most productive well (in terms of flow rate) is used as a production well. The other wells are used for the reinjection.

#### 7.4.4.3.4. Horizontal wells

The recent development of drilling technologies in the shale gas exploration allows drilling horizontal wells over several kilometers of distance and a great depth. These technologies are very promising for the EGS geothermal projects as they are supposed to minimize the risk of induced seismicity.

#### 7.4.4.3.5. Unconventional geothermal systems

Some project developers are promoting, worldwide, a technology that makes use of the shallow boreholes heat exchanger technologies (double U-tubes) but at a depth down to 10 km. The exact configuration of the double U-tubes differs from one project to the other. They pretend to be able to generate several hundred Mega Watt of power capacity. These numbers are very persuasive for fund raising. The technical feasibility of such an installation remains from the engineering point of view extremely questionable.

### 7.4.5. Well testing, tracer testing and logging phase

#### 7.4.5.1. General considerations

The well testing, tracer testing and logging phase aims at characterizing at best the properties of the well and of the target geothermal reservoir. This phase occurs usually directly after the achievement of the first exploration well. It might happen that other geological formations are tested during the drilling.

Well testing comprises the different technologies based on water or air pumping or injection in order to evaluate the quantity of water/gas/oil that can be extracted/injected from/to the reservoir.

Tracer testing consists of injecting solute compounds directly into the reservoir formation. The behavior of the solute compounds provides information about the hydrodynamic properties of the reservoir, such as porosity, permeability and dispersivity. It also enables the hydraulic connections between the reservoir and overlying or underlying aquifers to be detected.

Well logging describes all the technologies that are aimed at determining the properties of the well, the surrounding rock or the fluid itself, throughout the borehole profile.

#### 7.4.5.2. Well testing

With regards to well testing, it is necessary to distinguish between the well test technologies (such as air lift) and the well-test scheme (such as injection, pumping or a step-drawdown test). The choice of the technology and of the scheme depends on the investigated property. A clear definition of the objectives of the test is thus of prior importance to determine the type of test to carry out. A well test program is then defined.

The objectives of well test could be:

- Identification and evaluation of existing fracture systems;
- Assessment of fractures induced by hydraulic stimulation;
- Investigation of the transport properties of the matrix;

- Determination of the reservoir boundaries; and
- Compartmentalization of the reservoir.

#### 7.4.5.2.1. Production testing scheme

A pressure drawdown or pumping test measures the flowing bottom hole pressure while the well is flowing. It is primarily a method for measuring the Productivity Index (PI). A stable rate over a long period can be difficult to establish. This could induce some uncertainty in the analysis.

Pressure build-up or recovery tests measure the bottom hole pressure response during the shut in period that follows a pressure drawdown. It is also called the recovery phase. Such testing is useful for measuring reservoir properties and near well interferences such as skin effects, without perturbations of the pump itself. In this test the flow rate is known and equal to zero.

#### 7.4.5.2.2. Injection testing scheme

A step-flow and stimulation test consists of injecting water with a step-increased flow rate until reaching stimulation pressure. The aims are primarily to determine the minimum stimulation pressure of the reservoir and secondarily to reduce near well bore hydraulic impedances.

In a multi-rate-pre-fracturing hydraulic test, the injection flow rate is increased in steps. In each step the flow rate is maintained as constant until the injection pressure reaches an asymptotic value. The test delivers valuable information on the reservoir transmissivity, the significance of turbulence and on details of fracture dilation (Murphy et al., 1999).

#### 7.4.5.2.3. Testing techniques

For production, well tests are generally conducted using the air lift pumping technique. This technique consists of injecting air with the mean of a compressor. Air is injected in the production pipe at a depth usually comprised between 200 m - 500 m. Buoyancy will enable the air to circulate to the top of the production pipe, reducing the mean density of the fluid in the production pipe. Consequently, the down-hole pressure at the reservoir depth reduces, and the fluid will flow from the formation into the well. This technique is extremely simple and very easy to use for well tests carried out over a short period. The air can be replaced with nitrogen if required.

For injection tests, common surface pumps are generally used (see details in section 7.4.7.1).

#### 7.4.5.3. Tracer testing

Tracer testing is an efficient method to detect and characterize hydraulic connections between two deep geothermal wells. Tracer tests aim at understanding the migration process of injected and natural fluids, and at estimating the proportions in discharged fluids, the fluid velocities, flow rates and residence times.

Depending on the tracer test methodology, different information on transport properties and hydraulic connections can be obtained. This information is essential for characterizing heat exchange and for fluid re-injection in geothermal reservoirs (Sanjuan et al., 2006; Ghergut et al., 2007). Information is derived from the data collected during the tests after their interpretation through a modeling approach.

As the physicochemical behavior of the tracers under given reservoir conditions (high salinity fluid, very low redox potential, low pH, etc.) is not always well known, the use of a minimum of two tracers is recommended. Comparison with a natural tracer or laboratory experiments could be executed as well.

In the literature, the following tracer compounds (liquid phase tracers only) are recommended for application at high temperature conditions:

- Naphthalene (di, tri) sulfonates (nds, nts, ns) family: 1,5-, 1,6-, 2,6-, 2,7-nds, 1,3,5- and 1,3,6-nts, 1- and 2-ns (Rose, et al., 2001);
- Aromatic compounds: sodium benzoate or other benzoates (Adams, et al., 1992);
- Fluorobenzoic acids are water tracers widely used and preferred in oil reservoirs; and
- Fluorescein ( $T < 260^{\circ}\text{C}$ ; the other organic dyes are not recommended).

#### 7.4.5.4. Logging

##### 7.4.5.4.1. Temperature log

The aim of temperature logging is to provide direct information about the temperature in a borehole.

Drilling and drilling fluid circulation alter the original temperature by cooling the bottom of the borehole and heating the upper part of the borehole. In the case of deep boreholes the decay of the disturbances takes a few months. Due to economic reasons, it is generally not possible to wait to reach steady state conditions. The original formation temperatures can be corrected from repeated temperature logs measured during the recovery period (Horner, 1951). Undisturbed temperature profiles provide information about relevant heat transport processes near the borehole.

The temperature log is interpreted together with available geophysical, hydrogeological and geological data. One of the routine methods is the calculation of the heat flow per depth interval. The lithology along the borehole profile is known from core samples, cuttings, gamma ray and resistivity logs. The estimated thermal conductivity of the rock is based on the lithology. The heat flow is then calculated using the thermal conductivity and the temperature gradient that has been measured or derived from the temperature log. Heat flow variation with depth is indicative of groundwater flow.

Temperature measurements are also good indicators for locating drilling fluid losses or entry points of formation fluids into the borehole. These locations are marked by rapid temperature changes. Gas release into the borehole is indicated by a temperature drop. Temperature logs are also applied to check the quality of cementing behind the casing.

#### 7.4.5.4.2. Vertical seismic profile

As the reflection surface seismic method is hardly able to image subsurface structures within the crystalline basement, the borehole seismic techniques constitute an attractive way to collect spatial information about the major and potentially permeable structures in the vicinity of the geothermal wells drilled in fractured basement rocks. Vertical Seismic Profiling (VSP) permits acquisition of an inter-well image of the deep-seated rock beyond the borehole wall. The main permeable major faults can be imaged and localized by the VSP method. Moreover, VSP data allow a better constraint of the velocity model, useful for reflection and refraction interpretation. 3-D geophysics and VSP are not routinely used in geothermal exploration, due to their high costs.

#### 7.4.5.4.3. Borehole imaging and sonic log

Borehole acoustic imaging tools (such as “Ultrasonic Borehole Imaging” – UBI from Schlumberger or “Formation Micro Imaging” – FMI from Baker-Hughes) provide essential information concerning the fractures intersecting the borehole. Orientation and damage zone thickness of faults and fractures can be derived from such acoustic logs. Local variations of the fracture orientations can also give important information on the variations of the stress field orientation. A sonic log allows an estimation of variations in porosity along the borehole. Borehole electrical image logs are also a very valuable method for characterizing the fracture system and the present-day stress field in EGS.

#### 7.4.5.4.4. Gamma ray logs

Gamma ray logs provide valuable information about the natural radioactivity and the various lithologies penetrated by the well. Spectral gamma ray logs provide continuous variations of uranium, thorium, and potassium content of the well, which, combined with density, allows the calculation of heat production of the rock mass. In a granitic context, lithology variations as well as hydrothermal alteration can be evidenced from these logs.

#### 7.4.5.4.5. Resistivity log

Resistivity logs provide information about the electric conductivity of the rock. Resistivity is expressed in Ohm.m. It is sensitive to the type of rock and to the amount of water in the rock mass (depending on the porosity). Other factors also influence the resistivity, such as temperature and composition of the formation fluid. Therefore, the correlation between temperature, porosity and resistivity is not straightforward. In spite of this, contrasts observed in resistivity logs, cross-checked with other well data can provide information concerning the ability of the media to constitute an economical and accessible geothermal reservoir.

#### 7.4.5.4.6. Stress determination

The knowledge of the in-situ stress field within a geothermal reservoir is fundamental for the design of the stimulation tests.

The characterization of the in-situ stress field is mainly done by determining the orientation and the magnitude of the three principal stress components: the minimal horizontal stress, the maximal horizontal stress and the vertical stress.

The orientation and amplitude of the three principal stress components and their depth dependency have to be determined with sufficient accuracy.

A comprehensive review of stress characterization has been achieved for engineered geothermal systems (Evans et al., 1999).

To measure the stress field, the following methods could be applied:

- Stress measurement can be essentially achieved by overcoring and hydraulic fracturing.
  - Based on borehole sample analysis, overcoring allows the calculation of the magnitude and directions of the stresses existing in hard rocks.
  - Borehole hydrofracturing is used to measure the minimum horizontal stress and the orientation of the maximum horizontal stress. For example, the HTPF (Hydraulic Testing of Pre-existing Fractures) method provides a mean of determining the complete stress tensor (Cornet and Valette, 1984).
- UBI/FMI and caliper logs allow observation and analysis of vertically induced fractures, ovalization processes, borehole breakouts, en echelon fractures, or more general borehole instabilities. In cases of inclined wells, the rotation of borehole-near stress tensor need to be considered in analyzing artificial fractures. As such tools have their own system of inclinometry, the orientation of principal stresses can be deduced.
- On a more regional scale, the stress field could be determined by analyzing focal mechanisms of natural earthquake events within the area of interest. This analysis also allows characterizing the stress regime (Plenefisch and Bonjer, 1997).

If no information on stress magnitude is available, stress models can be developed. These models usually assume that in-situ stress magnitude in the crust does not exceed the condition of frictional sliding on well-oriented faults.

If the in situ stress field is known, geomechanical reservoir models could help defining local stress perturbations along faults and in compartment blocks.

The slip-tendency analysis helps to understand the fault behavior under changing stress conditions whilst drilling and stimulating the rock mass.

Wellbore stability and fault reactivation potential could then be quantified by classical geomechanical approaches.

## 7.4.6. Reservoir development phase

### 7.4.6.1. Chemical stimulation

Chemical stimulation consists of acid injection into the open hole at pressures low enough to avoid formation fracturing. It is used to increase the productivity of the reservoir. The main features of chemical stimulation are as follows:

- Dissolution of formation damage (drilling cuttings, mud cake);
- Mineral dissolution in the well vicinity and in fractures;
- Acid composition:
  - Conventional acids HCl-HF;
  - Chelating agents NTA; and
  - Retarded acid systems.

Three sequences are needed for the treatment of a classic geothermal reservoir: preflush, main flush and overflush. The preflush is performed most often with an HCl solution, first to displace the formation brines. The main flush is used to remove the damage and most often, a mixture of HF and HCl or organic acids is pumped into the well. Finally, the overflush performs the displacement of the non-reacted mud acid into the formation and of the mud acid reaction products away from the well bore.

Coiled tubing is a very useful tool for improving acid placement. Coiled tubing is of less use in fracturing acidizing because of pumping rate limitations. It is still best to pump fracturing treatments through larger strings, such as production tubing. In larger open-hole sections, acid diversion is important, otherwise only the interval, which breaks down or open fractures, will be treated first. Diversion can be achieved with packers.

### 7.4.6.2. Hydraulic stimulation

Hydraulic stimulation consists of large volumes of water injected at a high flow rate and in a pressure close to the breakdown pressure. As for chemical stimulation, it is used to increase the productivity of the reservoir. Two mechanisms should be distinguished:



- Shearing and opening of natural fractures through shear failure, at low pressures. The shearing of fracture planes induces seismicity; and
- Creation of artificial fractures (Hydrofrac or fracking), at high pressures (tensile fracturing).

It should be noted that shearing of large fracture planes could lead to large magnitude seismic events.

Since the early 1980s, research at various sites confirmed that shearing is the dominant process rather than tensile fracturing (Pine and Batchelor, 1984). Natural joints, favorably aligned with the principal stress directions, fail in shear mode. As a consequence, formations with high stress anisotropy and hence a high shear stress should be the best candidates for hydraulic fracturing in low permeability rock.

Knowledge about the stress regime is of great importance to understand or even to predict the hydraulic fracturing process. Borehole breakouts, borehole fractures, location and amplitude of microseismic events and stimulation pressures could be evaluated to better determine the orientation and amplitude of the principal stress components.

The response of the rock mass to hydraulic stimulation (fracking / stimulation) can be predicted with geomechanical analysis, and thus prior to the water injection. This analysis requires the following data:

- The fracture orientations distribution, resulting from the interpretation of a UBI log; and
- Knowledge of the orientation and magnitudes of the regional/local stress fields, through literature analysis and well tests (hydrofrac/minifrac test or HTPF Hydraulic Test in Pre-existing Fractures).

One method to reduce the risk of creating shortcuts is the isolation of intervals in the borehole. Stimulation is then performed successively along these intervals. The effective fracture area obtained by proceeding this way is larger than by applying a massive stimulation over a long open-hole section. Such strategy is also favorable to reduce the risk of inducing large seismic events. This methodology is limited by the efficiency of the open-hole packers, which are often subject to leaks in deep hot reservoirs.

Cases of induced seismicity were reported from hydraulic stimulation programs in geothermal wells. However, not all geological formations are prone to induce such events. Induced seismic events, which could be felt at the surface, have been reported from hard rock environments such as in Basel, Switzerland (Häring, et al., 2008) as well as in sedimentary sediments such as in 2013 in the City of St. Gall (Switzerland). Since the permeability in these formations is a fracture-permeability, the pressures generated to frac the formation can only diffuse through the fracture and fault network, which will lead to a reduction in the effective stress. In sedimentary environments, due to their matrix porosity and permeability, elevated pressures will not focus on fracture and fault pathways, but diffuse through the porous matrix. A potentially considerable sedimentary coverage of a hydraulically stimulated hard rock formation will also dampen induced seismic events.

## 7.4.7. Production phase

### 7.4.7.1. Production and injection

#### 7.4.7.1.1. Production pump

Self-flow of the well could occur due to artesian effect or due to a thermosyphon effect as soon as production starts. When self-flow is not sufficient to guarantee an economic viability of the power plant, the installation of a production pump is necessary. Depending on the setting depth and water temperature different types of pumps could be used. They include line shaft pumps, submersible pumps and turbopumps.

The shaft driven submersible pump comprises a multistage down-hole centrifugal pump and surface mounted motor plus long drive assembly extending from the motor to the pump. This pump is used for shallow depths down to 200 m, and 80-130°C temperature.

Electric Submersible Pumps (ESP) consist of a multistage centrifugal pump connected to an electrical motor, directly set in the base of the well. They can be used at larger depths and have a capacity up to 2,000 l/min, about seven times more than that of the shaft driven pumps. As 50% of the pump breakdowns are due to electrical problems, any water infiltration must be eliminated by the waterproof design for the motor. In the case of bottom hole high fluid temperature (200 °C), special electric oil filled motors are available.

Submersible turbopumps have a hydraulic part driven by a turbine, itself driven by pressurized geothermal water circulation aided by a surface pump. It has lower energy efficiency, but needs less maintenance.

#### 7.4.7.1.2. Injection pump

To minimize environmental impact and enhance fluid recharge into the geothermal system during exploitation, reinjection of

waste water becomes a model feature of all geothermal developments. As a standard practice, reinjection wells are located at a lower elevation than the production wells to eliminate the use of reinjection pumps. However in cases where this is not applicable because of topographical constraints and reservoir characteristics, the use of reinjection pumps becomes part of the production facilities. Usually, horizontal pumps are adopted for this purpose. They have a capacity up to 1,500 l/min and can operate within water temperatures of up to 80 °C.

#### 7.4.7.1.3. Corrosion and scaling

Effective protection from corrosion and scaling can take place by injecting into the fluid inhibitors based on quaternary amines, whose filming capacity ensures an optimum protection of the casing. Chemical inhibition systems, such as down-hole injection lines, have been installed in production wells at more than 40 plants in Europe.

#### 7.4.7.2. Reservoir management and monitoring

There is no standard procedure currently for monitoring of geothermal fields and their production. Goals, purpose and design of any geothermal monitoring program mainly depend on the local geological environment and production conditions. Potential monitoring parameters are the conditions of state, reservoir pressure and temperature, fluid chemistry, flow rate (spinner surveys), seismicity, gravity and the electrical potential. An adequate monitoring program helps to avoid overexploitation of the geothermal reservoir. It leads to a better understanding of the geothermal system and allows a more reliable reservoir modeling.

The implementation of a seismic monitoring network constitutes nowadays best practice in every geothermal project. A seismic monitoring network should be in place before the drilling phase, in order to monitor the natural seismicity.

Monitoring of the chemical composition of water and steam discharged from wells in exploited geothermal fields provides valuable information on the response of the reservoir to the production load. For example, withdrawal of deep reservoir fluid generally induces recharge, which may alter the chemistry of the fluid, especially if a significant portion of the recharge water has a very different chemistry. Monitoring of the dilution trends can provide information about the rate of lateral movement of the invasion front.

Any monitoring of a geothermal reservoir should commence at the latest at the time the actual production begins (Hunt, 2000). It should be performed frequently enough that natural variations can be distinguished from exploitation induced changes. The data have to be archived and documented in such a way that they are accessible for the potentially changing personnel that will interpret these data over the entire field life.

For reservoir management purposes, integrated numerical modeling at a geothermal site scale is more and more developed in Europe (instead of reservoir scale modeling).

## 7.5. Power plant technologies

### 7.5.1. General

Different types of power plant technologies can be applied, depending on the nature of the geothermal reservoir:

- Condensing plants (flash steam): The term flash steam refers to the process where high-pressure hot water is flashed (vaporized) into steam inside a flash tank by lowering the pressure. The vapor then drives a turbine, which drives a generator. If any liquid remains in the tank, it can be flashed again in a second tank to extract even more energy.
- Binary cycle plants: By using a working fluid (binary fluid) with a much lower boiling temperature than water, thermal energy in the reservoir water flashes the working fluid into steam, which then is used to generate electricity with the turbine. The water coming from the geothermal reservoirs through the production wells is never in direct contact with the working fluid. After some of its thermal energy is transferred to the working fluid with a heat exchanger, the water is sent back to the reservoir through the injection wells where it regains its thermal energy. Binary cycle plants can be ORC (Organic Rankine Cycle) or Kalina, depending on the binary fluid used.

In condensing plants, geothermal steam is directly injected into the turbine, whereas in binary cycle plants' technologies, an intermediate fluid will be used in a secondary loop (see Figure 7-1). Basically, binary cycle power plants are used for lower temperatures and in reservoirs where the steam content is not high enough. The global efficiency of binary cycle power plants is lower than the efficiency of condensing power plants. Regarding the temperature found in Lebanon, the technology used will be based on a binary cycle plant.

Regarding the temperature range of 120-140 °C (max. 200 °C considering EGS technologies) found in Lebanon at a depth accessible with the state of the art drilling technologies and reservoir technologies, the power plant technology used will be based on a binary cycle plant.

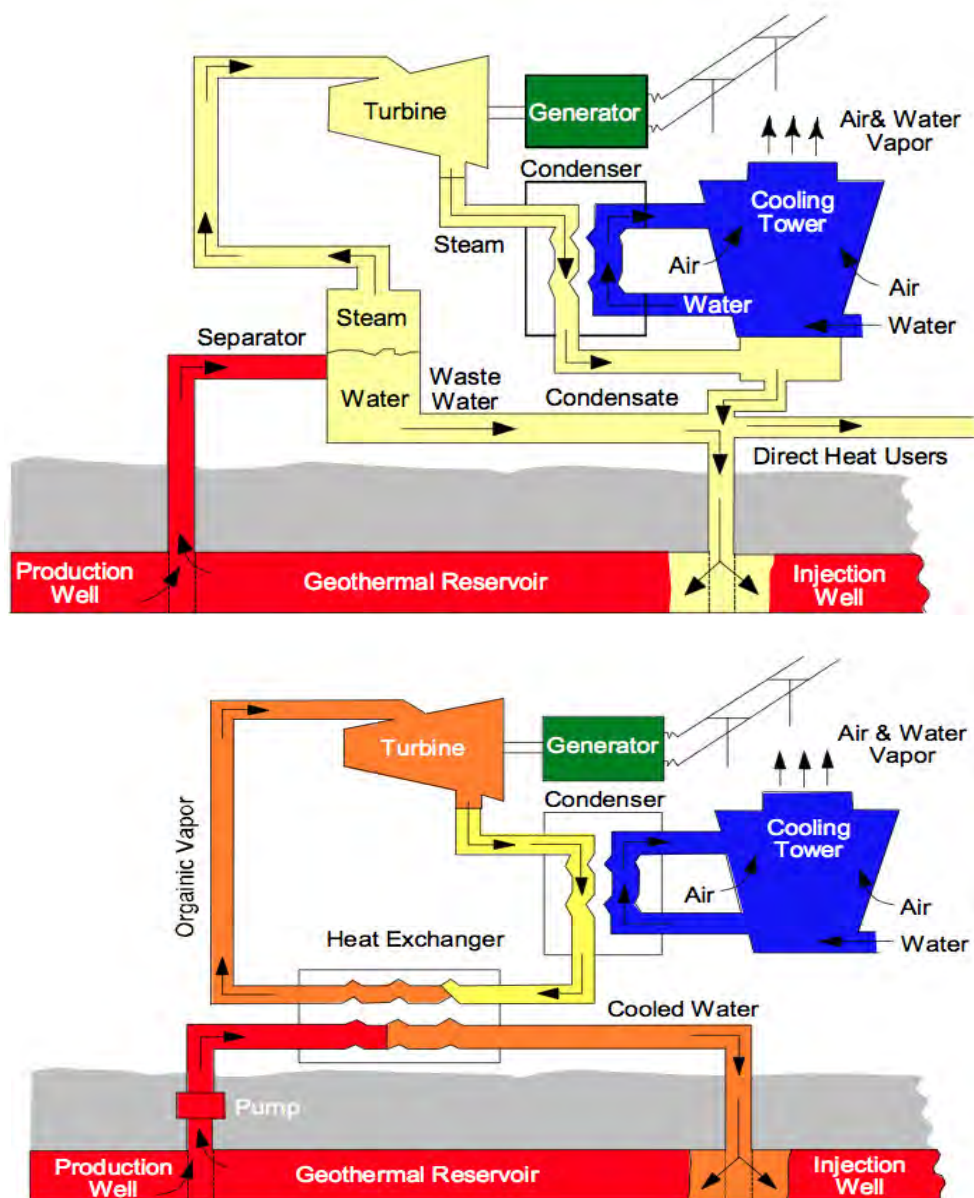


Figure 7-1: Schematic view of a condensing power plant (top) and of a binary cycle power plant (bottom) (Geo Heat Center)

## 7.5.2. Condensing power plants

Approximately 94% of the total generated power globally is derived by steam flash plants, the majority of which use condensing turbines, which in practice yield twice as much power output than atmospheric exhaust conventional steam turbines. In a condensing plant the steam is condensed at the turbine outlet, at an exhaust pressure of 0.10 - 0.12 bar, which results in improved cycle efficiency. Specific steam consumption of 7-8 kg/kWh<sub>e</sub> is typical for non-condensable gases content of 1%.

Production from water dominated fields requires the use of steam/water separators with either single or double flash cycles. In single flash plants, typical separation pressures are 5 - 7 bars optimizing the inlet pressure to the turbine. As the separated water is of 150 - 170 °C temperature and has a high energy content, it can be flashed further at a lower pressure of 2 - 2.5 bars and either supply the second stage of the turbine or feed a second turbine operating at lower pressure. The magnitude of separation pressure, and the decision of whether to use single or double flash units, depends on the scaling tendency of the fluid, e.g. higher separation pressures may be necessary in order to control silica or calcite scaling in the separator and brine lines.

Main equipment items may include steam scrubbers, wet steam turbines, dual admission turbines, condenser, controls and

remote control, condensate pumps, cooling water pumps, steam jet ejector, compressors, vacuum pumps, cooling towers, gas extraction equipment, hydrogen sulphide and mercury abatement equipment. In flash plants, the standard cooling down technology adopted almost exclusively is direct contact condensers coupled with wet cooling towers. However, if the plant is located close to a sea or river, where water availability in large quantities is not a problem, the direct contact condensers can be supplied by surface water in once-through systems, leading to improved conversion efficiency.

The flow charts of geothermal condensing plants are shown in Figure 7-2.

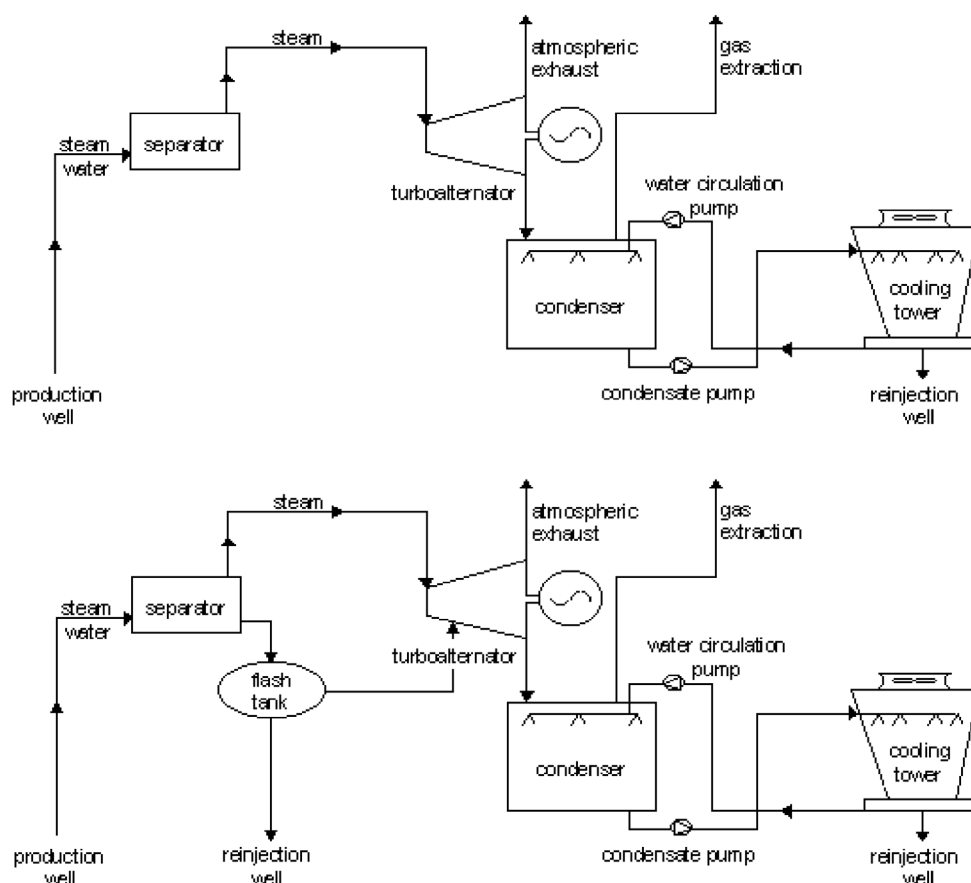


Figure 7-2: Flow chart of a single flash condensing geothermal power plant (top) and of a double flash condensing geothermal power plant (bottom)

### 7.5.3. Binary cycle plants

In case of geothermal fluid temperature less than 150 °C, the most common technology used is binary Organic Rankine Cycle (ORC) machines. In an ORC machine, the geothermal fluid transfers thermal energy to a closed loop of circulating fluid, or working fluid, through a heat exchanger. Typical working fluids used in ORC machines are either hydrocarbons (isobutane or isopentane) or fluoro-hydrocarbons, which operate at relatively low pressures. The circulating fluid evaporates within the geothermal heat exchanger mentioned above, and from there vapor is conveyed into a condensing turbine for power generation. The condenser, can either be water cooled (cooled by surface water or by water from a cooling tower), or air cooled. Then, the liquid working fluid is pumped into the geothermal heat exchanger and the cycle is repeated.

A similar cycle using a mixture of water and ammonia as working fluid may also be used, with the corresponding process termed as Kalina. Although a Kalina cycle initially had high expectations in terms of conversion efficiency and costs, operation of existing plants indicate more or less similar performance with ORC machines.



Present geothermal binary cycle plants are designed for cost effective operation with entering geothermal fluid temperature of at least 90 °C. Due to the low temperature of the geothermal heat source and their small size, binary cycle plants (ORC or Kalina) have higher capital costs per unit of installed power, compared with traditional condensing geothermal power plants.

ORC plants are computer controlled with automatic start-up. They require no supervision during operation - monitored and controlled remotely through a telephone line, or operated by part time semi-skilled personnel. They operate in a variety of load conditions, such as base load, peak load, fluctuating load, low load down to 0-25% of rated power. Conversion efficiency depends on both heat supply temperature and load, usually varying from 6.5-15% for geothermal fluids of 90 °C-150 °C.

Three main cooling options are used: a) surface water (once-through systems), b) wet type cooling towers, and c) dry type cooling towers. Cooling with surface water yields the lowest condensing pressure and temperature and the highest conversion efficiency, followed by wet cooling towers, and then by dry cooling towers. Regarding the need for cold water supply, the order is reversed. Typical values are 970 t/h, 30 t/h and zero t/h respectively per MW<sub>e</sub> of installed power. In terms of costs, once through cooling may require both high capital costs and electricity consumption for transporting water. Dry cooling is the most expensive option due to the much higher heat capacity and heat transfer coefficient of water compared with ambient air. A dry cooling tower for a binary cycle power plant of high conversion efficiency may cost 10 times more than its wet counterpart, which may result in raising overall power plant costs by 50%. In binary cycle plants, where the more expensive shell-and-tube or plate heat exchangers are used as surface condensers, the selection of the cooling system type is governed by water availability, local water use regulations and economics.

## 7.5.4. Heating applications

Heating applications using residual or waste heat include space and district heating, heating of soil and greenhouses, sea farming and heating of low temperature industrial processes such as drying, seawater desalination, and washing. The energy output of a geothermal low temperature heating plant can be improved by water source heat pumps. Heating applications used together with power generation are very interesting for the economic feasibility of a project.

## 7.6. Cost estimation Opex/Capex

### 7.6.1. Introduction

The costs for a geothermal power plant have been estimated for typical underground environments that are considered as suitable for the implementation of a geothermal project in Lebanon:

- Akkar (two environments)<sup>14</sup>
  - The Akkar region has been identified to be the most promising area for the development of a hydrothermal geothermal project in Lebanon, due to the probable presence of a thermal anomaly and to the relatively low depth of the Jurassic aquifer. Two environments are proposed. The first one aims at exploiting the Jurassic aquifer at a depth of 1,500 m, by means of hydrothermal technology. The second one considers EGS technologies at a depth of 4,000 m (see section 7.3), where a temperature of 180-200 °C is expected.
  -
- Bekaa (one environment)
  - The depth of the deep aquifers in the Bekaa Valley could be sufficient to have temperatures high enough for power generation, by means of hydrothermal technology. The expected temperatures are 110-130 °C.
- Beirut (one environment)
  - The depth of the deep aquifer on the coast line is not deep enough for exploiting the heat for power generation. However, the EGS technologies could be suitable (see section 7.3), by exploiting the heat at a depth greater than 6,000 m below ground level.

The four environments differ in terms of location, target reservoir and utilization technology. They are designed to allow an easy comparison of the cost estimates. Their location could be attributed to the four geothermal prospects identified in section 6.5 (see location in Figure 6-18). These prospects do not consider EGS technologies. Therefore, the Beirut environment is not represented in the map of Figure 6-18.

Given the transmissivity estimation of the geothermal reservoirs, our calculations indicate that the geothermal fluids could be extracted with a flow rate of around 46 l/s. As long as the reservoir has not been tested by in-situ tests (hydraulic tests), the transmissivity and related flow rate are very uncertain. The same value has been considered for the four scenarios, in order to allow a comparison of the cost estimations.

<sup>14</sup> To a certain extent, the Kaoukaba area in South could be considered in this underground environment as well.

The geothermal resource assessment carried on in this study indicates that the Cretaceous aquifer is not suitable for power generation, as there is no single location in Lebanon where the temperature in the Cretaceous aquifer is expected to be over 100 °C (see Figure 6-9).

However, this study allows predicting that the temperatures of the Jurassic aquifer (Kesrouane Formation) could exceed 100°C in several areas within Lebanon. A temperature of about 130 °C is expected in the Akkar district, in the north of Lebanon (see Figure 6-10). The Akkar district is, therefore, the most promising area for the implementation of a geothermal power plant. This area has been selected for first cost estimation scenarios. Two underground environments could be considered in the Akkar region. The first one is the deep Jurassic aquifers where a temperature of around 120 to 140 °C could be expected. This environment is considered to be the most realistic and is therefore considered as a reference case. The second one considers a deeper horizon where a temperature higher than 200 °C could be extracted by means of EGS technologies.

From the consumers and users point of view, the coast line and the Bekaa valley are the area where the heat demand is the highest (industry, agriculture, domestic usage) and thus preferable regions for the implementation of a geothermal power plant <sup>15</sup>. The geothermal resource assessment indicates that temperatures within the Jurassic aquifer are maximal in the Bekaa valley. The temperature prediction provides a temperature just below 100°C. Given the uncertainty of the parameters used to make this prediction, it cannot be excluded at that stage that the temperature in the Jurassic aquifer could exceed 100°C in the Bekaa Valley. Therefore, the deep aquifer of Bekka valley has been selected as an environment for a third cost scenario analysis.

For comparison purposes, the third scenario considers an EGS system exploiting a reservoir located at a depth of 6,000 m depth (BGL). This scenario could be considered as realistic for a geothermal project in the Beirut area, for instance.

The cost estimates for the four geothermal power plants scenario are based on similar costs estimations made for similar deep geothermal projects, such as in St. Gall (Switzerland) (first drilling achieved), Grob-Schlattigen (NE-Switzerland) (achieved), Solothurn (Central Switzerland) (planned) and in the United Kingdom (planned). Costs are given in US\$ on 2012 rate basis.

Since the overall costs are affected by many different factors and since they are highly dependent on local conditions and current market prices, these data can only be regarded as a rough cost estimation.

It should be noted at this point, that the estimated costs are effective costs. No support financial mechanism of any kind has been taken into account, such as subvention, feed-in tariff, insurances, and so on.

The costs of a deep geothermal power plant project can be divided into investment costs at the beginning of the project and the annual costs. The annual costs include the Capital Annuities (CAPEX) and the Operational Expenditures (OPEX). The total costs of a geothermal power plant are strongly dominated by the high-risk investment at the very early phase of the project, mainly coming from the drilling costs and the risk of non-discovery. Therefore, financial incentives at the very early stage of the project strongly help in the overall funding of a geothermal project.

Capital investments include the installation/construction of the following elements:

- Well doublet,
- Geothermal fluid cycle (primary),
- Power plant unit (including the secondary fluid cycle),
- Surface infrastructures.

The annual costs consist mainly of the annual operation and maintenance costs as well as the CAPEX.

The components of the Investments costs are described in more detail in Sections 7.6.2 and 7.6.4, respectively.

## 7.6.2. Investment Costs

### 7.6.2.1. Well doublet

Costs for a well doublet integrate well drilling, logging and testing, and reservoir stimulation. It represents the largest part of the costs of a deep geothermal project. Well costs depend on many factors and vary with time, location and the specific geological situation. The main costs are generated by:

<sup>15</sup> In case of use of cogeneration of heat (not considered in this study)

- rig rent and mobilization
- material (cement, drilling mud...)
- energy supply
- logging & testing equipment (rent)
- services

The cost for the rig rent depends on the rates and on the time it takes for well drilling, which can strongly vary depending on issues in the underground. It also strongly depends on the rig availability within a given region. Mobilization costs are generally fixed.

Material costs depend on the actual market price of cement and steel. These costs are, therefore, rather variable.

The costs for reservoir engineering depend strongly on the specific local situation and can only be roughly estimated.

### 7.6.2.2. Geothermal fluid loop

The costs for the geothermal fluid loop contain the following components:

- pumps
- heat exchanger
- pipes
- slop systems
- filters

In general, the production pump represents the main component of these costs, due to the high technical requirements such a pump has to meet.

The costs of the production pump depend on the effective flow rate, the production temperature and the chemical composition of the production fluid.

### 7.6.2.3. Power plant unit

The cost for the power plant integrates the following components:

- the turbine
- the generator
- the cooling unit
- buildings

Due to the temperature level in Lebanon, the cost estimation considers a binary cycle power plant.

The costs of a binary cycle power plant are mainly related to the installed capacity. Additional factors, which influence the total cost of the power plant unit, are the production temperature and the type of the cooling unit, which is used (air-, wet-cooling) to condensate the steam at the turbine exit.

### 7.6.2.4. Surface infrastructure

The surface infrastructure mainly consists of the following elements:

- the electric power station (feed-in),
- pipes, valves, etc..

The cost for the electric power station is mainly related to the installed capacity of the power plant. The costs of the pipes are mainly related to the production temperature and the flow rate.

## 7.6.3. CAPEX

Capital expenditures coming from investment costs are calculated considering the specific lifetime for each component of the investment, and a discount rate of 5%.

- The lifetime is estimated through experience of similar projects in Switzerland, France and Germany

- The investment for each component is then calculated by means of interpolation functions regrouped in a GEOWATT database. The database has already been used in cost estimation of several projects in Europe. If necessary, parameters have been adapted for the local conditions in Lebanon. The parameters for the interpolation functions are listed in Table 7-2. For instance, the cost for the infrastructure drilling site depends among other things on the total depth and the pumping rate. The cost for the cooling tower is a function of thermal power. All parameters are cross-correlated and allow us an estimation of the total price given different scenarios
- The low discount rate considers that geothermal energy is an innovative renewable technology that could benefit from better loan and lease conditions

Table 7-1: Lifetime for the different elements of a geothermal power plant

Parameter	Life time [yr]
<i>Well doublet</i>	
Infrastructure drilling site	30
Energy supply	30
Well 1 <sup>1</sup>	30
Well 2	30
Planning & Test	30
Reservoir engineering	30
<i>Geothermal fluid loop</i>	
Production- & injection pump	5
Heat Exc., filter, pipes	5
<i>Binary cycle Plant Unit</i>	
Turbine, transfo, generator unit	30
Building	30
Cooling unit	30
<i>Infrastructure</i>	
Pipes, valves, etc.	10
Electricity supply	10
Fees	30
Incidentals	30

## 7.6.4. Operational and Maintenance Costs (OPEX)

The operational and maintenance costs of a geothermal plant can be subdivided into the following cost components:

- Operating staff,
- Consumables,
- Overhaul,
- Maintenance,
- Electric power for the pumps,
- Distance to the local grid,
- Available voltage level

Cost for the operational staff is relatively low. Three persons a day are needed to operate a geothermal power plant. More people are however required to assure the complete maintenance of the power plant.

Overhaul and maintenance are supposed to be 1.5% of the total investment. Personal and consumables are fixed and supposed to be 300,000 US\$ per year (For three engineers at 80,000 US\$/year. 40,000 US\$ are supposed for consumables.)

The biggest cost factors are auxiliary power for the pumps and maintenance.

The costs for the replacement of the production pump should be considered as well. Production pumps are submersible pumps and have a limited lifetime, due to the physical and chemical conditions encountered in the deep reservoirs. It can be expected, that a pump has to be replaced several times during the overall lifetime of a power plant.

## 7.6.5. Cost breakdown

Cost breakdown are estimated for four underground environments in Lebanon. Parameters and hypothesis used are listed in Table 7-2. Some of these parameters are common to the four environments, such as the plant capacity factor, the plant lifetime, the injection temperature, the flow rate and the pump power consumption. The other parameters are specific to each environment, such as the depth of the reservoir and the production temperature.

The plant capacity factor of a geothermal power plant is higher than 90%, which is the highest of all technologies including nuclear. It defines the time per year where energy is available. A value of 90% is considered for the present calculations.

The summary of the cost breakdown including the investment costs, the CAPEX and the OPEX are then presented in Table 7-3. Cost estimations are provided in US Dollars.

The capital costs for the realization of a geothermal power plant in Lebanon are comprised between around US\$25 million in the Akkar District and around 70 million US\$ for an EGS project in Beirut. Operational costs are then more or less similar and are comprised between 0.6 US\$ and 1.2 million US\$ per year.

The difference in terms of costs is clearly related to the depth of the reservoir and the associated drilling costs, which vary from 4.7 million US\$ in the Akkar region to 36 million US\$ for the EGS scenario in Beirut.



Table 7-2: Parameters and hypothesis for the estimation of the capital and operational costs of the geothermal plant

Parameter	Unit	Akkar		Bekaa		Beirut	
		Hydrothermal	EGS	Hydrothermal	EGS	Hydrothermal	EGS
Plant capacity factor	-	0.9	0.9	0.9	0.9	0.9	0.9
Plant lifetime	year	30	30	30	30	30	30
Reservoir depth	m	1,500	4,000	2,800	2,800	6,000	6,000
Production temperature	°C	130	200	130	130	140	140
Injection temperature	°C	70	70	70	70	70	70
Flow rate	l/s	46	46	46	46	46	46
Pump power consumption	kW	577	577	577	577	577	577

Table 7-3: Cost breakdown (in Million US\$) for power plants in four underground environments in Lebanon

Parameter	Akkar Hydrothermal	Akkar EGS	Bekaa Valley Hydrothermal	Beirut EGS
Heat generation $MW_{th}$	13	29	13	16
Geothermal Power production $MW_{el}$	1,3	2,9	1,3	1,6
<b>Investment costs</b>				
<b>Well doublet</b>				
Infrastructure drilling site	1.4	2.0	1.7	2.4
Energy supply	0.1	0.2	0.2	0.2
Well 1	2.6	11.1	6.7	20.0
Well 2	2.1	8.9	5.4	16.0
Planning & Test	0.7	3.0	1.8	5.4
Reservoir engineering	2.0	2.0	2.0	2.0
<b>Geothermal fluid loop</b>				
Production & injection pump	1.6	1.6	1.6	1.6
Heat Exc., filter, pipes	0.6	0.7	0.6	0.6
<b>Binary cycle plant unit</b>				
Turbine & generator unit	4.2	7.8	4.2	4.7
Building	2.5	3.4	2.5	2.6
Cooling unit	1.0	1.2	1.0	1.0
<b>Infrastructure</b>				
Pipes, valves, etc.	0.9	1.3	0.9	1.0
Energy supply	0.7	0.7	0.7	0.7
Fees	1.4	2.0	1.4	1.5
Incidentals	3.1	6.6	4.4	8.7
<b>Total Investments (Mio US\$)</b>	<b>24.8</b>	<b>52.5</b>	<b>34.9</b>	<b>68.5</b>
<b>Annual costs</b>				
<b>OPEX</b>	<b>0.7</b>	<b>1.1</b>	<b>0.9</b>	<b>1.4</b>
<b>CAPEX</b>	<b>2.1</b>	<b>3.9</b>	<b>2.7</b>	<b>4.9</b>
<b>OPEX/CAPEX %</b>	<b>30</b>	<b>30</b>	<b>30</b>	<b>30</b>
<b>Total annual costs (Mio US\$/year)</b>	<b>2.8</b>	<b>5.0</b>	<b>3.6</b>	<b>6.3</b>

### 7.6.6. Economic feasibility

Table 7-3 provides the capital investment costs, the CAPEX and OPEX for four typical underground environments. As the quantity of power and heat generated by these four power plants differs significantly, an economic simulation over 30 years is required to evaluate the economic feasibility of these power plant scenarios.

The economic feasibility is done by calculating the costs for the production of 1 kWh electricity (net production), considering the four underground environments (Table 7-4).

The net energy production is calculated by subtracting the power required for making the pumps working to the gross power produced by the geothermal power plant.

Depending on the financial support mechanisms (Feed-in Tariff) it could make sense to make use of auxiliary power for the pumps. This option is not evaluated in the present economic feasibility.

The uncertainty or risk of non-discovery is related to the temperature and flow rate estimated in the four environments. It is considered to be medium in the Akkar region as there is already evidence of the presence of thermal water at depth. It is considered as high in the other regions, where there is either less information or where the available data is less reliable.

The risk is related to geothermal technology and the risk of induced seismicity. It is considered to be low to medium for hydrothermal projects and high to very high for an EGS project, especially if the project is located close to sensible areas, such as the city of Beirut.

The timeframe provides an indication of the period in which such a power plant could be effectively installed. EGS technologies are not yet mature to be implemented in a seismic area like Lebanon.

**Table 7-4: Summary of the CAPEX and OPEX for four Power Plant scenarios in Lebanon, and estimation of the net electricity production and the specific costs in US\$/kWh**

	Akkar (Hydrothermal)	Akkar (EGS)	Bekka (Hydrothermal)	Beirut (EGS)
<i>Heat generation <math>MW_{th}</math></i>	13	29	13	16
<i>Geothermal Power <math>MW_{el}</math></i>	1.3	2.9	1.3	1.6
Investment costs Mio US\$	24.8	52.5	34.9	68.5
OPEX	0.7	1.1	0.9	1.4
CAPEX	2.1	3.9	2.7	4.9
OPEX/CAPEX %	30	30	30	30
Net electricity prod. in GWh/year	6.0	18.2	6.0	7.7
Specific cost in US\$/ kWh	0.46	0.28	0.60	0.81
Risk of non-discovery	Medium	Medium	High	Medium
Technical risk	Low	High	Medium	Very high
Time horizon	2020	2025	2020	2030

An asset of geothermal power is the possibility to cogenerate heat in very large quantities. The commercial use of cogenerated heat could considerably increase the economic feasibility of a geothermal power plant. The heat cogeneration was not considered in the framework of this study, as no information about the heat demand was available and because the main focus was electricity generation. The heat demand for domestic use is moreover considered very low, due to the climatic conditions.

The proximity of energy users with high heat demand (industry, thermal spa, greenhouse agriculture...) could be a major asset for site selection of the geothermal power plant.

Regarding the hydrothermal project in the Akkar region, the economic feasibility strongly depends on the two main criteria that are fluid temperature and hydraulic conductivity. Sensitivity of these parameters is presented in Table 7-5.

It should be pointed out that the cost estimates are based on an intact reservoir, not disturbed by a fault zone. In a fault zone, a multiplication factor of 1.5 to 2 could be expected. In this case, the productivity of the reservoir would be increased by a similar factor. The effect on the cost estimations could be evaluated by considering the optimistic value of the transmissivity in Table 7-5 (shift of one column to the left).

Depending on geothermal conditions in the reservoir (temperature and transmissivity), the costs are estimated to be comprised between 0.21 US\$/kWh to 1.37 US\$/kWh, with an average cost of 0.46 US\$/kWh.

These costs are higher than the actual price of the electricity market in Lebanon. The costs for electricity is between 0.08 and 0.21 US\$/kWh depending on usage, customer category and period (base load, peak load). Electricity is imported at an average price of approximately 12 US\$/kWh.

Table 7-5: Cost per kWh in US\$ for different hydraulic transmissivity and reservoir temperatures of the Jurassic aquifer in the Akkar region

Temp [°C]		Transmissivity [m <sup>2</sup> /s]		
		10 <sup>-3</sup>	3.0•10 <sup>-4</sup>	10 <sup>-4</sup>
120	MW <sub>el</sub> (gross)	3.5	1.1	0.4
	GWh (net)	13.1	4.2	1.5
	US\$/kWh	0.33	0.64	1.42
130	MW <sub>el</sub> (gross)	4.2	1.3	0.5
	GWh (net)	18.61	5.97	2.12
	US\$/kWh	0.25	0.46	1.03
140	MW <sub>el</sub> (gross)	4.8	1.6	0.6
	GWh (net)	24.1	7.7	2.7
	US\$/kWh	0.20	0.37	0.81



# 08. Environmental aspects

## 8.1. Introduction

Geothermal energy, as a renewable energy form, is an indigenous energy source and its use results in stimulating local development and increasing local employment. In addition, as it replaces imported fossil fuels it results in improving the trade balance of Lebanon and reducing carbon dioxide emissions.

As geothermal power plants have, during the operational phase, practically zero carbon emissions per kilowatt-hour of electricity generated, the increase in deployment of geothermal energy will have a large net positive effect on the environment in comparison with the development of fossil fuels, which is in alignment with the Kyoto targets. In addition, geothermal power plants have considerably lower sulphur emission rates than fossil-fuel alternatives, including natural gas.

However, no energy source is completely free of adverse impacts on the environment. As sustainable geothermal energy provision has to result in benefits to the environment compared to other alternatives, environmental impacts need to be precisely assessed. Therefore, communicating environmental impacts and working on diminishing them is an integral part for further developing geothermal energy.

Although geothermal energy is environment friendly, its large-scale development is not entirely free from local environmental impacts. These impacts depend on practices of the geothermal contractor and on geothermal plant design. The most critical environmental problems are associated with the chemistry of the geothermal fluids, which can be chemically aggressive brines, as the hot water usually contains a lot of dissolved minerals. The steam evaporating from the brine as well as the water itself can have harmful effects on the environment and become a nuisance for the local population, if not properly taken care of. These problems normally only occur if water/steam is only produced but not reinjected into the subsurface. Reinjecting the cooled, liquid phase and proper plant design to eliminate the effect of non-condensable gases present in the steam usually solves these problems. In some cases, especially during the early exploration phase, escape of steam or hot geothermal brine to the surface or air may be inevitable, which may cause limited localized damages to plants, or a characteristic smell of sulphur in the vicinity of the wells. Other impacts may be the appearance of small earthquakes, which generally do not pose a threat to people and structures, but they may worry the local population. Nonetheless, these concerns have to be taken seriously and to be properly addressed. Some geothermal projects were abandoned due to strong opposition from local communities, associated with the above effects.

This chapter presents an overview of the key features related to social, environmental and legal aspects. It also provides some guidelines to be applicable for geothermal development in Lebanon, for reducing and mitigating the impacts. The purpose is to outline the requirements for an EIA which will have to be done for a specific geothermal project in Lebanon.

## 8.2. Phasing and EIA

A geothermal project is realized in four main phases, which are the exploration phase, the drilling phase, the construction phase and the operational phase. Each phase has its own type of impacts. Before a project starts, Environmental Impact Assessment studies will have to be performed for each of the main phases of the project.

## 8.3. Type of impact

### 8.3.1. CO<sub>2</sub> emissions

The positive environmental impact of all geothermal plants is attributed to low CO<sub>2</sub> and other gas emissions (e.g. carbon monoxide, carbon particles, nitrogen oxides, sulfur oxides), in comparison with fossil fuels. However, in some low enthalpy geothermal fields, the deep hot water may contain dissolved CO<sub>2</sub> in the form of bicarbonate ions. When these fluids are brought to the surface and their pressure is lowered, they tend to deposit calcite and release CO<sub>2</sub>. Such fluids are usually located at the margins of larger hydrothermal systems. The CO<sub>2</sub> emissions from a geothermal field can be reduced by engineering the exploitation scheme accordingly. For example, maximizing the energy extracted from a given flow rate by placing the users in cascade, results in minimum CO<sub>2</sub> emissions. In agricultural uses, the geothermal CO<sub>2</sub> can be directly released within the greenhouse, in order to increase the growth rate of the plants and save fossil fuels. Other impacts from long term low enthalpy geothermal utilization may be the decreasing water level of near surface aquifers and the flow

reduction or dry-up of nearby springs and shallow water wells. All these problems can be avoided by reinjecting the cooled liquid.

In high enthalpy hydrothermal systems, the steam phase of the geothermal fluid frequently contains small quantities of non-condensable CO<sub>2</sub>, the quantity of which varies from field to field but it is limited to a few percentage units, usually in the range 0.05 - 5 %. CO<sub>2</sub> emissions from geothermal power plants compared with conventional power plants are presented in the next table. When comparing these figures, the natural degassing of CO<sub>2</sub> from the subsurface has to be deducted from the effective CO<sub>2</sub> production, as only the difference has to be taken into consideration. CO<sub>2</sub> degassing occurs everywhere on Earth, especially in places with natural hot springs. Measurements in the Summaquiyeh well in the Akkar region have shown important concentrations of dissolved CO<sub>2</sub> (see Table 8-2). This would have to be considered in case of the realization of a power plant in the Akkar region.

Table 8-1: Comparison of CO<sub>2</sub> emissions between geothermal and conventional power plants

Location	Net Power, MW(e)	Conversion Efficiency	CO <sub>2</sub> emissions [kg / kWh <sub>e</sub> ]	Net effect, [kg CO <sub>2</sub> /kWh <sub>e</sub> ]
Milos, Greece	-	19%(*)	0.10	0.00
Upper Rhine Graben **	0.85	11%	0.06	0.06
North German Basin **	0.85	11%	0.08	0.08
Lago	8.3	13%	0.16	0.00
Monterotondo	8.19	13%	0.16	0.00
Molinetto	17.95	18%	0.29	0.00
Gabbro	16.52	15%	1.05	0.00
Radicondou	36.89	19%	0.34	0.00
Travale	40.75	21%	0.31	0.00
Natural Gas		50%	0.38	0.38
Diesel		33%	0.75	0.75
Coal		33%	0.90	0.90

(\*) steam phase only / (\*\*) life cycle analysis (LCA)

Additional and more intense effects on the local environment are associated with the chemistry of the steam, which may contain non-condensable gases, such as CO<sub>2</sub>, traces of H<sub>2</sub>S and entrained silica or other dissolved solids in the liquid phase. In Milos, Greece, sulfur smell and silica scale on car windows were two of the three factors that finally forced operators to abandon the pilot plant after only 2 years of operation, as it had completely lost acceptance by the local population. The Summaquiyeh well for instance, has been reported by (Acra, et al., 1982) to be rich in Silica, CO<sub>2</sub> and Sulfate (see Table 8-2), which may lead, in case of exploitation, to the above mentioned issues.

These problems can be effectively alleviated by minimizing the steam losses from the geothermal plant (in fact steam losses should be allowed only at the safety valves), and by conveying the non-condensable gases to the cooling tower draft, where they are diluted by large quantities of air. If these measures fail to limit the H<sub>2</sub>S concentration in the air below the smelling threshold, then an H<sub>2</sub>S treatment plant should be installed, such as the "Amis" technology developed by ENEL already installed in 16 power plants.

Another very effective way is to keep all geothermal fluid under pressure at a closed circuit and reinject all liquids, steam and gas phases back to the deep reservoir, and using a binary cycle plant for power generation. The application of this plant design however, is limited by the availability of down-hole pumps suitable for the high temperature, pressure and chemistry of the geothermal fluid.

Table 8-2: Comparison of hydrochemical characteristics in the Summaqiye well (thermal water) with other water in the Akkar region. Comparison with the standards for groundwater (OMS, 1971) (after (Acra et al., 1982). The comparison is shown here for information purpose only.

Characteristics	Standard for drinking water (WHO)	Average value in Akkar region	Summaqiye well (mean value 1970-1975)
Carbon dioxide free (CaCO <sub>3</sub> ) [mg/l]	-	-	31.4
Chloride [mg/l]	<250	131	1695
Hardness total	-	390	865
Iron [mg/l]	<0.3	14	55.4
Oxygen dissolved	-	6.4	3.62
pH	6.5-8	-	7.25
Silica [mg/l]	<20	4.8	41.55
Sulfate (SO <sub>4</sub> ) [mg/l]	<250	64.5	578
Sulfide (S) [mg/l]	-	0.17	0.240
Temperature [°C]	-	-	41.35
Turbidity [JTU]	<5	0.66	17.1
Conductivity [μs/cm]	<1400	730	4935

### 8.3.2. Microseismic activity

Experience from historical and recent geothermal projects has shown that the testing and exploitation of geothermal reservoirs could result in inducing seismicity or earthquakes. The “size” of an earthquake is commonly expressed in two ways - magnitude and intensity. The magnitude is a measure of the total energy released during an earthquake. In 1935, C.F. Richter created the magnitude scale that allows comparing earthquakes in relative terms. The Richter scale is logarithmic, meaning that an earthquake of magnitude 6 has ten times the energy released as an earthquake of magnitude 5. Earthquakes could also be described by their intensity, which measures the degree of damage and observable effects caused by an earthquake at a particular location (Table 8-3).

Seismic events induced by geothermal exploitation generally are of small magnitude, usually only registered by the seismographs and does not pose any threat to buildings or structures. Normally, seismicity induced by human intervention such as mining, gas exploitation, the building of dams for hydropower or geothermal exploration and exploitation activities, mostly – although not exclusively – occurs in tectonically active regions, where natural seismicity is the rule rather than the exception.

Table 8-3: Comparison between the modified Mercalli Scale that describes the intensity of an earthquake (damages, feelings...) and the Richter Magnitude Scale which described the quantity of energy released

Modified Mercalli Scale		Richter Magnitude Scale
I	Detected only by sensitive instruments	1.5
II	Felt by few persons at rest, especially on upper floors; delicately suspended objects may swing	2
III	Felt noticeably indoors, but not always recognized as earthquake; standing autos rock slightly, vibration like passing truck	2.5
IV	Felt indoors by many, outdoors by few, at night some may awaken; dishes, windows, doors disturbed; autos rock noticeably	3
V	Felt by most people; some breakage of dishes, windows, and plaster; disturbance of tall objects	3.5
VI	Felt by all, many frightened and run outdoors; falling plaster and chimneys, damage small	4
VII	Everybody runs outdoors; damage to buildings varies depending on quality of construction; noticed by drivers of autos	4.5
VIII	Panel walls thrown out of frames; fall of walls, monuments, chimneys; sand and mud ejected; drivers of autos disturbed	5
IX	Buildings shifted off foundations, cracked, thrown out of plumb; ground cracked; underground pipes broken	5.5
X	Most masonry and frame structures destroyed; ground cracked, rails bent, landslides	6
XI	Few structures remain standing; bridges destroyed, fissures in ground, pipes broken, landslides, rails bent	6.5
XII	Damage total; waves seen on ground surface, lines of sight and level distorted, objects thrown up in air	7

Thus, most of the seismic activity associated with geothermal developments takes place in existing and often known fault and fracture zones. Nonetheless, the magnitude of seismic events can become critical and cause some regional unrest among the population if measures to prevent such problems are not taken in advance. Such preventive measures have to follow two paths:

- Mitigate the risk of occurrence of large magnitude events, by applying appropriate mitigation techniques
- Inform local population and policy makers, gain their support and reduce the risk of social problems, through intensive communication program.

Understanding seismicity is a complicated venture, which has kept thousands of scientists busy for many decades. The EU funded GEISER project (Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs) synthesized the latest scientific advances in this domain (<http://www.geiser-fp7.fr/>).

The most prominent example of seismicity caused by fluid reinjection (and extraction) is probably The Geysers in California, USA (Majer & Peterson, 2007), where micro-earthquakes even of  $M > 4$  have been monitored and documented for most of its production history.

In 2006, a seismic event of magnitude 3.4 occurred during the stimulation of the EGS reservoir in Basel (Switzerland) at 4,500 m depth (Häring et al., 2008). Some minor property damages were reported, that have been covered by the operator's insurance. The project had been cancelled. The main reason for cancelling the project was related to the fear of local residents. The geothermal community in Switzerland together with local authorities concludes that this fear was due to a lack of communication between the operator, the authorities and the residents.

A lot of effort was invested in communication for the current St. Gall geothermal project in Switzerland. In this project no hydraulic stimulation was planned and no seism of large magnitude was therefore expected. The first borehole was achieved at a depth of 4,450 m. Usual pre-test operations were achieved in July 2013. These operations have created a connection with a gas reservoir, resulting in a gas blow out. For security reasons, massive amounts of water have been injected in the borehole to block the gas outcome. This injection of water induced a seism of magnitude 3.5. Like for the Basel project, almost no damage occurred. The project was suspended for several months, but due to the good communication of the operators, the project is again in process.

In order to mitigate the risk, the seismic history and local geology have to be known. If an active fault cuts the reservoir, seismic events are more likely to occur compared to tectonically quiet regions. In addition, densely populated areas in the vicinity of

the well are usually prone to increased public awareness and concerns, which require even more public communication and perhaps a reduction in injection activity to maintain long-term acceptance. In the case of The Geysers, the low population density and the naturally occurring seismicity of the region also help to keep acceptance levels sufficiently high.

Table 8-4: Maximum seism magnitude for some hydrothermal and EGS projects worldwide

Site		Year	Maximum Magnitude
The Geysers, United States	EGS	1997-2003	4.6
Cooper Basin, Australia	EGS	2003	3.7
Basel, Switzerland	EGS	2006	3.4
Rosemanowes Quarry (UK)	EGS	2007	1.9
Soultz-sous-Forêts, France	EGS	2007	2.9
St. Gallen, Switzerland	Hydrothermal	2013	3.5

Risk of induced seismicity has to be considered using a probabilistic approach. It means that the risk of producing large magnitude events does always exist. A range of mitigation techniques could be applied to reduce the risk of occurrence of large magnitude events. Authorization for a project should be delivered only if the residual risk of occurrence of large magnitude events is considered as acceptable, according to the local standards.

Mitigation techniques have to be applied already during the early phase of a project, for both Hydrothermal and EGS projects. Main mitigation techniques are the following:

- Seismic risk analysis during the feasibility study. This analysis should already include geomechanical aspects
- Seismic monitoring network: Installation of a specifically designed seismic monitoring network around the project site to precisely monitor the seismic activity before the project starts (several months), to obtain baseline information. The seismic network is then maintained during operations of drilling, testing and production. The seismic stations could be installed temporarily. Existing permanent seismic monitoring stations could be used for historical records
- Geomechanical investigations based on the information derived from well logging. A well logging program has to be correctly designed in the early phase of the project to allow the achievement of the geomechanical investigations (for instance, in-situ stress-field measurements, Ultrasonic Borehole Imager logging)
- Specific design of a well testing program considering the results of preliminary geomechanical investigations
- Application of advanced reservoir modeling techniques for real-time prediction of risk of large magnitude events, during stimulation or operation phase (Baujard et al., submitted)

In addition to the mitigation techniques, effort should be invested in a communication program, to increase the local acceptance.

### 8.3.3. Soil subsidence

Soil subsidence means sinking of the surface. It can be of one or more meters magnitude and should occur in the center of the production zone after many years of exploitation and withdrawal of large quantities of geothermal fluids. Horizontal soil movements are also possible. In Wairakei, New Zealand, a subsidence zone of more than 2 m deep covering an area of 1 km<sup>2</sup> has been observed at the borders of the production zone after 20 years of exploitation. Maximum reported subsidence was >9 m. The problem is solved by reinjecting all the separated liquid phase and the steam condensate back to the geothermal reservoir from the very beginning of the project. During the plant design phase, care should be taken not to locate in the subsidence zone any buildings, pipelines or other structures. Furthermore, monitoring micro-gravity transients and regular topographic surveys are necessary during exploitation, in order to study the evolution of the subsidence zone.

If the power plant is located close to inhabited areas, these aspects should be considered with extreme care.



### 8.3.4. Noise

Drilling takes place 24 hours a day and 7 days a week. Depending on the depth of the target reservoir, drilling could occur for several months, and this for each of the boreholes (in case of a geothermal doublet or triplet). Noise emissions are inevitable during the drilling phase. They must be minimized, especially if the project is located in the close vicinity of a residential area or other sensitive areas. Noise emissions during the drilling could be mitigated by installation of appropriate noise insulation, such as a noise barrier, for instance.

Noise can also be severe during the operation phase. Nuisance has been reported to local residents who live close to the geothermal plant. In Milos (Greece), noise was one of the three factors leading to complaints by the local population during the short time of operation of the pilot plant. Again, noise could be countered by proper plant engineering (e.g. avoiding noisy equipment) and by placing noise barriers if necessary.

Compliance with the legal limits (if any) is being checked through noise measurements during drilling and operation phases. The EIA needs to make an estimate, beforehand, for defining required measures.

Noise emission is regulated by law number 444 of the Lebanese legislation related to the “protection of environment” issued on July 29, 2002 (see section 4.3).

### 8.3.5. Nature (Flora and Fauna)

Damage to local flora can occur every time steam or hot geothermal fluids are released on local plants. It happens due to the high temperature and salinity of the geothermal fluids. This is usually not a problem when fluids are reinjected. Care should be taken during the exploration and field development phases for proper disposal of fluids delivered to the surface. Removal of damaged trees, plants, etc., may be necessary for improving local aesthetics, while compensation for damaged property must be foreseen. Potential damages have to be assessed in the EIA.

Impact on Flora and Fauna and nature management has to be assessed in the EIA, for both the drilling and constructions phases.

Light emission during drilling at night could be an issue if the project is located close to a natural protected area (effect on avifauna and insects).

Zone of remarkable interest in terms of nature and biodiversity (see list in Table 8-5) such as the protected natural sites, should not be selected as a priority site for the development of a geothermal project (see Figure 8-5, Figure 8-6, and Figure 8-7).

### 8.3.6. Aesthetics

Although drilling installation could have an important aesthetic and visual impact (Figure 8-1), these are to be considered of minor importance as they occur only during a limited time period (around 6 months per borehole). Therefore, aesthetical aspects mainly concern the power plant.

Installations for direct use (heat only) have a very limited visual impact, such as for the Riehen installation in Switzerland (Figure 8-2), where the production borehole reaches a depth of 1,500 m. Thermal heating plants can be integrated within the urban landscape since all equipment including the pipes of large district heating systems can be placed underground. Other uses of geothermal energy such as horticulture and fish farming tend to have relatively minor visual appearance, depending on the scale of development and the nature of the terrain in which these activities occur.

Electrical generation plants have a bigger impact than heat-only installations. They can have relatively minor visual impacts, certainly no greater than the conventional fossil fuel burning plants. The main impact is related to the cooling towers (see in the satellite view of Figure 8-4).

With proper design, the geothermal plant can be transformed to a tourist attraction, such as in cases of Larderello in Toscana, where a geothermal museum has been opened.

Because of visual impact, zones of remarkable interest in terms of landscape (see list in Table 8-5) should not be selected in priority for the implementation of a geothermal installation involving power generation (see Figure 8-5).



Figure 8-1 : Impact of drilling operations of the St. Gall Project in Switzerland (2013). Drilling operations are temporary. Impact in terms of noise, vibrations and aesthetics are relevant for several months



Figure 8-2: Example of visual impact of the Riehen heat only installation (production borehole of 1,500 m depth) (Background: Google Earth)

### 8.3.7. Water quality (groundwater, surface water), soil protection, heat pollution

In the environmental impact assessment phase, it is important to know if usable groundwater exists on the location of the well and if surface water (rivers, lakes) are nearby and could be affected through chemicals (additives, acids, loss of oils, diesel...).

For protection of groundwater and soil, the drilling site must be sealed as well as elevated (in case of nearby surface water that could cause flooding). The runoff of the drilling site might be chemically contaminated and/or consisting in high turbidity. Therefore, an appropriate wastewater system must be put in place. Chemicals must all be stored securely.

A monitoring system of the water quality should be installed during the whole duration of the drilling phase. Substances to be monitored are mud components and additives (if information available).

For deep geothermal projects it is possible that the drilling will pass through surface aquifers that are maybe used for domestic usage. Prevention techniques should be applied to avoid any loss of mud and chemicals in the surface aquifer.

In many countries, it is also forbidden to create a connection between different aquifers located at various depths. Prevention techniques should be applied to correctly seal the casing and the borehole.

The exploitation of deep aquifers for geothermal use could lead to a long-term drawdown of the pressure within the aquifer, leading to a drying up of the resource. This could also lead to geotechnical issues at the surface (See section 8.3.3). Reinjecting the water into the reservoir could simply solve these issues.

Heat pollution occurs when waste heat is released into local environment. This problem can be avoided by minimizing the waste heat disposed to the surface from the plant, i.e., proper cooling, considering the fact that the cooling tower might have a considerable amount if located in a residential area. Effective solutions are reinjection, and geothermal heat and power cogeneration.

Some changes in the thermal manifestations can occur especially in reservoir exploitation, the hot springs and fumaroles intensity depend on the pressure drawdown of the reservoir and it is more evident when these thermal manifestations are directly connected to the reservoir. Some hydrothermal eruptions could also be correlated with the exploitation. Actually the “Craters of the Moon” in the Wairaki field New Zealand is the only evidence of hydrothermal eruption correlated with the exploitation.

### 8.3.8. Waste management (solids and fluids)

In deep geothermal drilling, the following types of waste occur:

Solide waste:

- Cuttings
- Cement slurry
- Mud
- General construction waste

Fluids:

- Runoff/storm water from drilling site

Waste management requires a disposal and monitoring concept that needs to be adapted during the different phases of the project. Indeed, the concept will depend on the well location and depth, but also on the drilling company and the type of product they are using. A general disposal concept needs to be generated, thinking about the possible ways of waste disposal. Fundamentals for this general disposal concept are:

- Type of waste (list and expected volumes)
- Possibilities of disposal (landfill)
- Possibilities of treatment (wastewater)
- Legal conditions for treatment and disposal

In definitive, each substance that might have a potential negative effect on the environment needs to be identified and its effects evaluated during the EIA. The main difficulty is that if the type of substance potentially used by a drilling company could be more or less estimated during the planning phase, the exact quantity of additive used is company recipes that are strictly secret. It leads to a difficulty in planning adequate waste treatment systems.

### 8.3.9. Land use

Land use for a deep geothermal project is relatively limited. For a geothermal project with a drilling of around 4,500 m depth, a surface of around 10,000 m<sup>2</sup> is required. The power plant is generally constructed in the direct vicinity of the borehole. Therefore, the same surface is generally used for the drilling phase and for the construction of the power plant.

Figure 8-3 and Figure 8-4 provides two satellite views of the preparation phase of the borehole site of the 4,500 m depth St. Gall project in Switzerland and of the operational Landau power plant in Germany, respectively.

The size of the parcel is equivalent to a small capacity conventional gas power plant. The parcel is then used during the whole life span of the project (around 50 years).



Figure 8-3: Landuse during the preparation of the drilling site of the St. Gall project in Switzerland (2012) - 4,500 m deep borehole (background: Google Earth)



Figure 8-4: Land use of the Landau power plant in Germany (3MWe installed capacity) (background: Google Earth)

## 8.4. Legal aspects related to the protection of environment

As already mentioned in Chapter 04, the protection of the environment in Lebanon is controlled by several laws and decrees. They are summarized below:

Law number 444 related to the “protection of the environment “ issued on July 29, 2002:

This law provides that parties of the private and public sectors initiating any project in the implementation of construction works or other types of facilities and “any intervention in the natural surroundings, including those that include the work of extraction of natural resources”, are bound to present either an Initial Environmental Examination or the Strategic Assessment of the Environmental Impact of projects that may threaten the environment, because of their size, nature or activities.



- The Ministry of Environment approves these studies after making sure that their content complies with the purpose of preserving the safety of the environment and sustainability of the natural resource.
- Shall be punished by either imprisonment of one month to one year, either a fine of 15 to 200 million Lebanese pounds or both of them:
  - Whosoever executed a project that requires an Initial Examination, or a Strategic Assessment of the Environmental Impact without presenting such studies for approval to the Ministry of Environment prior to the commencement of the project;
  - Whosoever executes a project contrary to the content of the studies submitted by him, and that won the approval of the Ministry of the Environment and other relevant ministries;

Section V of Law number 444 deals with measures taken to fight and prevent air pollution and disturbing smells. In addition to that, some other measures emphasize protecting underground resources (among which is the underground water) and preventing noise pollution.

The guiding principles of the Environmental Protection Law are summarized below:

- Precaution (cleaner production techniques)
- Prevention (best available technologies)
- Polluter-Pays-Principle (polluters pay for pollution prevention and control)
- Biodiversity conservation (in all economic activities)
- Prevention of natural resources degradation
- Public participation (free access to information and disclosure)
- Cooperation between central government, local authorities, and citizens
- Recognition of local mores and customs in rural areas
- Environmental monitoring (pollution sources and pollution abatement systems)
- Economic incentives to encourage compliance and pollution control
- EIA process to control and mitigate environmental degradation

#### Decree number 8157 related to the creation of a National Council for Environment (NCE):

The National Council for Environment (NCE) has many prerogatives. Some of them are enumerated herein below:

- Concerning the general policy, the NCE has to follow implementation of all treaties, protocols useful to the Environment General Policy and the country's "needs" (among which we can deduce the need for electricity at a lower price and using environmental friendly technologies);
- On a technical level, the NCE can give its propositions concerning any project involving the use of natural resources and having an impact on the environment;
- On a legislative level, the NCE can help moving forward to legislations that guarantee the sustainability of natural resources (to move forward and implement the draft of the renewable energies law)

#### Decree number 8213 related to the "Strategic Environmental Assessment"(SEA):

The SEA as defined by the decree is a planning tool that aims at fighting pollution and diminution of natural resources.

Therefore, for each project that concerns a certain sector or a Lebanese region, an estimating assessment will be made revealing the potential negative impacts of the project on the environment in order to reduce its consequences.

Based on the SEA estimations, the project will either be approved or rejected by the Ministry of Environment (MOE).

The required procedure by Decree number 8213 consists of the following steps:

- The project proposal must be presented to the Ministry of Environment
- MOE does the screening to see whether the project has or does not have a potential impact on environment (negative or positive)
- MOE decides whether the project needs to put a SEA or not



**Decree number 8471 related to the Environmental Compliance for Establishments:**

This law regulates all activities of classified establishments such as industrial ones that may cause harmful pollution and environmental degradation.

If a project is classified by the Ministry of Environment as falling within the categories indicated by the decree, it will need to comply with the environmental requirements indicated by the decree.

A certificate for environmental compliance will be delivered by the MOE if the project complies with the requirements granting therefore registration of establishments in the Special Register for Establishments.

**Decree number 8633 related to Environmental Impact Assessment (EIA):**

Environmental Impact Assessment (EIA) is regulated by Decree number 8633. This decree provides that all projects, coming either from the private or from the public sector, are subject to the EIA. The main purpose of the EIA is to prevent any negative impact or damage to the environment due to the establishment, operation or relinquishment of the project.

The EIA indicates the measures to be taken in order to reduce the negative impact of the project and to increase its positive effects on the environment and natural resources prior to delivering approval or refusal of the project.

Annex 1 of the Decree mentions the projects upon which the EIA is mandatory. Among these projects requiring by force of the law an EIA are those that aim at establishing power plants in order to generate or convert energy. A geothermal project for power generation or conversion may have a significant impact on the environment. Therefore, an EIA is required.

The EIA must be done by the project owner, and then submitted to the MOE for approval.

In case of denial, a procedure of reviewing the decision must be pursued before going to other relevant authorities in order to fulfill other requirements.

## 8.5. Discussion

In comparison to other technologies, geothermal power presents the following advantages related to the environment:

- Low CO<sub>2</sub> and other gas emissions. A 40MW power plant nowadays saves up to 28,000 CO<sub>2</sub> tons per year. Carbon footprint is better than photovoltaic.
- Limited impact on the landscape, land use and limited noise during the operation phase. A geothermal power plant could easily be implemented close to residential areas.

A geothermal power plant is considered as a construction site with the aim of generating power. In terms of environmental impact it is thus subjected to the same regulations as any construction. The legal aspects could be summarized as follows:

- Facilities or whatever types of construction, vehicles used in the geothermal project shall be subject to a self-control procedure so that it could measure the pollution that it is causing and the impact of its activities on the environment. This point will more specifically concern:
  - The Exploration Campaign
  - The Drilling Site
  - The construction of the geothermal power plant
- The geothermal project must commit itself to not cause emission of air pollutants, including disturbing or harmful smells beyond the allowable limits/standards as defined by national standards of quality of the environment (fixed by a decree of the Minister of the Environment). Again, this point must be treated independently for the drilling site and for the construction and operation phase.
- The project must not cause any pollution to the underground water during the drilling operations and during the period of extracting heat from the water. Extracting heat from the water phase constitutes the basis concept of any geothermal project. MEW should therefore concede special authorization for geothermal projects.

- The project must commit itself not to cause noise pollution that is beyond what is acceptable or allowable with regards to the national standards of quality of the environment as defined upon a decree issued by the Minister of Environment. The EIA should propose mitigation procedures to guarantee the noise pollution remain below the acceptable level all through the project.
- The creation of the NCE will definitely put Lebanon on the path of fulfilling its international obligations in reducing greenhouse gases by supporting, at the same time, the switch to renewable energies, mainly through encouraging the adoption of more cutting-edge legislations.
- The information provided in Table 8-5 and in Figure 8-5 to Figure 8-8 will serve as a basis for evaluating potential project sites in the framework of the EIA that will have to be prepared for the Project. As mentioned earlier, areas of special value or interest (like National Parks, Cultural Heritage sites, areas of special scenic interest, etc.) should not be affected by such projects.”
- Concerning the legal basis for impact assessment, it should also be noted that depending on the mode of financing of the project, international standards and guidelines might also have to be taken into consideration (e.g. World Bank safeguards, EBRD guidelines, Equator Principles, depending on the financing institution). All these institutions also place emphasis on social impact assessments, mainly on resettlement and/or compensation in the case of a directly affected population.

Table 8-5: Zones of remarkable interest in terms of nature protection, landscape, urban planning and patrimony (modified after (DAR-IAURIF, 2005))

Protected natural reserves (Mahmiyyat) (Laws voted by the Parliament between 1992 and 1999)	Machaa' HÖrsch Ehden Palm Island – Ramkine – Sanai Chouf Cedars Coast of Tyr Tannourine Cedars Bentaël Yammouneh	In general, these sites are located on M'shaa lands, public domain or State owned lands, and protection consists of forbidding construction, quarries, cutting of trees and grazing.
Protection of natural landscape (Decree no 343 dated March 28, 1942 (amended by Decree no 836 of 09/01/50), based on the Law of July 8, 1939)	Becharre Cedars Deir el Qalaa Bois de Boulogne Sindiane el-Mrouj Horsh Beirut Yammouneh lake Natural Bridge of Nabaa el-Laban Antique Ruins of Baalbeck	Protection consists of a zoning regulation on construction rights as well as prospects regulations.
Natural sceneries and sites (law on natural sceneries and sites of 1939, Decree 9501 dated November 7, 1996 and Article 12 of Law 667 dated December 29, 1997)		
River Beds	Nahr Ibrahim Nahr Jaouz Nahr el-Kalb and its tributaries Sannine-Salib-Msann Nahr ed-Damour and all its tributaries starting from Nabaa es-Safa Nahr Beirut and its tributaries in both valleys Nahr Awali – including Barouk and Bisri Nahr Aarqa and its tributaries Nahr el-Aassi	River protection consists in general of a 1,000 m wide zone following the centerline of the river, within which all activities are subject to MoE authorization. This zone extends to 3,000 m for the authorization of quarries.
Forests	Aïn el Haour Darayya Debbiyeh Bourjeïn Sheikh Osman Deir Moukhalles Aïn ou Zayn Dalhoun Wadi al-Mal Kafra Wadi Aghmid Wadi Aïn Baal	The perimeter of protection of forests forbids construction, quarries, cutting of trees and grazing.
Highland Sites	Jabal Makmel with its peak Qornet es-Saouda	-
Remarkable natural sites	Karm Shbat Valley of Qadisha Qammouaa plateau Valley of Qaraqir Baatara gorge	-

Forested zones (Decisions from the Ministry of Agriculture prior to 1996 law)	Protected natural zones on public lands M'shaas of Maasser esh, Chouf, Barouk, Ain Zhalta and Ain Dara (1991)	Protection of these zones is limited to forbidding cutting of trees and camping, and includes programs for reforestation, preservation and management of these zones.
Protected marine area (1991)	Batroun	
Protected zone (1992)	Kherbet Silm Zaïdani Wadi el-Hajair (caza of Bent Jbayl) Kfar Zabad (caza of Zahle)	
Coniferous woods and forest on the M'shaa and public properties (Decisions from the Ministry of Agriculture prior to 1996 law based on Law 558, dated July 24, 1996)	Bezbinda (Akkar) Qammouaa (Akkar) - Soueyssa (Hermel) Cedars (Besharre) Tannourine Hadath el Jebbe Jaje Karm Shbat (Akkar) Qnat Merbyn Wadi Jhannam Qariet es- Safina (Akkar) Jurd en-Njas Jabal el-Arb'ine Danniyeh Ain Qlailat Karm el- Mahr Qornet el-Kaïf Mashaa Shalout Danniyeh (North) Bkassine-Jezzine (Jezzine)	
Urban planning (decrees are proposed by the Directorate General of Urban Planning (GDUP) after notification by the Higher Council for Urban Planning (HCUP))	i.e. Nahr Damour valley	These decrees are proposed by the Directorate General of Urban Planning (GDUP) after notification by the Higher Council for Urban Planning (HCUP). Protection consists of severe regulations on construction, in the frame of a land use master plan or a specific urban planning document. Most of these general plans, especially those decreed recently, stipulate zones with limited constructability.
World Heritage record of UNESCO	Valley of Qadisha Cedars of Besharre	This registration does add to the protection provided by the local legislation. It has a moral commitment and motivates creation of plans for protecting and benefiting from these zones.

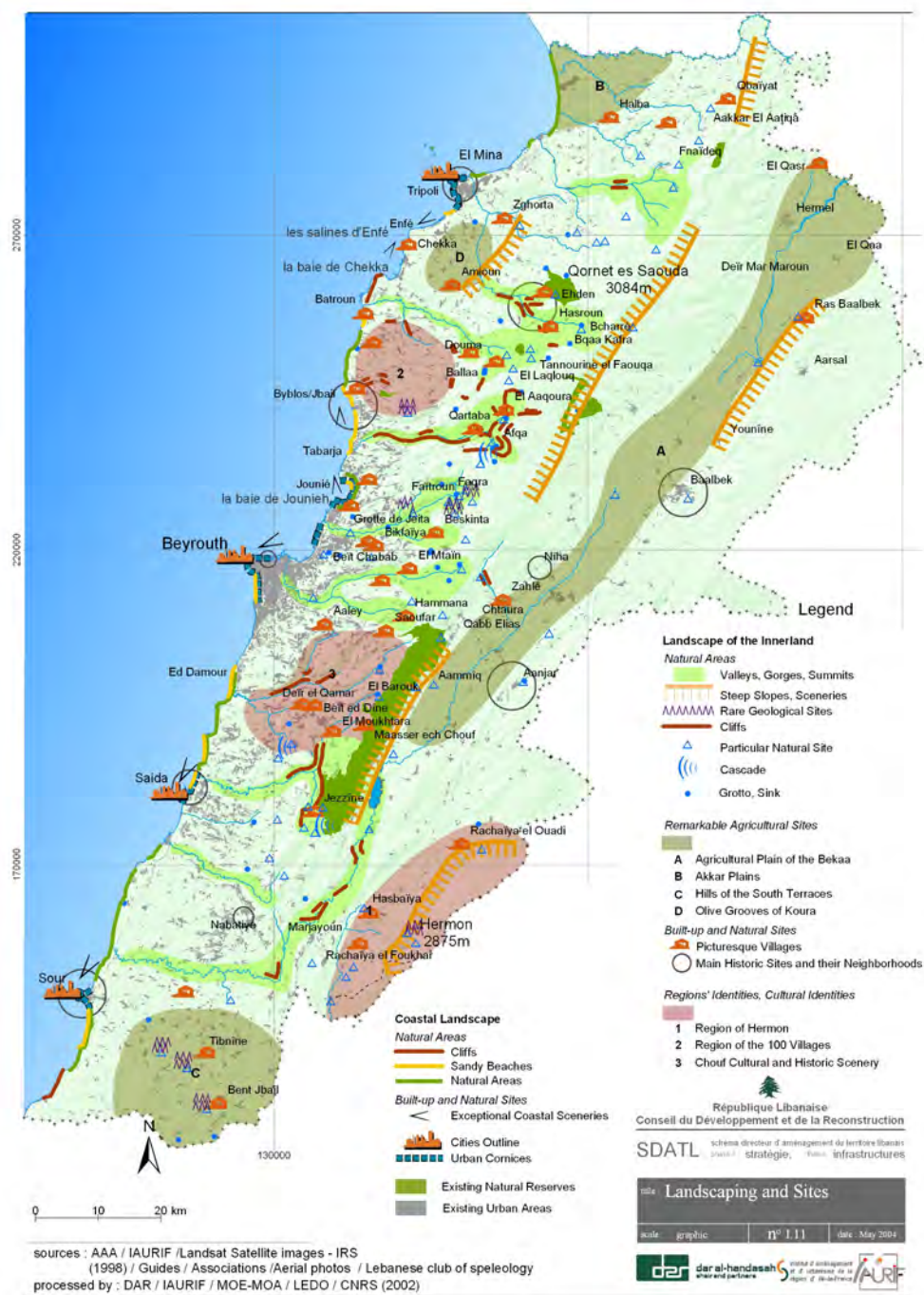


Figure 8-5: Landscaping and Sites (DAR-IAURIF, 2005)



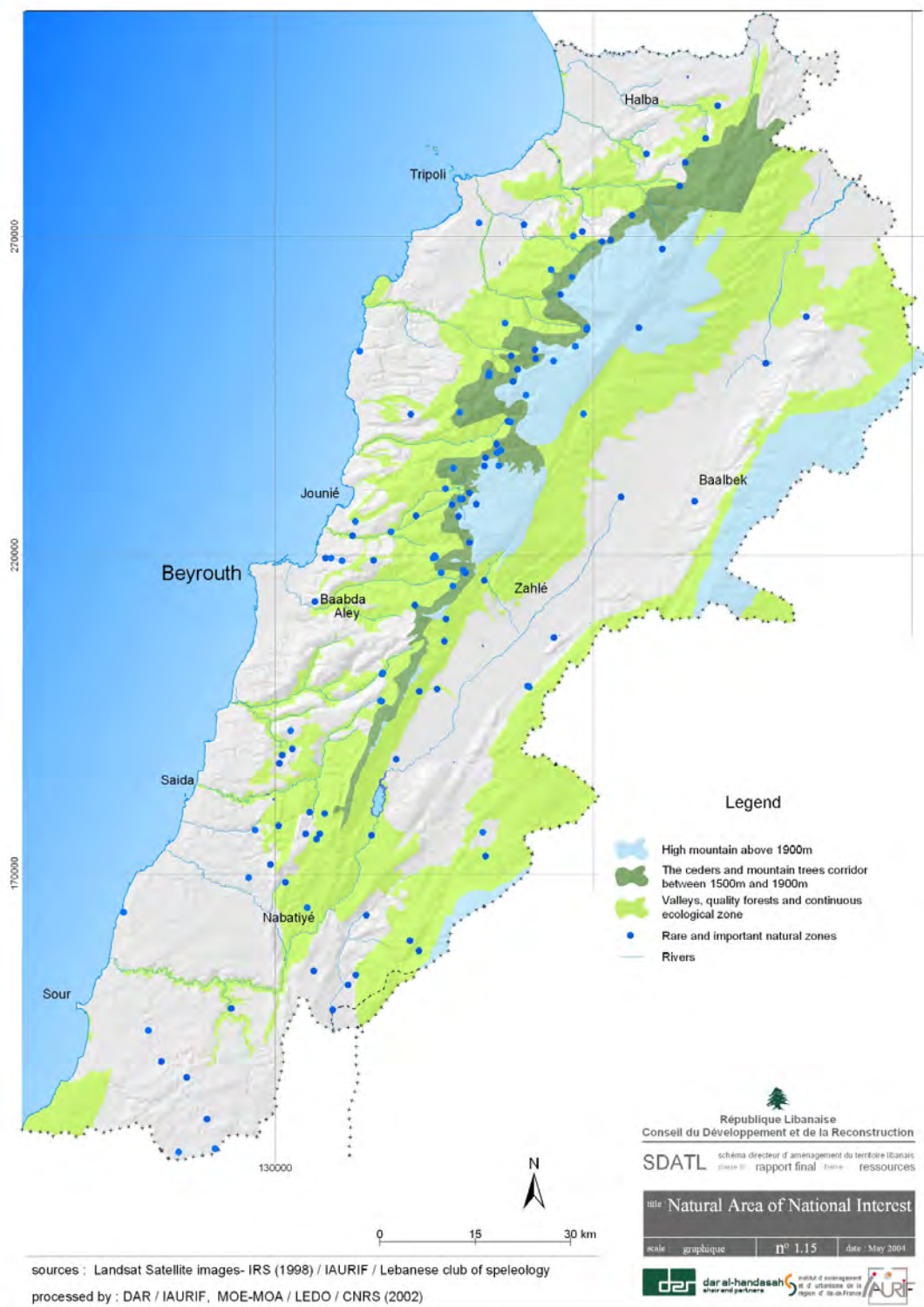


Figure 8-6: Natural domain of national interest (DAR-IAURIF, 2005)

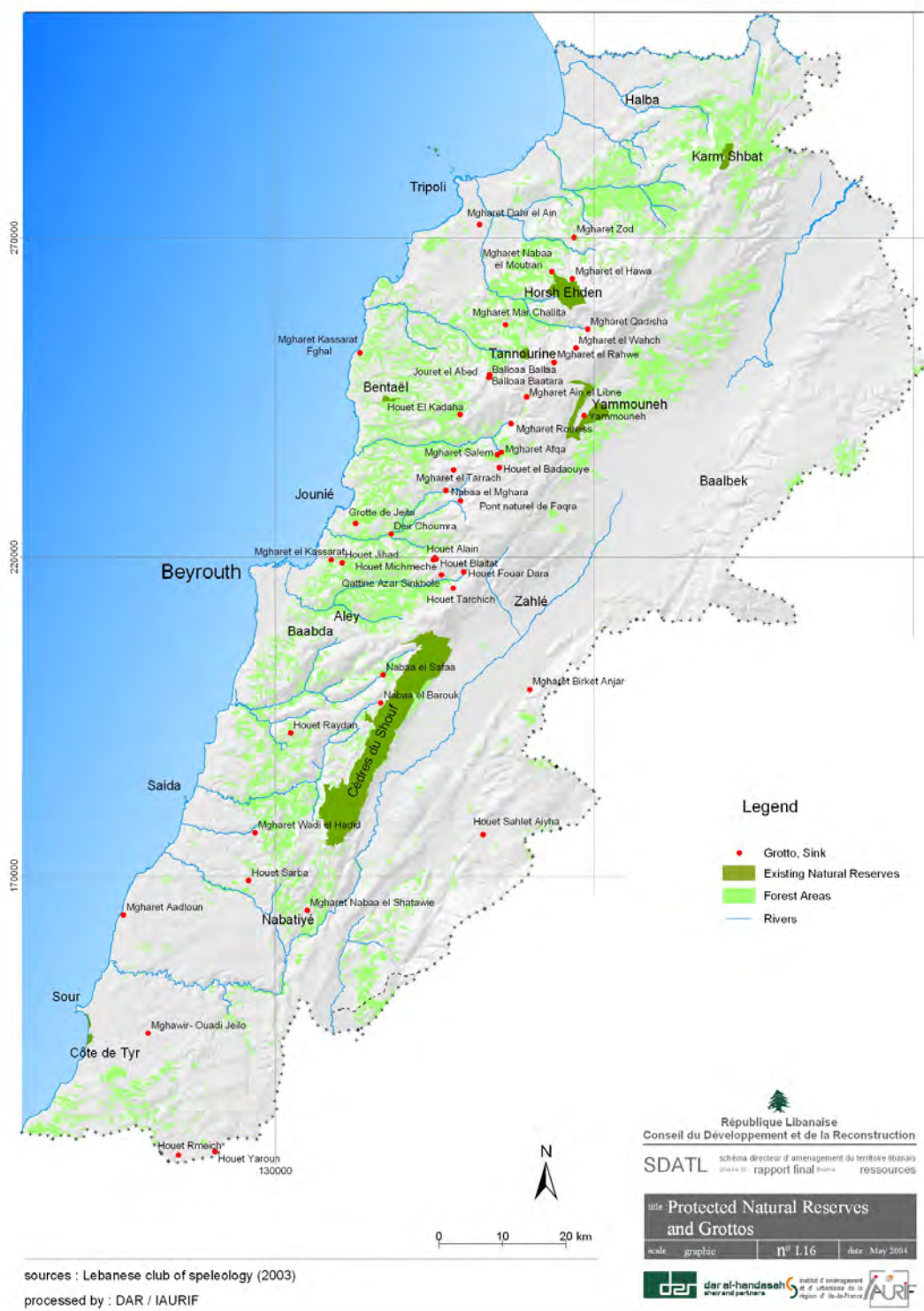


Figure 8-7: Protected natural reserves and grottos (DAR-IAURIF, 2005)

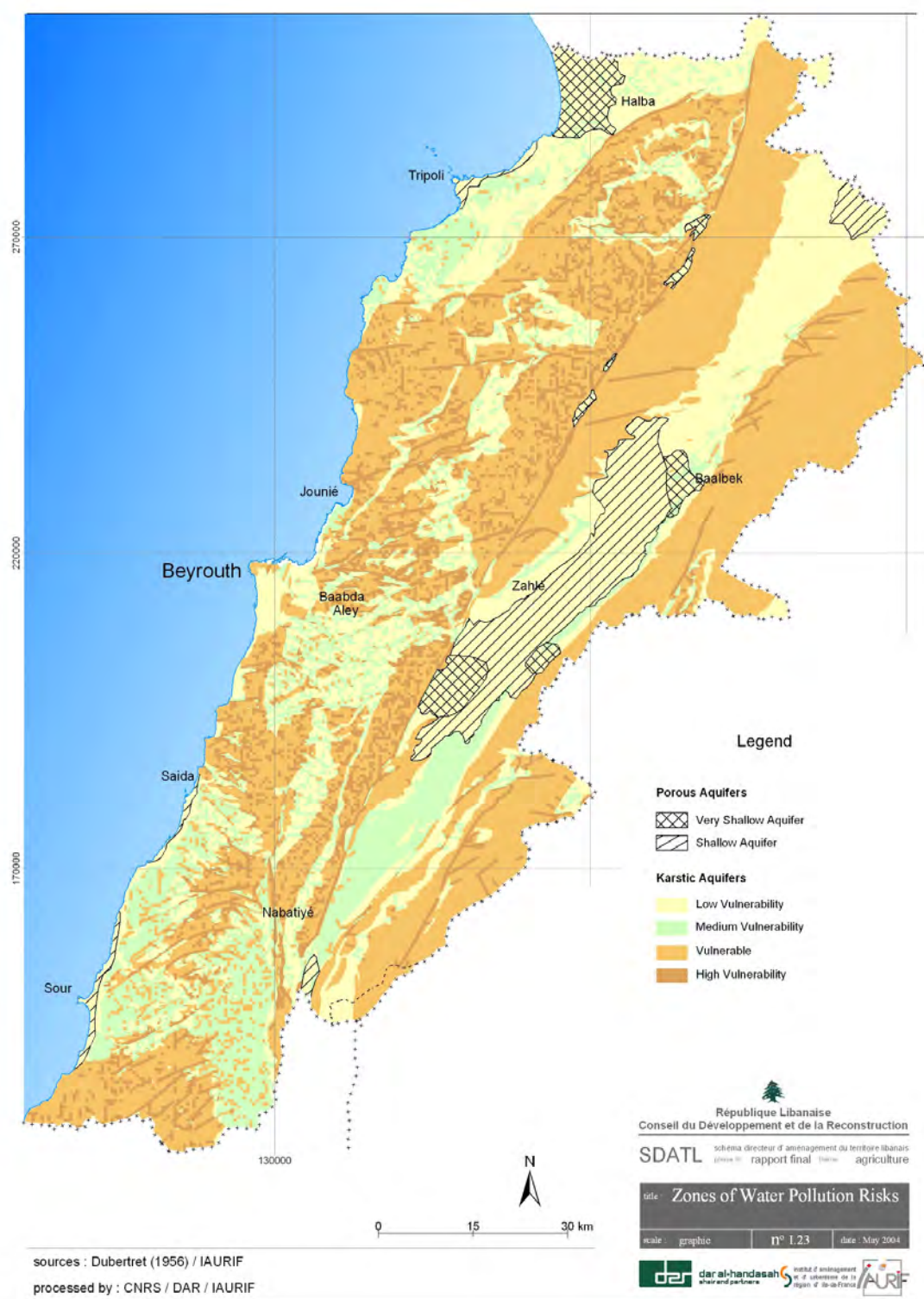


Figure 8-8: Zones of water pollution risks (DAR-IAURIF, 2005)



# 09. Conclusions and recommendations

## 9.1. Opportunities

An assessment of geothermal resources in Lebanon has been carried out in the framework of this study and the results expressed in terms of geothermal potential (heat in place, recoverable heat). The work undertaken in this study can be used for several purposes and sectors, as indicated in Appendix 34. The economic feasibility for several scenarios of power plants has been evaluated and presented as well.

The potential of existing geothermal resources in Lebanon is based on research and data gathered from a range of publically available authoritative references. These data have been complemented by field and laboratory measurements performed in the framework of this study. Our conclusions and all the results presented in this report are based on the current understanding of the Lebanese geothermal resources, but if this understanding develops in the future from further research and investigation programs, then the conclusions of this report would need to be revised.

Nowadays, no volcanic activity is present in Lebanon. Despite the evidence of thermal activity in the Akkar region (Summaqiye well and Ain-Esamak spring) as well as in the South (Kaoukaba and Tyr area), it is likely that temperatures suitable for high-enthalpy installations ( $T > 200\text{ }^{\circ}\text{C}$ ) are found only at depths deeper than 3,000 m. Only low to medium enthalpy installations can be developed in Lebanon with reasonable costs in the near future.

Temperatures of  $42\text{ }^{\circ}\text{C}$  have been measured in the 70's in the Cretaceous aquifer in the Summaqiye well of the Akkar region at a depth of 470 m. Given the characteristics of the flow system in that area, higher temperatures are not expected to be found in this shallow aquifer (karstification and cooling effect by fast water velocities). However, this temperature gives evidence for the presence of a thermal anomaly in this area. It could be assumed that this anomaly is related to the residual heat of an old magmatic chamber. However, the estimation made in this study indicates that the underlying Jurassic aquifer of the Kesrouane Formation could have temperatures of around  $130\text{ }^{\circ}\text{C}$  in the Akkar region, at a depth of 1,500 m. This prediction makes the Jurassic aquifer in the Akkar region the most promising area in Lebanon for the development of a low enthalpy geothermal installation in Lebanon, based on hydrothermal technology.

Evidences of thermal water have also been reported in the Kaoukaba well and in the area of Tyr in South Lebanon (Kfar Syr well). In Kaoukaba, the aquifers are in contact with Miocene to Pliocene basalt units. No confirmation of such thermal anomaly could have been found in the framework of this study. This thermal water could be related to the presence of a thermal anomaly resulting from the residual heat coming from a magmatic chamber located south from Lebanon and responsible for the recent volcanic activity in Golan Plateau. Simulations performed in the framework of this study have shown that the center of the magma chamber is probably too far away in the South to have a major influence on the temperature in the deep underground of Lebanon. The presence of regional faults could explain the thermal anomalies in Tyr and in Kaoukaba as well. In this case, the fault zone allows deep hot thermal fluids circulating towards the surface and creates a thermal anomaly. A damping of the thermal anomaly is expected by mixing with cold surface water. Further investigations are required to ascertain the presence of a thermal anomaly in these areas.

In the rest of Lebanon, the Jurassic aquifer is unfortunately not deep enough to expect water temperatures higher than  $100^{\circ}\text{C}$ . Apart from the Akkar district, the highest temperatures are found in the Bekaa valley at a depth of around 3,500 m below ground level. The simulation gives temperatures comprised between  $80$  and  $90\text{ }^{\circ}\text{C}$ . Given the uncertainty of the parameters used for this estimation (mainly the heat flux), it could not be excluded that temperature higher than  $100^{\circ}\text{C}$  can be found in the Jurassic aquifer in this area. The confidence level is, however, relatively low.

EGS technologies could, in principle, be implemented everywhere in the world and therefore in Lebanon as well. Considering the current development state of EGS technologies and the related technological risk (i.e. induced seismicity), EGS technologies are not considered to be mature enough to assist the Lebanese government to reach 12% of the total energy needs from renewable energy by 2020. This technology is still to be developed in areas with low risk of seismicity, such as England, Australia and USA. Considering the slow progress in R&D presently, we expect that this technology will not be available before 2025 at the soonest. Massive financial investments worldwide would accelerate the development of this technology significantly. Only hydrothermal technology is therefore considered to be technologically and financially feasible in assisting the Lebanese government in reaching its objectives.

## 9.2. Barriers for geothermal development

Barriers for the development of geothermal technologies in Lebanon could be grouped in three main categories:

- Physical barriers related to the geographical, geological and thermal conditions found in Lebanon
- Technological barriers related to the kind of technology used for geothermal power generation
- Legal barriers related to the legal framework of the Lebanese legislation and general acceptance of the public community,
- Economic, insurances and social barriers

### 9.2.1. Physical barriers

The physical barriers are related to the geographical, geological and thermal conditions found in Lebanon.

Three key parameters need to be determined in order to assess the geothermal potential of a given area and to study the economic feasibility of a geothermal installation:

Lack of  
information at  
depth

- The depth of the geothermal reservoir
- The temperature within the reservoir
- The permeability and thickness of the reservoir

Most of the geological and hydrogeological investigations that have been carried out in Lebanon during the last decades were dedicated to finding water resources to be exploited for irrigation or domestic usage. Because of the presence of a shallow aquifer of excellent productivity, there have been no needs to explore other aquifers located at greater depths. Therefore, the knowledge of deep aquifers and the related deep structures are very limited in Lebanon.

Moreover O&G exploration campaigns that occurred in Lebanon during the 70's did not discover economic reserves of gas and oil. Exploration was stopped rapidly. Only seven deep oil and gas exploration boreholes were drilled. Moreover, no seismic profiles have been performed at that time.

The quantity of geological and structural information available for greater depth is very sparse, and this is true especially considering the size of the Lebanese territory and the complexity of the geology.

The second important parameter is the temperature of the reservoir. This parameter is calculated by means of a 3D numerical model that allows providing the best estimate of the temperature at depth. However, the model needs to be calibrated on suitable temperature data. Very few suitable temperature data is available in the literature, and the quality is questionable. Several attempts for new temperature data acquisition have been performed in the framework of this study. The first strategy was to measure temperature gradient in shallow inactive groundwater wells. These measurements have shown that the whole massive is cold, due to the circulation of cold water in the rock massive. The second attempt aims at measuring temperature gradients in the deep O&G exploration boreholes. Inspection visits lead to the conclusion that these boreholes are plugged and cemented. The boreholes were not able to be reopen in the framework of this study

The third parameter is the transmissivity of the reservoir. No transmissivity value for the deep reservoirs has been found in the framework of this study. Cost estimation and economic feasibility evaluation are therefore based on optimistic and pessimistic scenarios.

In conclusion, the first and main physical barrier for the development of geothermal technology in Lebanon is related to lack of knowledge about the deep underground structures and the temperature in Lebanon. This barrier could be removed by proceeding to a comprehensive geophysical exploration program (see recommendations below). Ideally this geophysical exploration program should be designed primarily for geothermal energy. An O&G exploration program should provide very valuable information as well.



Karst is found almost everywhere in Lebanon. Karstic units are excellent aquifers which are used for domestic and irrigation groundwater use. Karst provides pros and cons regarding the use for geothermal energy, and therefore could be considered as a barrier as well. If the Jurassic aquifer in the Akkar district is karstified, then the expected productivity for power generation could be extremely high. However if the Kesrouane Formation is not karstified or if the karst network is plugged, then the productivity is more likely to be too low to make a project economically viable. Unfortunately, no indirect geophysical method could be applied to evaluate the transmissivity of the Jurassic aquifer at 1500 meter depth. The most suitable method would consist in drilling one exploration borehole to confirm the reservoir productivity (temperature, transmissivity). Another drawback of karst is the cooling effect due to the circulation of cold water in the rock massif. This circulation has for effect to lower the temperature gradient in the top surface and to mask any thermal anomalies that could occur at greater depths.

Intensive  
degree of  
karstification

Information collected about the heat flow and geothermal gradient shows very low values in comparison to the world average heat flow density of 75 mW/m<sup>2</sup> and geothermal gradient of 3 K/100 m. In Lebanon, the normal heat flow is around 30-40 mW/m<sup>2</sup>, leading to a geothermal gradient of around 1.5-2.0 K/100 m. With this gradient the temperatures at depth are too low to allow using geothermal technologies in an economic way. These values are, however, very questionable and are in contradiction with the presence of thermal water in the Akkar district in North Lebanon. Therefore we cannot exclude at present stage that better geothermal conditions could be found in Lebanon. Akkar district remains an exception, as the conditions appear to be optimal. Specific exploration methods could be applied to assess the geothermal gradient in Lebanon.

Apparent low  
heat flow  
intensity and  
low geothermal  
gradient

The next physical barrier is related to the risk of induced seismicity. Experience from current and past geothermal projects worldwide has shown that the exploitation of a geothermal reservoir is often related to induced seismicity, especially by the use of EGS technology, but also in the hydrothermal systems. Because Lebanon is located on an active tectonic area, the risk of inducing earthquakes during the geothermal reservoir development or during the operation should be considered with extreme care. A comprehensive risk assessment study should therefore be performed at the stage of a feasibility study, and specific safety measures should be implemented for each future geothermal project.

Risk of induced  
seismicity

Finally, Lebanon is extremely rich in terms of historical sites, landscapes, patrimony and natural reserves. Because the land use and the visual impact of a thermal power plant are quite limited, these aspects should not constitute an important barrier for the development of geothermal technologies. Notwithstanding, these aspects could be very restrictive during the site screening phase, and this is especially true if the project is located in the vicinity of one of the national natural reserves in the country. These aspects should be covered by an environmental impact assessment study, during the feasibility study phase.

Protection of  
sites, landscape  
and patrimony

## 9.2.2. Technological barriers

Technological barriers are related to the technology used for power generation.

Drilling costs could be prohibitive for geothermal reservoirs located at great depth. Development in the drilling technologies could strongly reduce the cost making the exploitation of the geothermal reservoirs in Lebanon much more interesting from an economic perspective.

Drilling  
technologies

Energy conversion at a temperature close to 100 °C is unfortunately not very efficient. Further development of these technologies could strongly increase the quantity of energy produced by a geothermal power plant.

Conversion  
technologies

EGS is seen to be the ultimate solution in the future as it could be implemented everywhere and that it is not dependent of local geological conditions. Despite the intensive effort in developing EGS technologies, these technologies are not yet mature. The main drawback is the risk of induced seismicity. The development of these technologies in a region with high seismicity should be handled with extreme care.

EGS technology  
not mature yet

### 9.2.3. Legal barriers

The main legal barrier to enhanced geothermal development in Lebanon is a lack of appropriate legislation in light of the lack of clarity in the energy, water, electricity and environmental legislation. The first step would be to define these aspects in the relevant laws and decrees, starting with the definition of “renewable energy”, “geothermal energy” and/or “geothermal resources”.

Lack of appropriate legislation

Lebanon’s first step in seeking to remove those barriers, started by the adoption of the ministry of energy and water of the “Policy Paper for the Electricity Sector” on July 21, 2010. As a result of the strategic initiative 6, the MEW proposed on December 21, 2010 the National Energy Efficiency Action Plan (NEEAP) which was approved by the Council of Ministers on the November 10, 2011. In this plan, Lebanon committed to reach 12% of renewable energy by 2020 and to adopt a new energy conservation law.

At present this lack of legislation is considered as a barrier but it can be easily removed and transformed into an incentive when adopted and voted by the parliament.

A new project law for “Energy Conservation” is yet to be discussed by the parliament energy committee and further adopted by the parliament.

Adoption of the law for Energy Conservation

The following issues are at the core of this project law:

- Definition of renewable energy which includes the geothermal energy,
- Use and development of renewable energy,
- Creation and regulation of the Lebanese Center for Energy Conservation (LCEC),
- Energy audits,
- Energy efficiency standards and labels,
- Financial and Tax incentives including the exemption from Value Added Tax (VAT) and the import tax for imports and the supply of goods and equipment related to renewable energy projects, and
- Net-metering.

According to the NEEAP, the timeline set for the adoption of the energy conservation law was scheduled to be by end of 2011, and the issuance of the implementation decrees were expected to be issued by June 2012.

Obviously, the timeline set was not met and this delay might be perceived as a risk factor for developers in this sector as they seek more robust legislative infrastructure for geothermal power in Lebanon that would encourage and secure their investment.

The construction and operation of a geothermal power plant requires various administrative permits and various legislations have to be obeyed in the permitting process, including environmental protection, water, health and safety laws.

Simplification of administrative process and licensing

A non-exhaustive list of the required permits that are considered as barriers is provided in Table 9-1.

Table 9-1: List of required permits for the construction of a geothermal power plant

Permit for exploitation of the underground resources	<p>The permit must be granted by the Ministry of Energy and Water in case Hydrocarbon and other extractables are targeted.</p> <p>The permit must be granted by the Ministry of Environment in case of extraction of building materials such as cement, rocks, etc.</p> <p>Mining law number /8803/ dated October 4, 2002 allows the license for exploitation for a 5-year period with possible extension to 10 years.</p>
Permit for construction of the geothermal plant	<p>There is no special reference to geothermal plants in the existing laws. In general, according to the building code, the urban department should issue the permit and the municipality or the Kaemmakam of the concerned constructions are outside the municipal scale.</p>
Application for Environmental Impact Assessment	<p>According to annex 1 of the law decree number /8633/ related to the Electricity Regulatory Authority (ESA), the installation of power generation plants and energy conversion plants requires a scoping report.</p>
Permit for investment in industrial enterprises	<p>Law decree /4917/ dated March 24, 1994 considered the activity of production of electricity, steam or hot water as production plants listed as category number 1.</p> <p>According to law decree number /8018/ dated June 12, 2002, Category number 1 is the category that results in a serious risk to the environment and the surrounding areas and public health, which requires installing it far from houses to prevent all resulting damages.</p>

In addition to the various legislations, special approvals are therefore necessary for any project such as land owner approval and the public community which might delay the process of development of a geothermal plant.

In case of locating geothermal resources in private lands, the approval of land owners must be obtained whether by signing a lease agreement or buying the property from the owner and a third option would be to get an expropriation decree by the Lebanese authorities.

Approval by land owners

In case a geothermal plant is built within a populated area or an industrialized area, the opinion of the local authorities and the population affects the continuity of the project. The effects of a geothermal plant on the noise and emissions resulting from the construction and operation phase will affect the opinion of the locals. Therefore, increasing the acceptance of geothermal energy will require education and awareness campaigns at all levels and should be regarded as an opportunity to local employment. Also, other series of permits might be required from the other ministries or the local authorities for road and pipeline construction, air emissions and water and sewage disposal.

General acceptance by the public community

Permit from the Ministry of Culture might be needed in case the geothermal plant is located close to an archeological site.

Protection of sites

In conclusion, the main barriers are related to the permitting processes which is complicated and extends over a long time span in the actual legislation since the needed permits involve several different authorities. We recommend that the legal frameworks and regulations, concerning the ownership and exploitation and development of geothermal energy, be clarified and permit procedures harmonized and streamlined in a coherent way. The most effective way is to create one authority to coordinate most of the permitting process. The Lebanese government did a good step in this regard by creating an authority by law number 462 but unfortunately the implementation decrees have not been issued yet and the Electricity Regulatory Authority (ERA) has not yet been formed.

Harmonization  
of the  
procedures

#### Creation of the Electricity Regulatory Authority as per Law number 462 dated the September 2, 2002

Although law number 462 relative to the organization of the regulation of the electricity sector was duly published in the official gazette and is in force, however the implementation decrees weren't issued yet and we refer specifically to the ERA which is created by this law but still needs to be constituted by the council of ministers.

According to article 7, ERA is an autonomous administrative entity that enjoys financial and administrative autonomy. In a nutshell, its role is to regulate and monitor the electricity sector and to manage the day-to-day operations of Electricity Activities in Lebanon.

The constitution of ERA is a major challenge for it leads to the improvement of the renewable energy sector in Lebanon as it will be the regulating body of the electricity sector and it will be able to issue permits and licenses for a duration of 50 years as per the following: article 5

- Through public tender: for power plants whose production capacity is 25 MW and more, and for distribution in areas where the electricity consumers exceed 50,000.
- Through a call for bids: for power plants whose production capacity is below 25 MW, and for distribution in areas where the electricity consumers do not exceed 50,000.<sup>2</sup>

The installations of a power plant for private use where production capacity is below 1.5 MW is not subject to a license. However, it shall observe at all times the environmental, public health and safety requirements. Those requirements are defined by the Electricity Regulatory Authority (ERA) after consultation with the Ministry of Environment and the relevant institutions.

### 9.2.4. Economic, insurances and social barriers

Geothermal exploration and development is an acknowledged high-risk investment, especially in areas where geothermal resources are not found at the surface, such as in Lebanon or in Switzerland. The risk in geothermal development is mainly related to the uncertainty associated with the discovery of natural resources, especially the temperature and the permeability of the reservoir. These parameters cannot be characterized without relatively large expenditures for drilling (see drop of the risk curve of Figure 9-1).

Uncertainty of the  
resource

Another risk is related to the long time period required for developing a geothermal project, starting from the feasibility study to the construction of the power plant. We expect 1 pilot installation of 1-2 MW<sub>el</sub> to be realized in Lebanon in a time period of 3-5 years, depending on the political willingness. Five to 10 additional similar installations could then be realized in a timeframe of 5-10 years.

Long time period for  
project development

Although the barriers represented in the lack of proper legal framework for geothermal development do exist, but other barriers can be much more significant such as the high cost of the drilling activities and the financial resources needed. The state's willingness to support renewable energy development was observed by the BDL issuance of the relevant circulars to support private investors and individual initiatives. As an implementation to the BDL Circulars, Lebanese private banks have tailored green loans in collaboration with BDL and UNDP to attract developers and investors in the renewable energy sector. However, a statistical study must be undertaken to check the efficiency of these loans on the sector. Also, it should be noted that although these loans are granted with favorable interest rates, the risks for investors might still be high especially in case the geothermal plant was not economically resourceful. Lebanese regulations do not include the possibility in that case of transfer of the loans into grants to encourage investments in the sector.

Loan with favorable interest rates

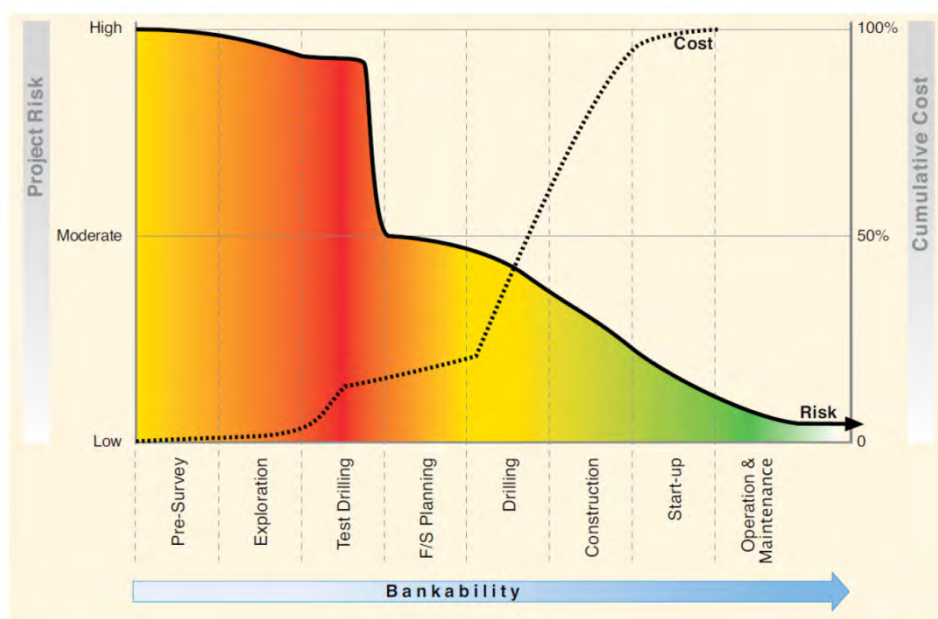


Figure 9-1: Typical risk profile for a geothermal project vs. time and project phases (ESMAP World Bank, 2012). The risk profile is greatest during the preliminary surveying and exploration phases, but in that part of the project expenditures are relatively low. Moving forward to the test drilling phase requires an accelerated level of expenditures while there is still a high level of risk and uncertainty. This step in expenditure is frequently the stumbling block or hurdle to the project processing further (IGA, 2013)

### 9.3. Overall potential of Lebanon

The overall potential of Lebanon is calculated to estimate the ability of this technology in assisting the Lebanese government in reaching its objective to cover 12% of the total energy needs by means of renewable energy.

If the quantity of heat present in the deep underground of Lebanon is incommensurable, the quantity that could be recovered and used by means of the available technologies is very small. This quantity strongly depends on the political willingness.

The quantity of geothermal energy that could be produced considering a realistic scenario and given a certain timeframe is therefore even more limited.

The total energy needs in Lebanon was around 8,630 GWh in 2000. Forecasts for 2015 estimate the energy demand to be around 14,087 GWh (Chedid et al., 2005).

The total energy stored in the underground in Lebanon at a temperature over 100°C and at a depth less than 7,000 m below ground level is in theory of  $1.0 \cdot 10^9$  GWh, the equivalent of around 70,000 times the yearly energy demand in Lebanon.

Only part of this heat could be technically extracted by means of the current state of the art techniques. The recoverable heat corresponds to 10% of the stored heat, meaning  $1.0 \cdot 10^8$  GWh or 7,000 times the yearly energy demand in Lebanon.

Due to the risks related to EGS technologies, only hydrothermal techniques are considered to be suitable for Lebanon. The part of the heat which could be theoretically used for geothermal production by means of hydrothermal technologies is around  $1.2 \cdot 10^5$  GWh<sub>th</sub>. By exploiting 100% of this resource, the amount of generated power is around 12,000 GWh<sub>el</sub>, which is approximately equal to the energy demand of Lebanon by 2015. Of course, to exploit the whole amount of this energy,



around 2,000 power plants of 1.3 MW<sub>el</sub> gross capacity, would have to be constructed within the same timeframe.

An optimistic but realistic scenario could consider the implementation of maximum of one pilot installation of 1.3 MW<sub>el</sub> gross capacity, for instance in the Akkar region, by 2020. In case of success and positives results, four additional power plants would be constructed by 2025. In the most optimistic case, the capacity of the power plant could be 3-5 times higher, if the productivity of the reservoir is higher than expected.

The total electricity production by 2020 by means of geothermal energy would be around 6 GWh<sub>el</sub>. By 2025, the total production would be 30 GWh<sub>el</sub> which would be around 0.2% of the total energy demand at that time (Figure 9-2).

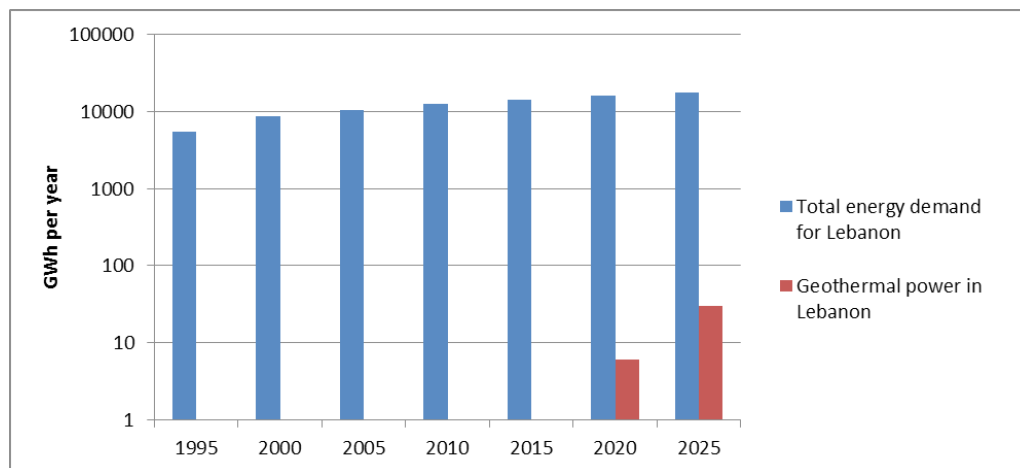


Figure 9-2: Comparison between the energy demand and the energy that could be produced by means of geothermal technologies by 2025, based on the current state-of-the-art technologies and knowledge of the deep underground in Lebanon

## 9.4. Recommendations

Given the opportunities and barriers listed in the previous sections, our recommendations are the following:

- The main barrier is related the lack of geological and structural information at great depths. This lack of information leads to a relative high uncertainty of the estimations of the geothermal potential in Lebanon. The results of this study showed that the potential of geothermal energy for power generation is quite low. Hypothesis for this estimation are considered quite conservative. If good permeability values are found in the Jurassic aquifer in the Akkar region for instance, the overall potential for power generation in Lebanon by means of geothermal energy could be increased by a factor 3 to 5. To better ascertain the resources estimates we would therefore recommend in proceeding in further exploration uppermost in the Akkar region in the North and in a second priority in the South, either in Tyr or in the area of Kaoukaba. Although one could benefit from O&G exploration, this program should be specifically dedicated to geothermal exploration.
- The aim of the exploration program would be to assess the hydrothermal properties of the aquifers and to measure the geothermal gradient in the North and in the South, in order to reduce the project risk (non-discovery) while increasing the chance of bankability (see the typical risk profile of Figure 9-1). The target would be more specifically a fault zone within this aquifer, to increase the chance of getting high values of permeability.
- In both regions, a three phase exploration program could be realized as follows (The time required is estimated to be around three years):
  - The first phase (year 1) would consist in drilling geothermal gradient boreholes around the 2-3 identified prospects to better estimate the local geothermal gradient and to calibrate the 3D thermal model. Based on this evaluation, one or two prospects would be selected for an exploration borehole.
  - Geothermal gradient boreholes would be recommended to be drilled in the Bekaa valley to measure a geothermal gradient in order reduce the uncertainty of the temperature predictions in the Jurassic aquifer in the Bekaa valley. Reopening the existing O&G boreholes could be an option as well.
  - The second phase (year 2) would consist in performing a 2D seismic campaign to assess the depth of the aquifers and to locate potential faults zones. If available, the seismic profiles acquired in 2012 onshore of Lebanon would need to be evaluated as well.
  - The third phase (year 3) would consist in drilling of an exploration borehole in the target reservoir (for instance the Jurassic aquifer at a 1500 meter depth in the Akkar region). The exploration borehole is in our point of view, the only available exploration techniques to ascertain the geothermal potential.

- The third phase includes a testing and logging program that needs to be performed in the exploration boreholes to test the productivity of the reservoir and to assess the temperature.
- Cost estimates for the above mentioned exploration program would be around 5 Million US\$, inclusive of one exploration borehole, planning costs and incidentals. Details of the costs are presented in Table 9-2.
- The results of the exploration program will allow refining the numerical model and to make new predictions of the temperature at depth in Lebanon.
- Given the relative high costs and uncertainty for the development of geothermal energy in Lebanon, strong incentives are required for the exploration and for the first pilot installation. These incentives could be done in forms of loans or leases, or could be in a form of a grant-aid feed-in tariff.
- Simplification of the administrative procedures by adapting the relevant laws and decrees would strongly help the potential investors in developing a first geothermal installation.
- Concerning the legal basis for impact assessments, it should also be noted that depending on the mode of financing of the project, international standards and guidelines might also have to be taken into consideration (e.g. World Bank safeguards, EBRD guidelines, Equator Principles, depending on the financing institution). All these institutions also place emphasis on social impact assessments, and mainly on resettlement and/or compensation in the case of a directly affected population.

Table 9-2: First cost estimates for the realization of the proposed exploration program

Phase 1: Surface exploration (2-3 sites)	Costs in US\$
Thermal gradient boreholes	500,000
Planning	100,000
Total for Phase 1	600,000
Phase 2: Seismic acquisition (1 site)	
Seismic acquisition	500,000
Planning and Incidentals	200,000
Total for Phase 2	700,000
Phase 3: Drilling, testing and logging (1 site)	
Exploration well	2,600,000
Testing and Logging	500,000
Planning and Incidentals	500,000
Total for Phase3	3,600,000
Total for Phase 1, 2 and 3	4,900,000

# 010. Bibliography

- Abbud, M. & Aker, 1986. The study of the aquiferous formations of Lebanon through the chemistry of their typical springs. *Lebanese Science Bulletin*, 2(2), p. 18.
- Acra, A., Milki, R. & Karahagoplan, Y., 1982. Change in quality of thermal groundwater from a unique resource in Lebanon. *Intern. J. Environmental Studies*, Volume 19, pp. 63-68.
- Adams, M., Moore, J., Fabry, L. & Ahn, A., 1992. Thermal stabilities of aromatic acids as a geothermal tracers. *Geothermics*, Volume 21, pp. 323-339.
- Badino, G., 2005. Underground drainage systems and geothermal flux. *Speleogenesis and evolution of karst aquifers*, 2(34), pp. 277-316.
- Baujard, C., Schoenball, M. & Dorbath, L., submitted. The use of the Hydraulic Energy as a Prox for Mmax prediction during stimulation and operation of geothermal reservoirs. *Geothermics*.
- Beydoun, Z., 1977. Petroleum Prospects of Lebanon: Reevaluation. *The American Association of Petroleum Geologists Bulletin*, 61(1), pp. 43-64.
- Bourgoyne Jr, A., Millheim, K., Chenevert, M. & Young Jr, F., 1986. *Applied drilling engineering*. Volume 2. s.l.:s.n.
- Brew, G., Barazangi, M., Al-Maleh, A. K. & Sawaf, T., 2001. Tectonic und geologic evolution of Syria. *GeoArabia*, 6(4), pp. 573-616.
- Chedid, R., et al., 2005. A sub-regional outlook of renewable energy potential: the case of Jordan, Syria and Lebanon. Conference paper prepared for "Renewable Energy" working group global network on energy and sustainable development.
- Cornet, F. & Valette, B., 1984. In situ stress determination from hydraulic injection data. *Journal of geophysical research*, Volume 89, pp. 11527-11537.
- DAR-IAURIF, 2005. *National Physical Master Plan of the Lebanese Territory*, Beirut: s.n.
- Dubertret, L., 1955. *Carte Géologique du Liban*. République Libanaise: Ministère des travaux publics.
- Durrance, E., 1986. *Radioactivity in geology*. ISBN 0-85312-761-1 ed. Chichester, England: Ellis Horwood Limited.
- Durrance, E., 1986. *Radioactivity in geology*. Chichester: Ellis Horwood Limited.
- ELARD & BURGEAP-IGIP-RIBEKA, 2012. *Nationwide Assessment of Groundwater Resources Across Lebanon; Public Well Report*, Beirut: UNDP.
- El-Hajj, A., 2008. *L'aquifère carbonate karstique de Chekka (Liban) et ses exutoires sous-marins. Caracteristiques hydrogéologiques et fonctionnement*, Université Montpellier II/Universtié St.Joseph (Beirut): Thèse.
- Elias, A. et al., 2007. Active thrusting offshore Mount Lebanon: source of the tsunamigenic A.D. 551 Beirut-Tripoli earthquake. *Geology*, Issue 35, pp. 755-758.
- ESMAP World Bank, 2012. *World Bank: ESMAP Geothermal Handbook: Planning and Financing Power Generation: Technical Report 002/12..* s.l.:s.n.
- Evans, K. et al., 1999. Stress and rock mechanics issues of relevance to HDR/HWR engineered geotheraml systems: review of development during the past 15 years. *Geothermics*, Volume 28, pp. 455-474.
- Geothermex Inc., 2013. *Geothermal exploration best practices: a guide to resource data collection, analysis, and presentation for geothermal projects*. s.l., IGA.
- Ghergut, I. et al., 2007. Tracer tests evaluating hydraulic stimulation at deep geothermal reservoirs in Germany. *Proceeding 32<sup>nd</sup> workshop on geotheraml reservoir engineering*, pp. 22-24.
- Goldscheider, N. & Drew, D., 2007. *Methods in Karst Hydrogeology*. Taylor & Francis ed. London: s.n.
- Gringarten, A., 1978. Reservoir lifetime and heat recovery factor in geothermal aquifers used for mountainous terrain: a model study. *Journal of Geophysical Research*, 94(B7), pp. 9439-9451.
- Haddad, S. S. A., 2006. *Petrographic and geochemical characterization of the hasbya asphalt and related host rocks (senonian chekka formation – south lebanon)*, s.l.: s.n.
- Haenel, R., Stegana, L. & Rybach, L., 1988. *Handbook of terrestrial heatflow density determination*. Solid Earth Sciences Library, Volume 4.

- Häring, M. O., Schanz, U., Ladner, F. & Dyer, B. C., 2008. Characterisation of the Basel 1 enhanced geothermal system. *Geothermics*, 37(7), pp. 469-495.
- Horner, D., 1951. Pressure build-up in wells. The Hague: Third World Petroleum Congress.
- Huijjer, C. E., 2010. Implications of the recent mapping of the offshore thrust fault system on the seismic hazard of Lebanon, Beirut: American University of Beirut.
- Huijjer, C., Harajli, M. & Sadek, S., 2011. Upgrading the seismic hazard of Lebanon in light of the recent discovery of the offshore thrust fault system. *Lebanese Science Journal*, 12(2).
- Hunt, T., 2000. Five lectures on environmental effects on geothermal utilization. The United Nations University, Geothermal training programme. Volume Reports, Number 1, pp. 51-61.
- IGA, 2013. Geothermal exploration best practices. A guide to resource data collection, analysis, and presentation for geothermal projects. Bochum: s.n.
- IOC, I. B., 2003. Centenary Edition of the GEBCO Digital Atlas. s.l.:s.n.
- Jackson, W., 2000. Drilling a straight hole - rotary drilling series unit 2 - Lesson 3. 3 ed. s.l.:PETEX.
- Kenouard, G., 1955. Oil prospects of Lebanon. *Bulletin of the American association of petroleum geologists*, vol. 39, pp. 2125-2169.
- Khair, K., Aker, N. & Zahruddine, K., 1992. Hydrogeological unit of Lebanon. *Applied Hydrogeology*, Volume 2, pp. 34-49.
- Khayat, Z., 2001. Groundwater conditions in the Koura-Zgharta Miocene limestone aquifer, Lebanon: Department of Geology, American University of Beirut.
- Kohl, T. & Hopkirk, R. J., 1995. "FRACTure" a simulation code for forced fluid flow and transport in fractured porous rock. *Geothermics*, Volume 24, pp. 345-359.
- Majer, E. & Peterson, J., 2007. The impact of injection on seismicity at the Geysers, California, geothermal field. *International Journal of Rock Mechanics and Mining Sciences*, 8(1079-1090), p. 44.
- Margane, A. & Stoeckl, L., 2013. Monitoring of spring discharge and surface water runoff in the groundwater contribution zone of Jeita spring, Raifoun: CDR and BGR.
- Mouty, M. et al., 1992. The volcanic activity in Syria and Lebanon between Jurassic and Actual. *Schweiz. Mineral. Petrogr. Mitt.*, Volume 72, pp. 91-92.
- Mudallal, S., 1989. Water resources in Lebanon, (in Arabic): Science and Technology.
- Murphy, H. et al., 1999. Hydraulics and well testing of engineered geothermal reservoirs. *Geothermics*, 28(4-5), pp. 491-506.
- Nader, F., 2011. The Petroleum prospectivity of Lebanon: an overview. *Journal of Petroleum Geology*, April, pp. 135-156.
- Nader, F. & Swennen, R., 2004. Petroleum prospects of Lebanon: some remarks from sedimentological and diagenetic studies of Jurassic carbonates. *Marine and Petroleum Geology*, pp. 427-441.
- Nader, F. & Swennen, R., 2004. The hydrocarbon potential of Lebanon: new insights from regional correlations and studies of jurassic dolomitization. *Journal of Petroleum Geology*, Vol. 27 (3), pp. 253-275.
- Nations Unies, 1967. Carte hydrogéologique du Liban. Beirut: UNDP.
- Nguyen, W., 1996. Drilling. s.l.:TECHNIP.
- Pine, R. & Batchelor, A., 1984. Downward migration of shearing in jointed rock during hydraulic injections. *Volume Abstr.* 21, pp. 249-263.
- Plenefisch, T. & Bonjer, K.-P., 1997. The stress field in the Rhine Graben area inferred from earthquakes focal mechanisms and estimation of frictional parameters. *Tectonophysics*, Volume 275, pp. 71-97.
- United Nations Development Programme , 1970. Liban: étude des eaux souterraines, New York: Nations Unies.
- Renouard, G., 1955. Oil prospects of Lebanon. *Bulletin of the American Association of Petroleum Geologists*, 39(11), pp. 2125-2169.
- Rose, P., Benoit, W. & Kilbourn, P., 2001. The application of the polyaromatic sulfonates as tracers in geothermal reservoirs. *Geothermics*, Volume 30, pp. 617-640.



- Sanjuan, B. et al., 2006. Tracer testing of the geotheraml heat exchanger at Soultz-sous-Forêt (France) between 2000 and 2005. *Geothermics*, 35(5-6), pp. 622-653.
- Shaban, A., 1999. Air borne thermal infrared scan of fresh water sources in the marine environment. *Proceed. Symposium CTM/UNEP, Beirut*, pp. 9-13.
- Shaban, A., 2010. Geothermal water in Lebanon: an alternative energy source. *Low Carbon Economy, Volume 1*, pp. 18-24.
- Shaban, A., 2010. Geothermal Water in Lebanon: an Alternative Energy Source. *Low Carbon Economy*, 1, pp. 18-24.
- Shaban, A. & Khalaf-Keyrouz, L., 2013. The geological controls of geothermal groundwater sources in Lebanon. *International J. of Energy and Environment*, 4(5), pp. 787-796.
- Stahl, P. & Plassard, J., 1967. Carte gravimétrique du Liban. République libanaise: Ministère des travaux publiques - Bureau gravimétrique international.
- Ukla, S. M., 1970. *Subsurface Geology and Well Correlation*, s.l.: s.n.
- Ukla, S. M., 1970. *Subsurface Geology and Well Correlation in North and Central Lebanon*. Beirut: Department of Geology, A.U.B..
- UNDP, 1967. Carte hydrogéologique du Liban, s.l.: s.n.
- UNDP, 1970. Liban, étude des eaux souterraines, s.l.: s.n.
- Walley, C., 1997. The Lithostratigraphy of Lebanon: a review. *Lebanese Science Bulletin*, 10(1), p. 20.
- Walley, C. D., 1988. A braided strike-slip model for the northern continuation of the Dead Sea Fault and its implications for Levantine tectonics. *Tectonophysics*, 145 (1-2), pp. 63-72.
- Wannamaker, P. et al., 2002. Fluid generation and pathways beneath an active compressional orogen, the New Zealand southern Alps, inferred from magnetotelluric data. *J. Geophys. Res.*, 107(6), pp. 1-22.

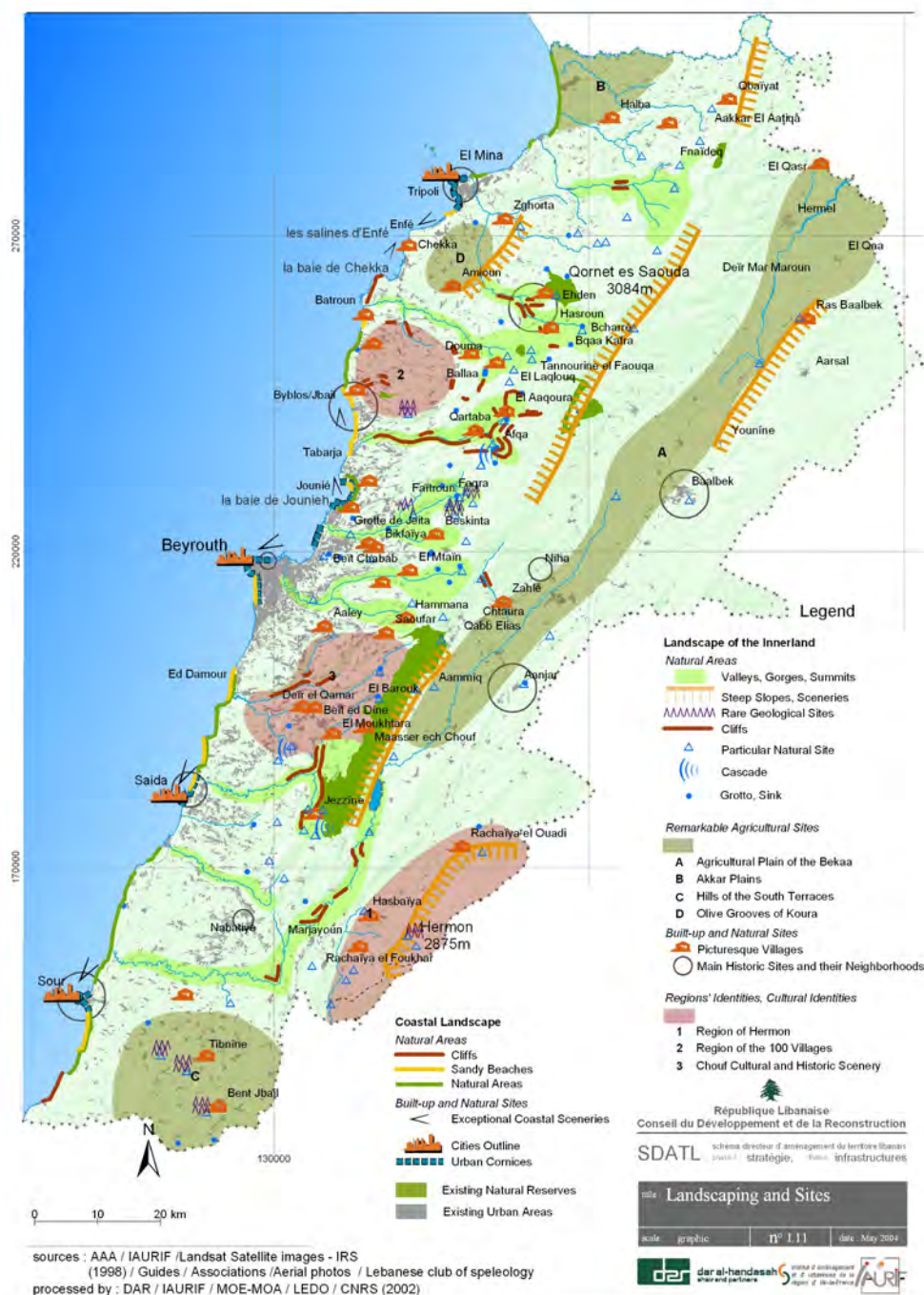


# Appendices

Appendix 1: Landscaping and sites (DAR-IAURIF, 2005).....	194
Appendix 2: Natural area of national interest (DAR-IAURIF, 2005) .....	195
Appendix 3: Protected natural reserves and grottos (DAR-IAURIF, 2005) .....	196
Appendix 4: Geological map of Lebanon (Dubertret, 1955) .....	197
Appendix 5: Detailed stratigraphic column of Lebanon .....	198
Appendix 6: Seismicity of Lebanon, 2006-2009 with Magnitudes (source: CNRS).....	199
Appendix 7: Seismic risk level in Lebanon (DAR-IAURIF, 2005) .....	200
Appendix 8: Extent of the rock formations regarding to the degree of karstification (DAR-IAURIF, 2005).....	201
Appendix 9: Regional heat flow map (using data of the international heat flow commission) .....	202
Appendix 10: Temperature distribution based on temperature groundwater measurement .....	203
Appendix 11: Difference between the groundwater temperatures measured in shallow groundwater wells (TW) and the average surface temperature (TS) .....	204
Appendix 12: Distribution of basalts in Lebanon .....	205
Appendix 13: Hydrogeological map of Lebanon .....	206
Appendix 14: Depth of the Cretaceous aquifer.....	207
Appendix 15: Depth of the Jurassic aquifer .....	208
Appendix 16: Temperature of the Cretaceous aquifer .....	209
Appendix 17: Temperature of the Jurassic aquifer.....	210
Appendix 18: Temperature in a depth of 4,000 m (BGL).....	211
Appendix 19: Temperature in a depth of 5,000 m (BGL).....	212
Appendix 20: Temperature in a depth of 6,000 m (BGL).....	213
Appendix 21: Temperature in a depth of 7,000 m (BGL).....	214
Appendix 22: Stored heat (HIP) for the Cretaceous aquifer.....	215
Appendix 23: Stored heat (HIP) for the Jurassic aquifer .....	216
Appendix 24: Stored heat (HIP) for the depth interval 4,000-4,500 m .....	217
Appendix 25: Stored heat (HIP) for the depth interval 5,000-5,500 m .....	218
Appendix 26: Stored heat (HIP) for the depth interval 6,000-6,500 m .....	219
Appendix 27: Stored heat (HIP) for the depth interval 7,000-7,500 m .....	220
Appendix 28: Recoverable heat (RH) for the Cretaceous aquifer .....	221
Appendix 29: Recoverable heat (RH) for the Jurassic aquifer .....	222
Appendix 30: Recoverable heat (RH) for the depth interval 4,000-4,500 m.....	223
Appendix 31: Recoverable heat (RH) for the depth interval 5,000-5,500 m.....	224
Appendix 32: Recoverable heat (RH) for the depth interval 6,000-6,500 m.....	225
Appendix 33: Recoverable heat (RH) for the depth interval 7,000-7,500 m.....	226
Appendix 34: Possible applications of the geothermal Atlas	

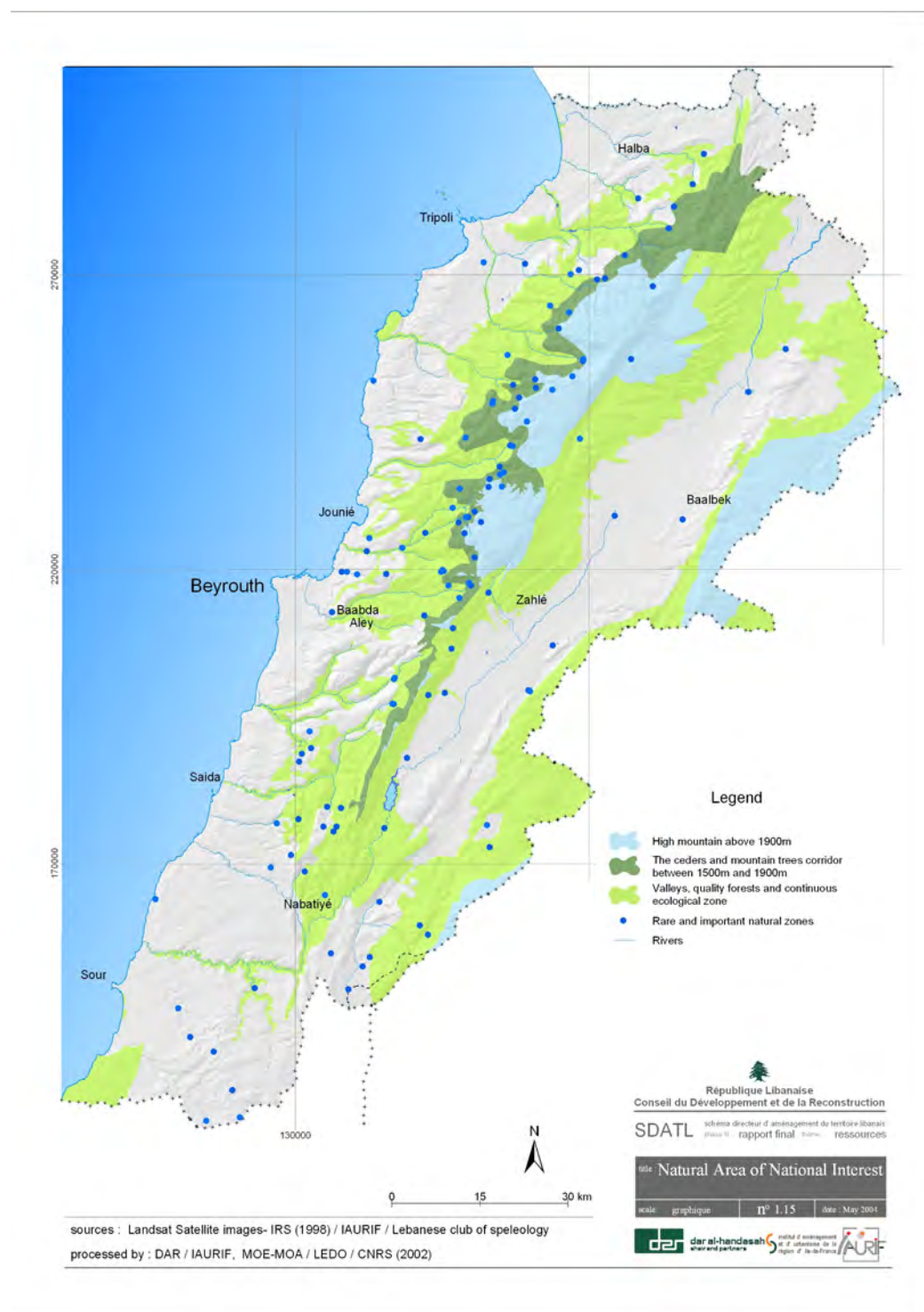


# Appendix 1: Landscaping and sites (DAR-IAURIF, 2005)

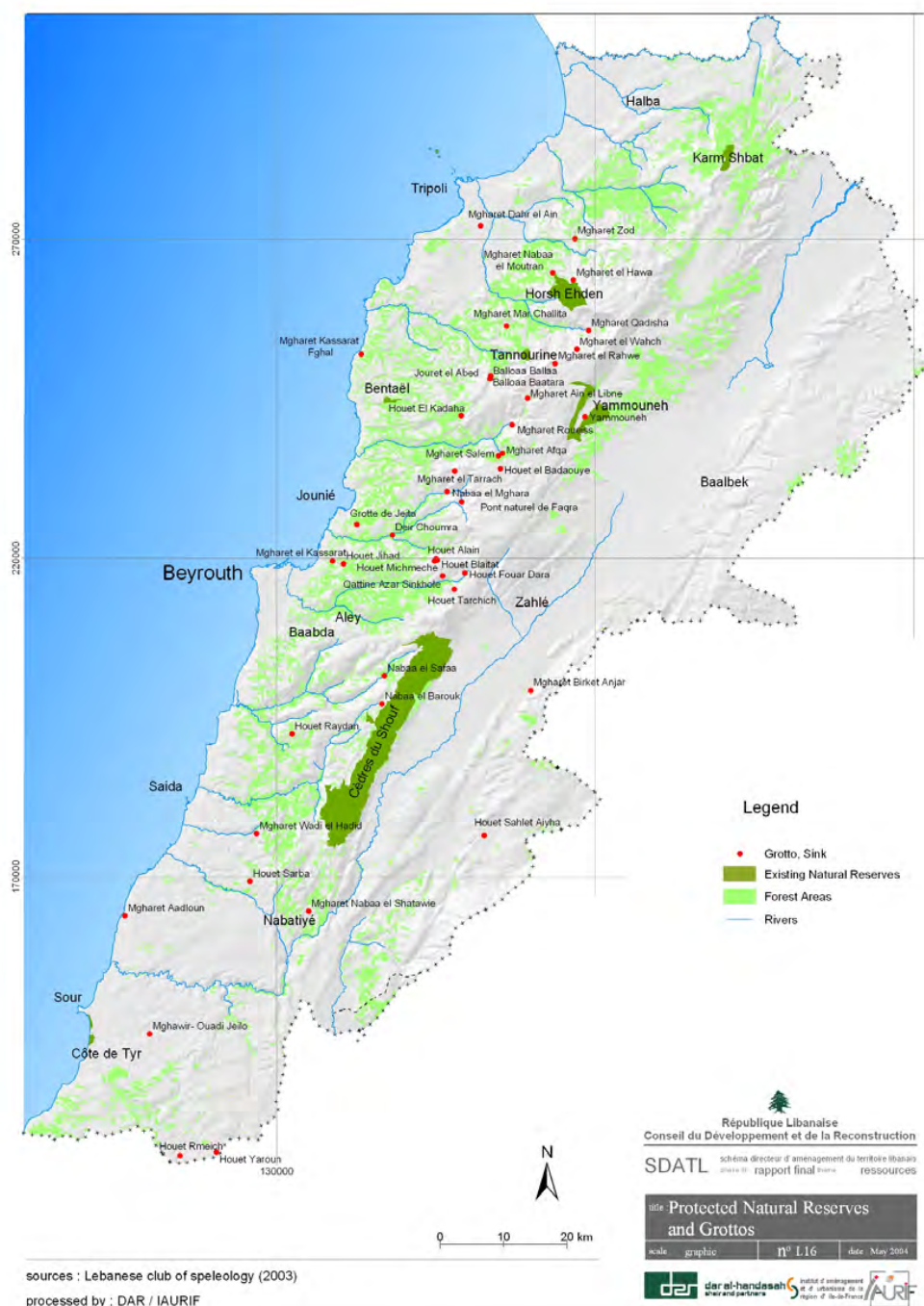




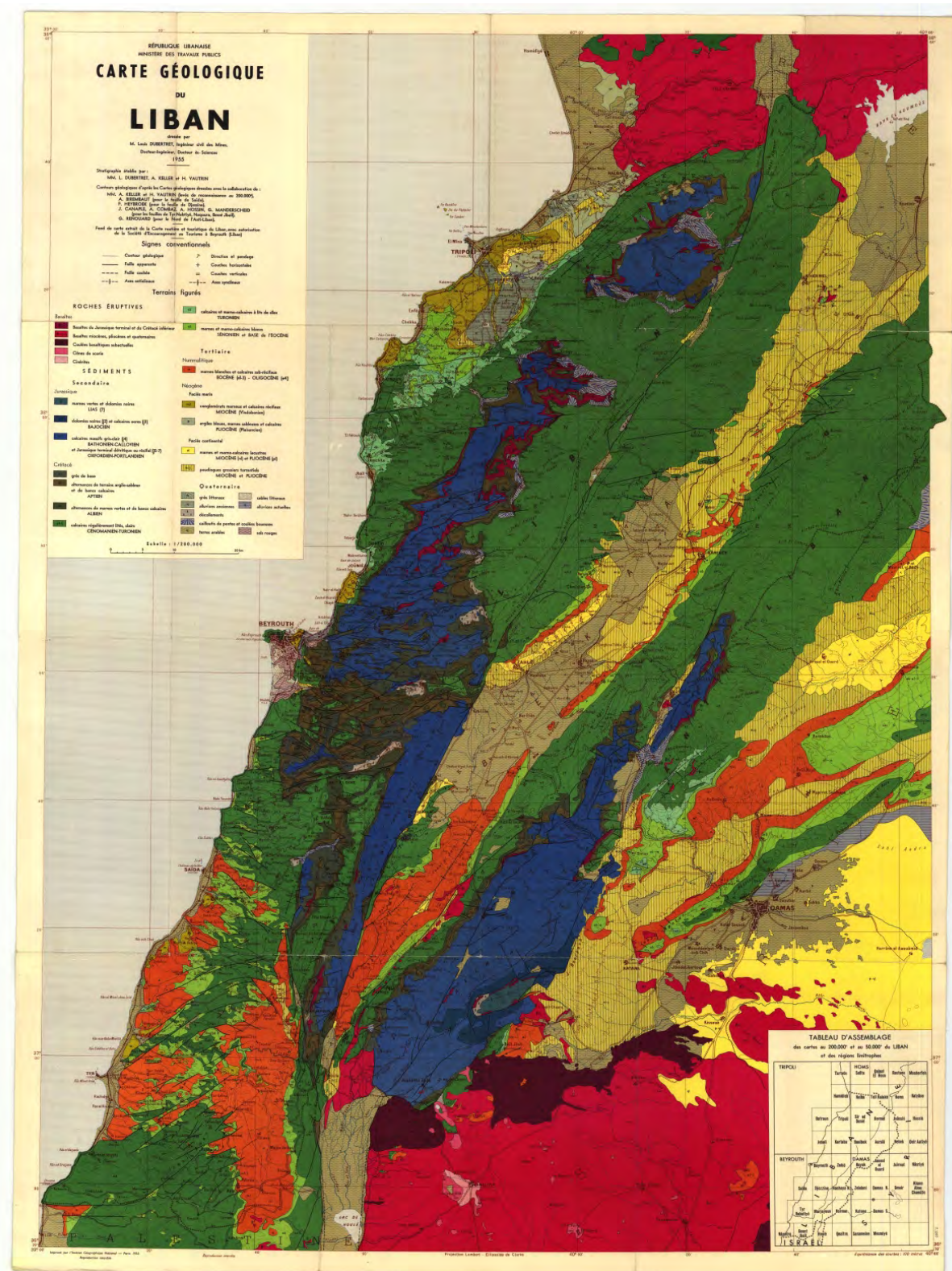
Appendix 2: Natural area of national interest (DAR-IAURIF, 2005)



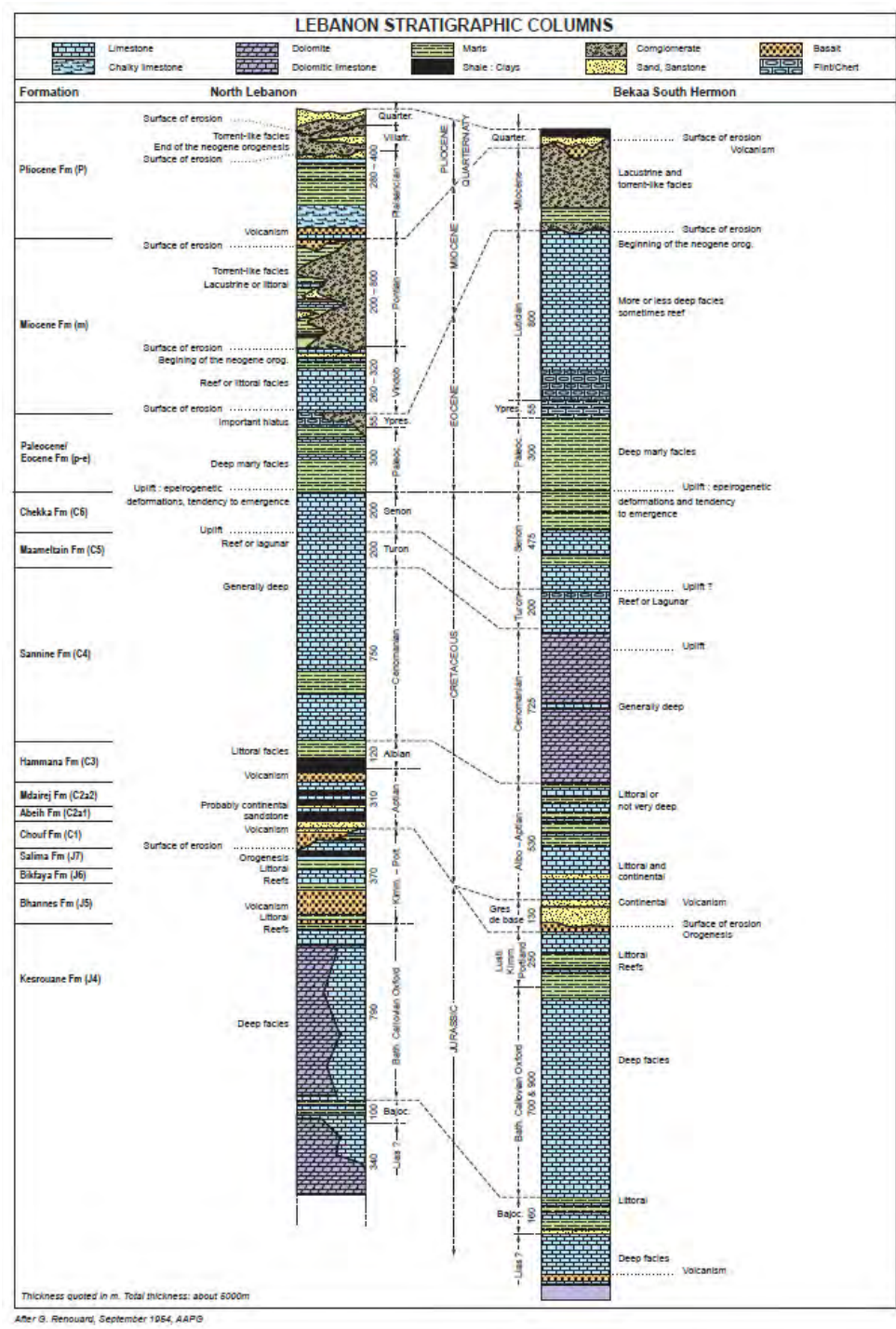
# Appendix 3: Protected natural reserves and grottos (DAR-IAURIF, 2005)





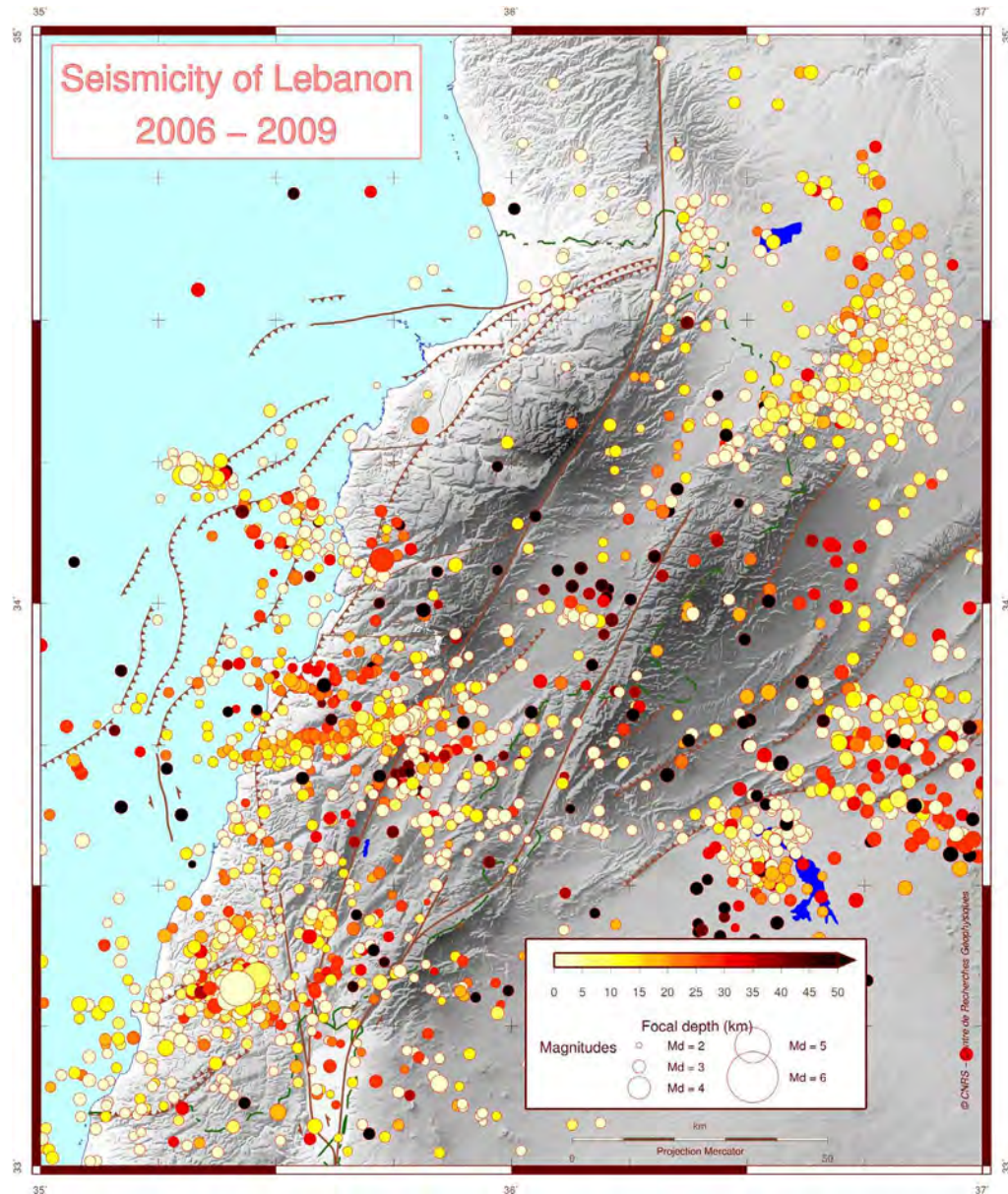


Appendix 5: Detailed stratigraphic column of Lebanon



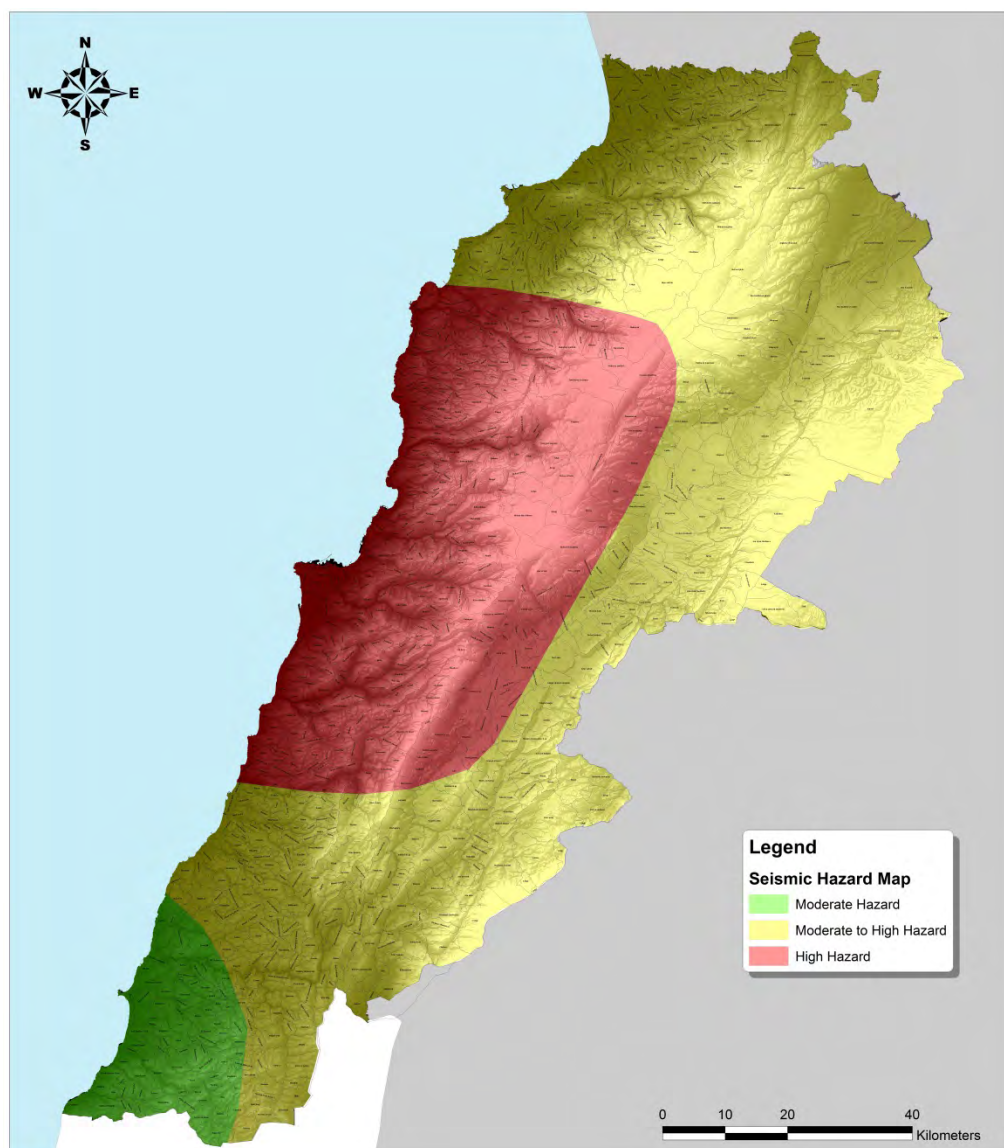


Appendix 6: Seismicity of Lebanon, 2006-2009 with Magnitudes (CNRS)

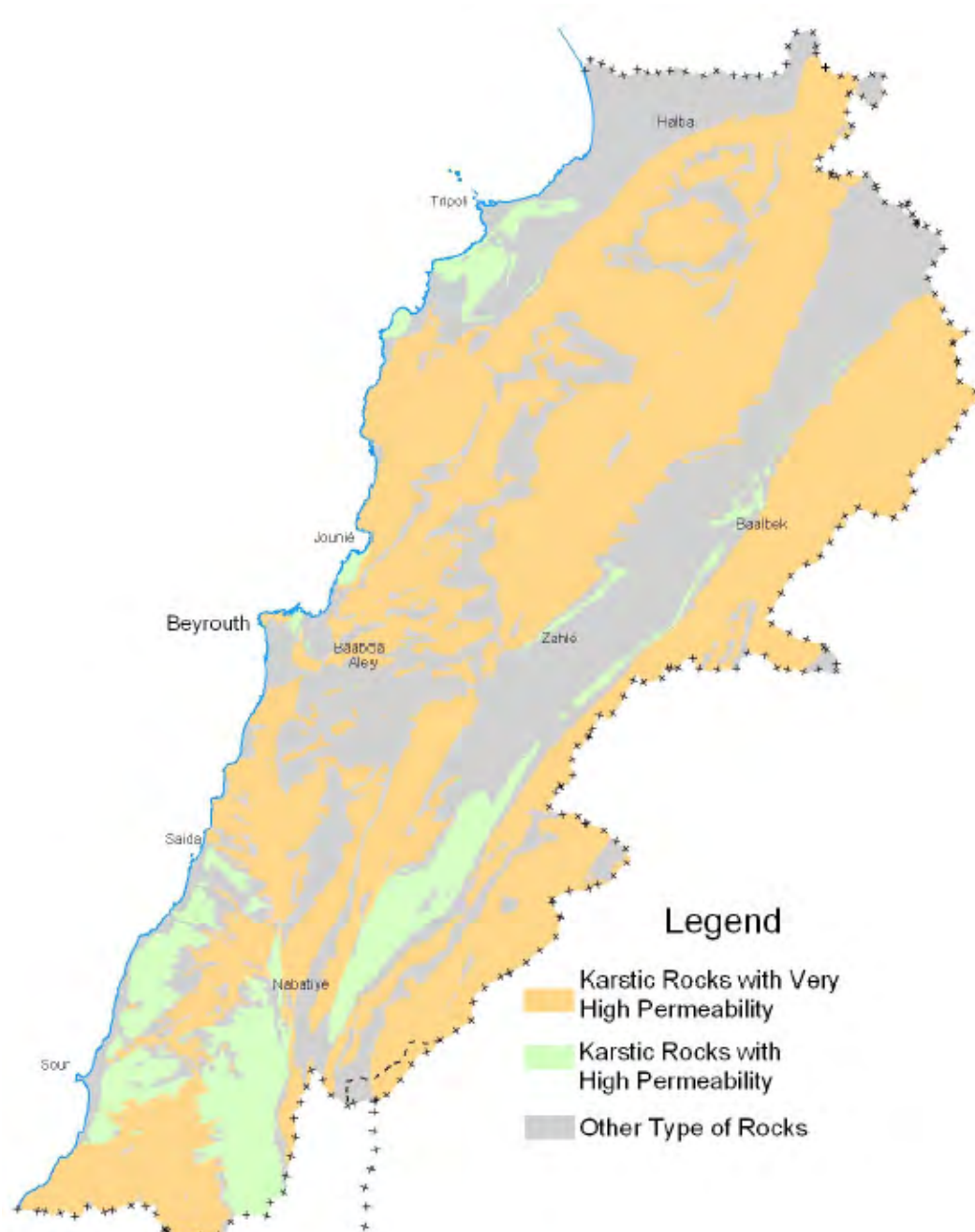




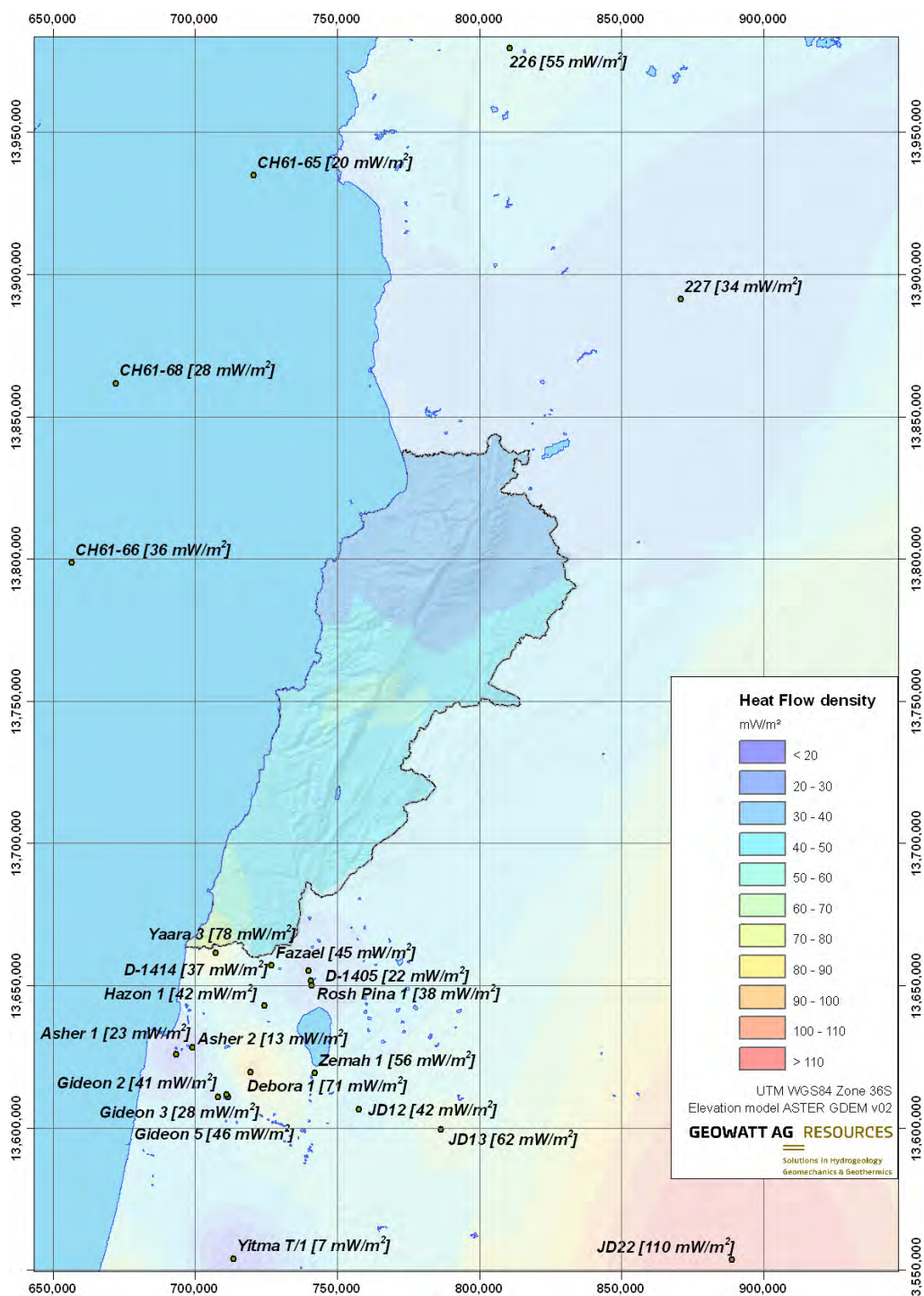
# Appendix 7: Seismic risk level in Lebanon (DAR-IAURIF, 2005)



Appendix 8: Extent of the rock formations regarding to the degree of karstification (DAR-IAURIF, 2005)

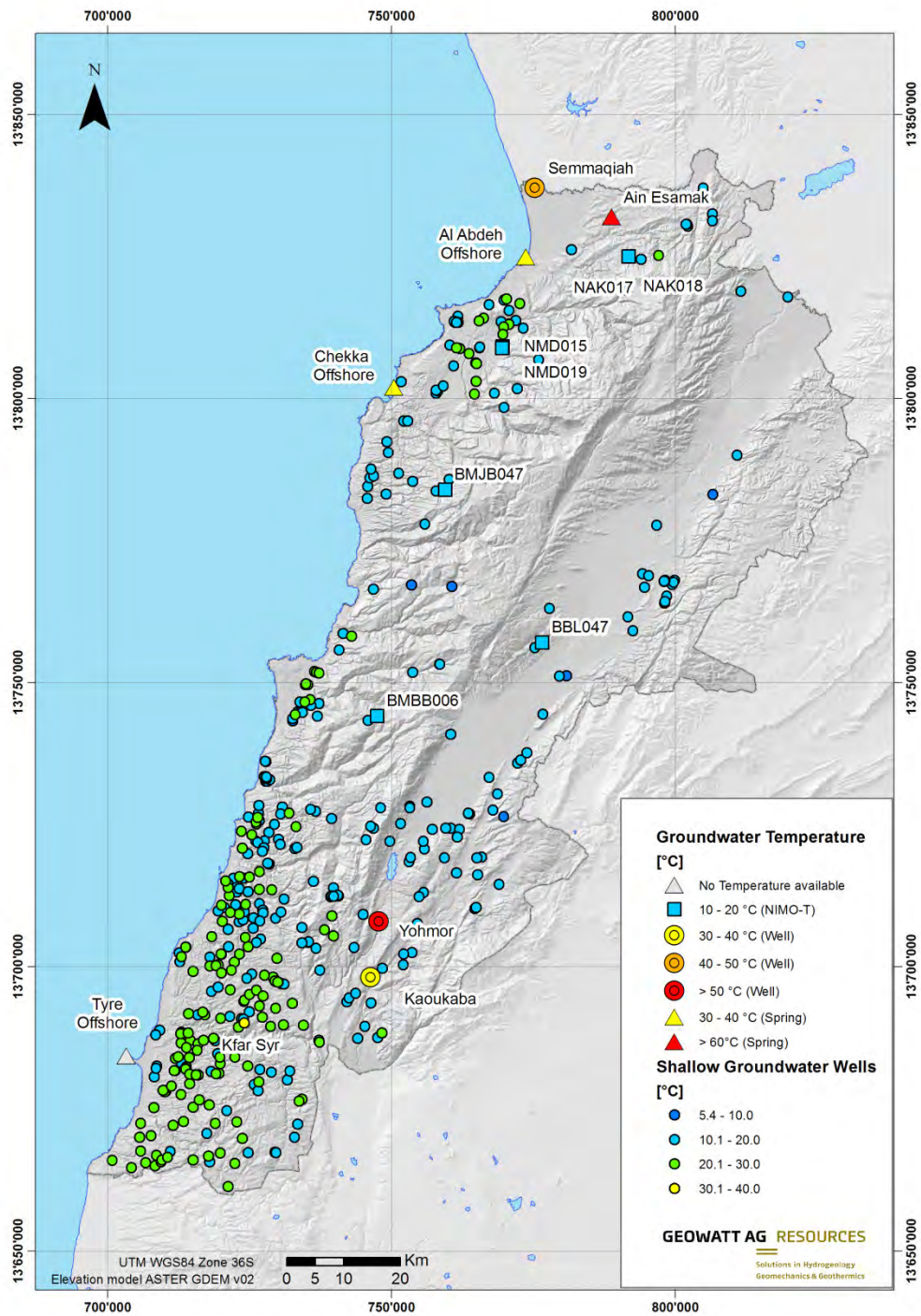


# Appendix 9: Regional heat flow map (using data of the international heat flow commission)

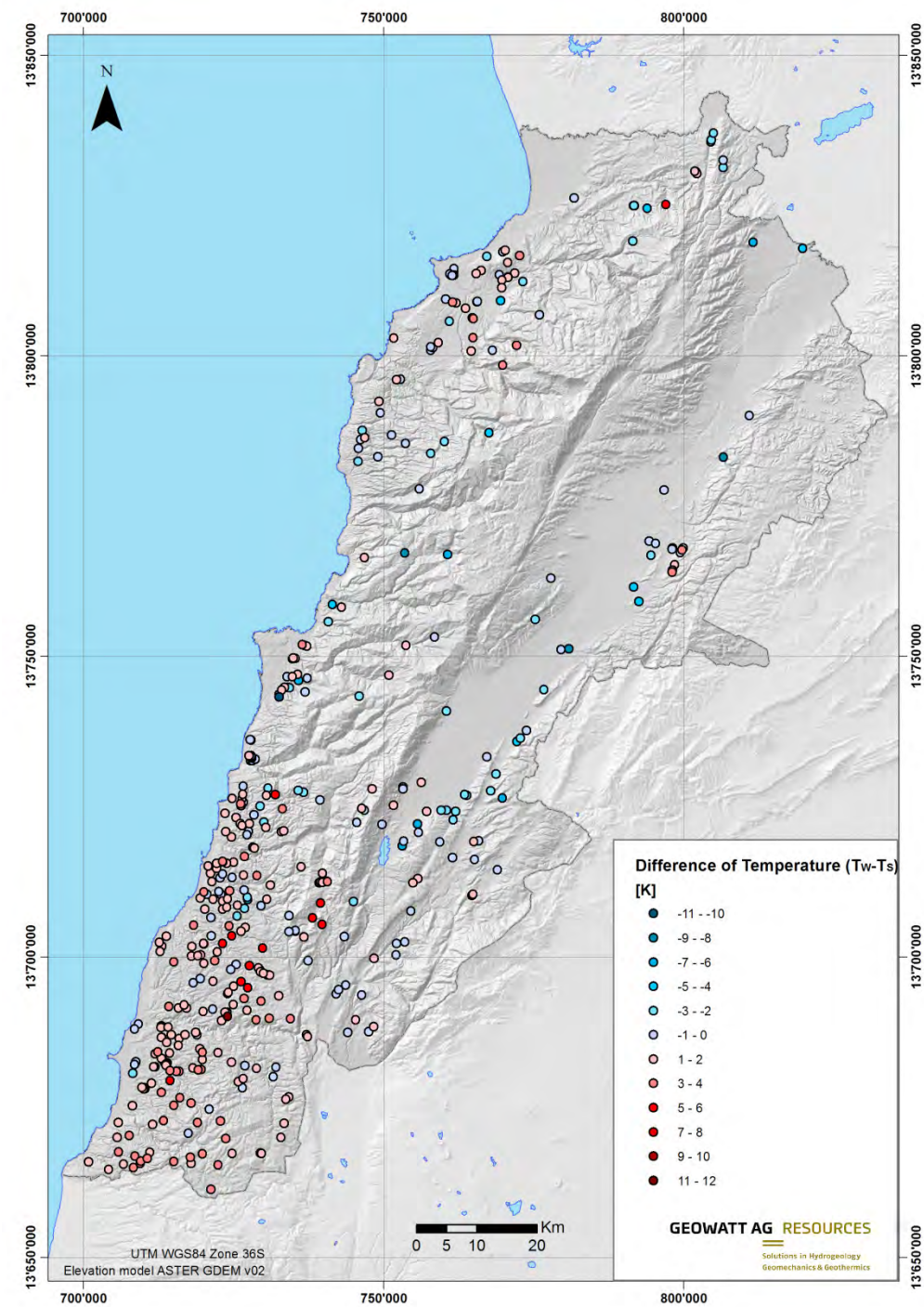




# Appendix 10: Temperature distribution based on temperature groundwater measurement

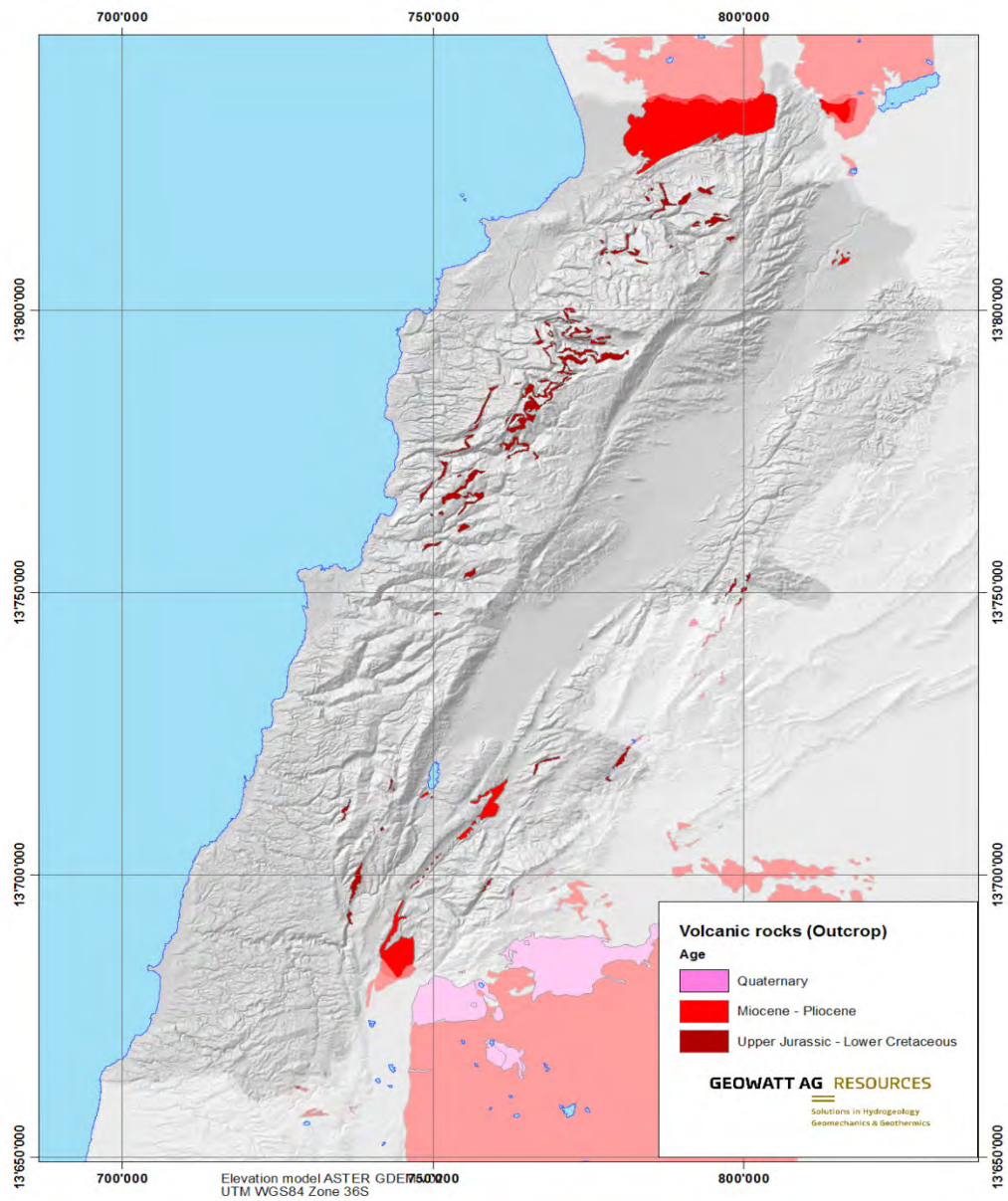


Appendix 11: Difference between the groundwater temperatures measured in shallow groundwater wells (TW) and the average surface temperature (TS)



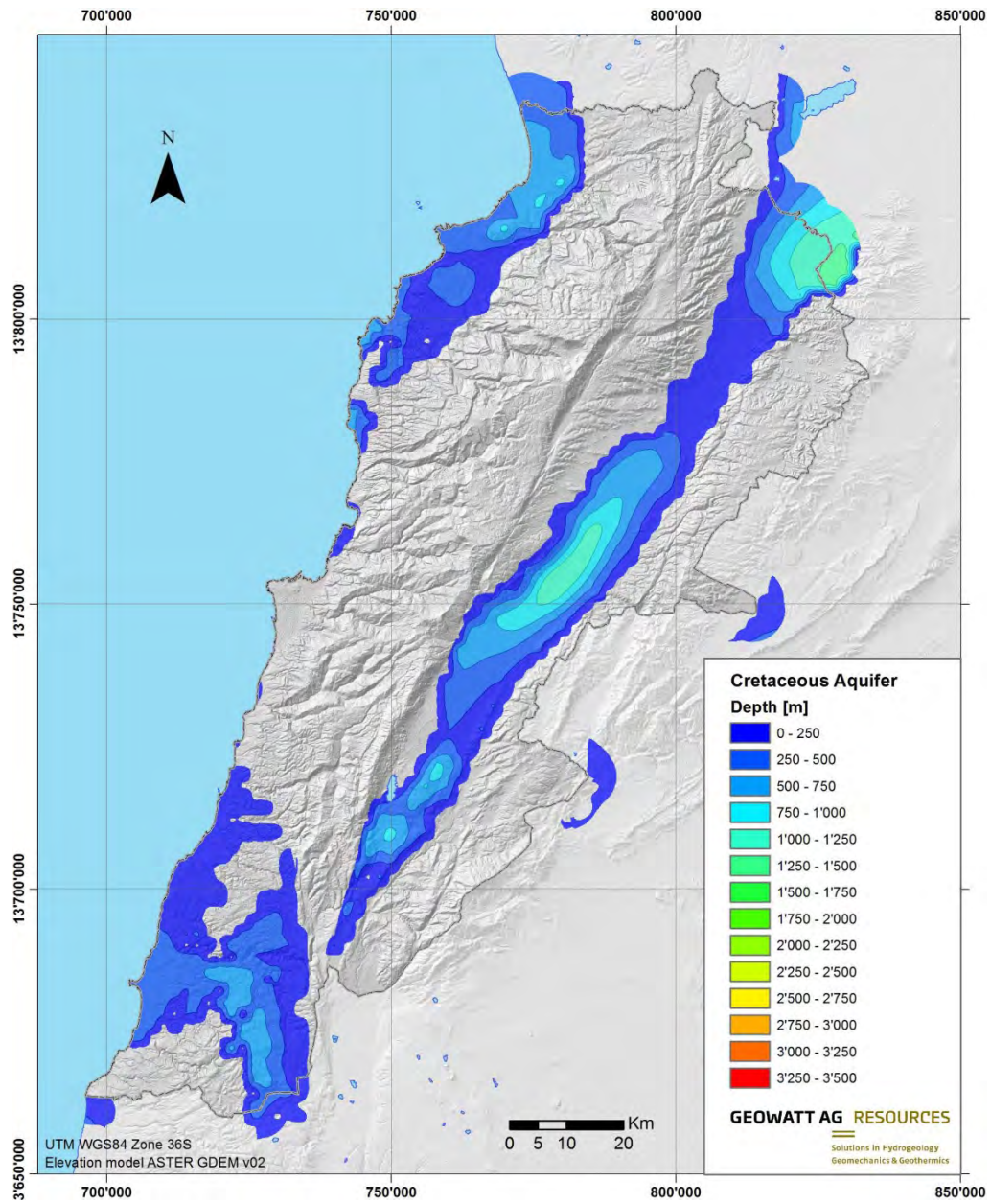


## Appendix 12: Distribution of basalts in Lebanon



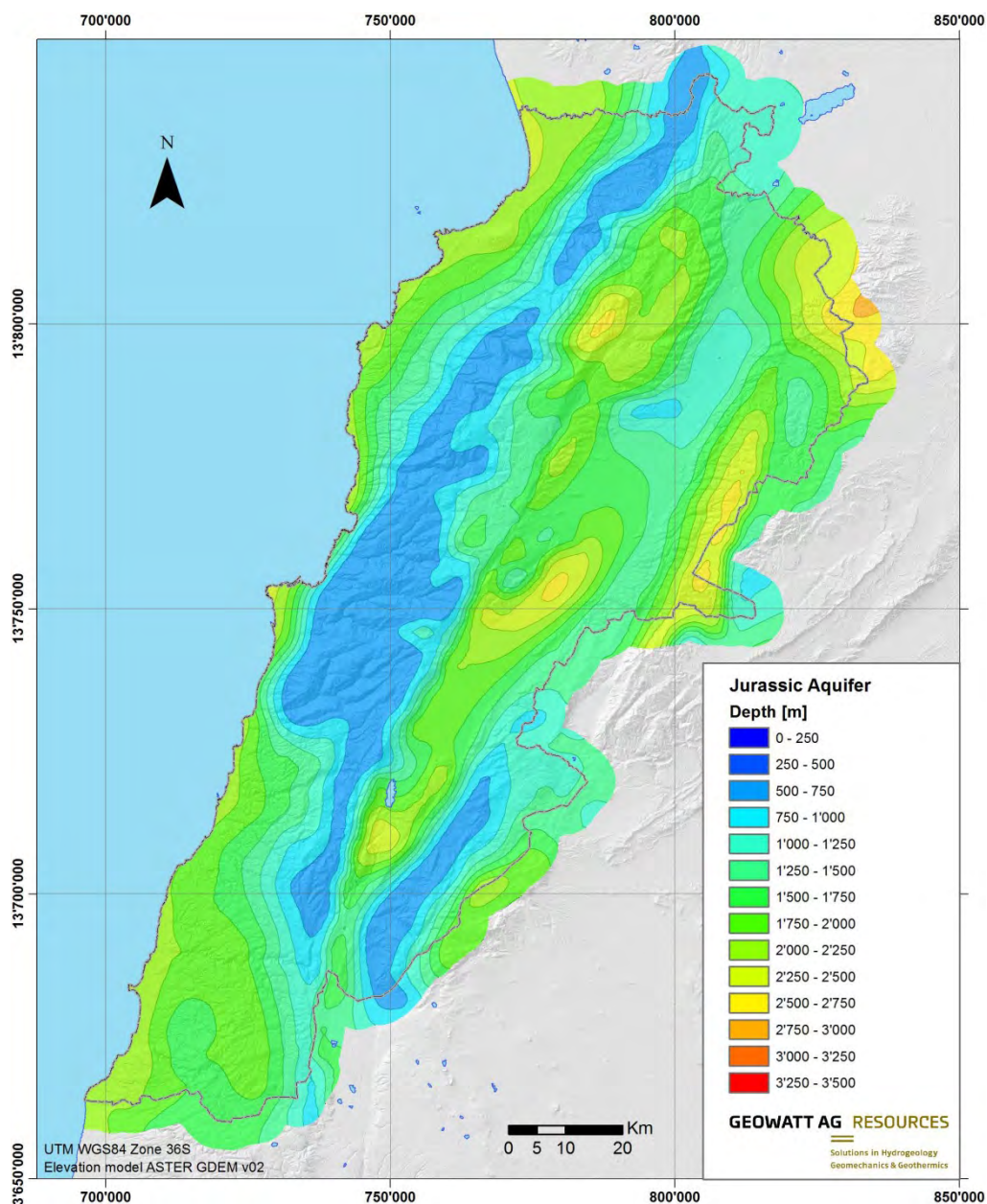


# Appendix 14: Depth of the Cretaceous aquifer

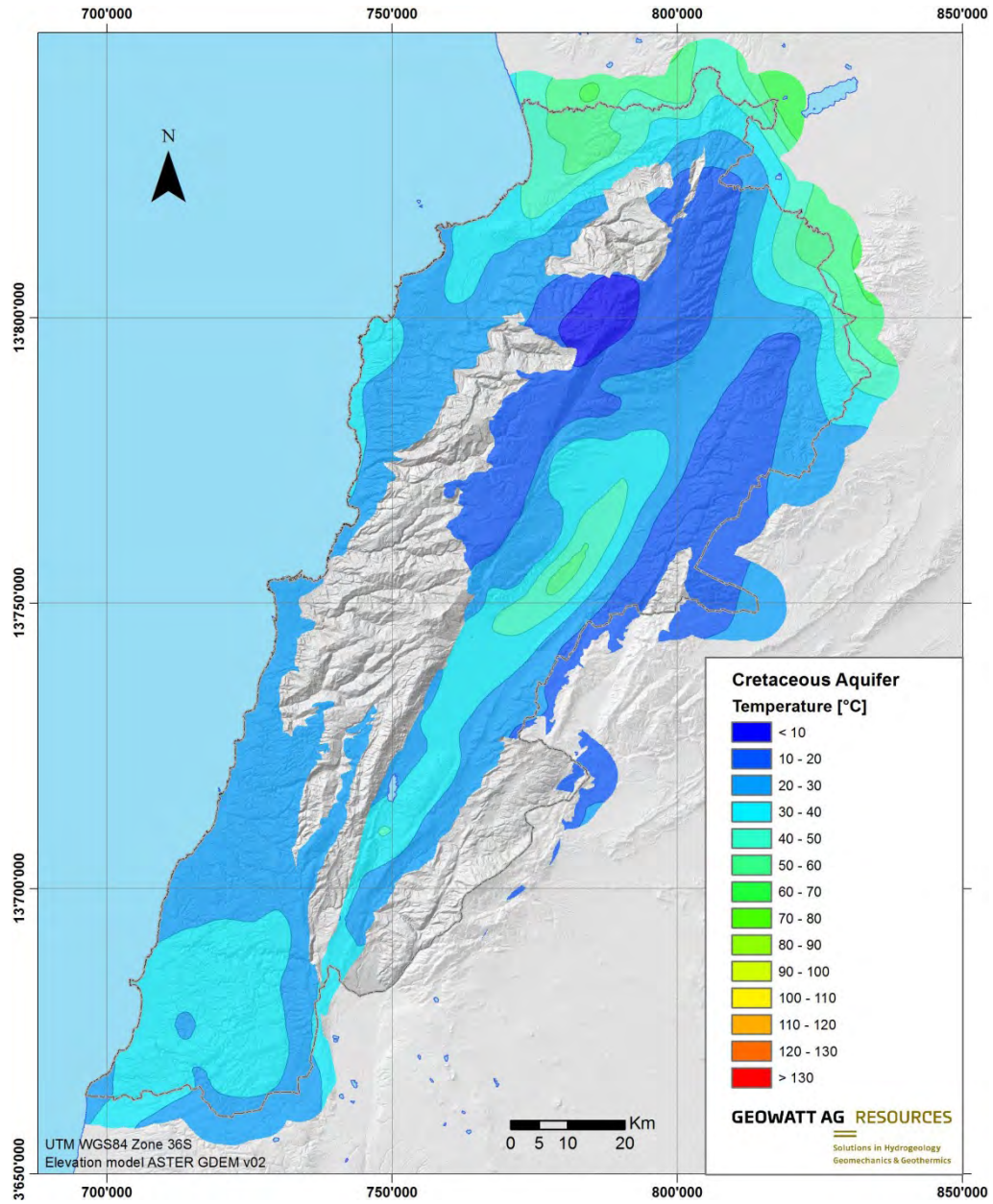




# Appendix 15: Depth of the Jurassic aquifer

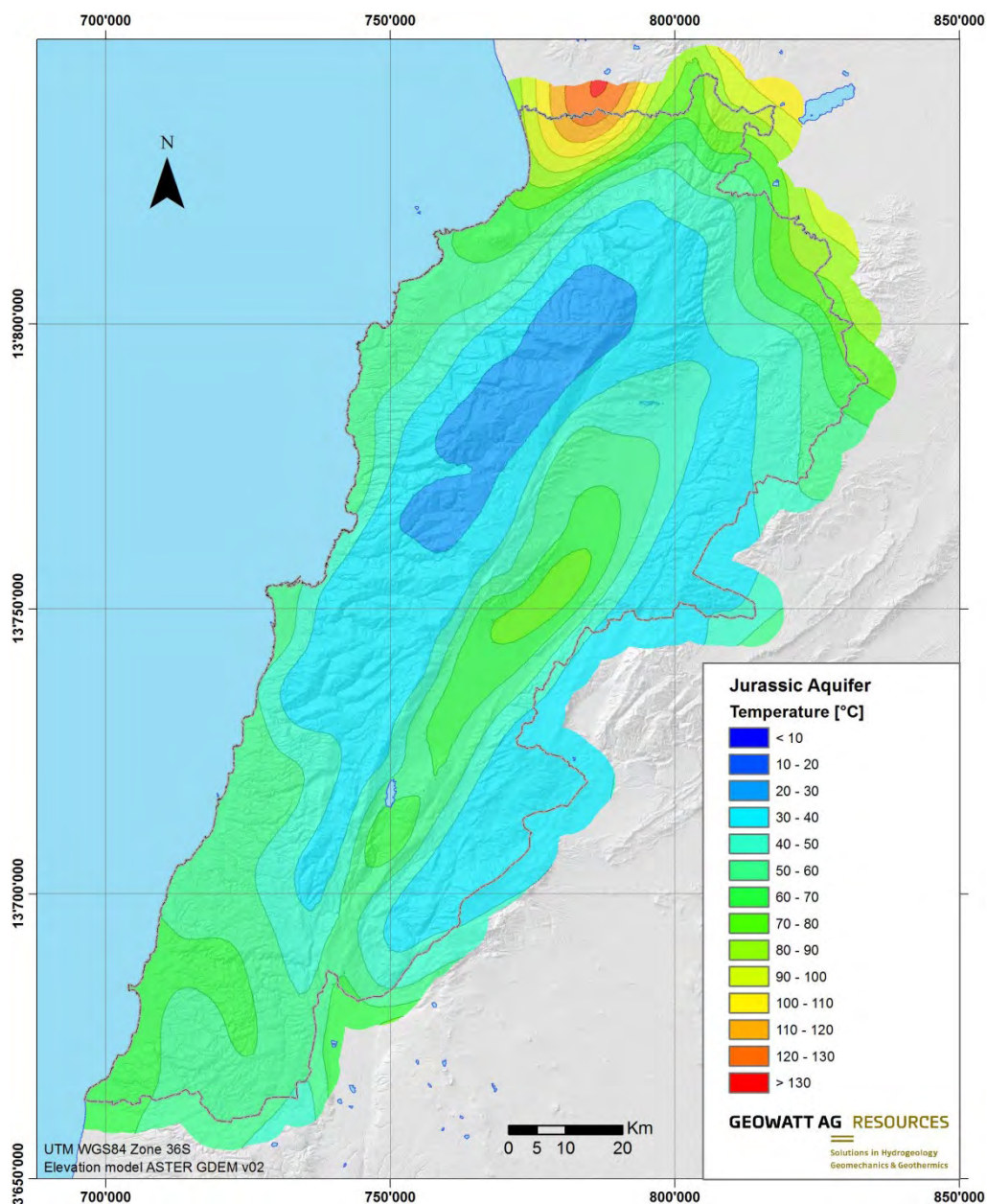


# Appendix 16: Temperature of the Cretaceous aquifer

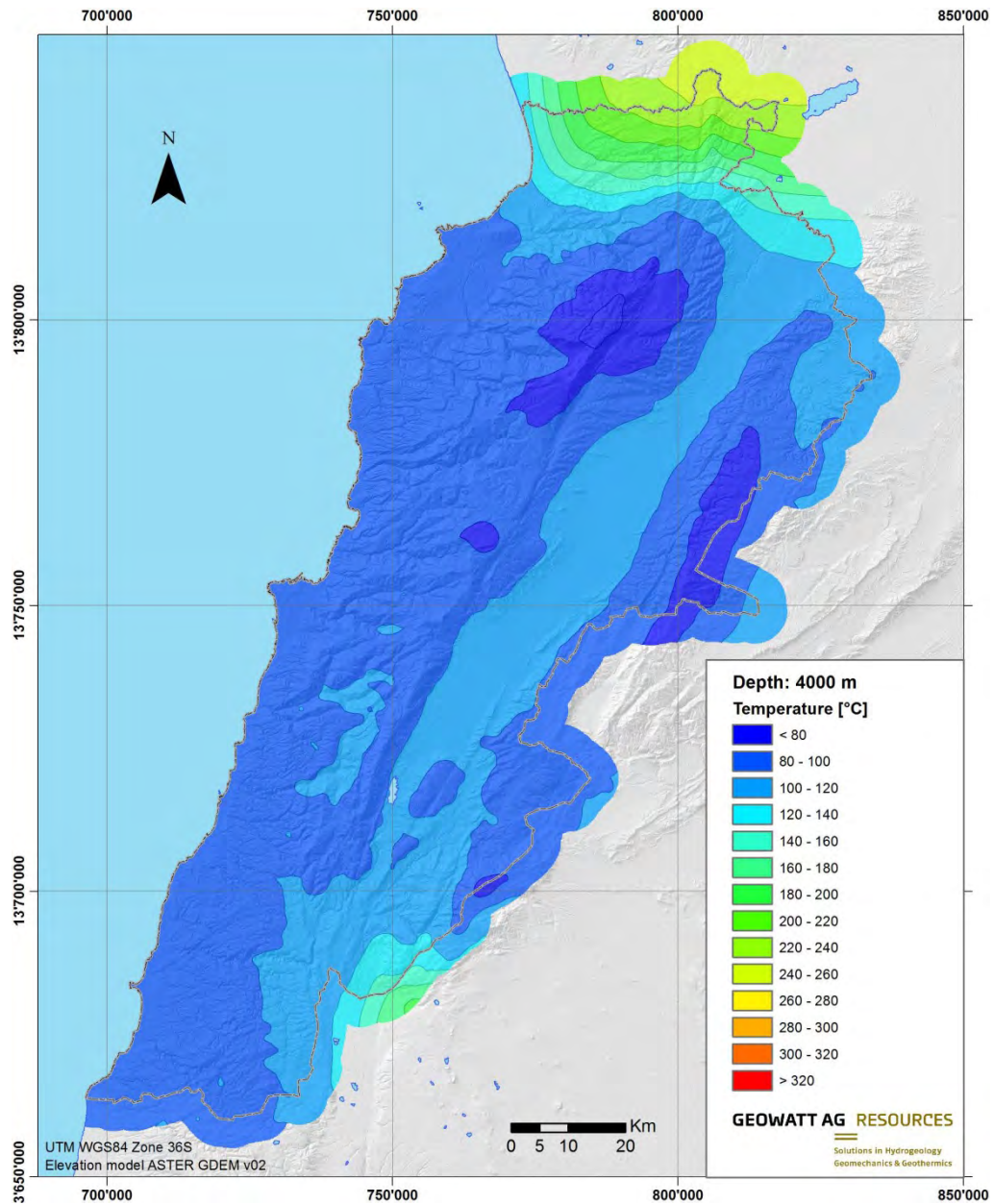




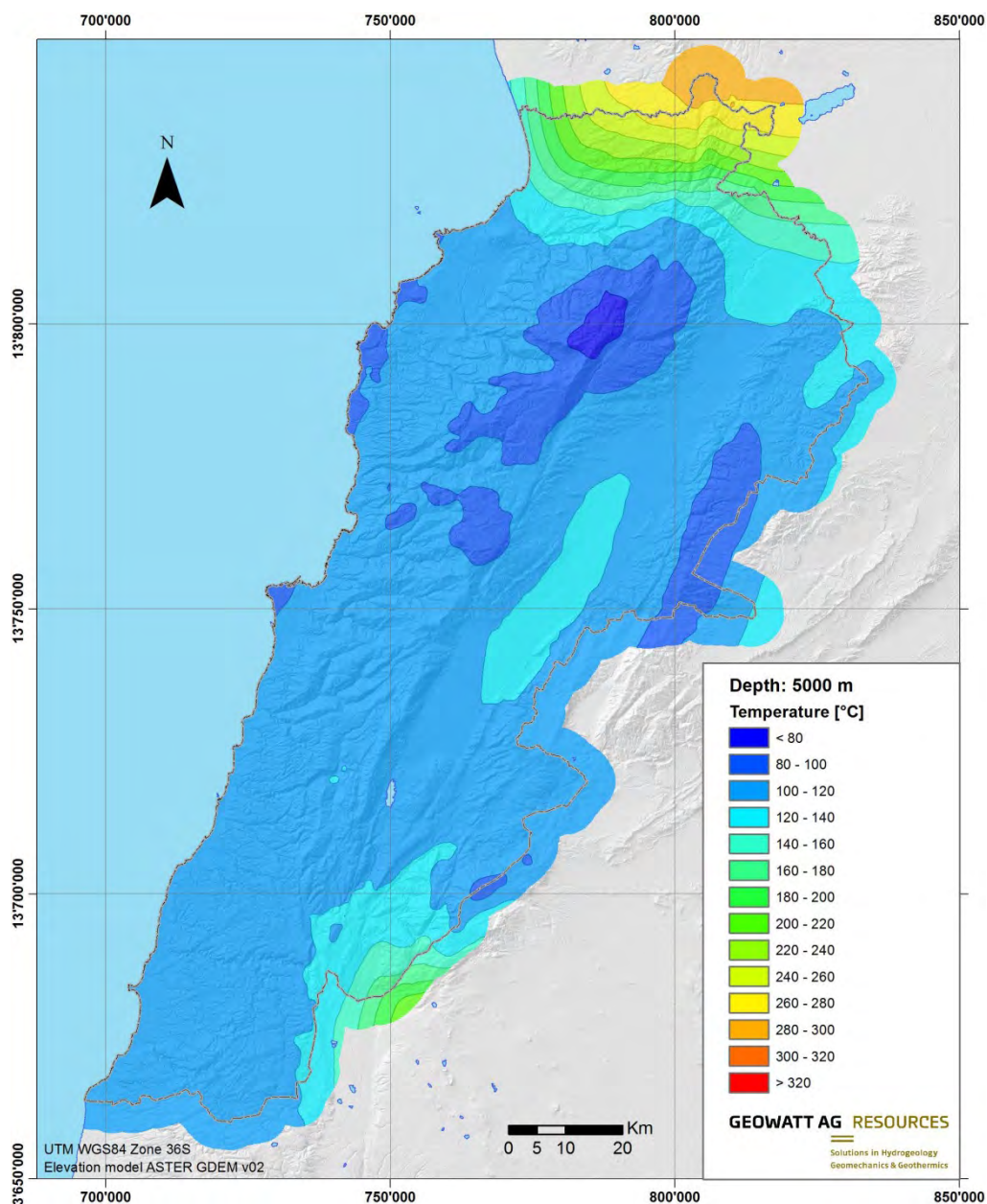
# Appendix 17: Temperature of the Jurassic aquifer



Appendix 18: Temperature in a depth of 4,000 m (BGL)

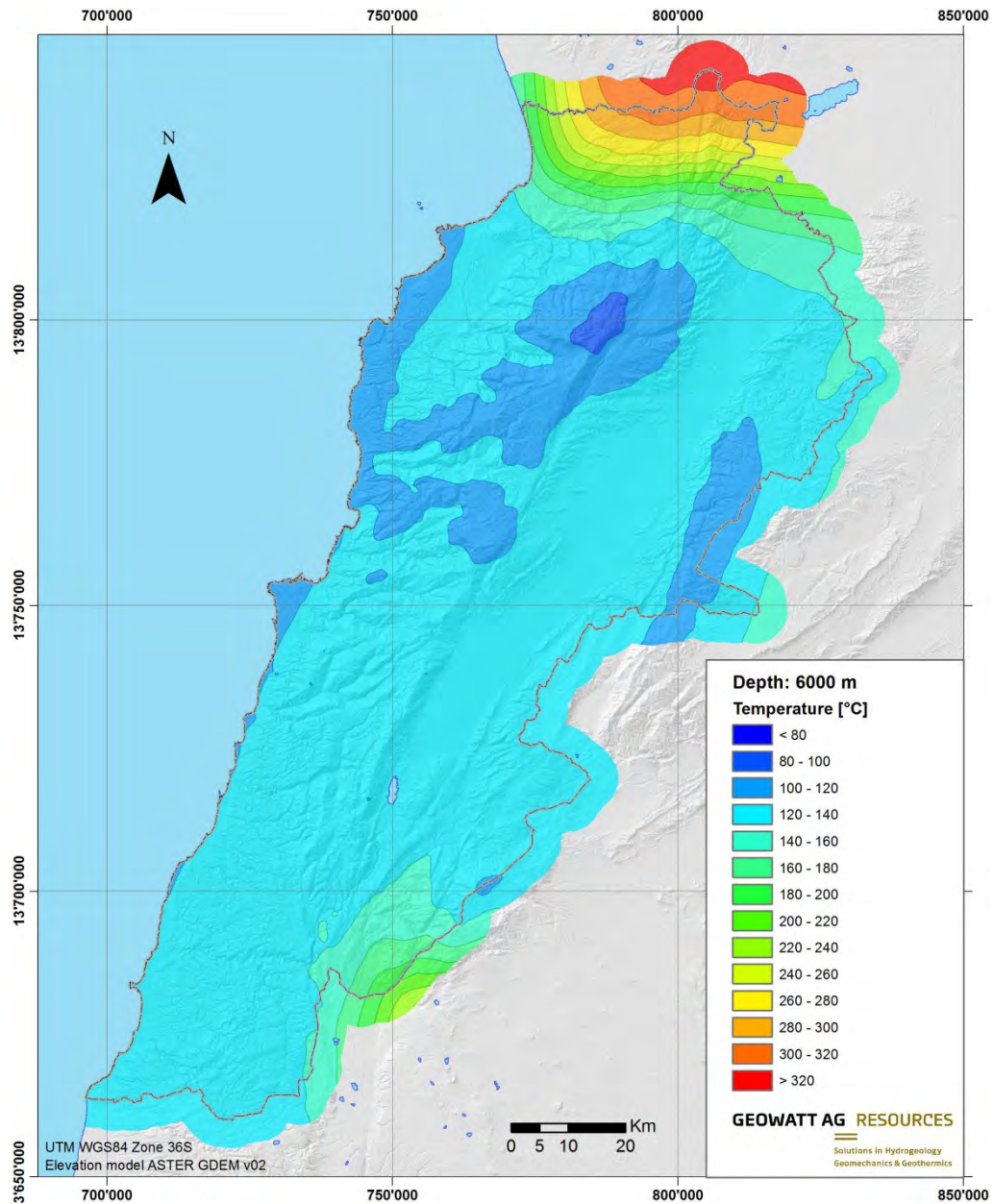


# Appendix 19: Temperature in a depth of 5,000 m (BGL)

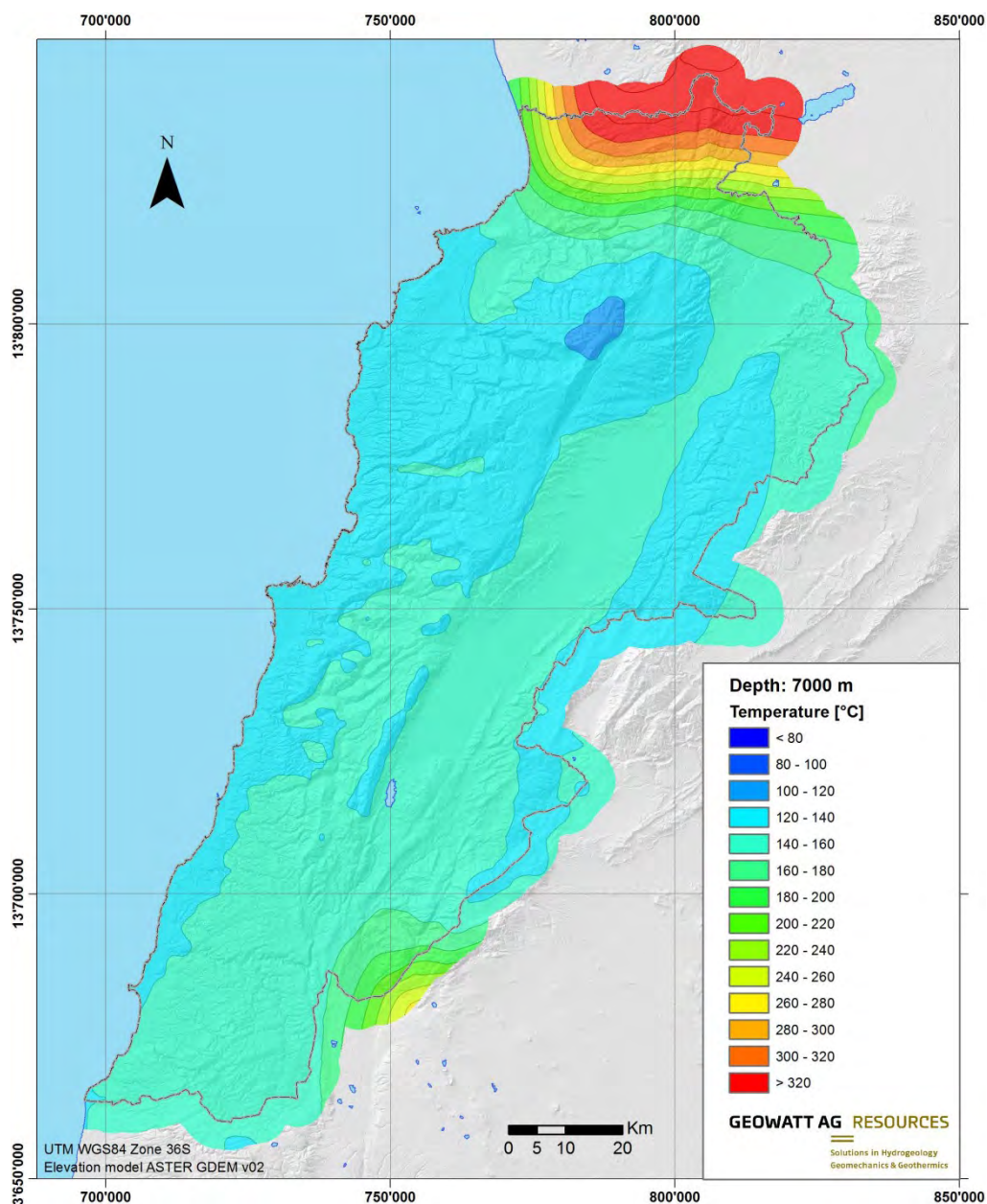




Appendix 20: Temperature in a depth of 6,000 m (BGL)

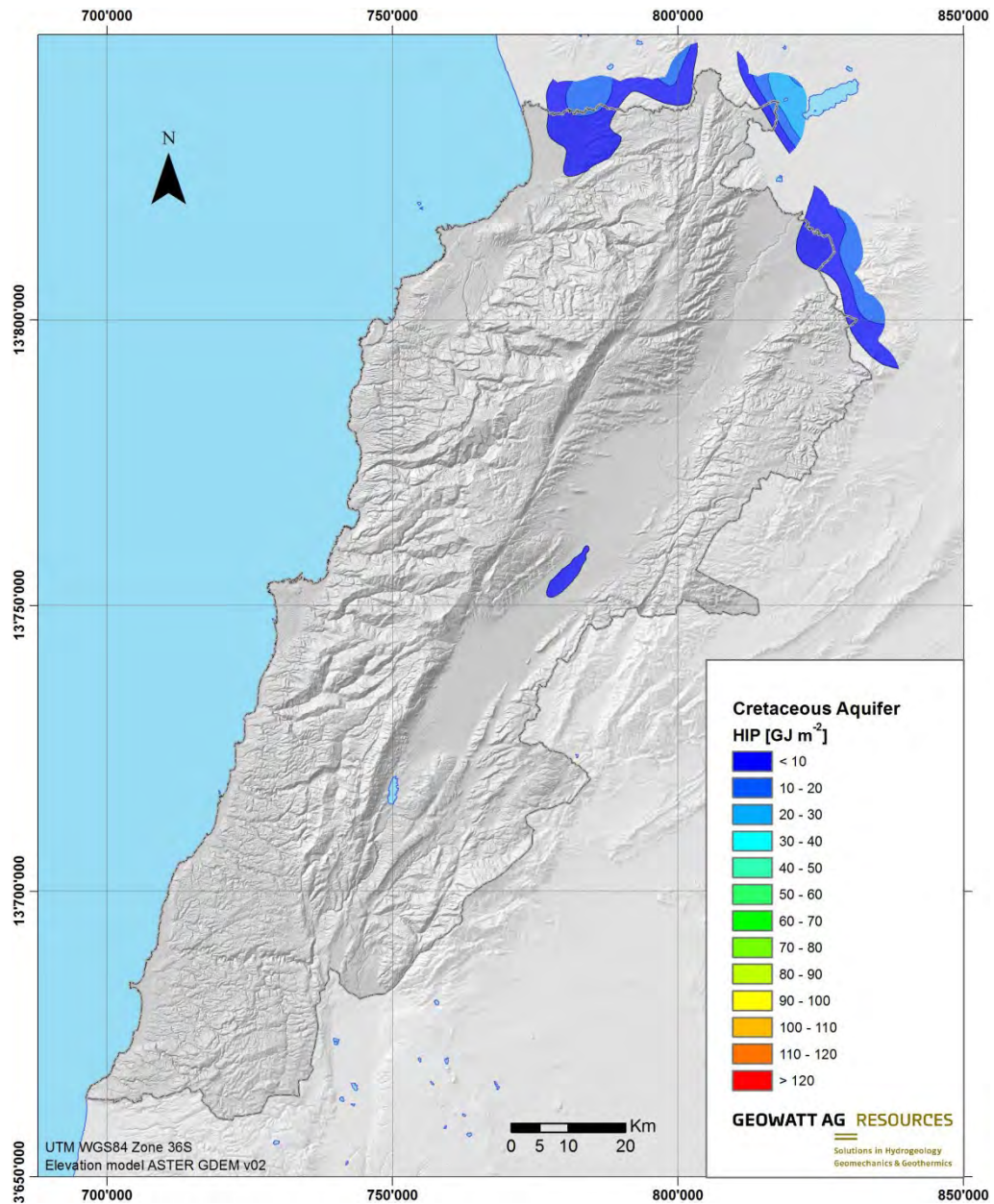


# Appendix 21: Temperature in a depth of 7,000 m (BGL)

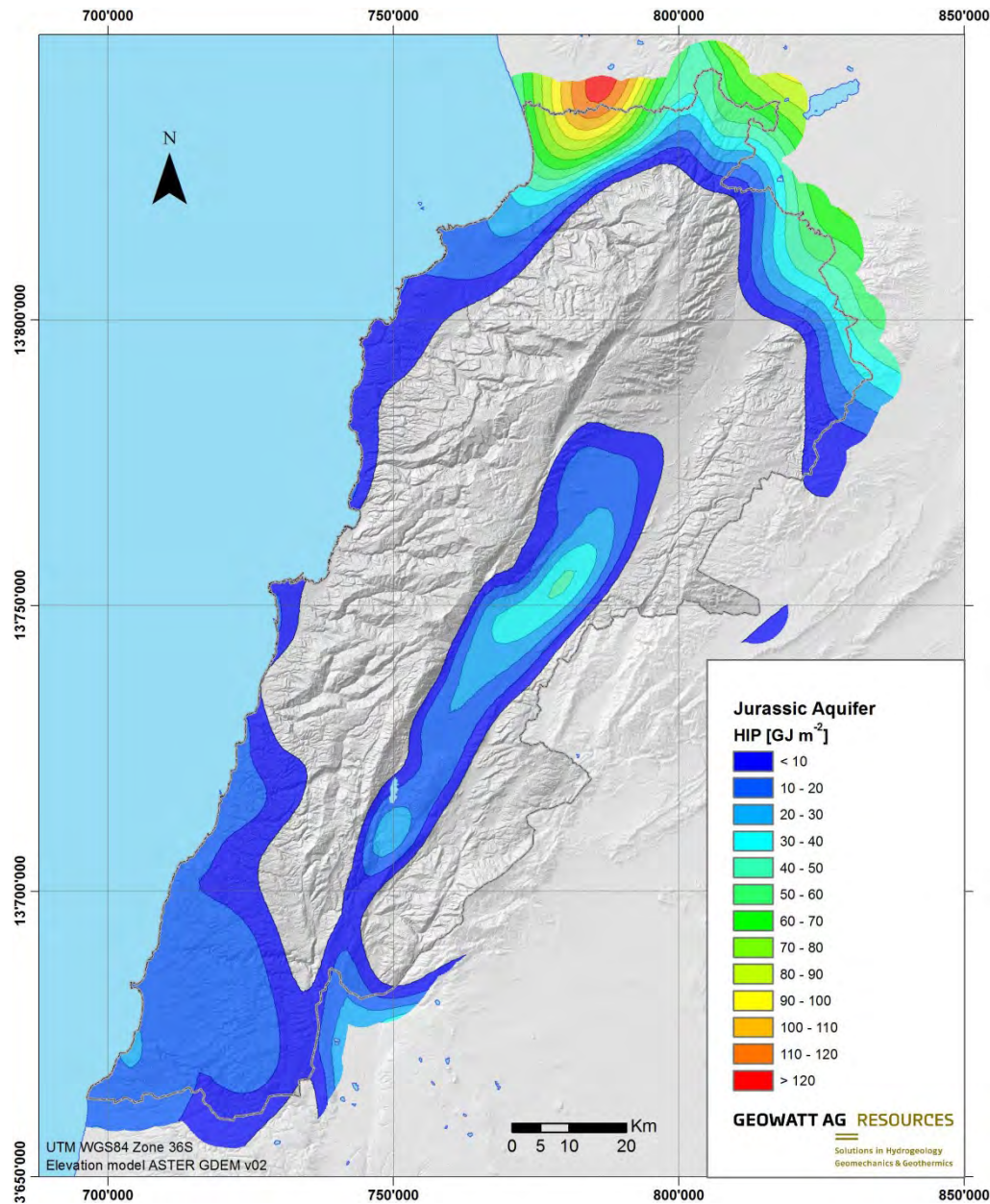




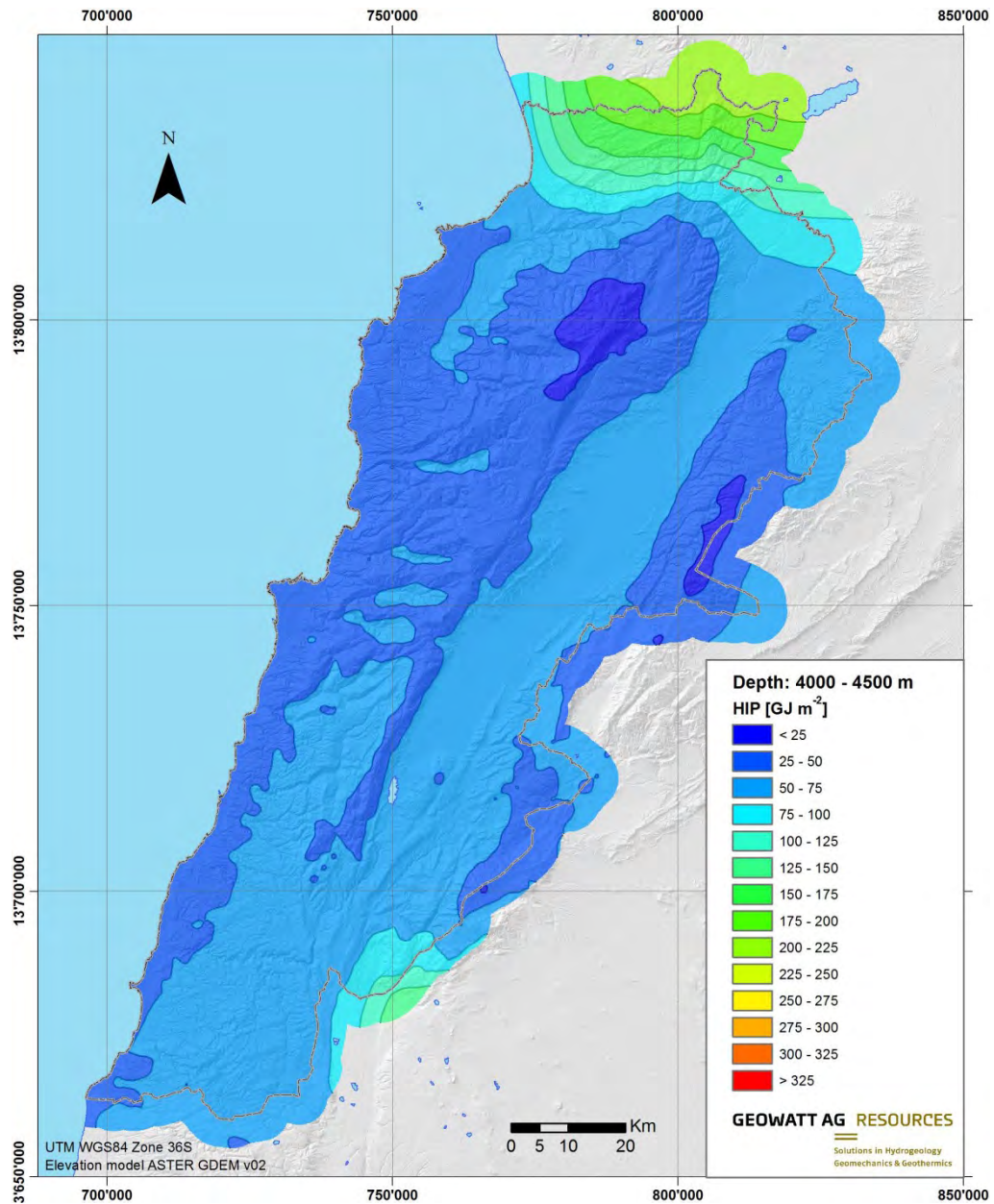
## Appendix 22: Stored heat (HIP) for the Cretaceous aquifer



Appendix 23: Stored heat (HIP) for the Jurassic aquifer

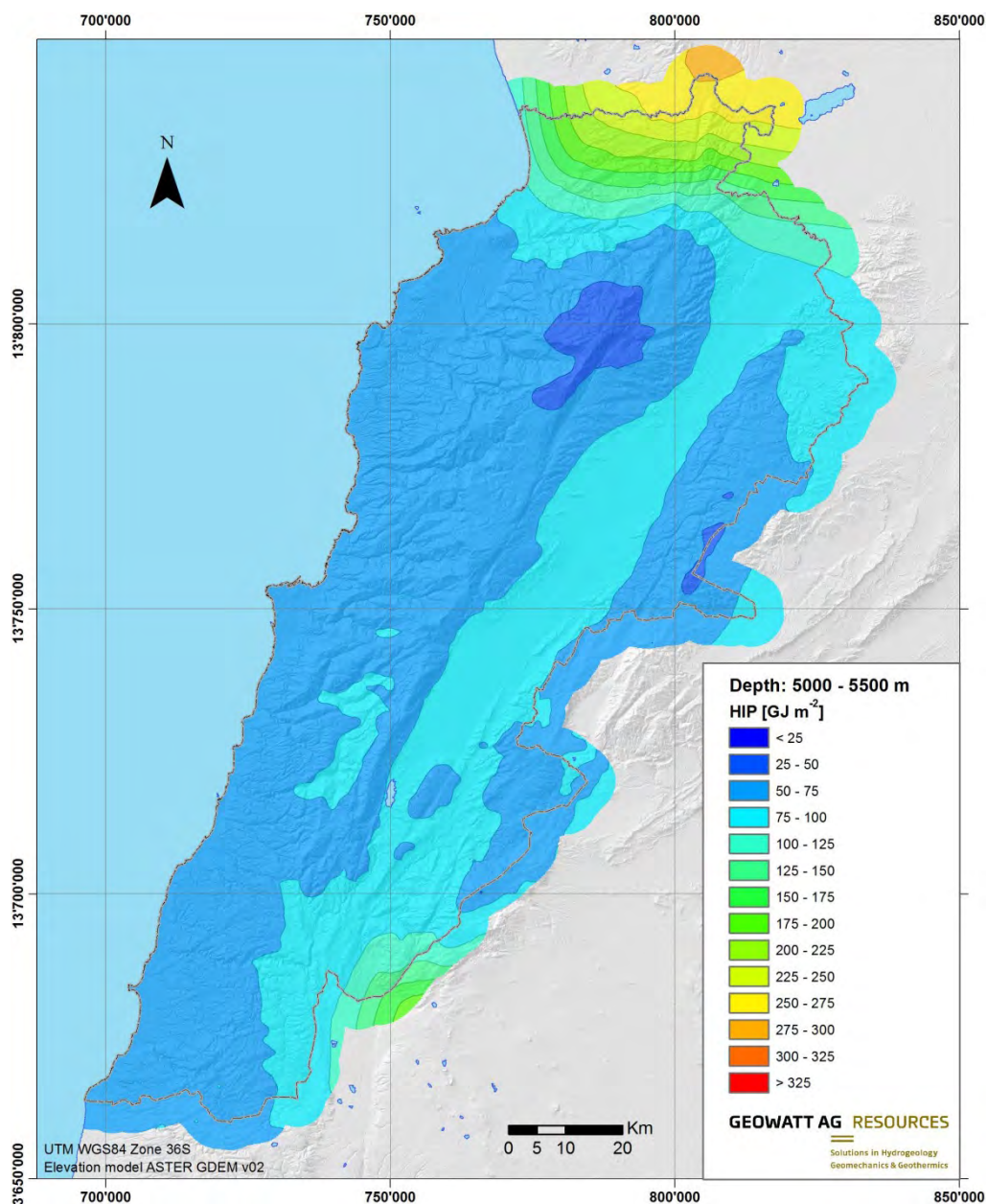


Appendix 24: Stored heat (HIP) for the depth interval 4,000-4,500 m

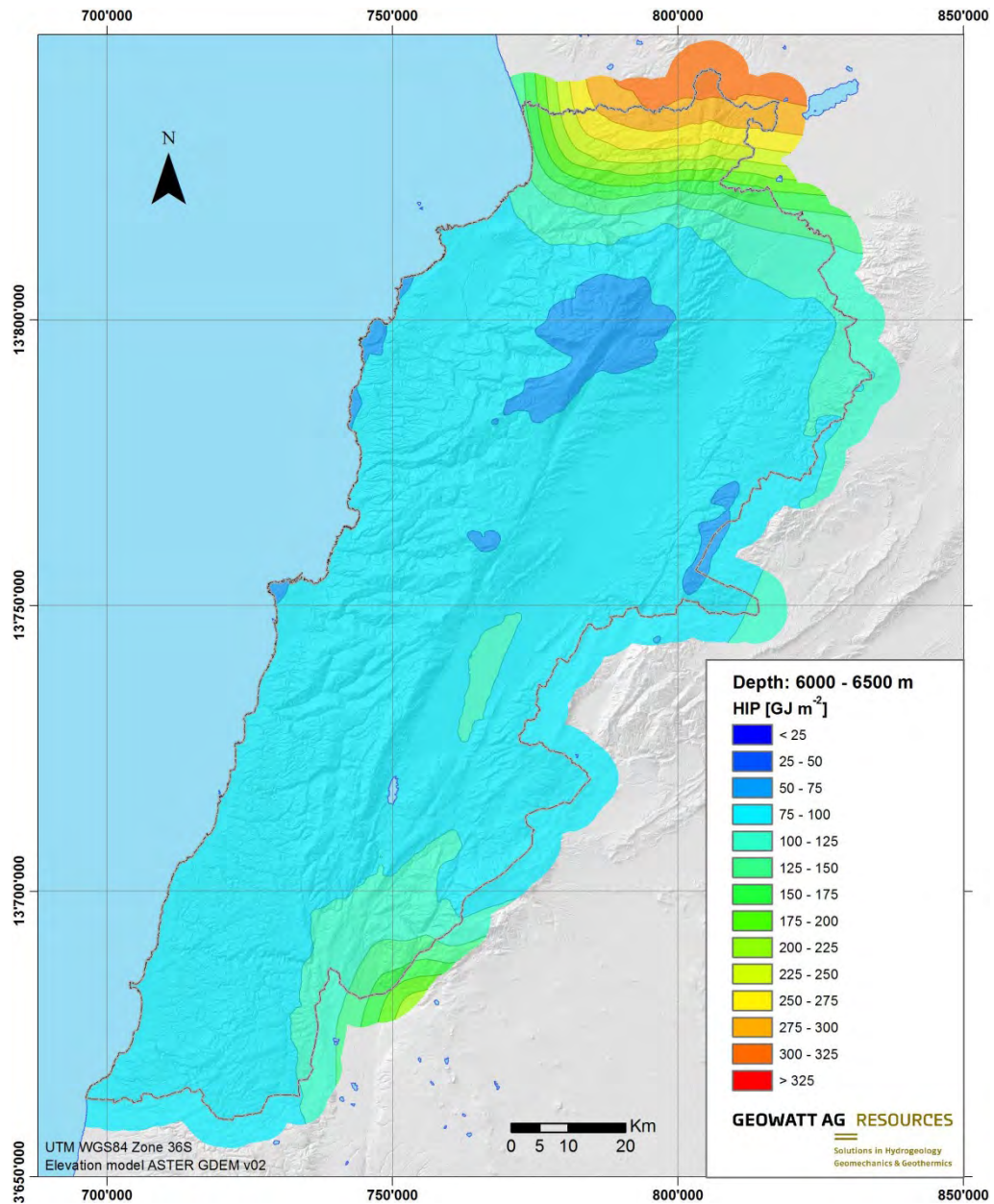




# Appendix 25: Stored heat (HIP) for the depth interval 5,000-5,500 m

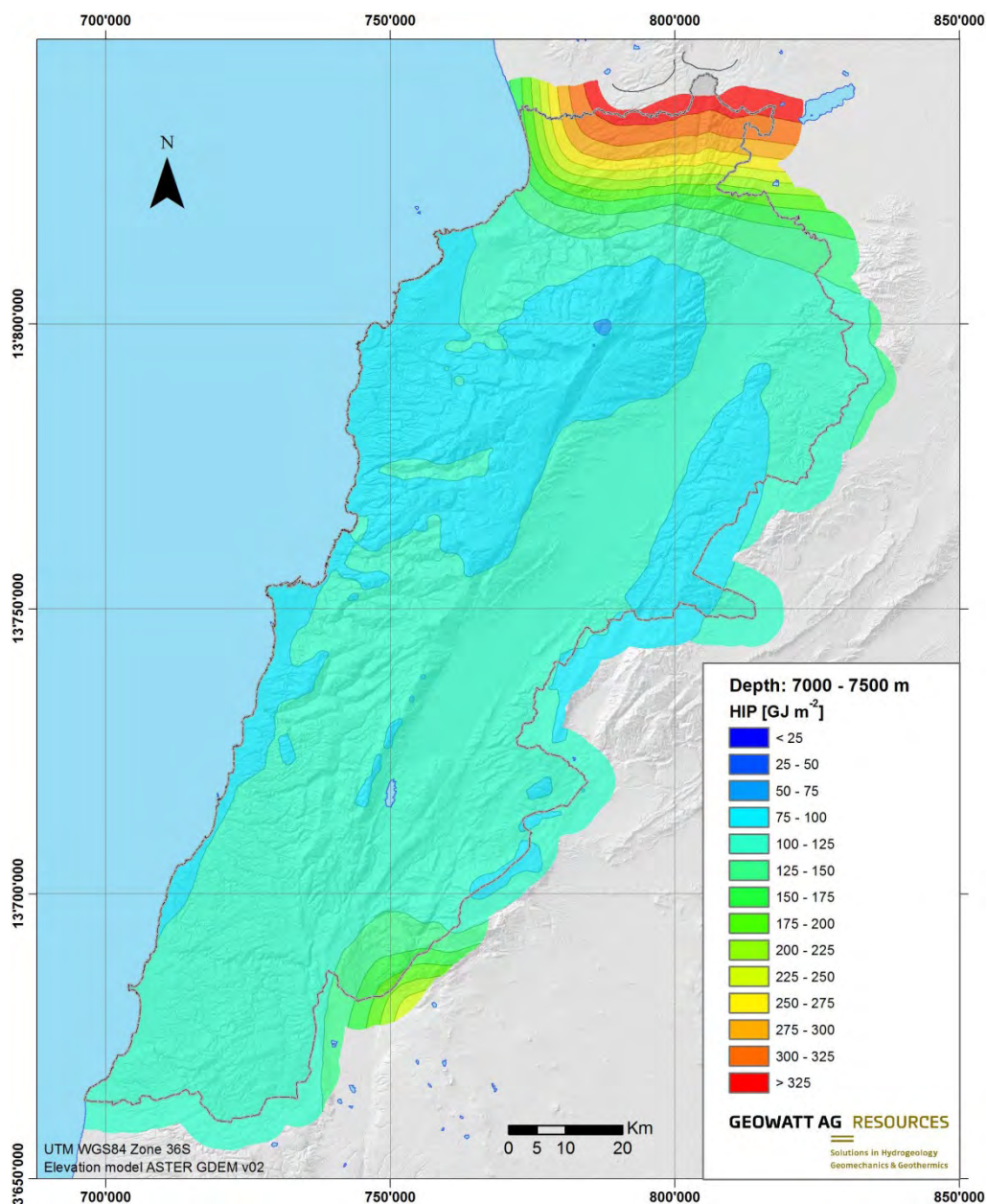


Appendix 26: Stored heat (HIP) for the depth interval 6,000-6,500 m

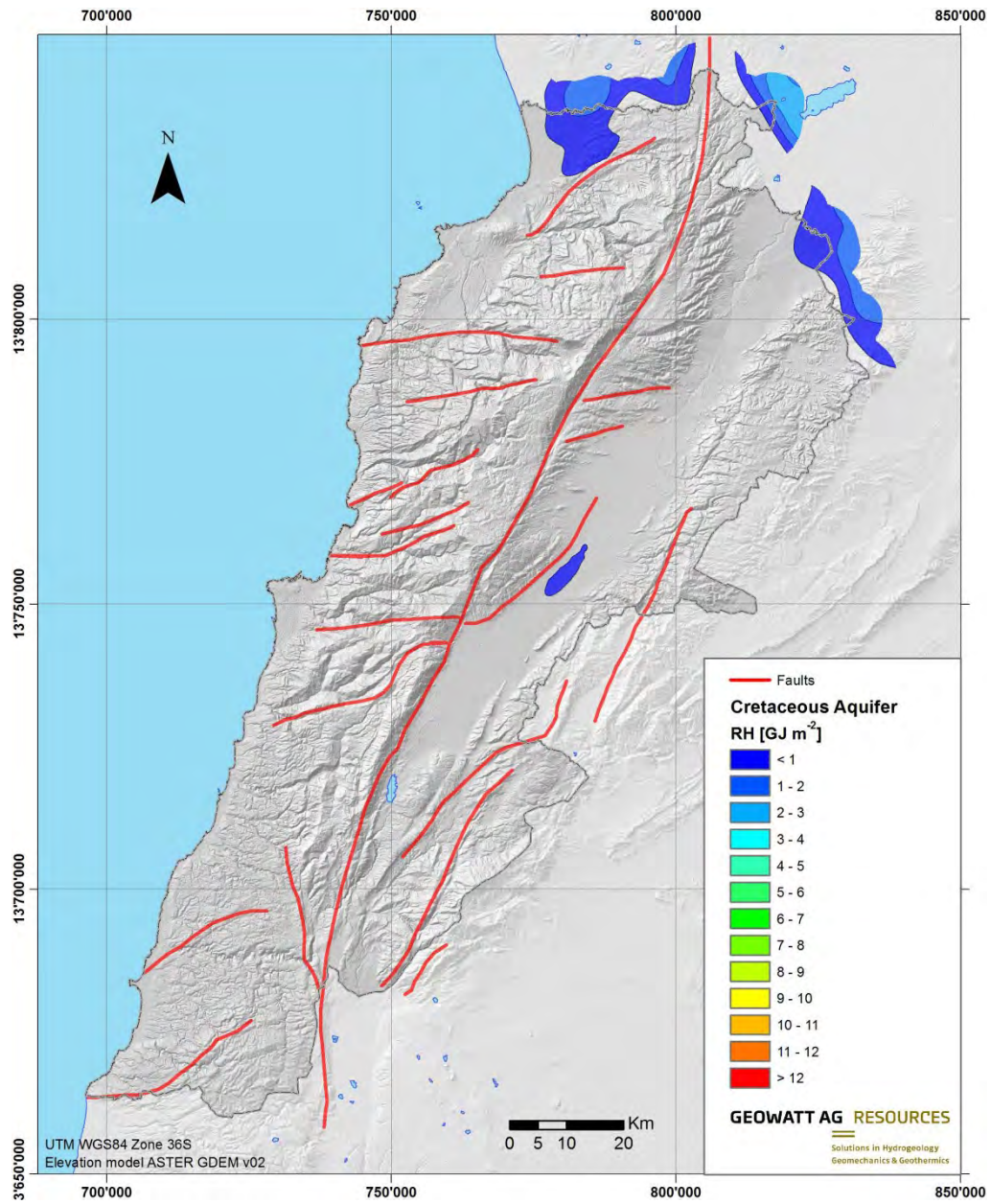




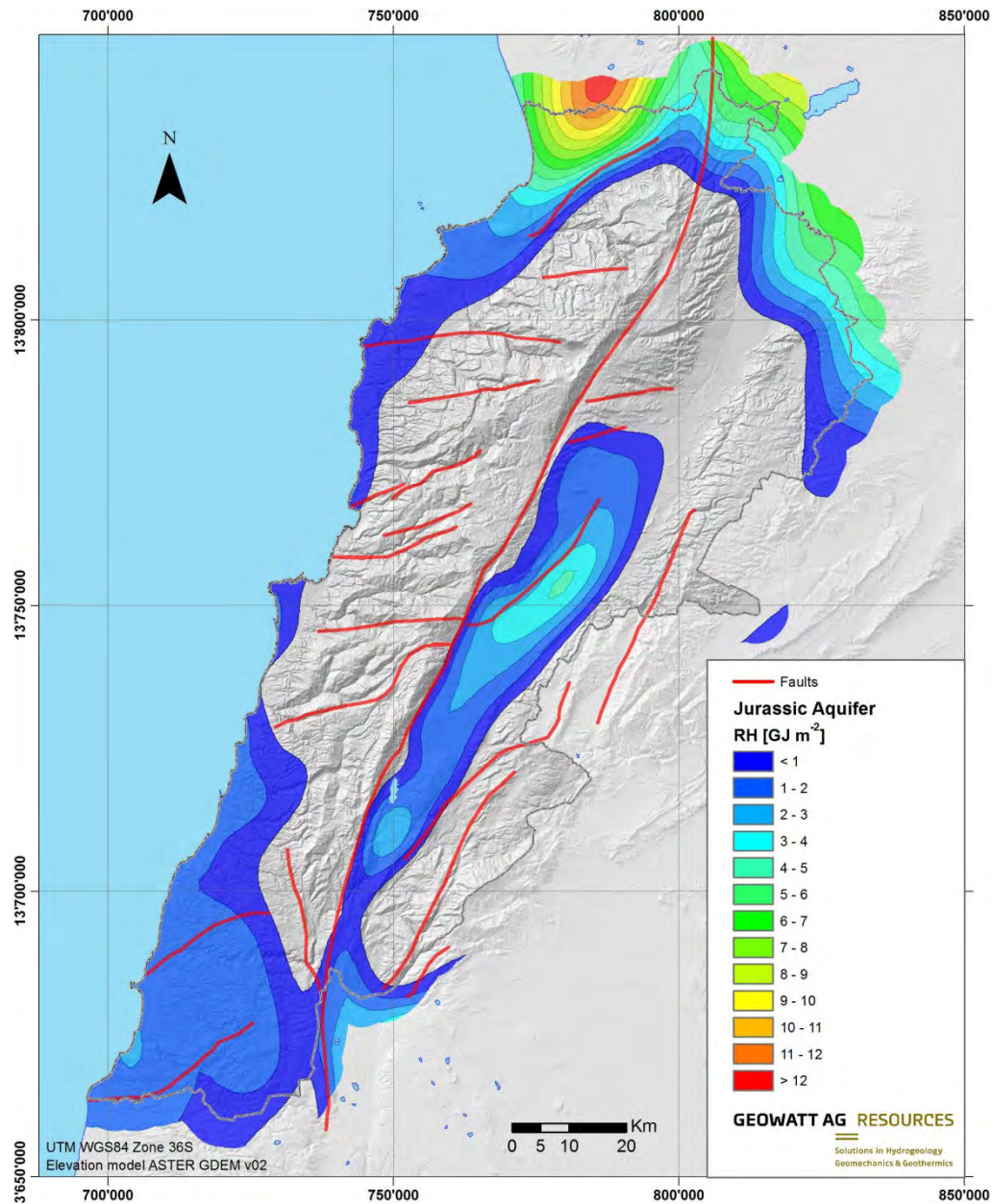
# Appendix 27: Stored heat (HIP) for the depth interval 7,000-7,500 m



# Appendix 28: Recoverable heat (RH) for the Cretaceous aquifer

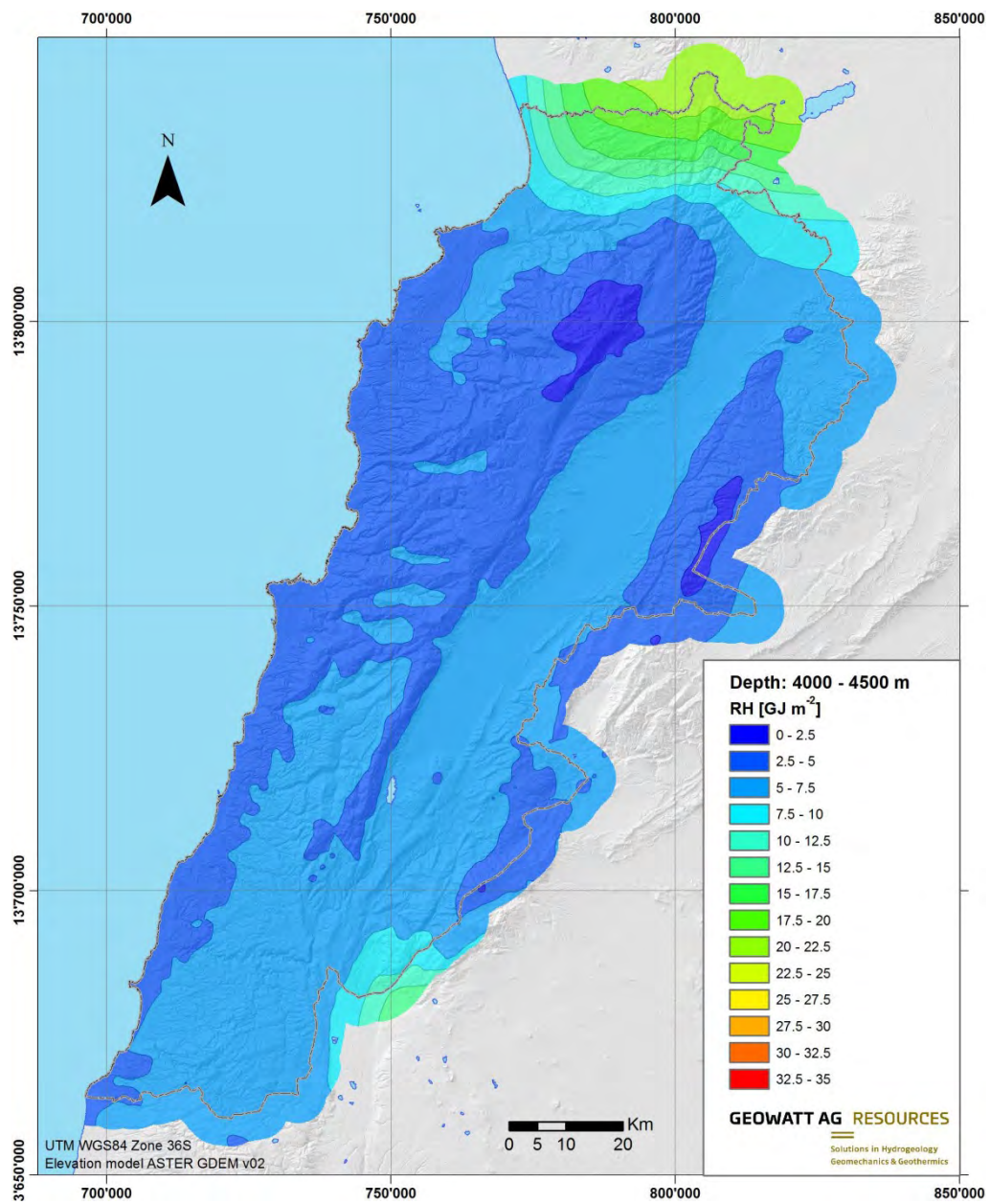


Appendix 29: Recoverable heat (RH) for the Jurassic aquifer

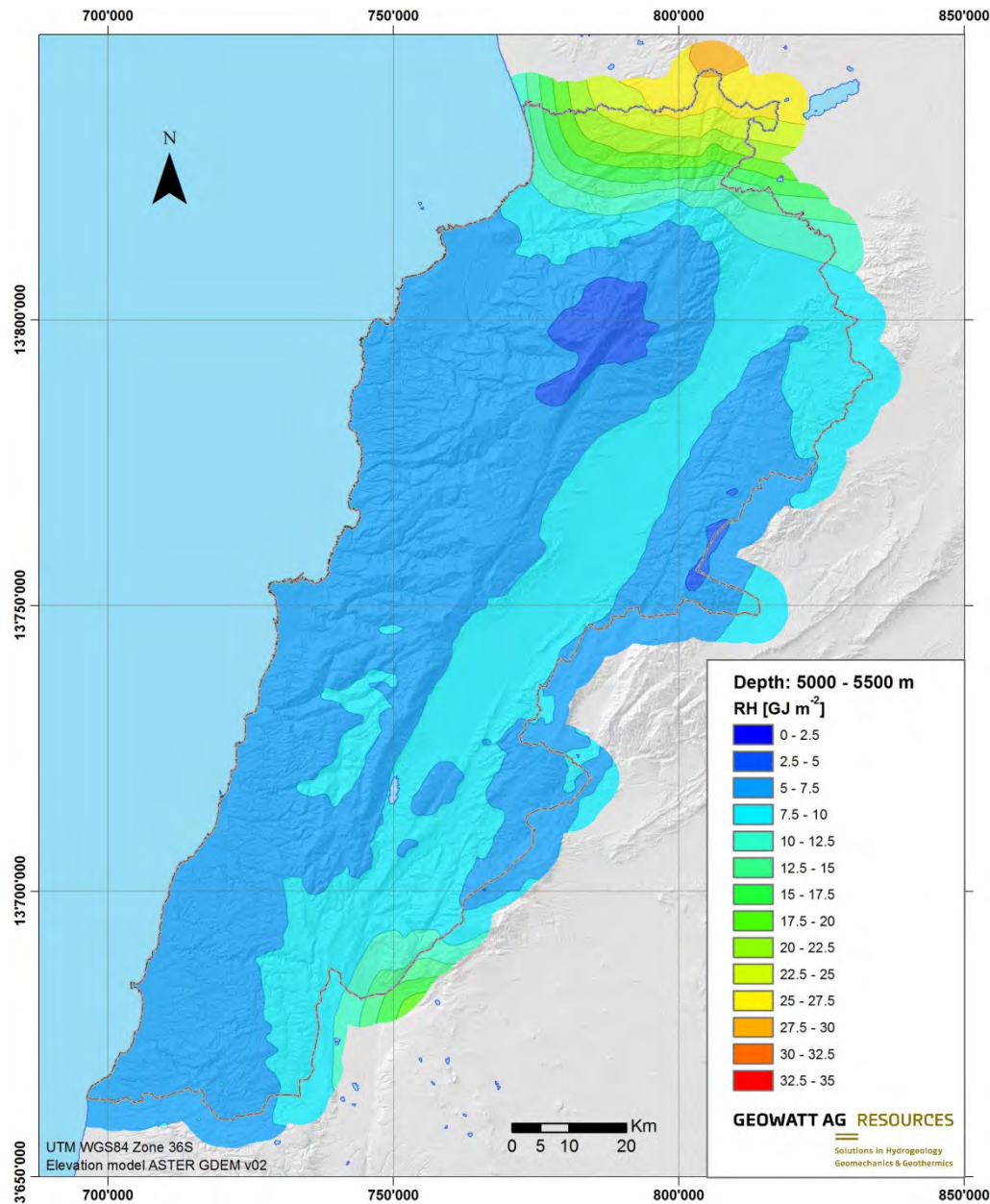




Appendix 30: Recoverable heat (RH) for the depth interval 4,000-4,500 m

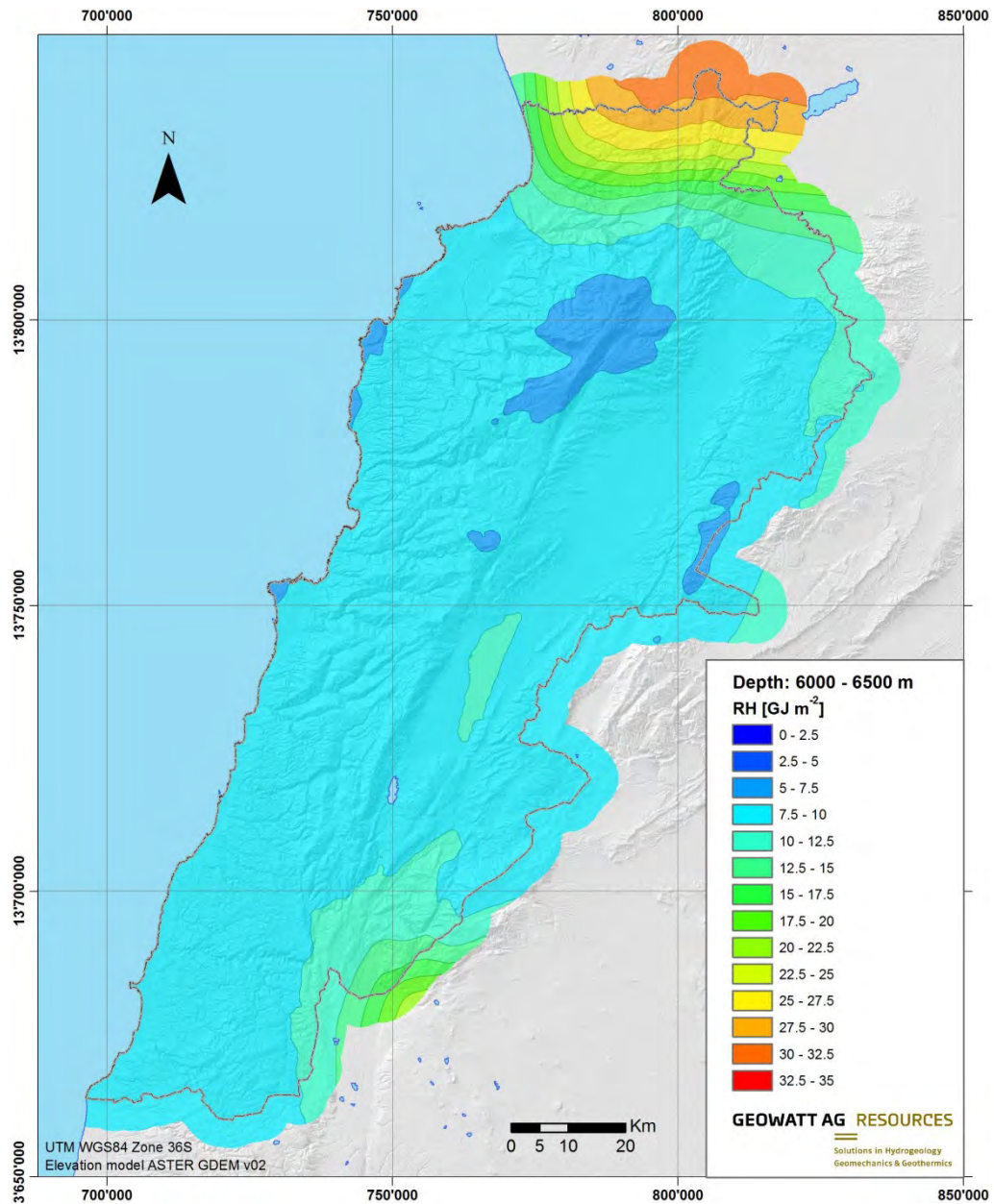


Appendix 31: Recoverable heat (RH) for the depth interval 5,000-5,500 m

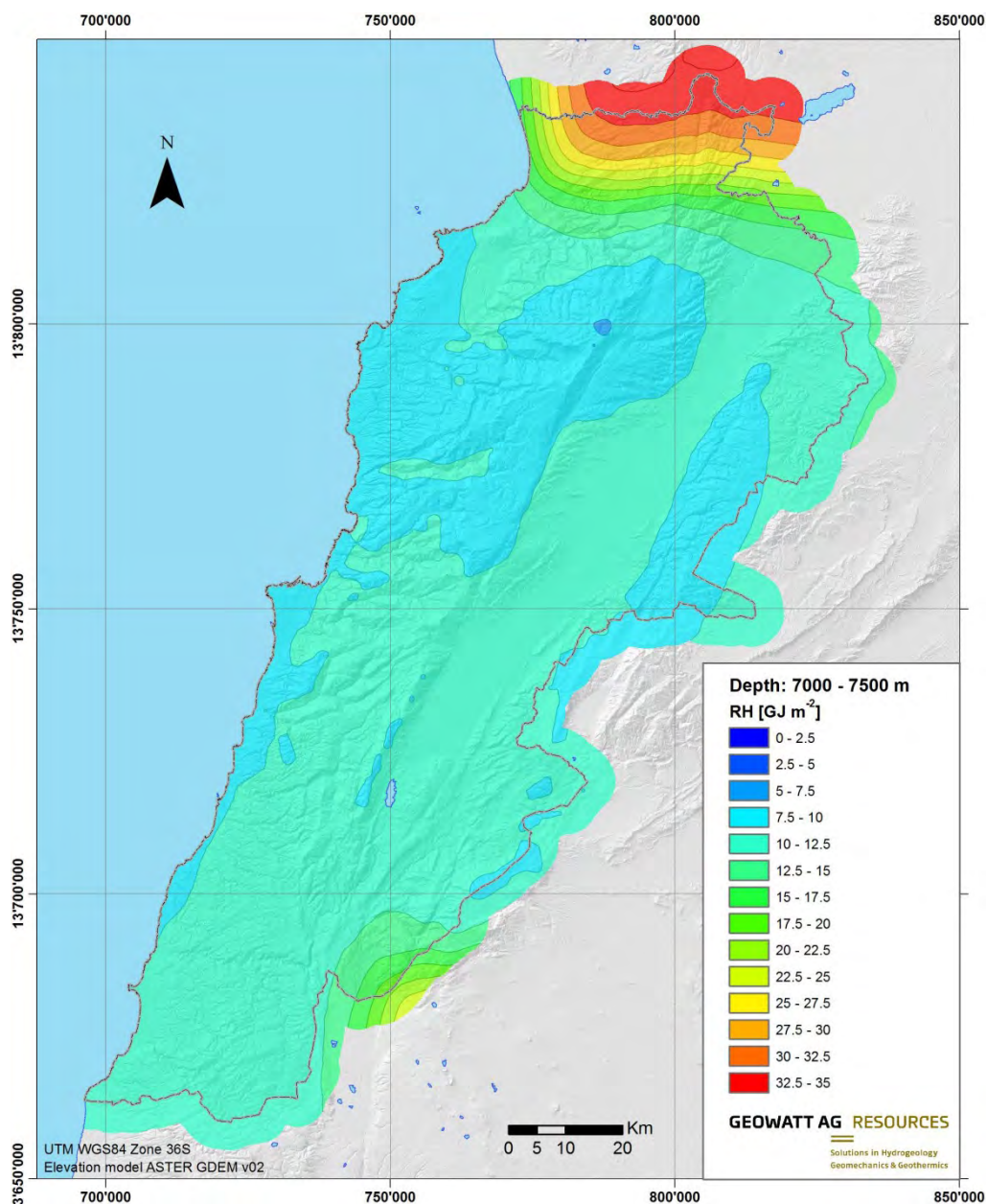




Appendix 32: Recoverable heat (RH) for the depth interval 6,000-6,500 m



# Appendix 33: Recoverable heat (RH) for the depth interval 7,000-7,500 m



<p>Power Generation Heat Production Combined Heat and Power</p> <p>Possible applications:</p> <ul style="list-style-type: none"> <li>- Power generation</li> <li>- Heating</li> <li>- Agriculture (green house)</li> <li>- Industry</li> <li>- Spa/Thermal Center</li> <li>- Healthcare</li> <li>- Tourismus</li> </ul>	<p>The Geothermal Atlas could be used by project developers (public or private) to get a first estimate of the relevant parameter of a geothermal project, all over Lebanon. Based on these parameters a technical and economic feasibility study could be established.</p> <ul style="list-style-type: none"> <li>- Site selection process to locate the most suitable areas for a pilot project;</li> <li>- Estimation of the depth and temperature of the reservoir;</li> <li>- Estimation of the heat in place and recoverable heat;</li> </ul> <p>These maps are estimates based on the current knowledge and consider the present state of technology. Thanks to the applied methodology (3D numerical modelling), new estimates for available heat and power could be obtained with a minimum of effort.</p> <p>Although EGS technologies are not mature yet to be applied in Lebanon, the geothermal atlas provides maps of the heat in place, which corresponds to the theoretical energy stored in the underground in form of heat. Depending on the future development of the EGS technologies, recoverable heat maps could be deduced from the HIP maps simply by modifying the recovery factor.</p>
Shallow Geothermal Energy	<p>The main focus of the Geothermal Atlas was on technologies applied for power generation. The Atlas could still be used as a background study for the design and realization of shallow geothermal installations, based on heat pump technologies.</p> <p>Groundwater use and seasonal storage installations could be investigated as well.</p>
Oil and gas energy	<p>The maps provided in the geothermal atlas are based on a 3D structural model. This model could be used by the oil and gas industry in order to better understand the deep structures in Lebanon.</p> <p>The temperature prediction at depth could provide important insights to estimate the degree of maturity of hydrocarbons.</p>
CO <sub>2</sub> sequestration	<p>CO<sub>2</sub> sequestration constitutes one the solutions investigated by many countries in the world to assist in reaching the Kyoto Protocol objectives. This study could be used as a basis for studying the potential of Lebanon for CO<sub>2</sub> sequestration in deep geological layers.</p>

Groundwater management (deep aquifers)	The understanding of the deep geological structures has also many implications on the groundwater management, for agriculture or domestic use. The resource of deep aquifers is generally much better protected against contamination than water located at shallow depth. Deep groundwater is therefore very strategic. This study contributes in the understanding of the deep aquifer structure.
Infrastructure (Tunnels)	The 3D geological model of Lebanon could be used for planning of deep underground infrastructures, such as tunnels for instance.
General Scientific Background	<p>The study provided an important contribution to the general understanding of the deep geological structures in Lebanon and could be used for further R&amp;D activities related to the underground usage.</p> <ul style="list-style-type: none"> <li>- A 3D geological model of Lebanon has been developed</li> <li>- Prediction of the temperature at depth are provided</li> <li>- New measurements of temperature in shallow abandoned groundwater wells have been performed.</li> <li>- Thermal conductivity measurements have been performed on around 15 rock samples, representative of the main rocks formation in Lebanon.</li> </ul>

(Footnotes)

1 This value is based on the maximal thermal breakthrough time in the reservoir. Depending on the chemical conditions in the reservoir, the lifetime could be reduced to 20 years.

2 The electrical power of a pilot geothermal installation in Lebanon is expected to be comprised between 1 to 3 MW<sub>el</sub>.