# *Methodologies for geothermal resource assessment, with special reference to the Mutnovsky Geothermal Power Project*

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# *The Mutnovsky Field*

- Most thoroughly studied in Russia
- Largest geothermal development in Russia
  - first plant in 1999: 12 MWe
  - second plant in 2003: 55 Mwe
- Located in Kamchatka
- Comparable to other high-temperature geothermal systems on the Pacific Rim

# *What do we mean by "Resource Capacity" ?*

> The assessment of "resource capacity" for a geothermal system can be based on a number of different criteria

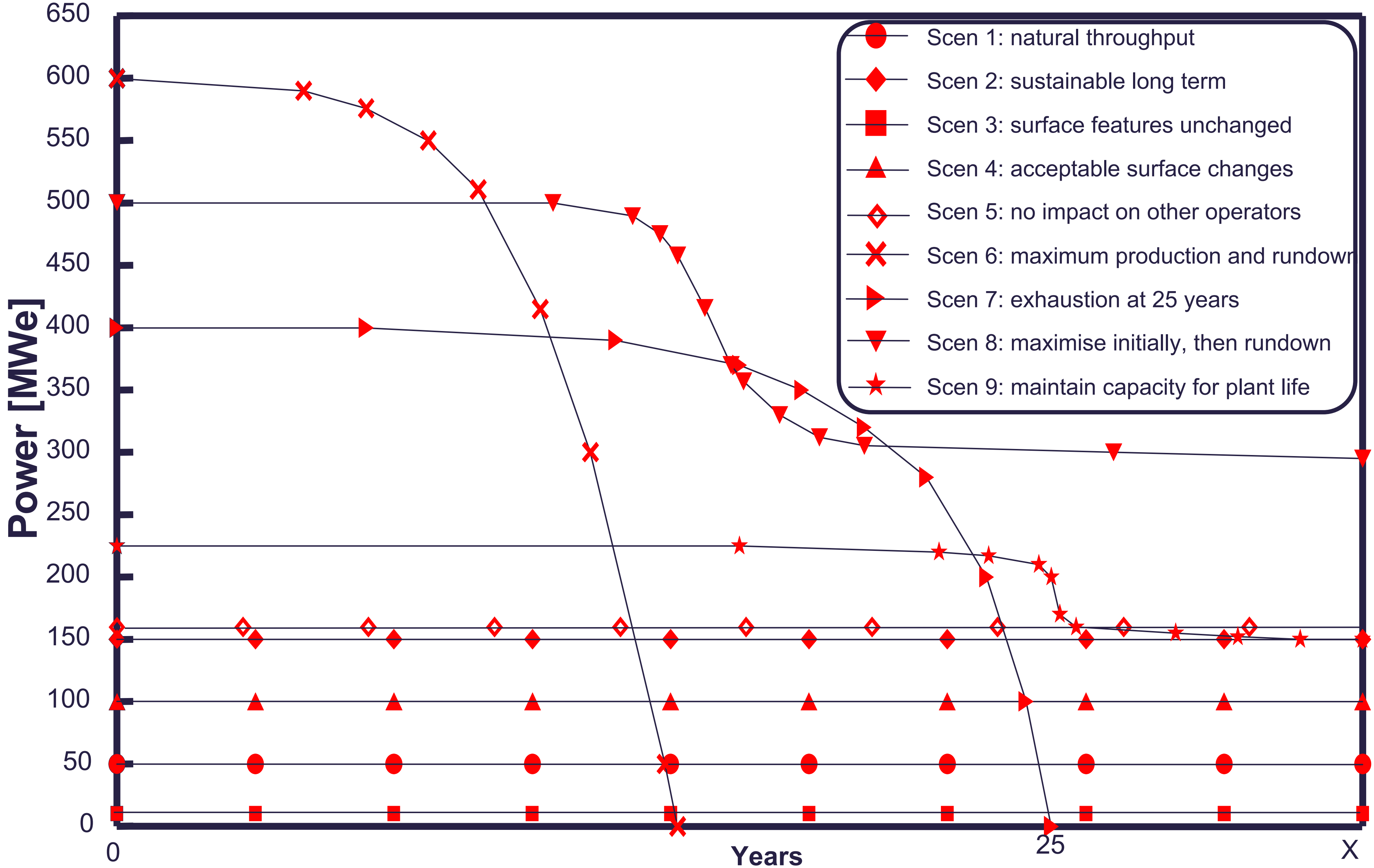
> Usually we mean "the output that can be sustained for a 20-30 year project life, with a suitable contingency"

> But there are other possibilities, e.g. minimising environmental effects, maximising economic return

## *Examples of various capacity estimates for a single field*

| Scenario | Description | Production Level (MW) |
|---|---|---|
| 1 | Natural throughput | 50 |
| 2 | Sustainable long term | 150 |
| 3 | No impact on surface features | 10 |
| 4 | Acceptable surface changes | 100 |
| 5 | No impact on other operators | 160 |
| 6 | Maximum production rate | 600 / 0 |
| 7 | Field exhausted after 25 years | 400 / 0 |
| 8 | Maximum initially; rundown | 500 / 300 |
| 9 | Maximum for plant life | 225 / 150 |

# *Depletion curves*



# *For Mutnovsky*

The recent resource capacity estimates for Mutnovsky are based on what is reasonably physically sustainable, at an acceptable level of drilling and piping cost, for a 25 year project life

# *Preliminary assessment methods*

Heat flux method

- based on estimate of natural heat flow
- gives a minimum sustainable output
  - but usually very much an underestimate of what is actually achievable
- can use a correction factor to estimate possible development size ?
  - eg. Iceland; factor of 10x
- For Mutnovsky using this method
  - initial estimate of 75 MWe
  - later 105 MWe for part of field only
  - proved to be suitably conservative

# *Preliminary assessment methods*

## Areal method

- based on an empirical analogy with other fields
- assume a power density (MW/km2)
  - minimum value of 10
  - maximum value of 25
    - where there is proven high enthalpy and permeability
  - note some studies have used unrealistically high factors, eg. 40-60 MW/km2
- multiply by area

# *Examples of production density*

| Field | Installed Capacity (MWe) | Area ($km^2$) | | Extraction Rate ($MWe/km^2$) | |
|---|---|---|---|---|---|
| | | Whole Field | Bore Field | Whole Field | Bore Field |
| **Bulalo** | 370 (+40) | 20 | 8.8 | 19 | 42 |
| **Tiwi** | 330 | 12 | 10 | 28 | 33 |
| **Tongonan I** | 112.5 | 40 | 4 | 2.9 | 28 |
| **Leyte (total)** | 670 | 30 | 15 | 22 | 45 |
| **Palinpinon** | 192 | 18 | 10 | 11 | 19 |
| **Bacon Manito** | 150 | 16 | 6 | 9 | 25 |
| **Gunung Salak** | 330 | 18 | 5 | 18 | 66 |
| **Cerro Prieto** | 620 | 20 | 20 | 32 | 32 |
| **Ahuachapan** | 125 | 6.4 | 1.3 | 20 | 20 |
| **Otake & Hatchobaru** | 67.5 | 12 | 0.03 | 5.6 ( | 367 |
| **Ohaaki** | 116.2 | 12 | 1.7 | 9.7 | 68 |
| **Wairakei** 1998 (I) | 184 | 25 | 2.5 | 7.4 | 74 |
| **Lardarello** | 400 | 180 | | 2.2 | |
| **The Geysers** | 1,000 | 78 | | 13 | |

# *Areal method at Mutnovsky*

> This is the basis of the “Russian Standard Method”, which has been applied twice at Mutnovsky, giving estimates of 324-330 MWe for the whole field, divided into various levels of confidence

> A good method for early assessment, but it now needs updating to take account of new data and greater plant efficiency

# *Later assessment methods*

Well outputs

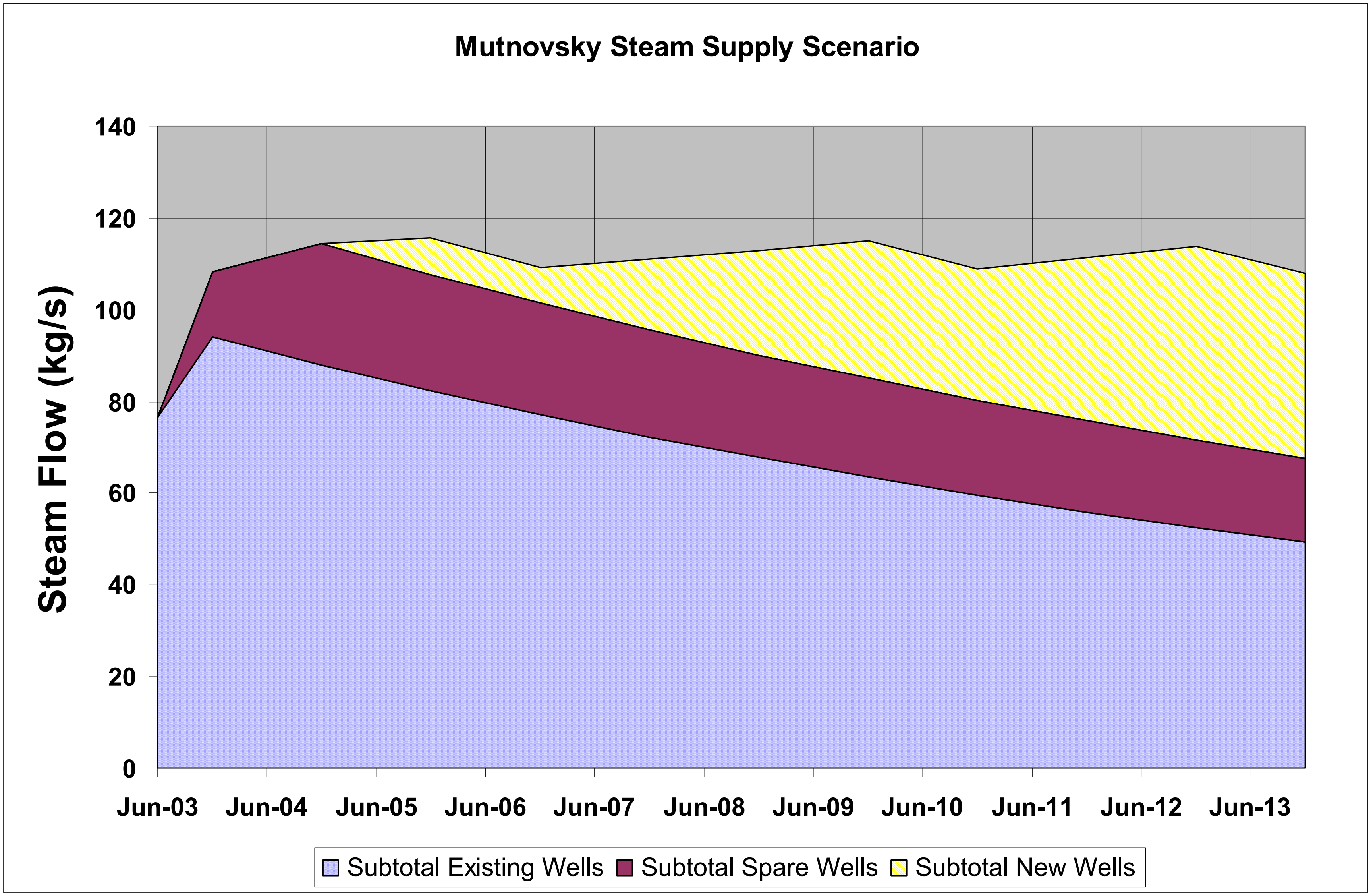
> total of measured outputs

> extrapolate using wellbore simulation fro future wells

> not specifically done as a method of overall resource assessment at Mutnovksy,  but done informally at various stages

> reveals the need for on-going drilling

# *Mutnovsky total well outputs, stage I*



# *Later exploration / delineation*

Stored heat method

> estimate heat stored in reservoir volume
> includes both rock and fluid (steam/water)
> corrected for recovery / efficiency of conversion
> note: Mutnovsky plant more efficient than most

$$Q = A \cdot h \cdot \left\{ \left[ C_r \cdot \rho_r \cdot (1-\phi) \cdot (T_i - T_f) \right] + \left[ \rho_{si} \cdot \phi \cdot (1 - S_w) \cdot (h_{si} - h_{wf}) \right] + \left[ \rho_{wi} \cdot \phi \cdot S_w \cdot (h_{wi} - h_{wf}) \right] \right\}$$

heat in rock — heat in steam — heat in water

$$E = \left[ \frac{Q \cdot R_f \cdot \eta_c}{F \cdot L} \right]$$

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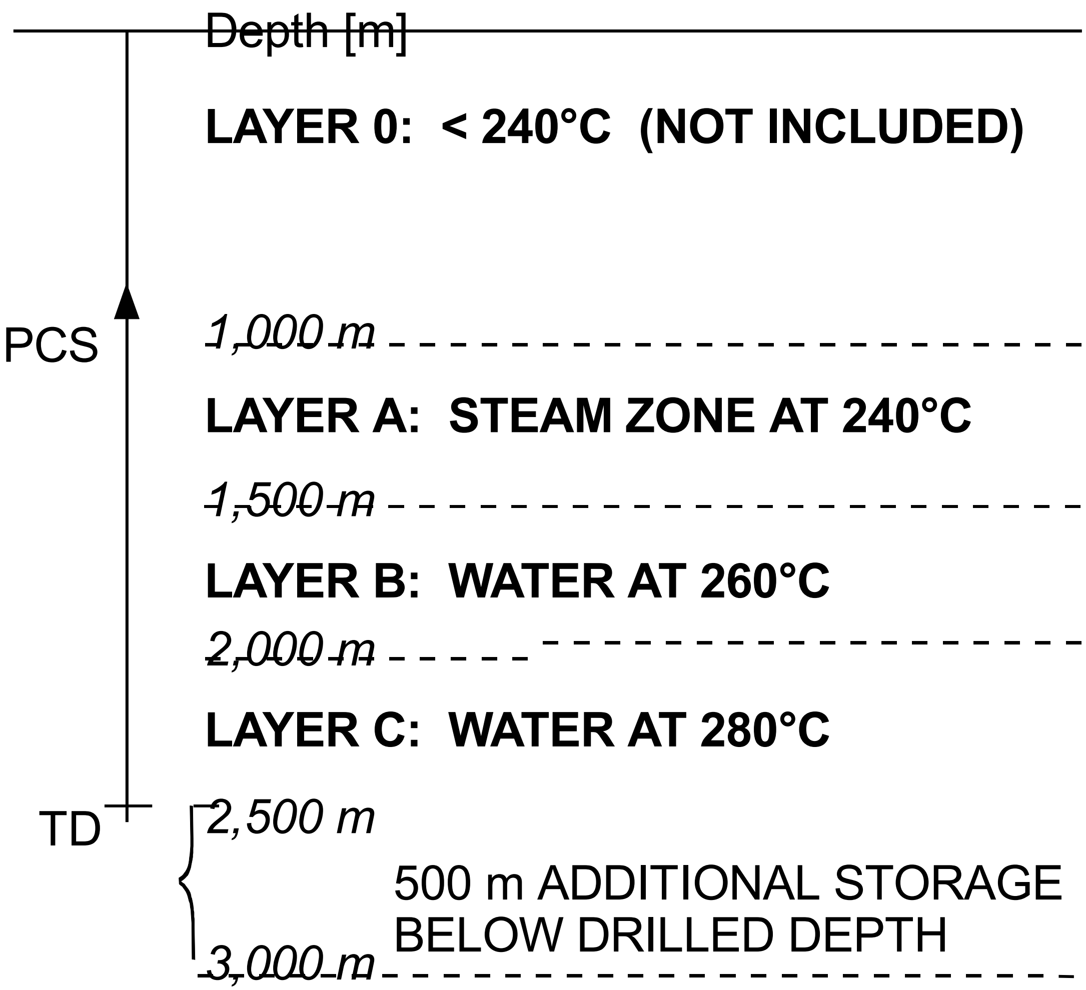
# *Stored heat model*

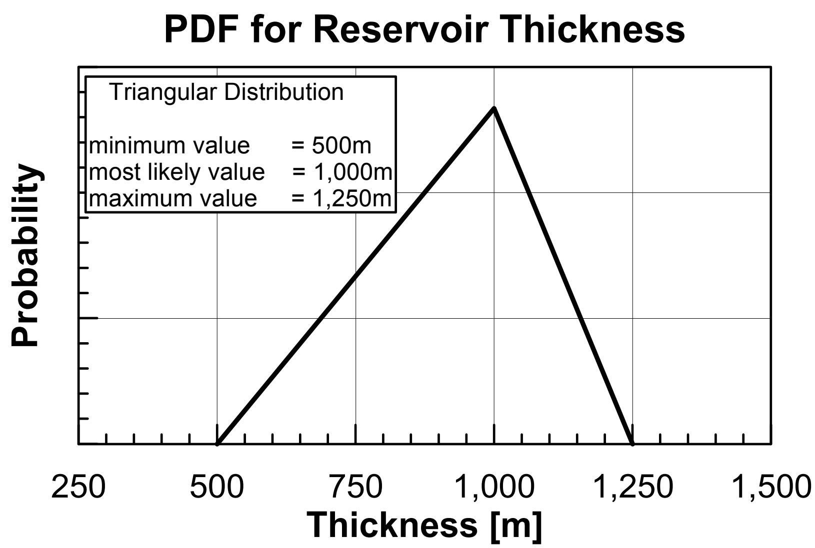


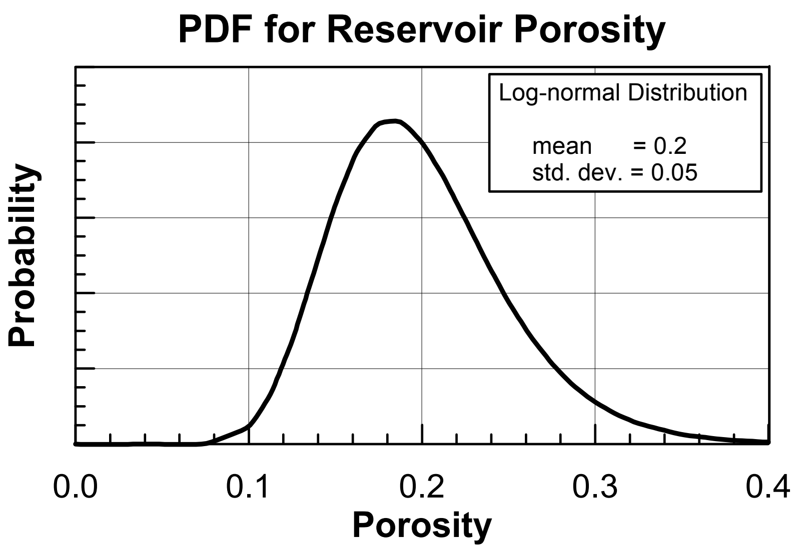
# *Later exploration / delineation*

## Monte Carlo Simulation

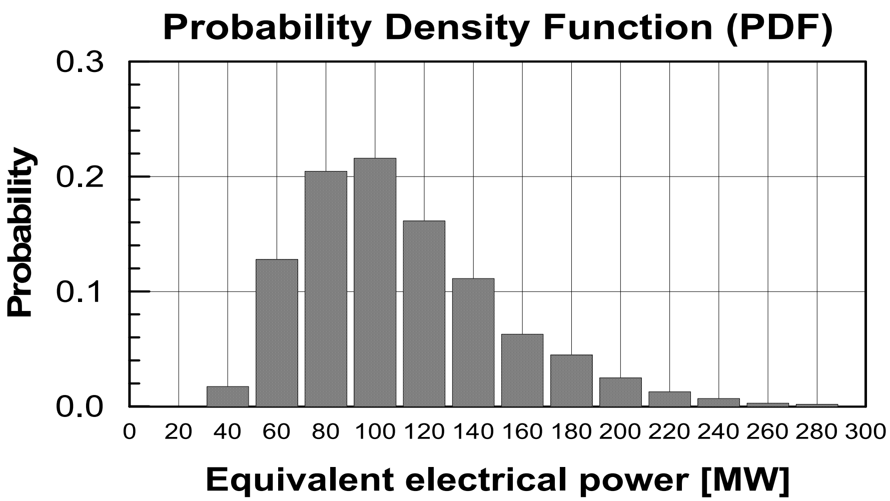
- refinement of stored heat method
- based on “probability ranges” for parameters rather than point values
- model generates values for stored heat parameters
- stored heat calculations repeated many times (2,000) until probability distribution for field output obtained

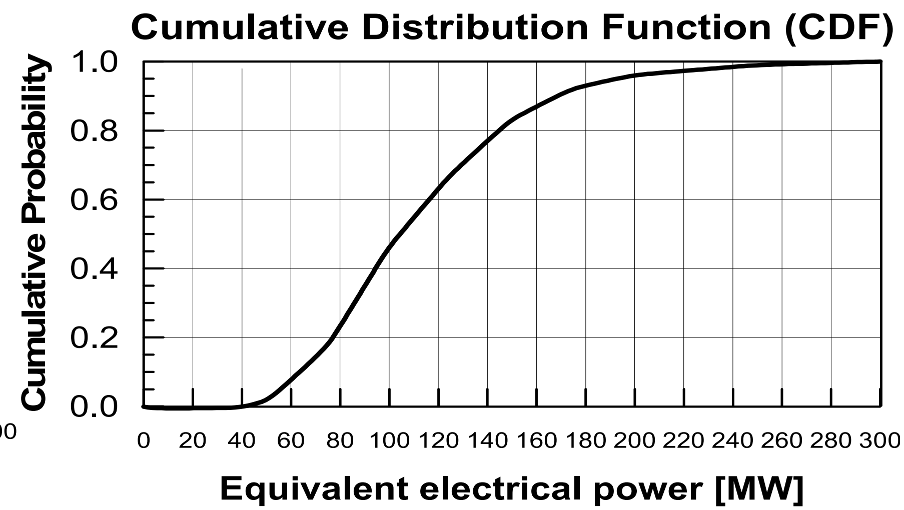
# *Probability distributions*



# *Monte Carlo simulation of resource capacity*

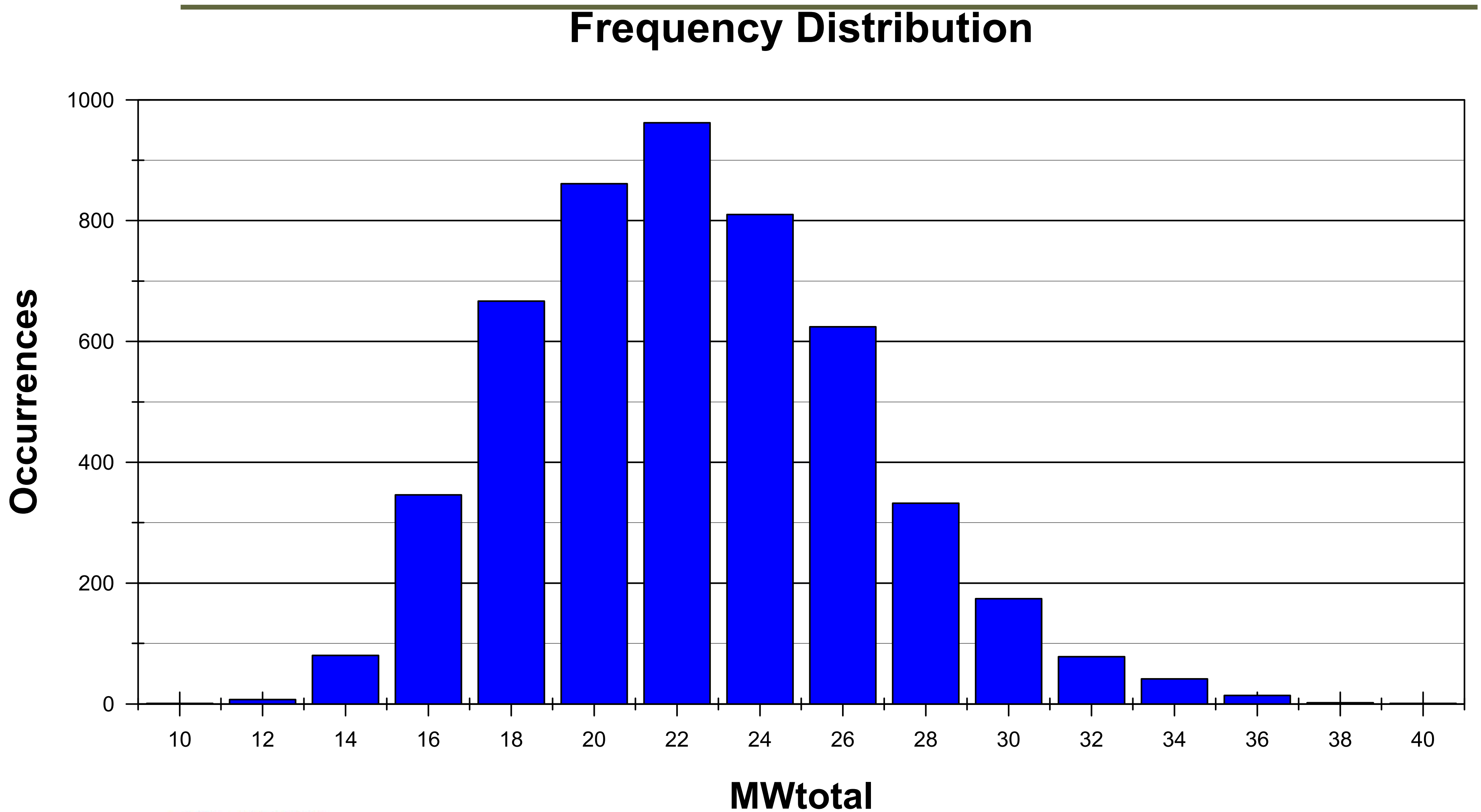


# *Input parameters for Mutnovsky stored heat estimate*

| Sector | Layer | Temp °C | | | Thickness m | | | Area $km^2$ | | | Porosity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Min | Med | Max | Min | Med | Max | Min | Med | Max | Min | Med | Max |
| Northern Dachny | 1 | 180 | 220 | 230 | 300 | 500 | 600 | 3.0 | 3.9 | 4.2 | 0.10 | 0.12 | 0.15 |
| | 2 | 220 | 240 | 250 | 450 | 450 | 450 | 3.0 | 3.9 | 4.2 | 0.08 | 0.10 | 0.12 |
| | 3 | 2.4 | 270 | 280 | 300 | 950 | 1450 | 3.0 | 3.9 | 4.2 | 0.04 | 0.06 | 0.08 |
| Central Dachny | 1 | 200 | 240 | 250 | 300 | 500 | 600 | 0.8 | 1.3 | 1.5 | 0.10 | 0.15 | 0.15 |
| | 2 | 240 | 260 | 270 | 450 | 450 | 450 | 0.8 | 1.3 | 1.5 | 0.08 | 0.10 | 0.12 |
| | 3 | 280 | 300 | 310 | 450 | 950 | 1450 | 0.8 | 1.3 | 1.5 | 0.04 | 0.06 | 0.08 |
| Southern Dachny | 1 | 200 | 240 | 250 | 300 | 500 | 600 | 1.6 | 2.9 | 3.2 | 0.10 | 0.12 | 0.15 |
| | 2 | 240 | 260 | 270 | 450 | 450 | 450 | 1.6 | 2.9 | 3.2 | 0.08 | 0.10 | 0.12 |
| | 3 | 280 | 300 | 310 | 400 | 950 | 1450 | 1.6 | 2.9 | 3.2 | 0.04 | 0.06 | 0.08 |
| Vulkanny | 1 | 180 | 230 | 240 | 200 | 500 | 600 | 3.3 | 6.3 | 7.0 | 0.10 | 0.12 | 0.15 |
| | 2 | 230 | 260 | 270 | 450 | 450 | 450 | 3.3 | 6.3 | 7.0 | 0.08 | 0.10 | 0.12 |
| | 3 | 240 | 280 | 290 | 300 | 950 | 1450 | 3.3 | 6.3 | 7.0 | 0.04 | 0.06 | 0.08 |
| V. Mutnovsky | 1 | 180 | 210 | 220 | 100 | 500 | 500 | 2.0 | 3.6 | 4.0 | 0.10 | 0.12 | 0.12 |
| | 2 | 210 | 230 | 240 | 450 | 450 | 450 | 2.0 | 3.6 | 4.0 | 0.08 | 0.10 | 0.12 |
| | 3 | 240 | 260 | 270 | 400 | 800 | 1000 | 2.0 | 3.6 | 4.0 | 0.04 | 0.06 | 0.08 |
| | 4 | 240 | 300 | 300 | 0 | 150 | 550 | 2.0 | 3.6 | 4.0 | 0.04 | 0.05 | 0.08 |

# *Capacity of Central Dachny Sector based on stored heat*

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# *Mutnovsky Monte Carlo stored heat estimates*

| Sector | MWe in 25 years | | | $MW/km^2$ |
|---|---|---|---|---|
| | $5^{th}$% | Median | $95^{th}$% | |
| Northern Dachny | 27 | 42 | 76 | 11 |
| Central Dachny | 16 | 22 | 30 | 17 |
| Southern Dachny | 33 | 46 | 63 | 16 |
| Vulkanny | 50 | 74 | 104 | 12 |
| V. Mutnovsky | 45 | 65 | 79 | 18 |
| Totals | 144 | 207 | 276 | 12 |

# *Reservoir modelling*

Covers wide range of activities for analysis of dynamic conditions and estimating fluid reserves

> Methods include:
  - Analytical Modelling
  - Decline Curve Analysis
  - Lumped Parameter Modelling
  - Numerical Simulation Modelling

# *Analytical modelling*

- Based on same techniques as pressure transient analysis using superposition in time and space
- Used to estimate reservoir pressure changes in response to production/injection
- Proven to be useful in single phase water and steam reservoirs
- Not yet applied at Mutnovsky except for some individual wells

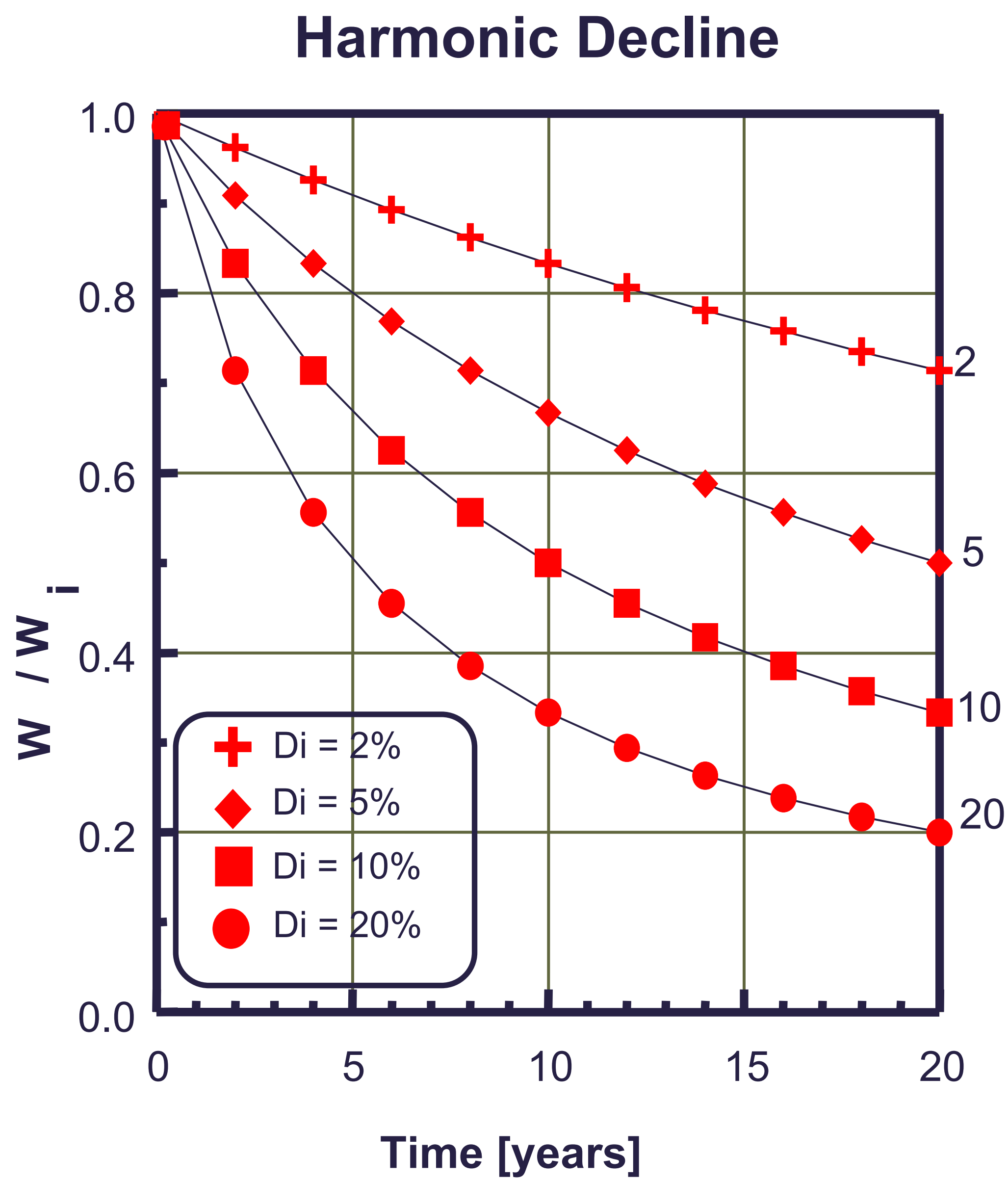
# Decline curve analysis

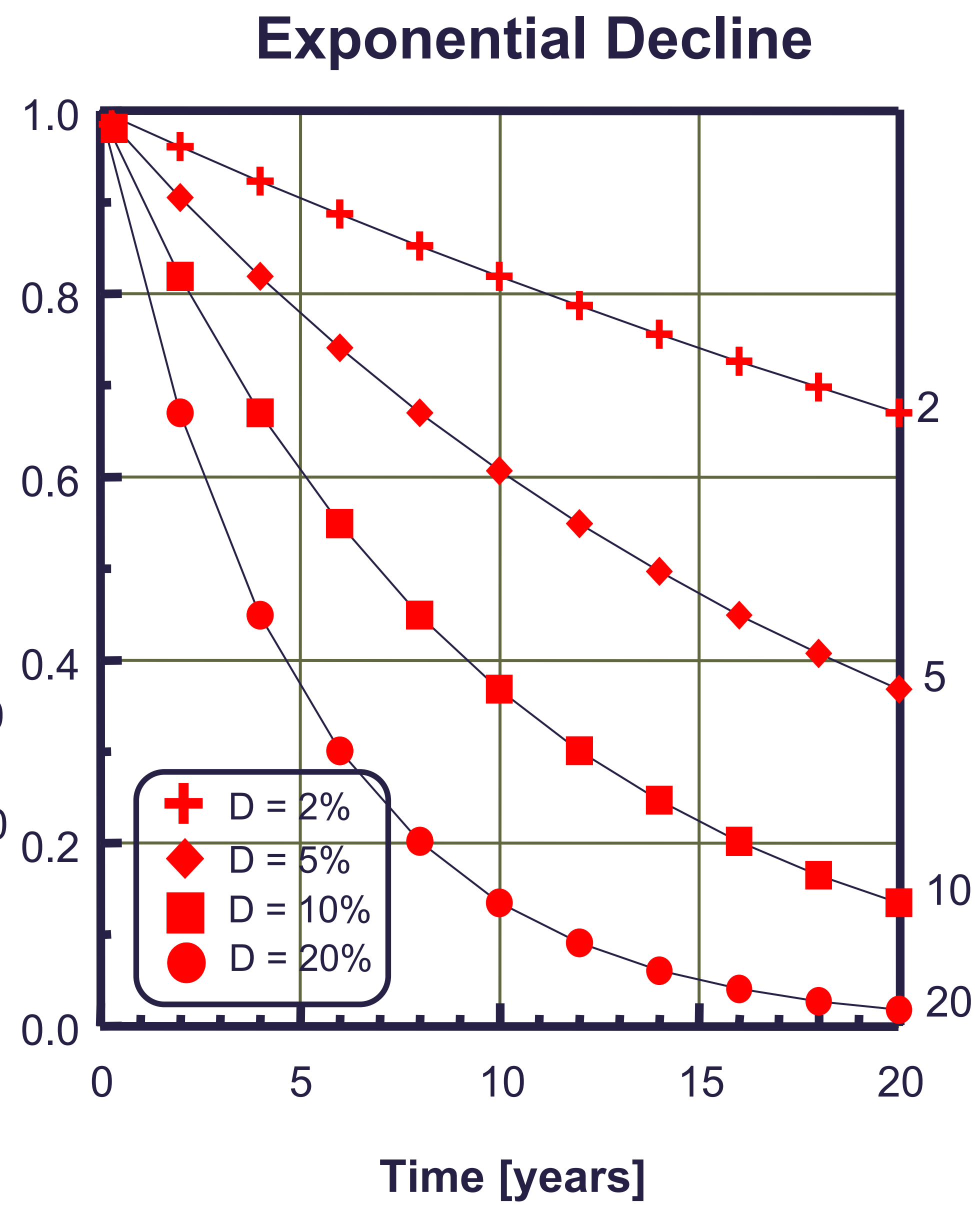
- Used to determine decline in well/field flow rate with time
- Based on empirical method (matching production data to exponential or harmonic decline trends)

$$W = \frac{W_i}{1 + D_i \Delta t} \quad \text{(harmonic decline)}$$

$$W = W_i \cdot e^{-D\Delta t} \quad \text{(exponential decline)}$$

# *Decline curve analysis*



# *Decline curve analysis*

> Popular in vapour dominated reservoirs (eg. The Geysers)

> Used in Cerro Prieto to make short term forecasts

> Not yet applied at Mutnovsky except for some individual wells, but it could soon be applied to the steam zone

# *Lumped parameter modelling*

- System treated as a “tank” with average reservoir properties; may include recharge/injection
- Used to match/forecast overall field performance and changes in individual wells
- May be used as first stage of a numerical modelling study
- Not yet applied at Mutnovsky

# *Numerical simulation modelling*

> System treated as a series of interconnected “blocks”; allows rock and fluid properties to vary through reservoir

> Calibrated by matching conceptual model and known well/field performance

> Used to forecast changes in reservoir in response to production/injection scenarios

# *Numerical simulation modelling*

- Previously done at Mutnovsky (early 1990’s)
- Demonstrated at least 80 MW sustainable
- Now needs updating

# *Assessment during production*

- Continued assessment required to update conceptual and numerical models
- Confidence in models and resource will increase as additional data are collected and incorporated
- Will be basis for future decisions on additional development, if justified

# *Summary of Mutnovsky resource estimates*

| Method | Resource Capacity, MWe | | | | | |
|---|---|---|---|---|---|---|
| | V. Mutnovsky | Dachny | Central Dachny | S. Dachny | Vulkanny | Total Resource |
| Stored heat | 65 | 42 | 22 | 46 | 74 | **207** |
| Chemistry/surface fluid flow | | | | | | **~75** |
| Volc. Inst. (1976) | | | | | | **400** |
| Standard Method (1987) | 83 | 156 | | | 85 | **324** |
| Reservoir Model | | 80[1] | | | | |
| Standard Method (1990) | 57 | 188 | | | 85 | **330** |
| Fluid Upflow Rate | | | 32.5 | 72.5 | | |
| Areal Analogy | | | 13-26 | 29-58 | | |

# Conclusions for Mutnovsky

- The whole resource is adequate to support both the current development and probably a significant expansion
- The current production sector at Dachny, by itself, is not sufficient to support much expansion. A bigger area will be needed
- The next step in resource assessment for Mutnovsky is to produce an updated reservoir model