Modelling blow-out from a CO_2 well

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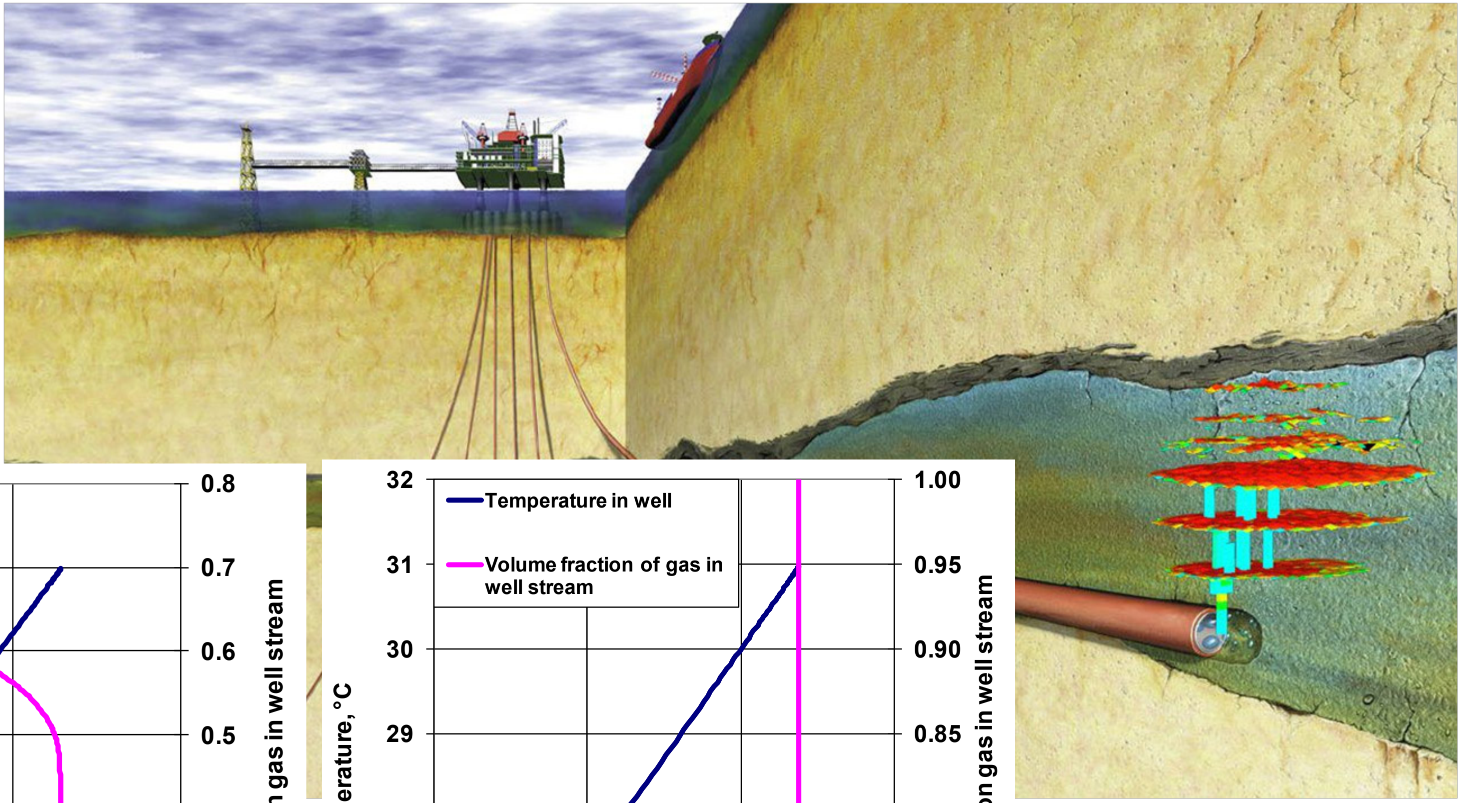
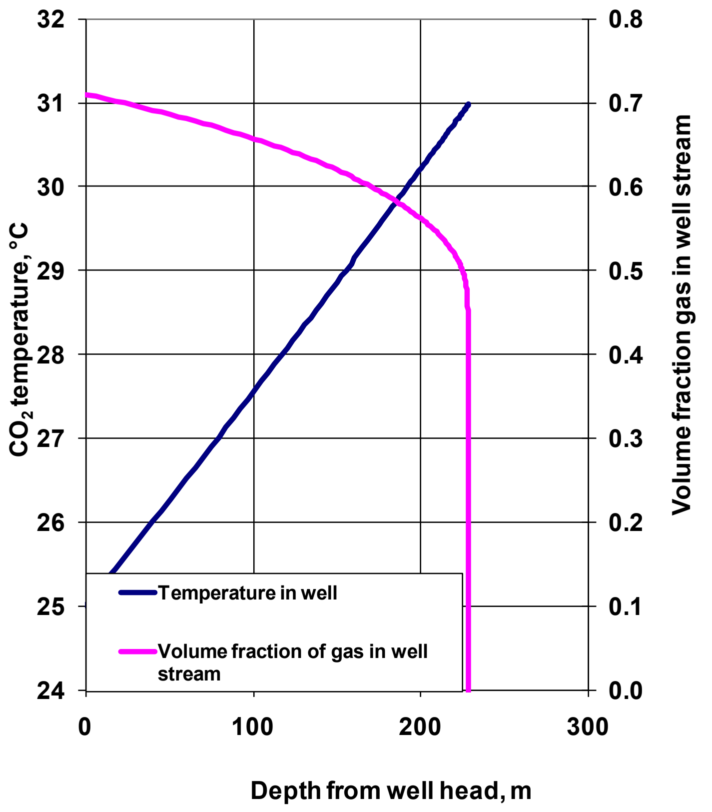
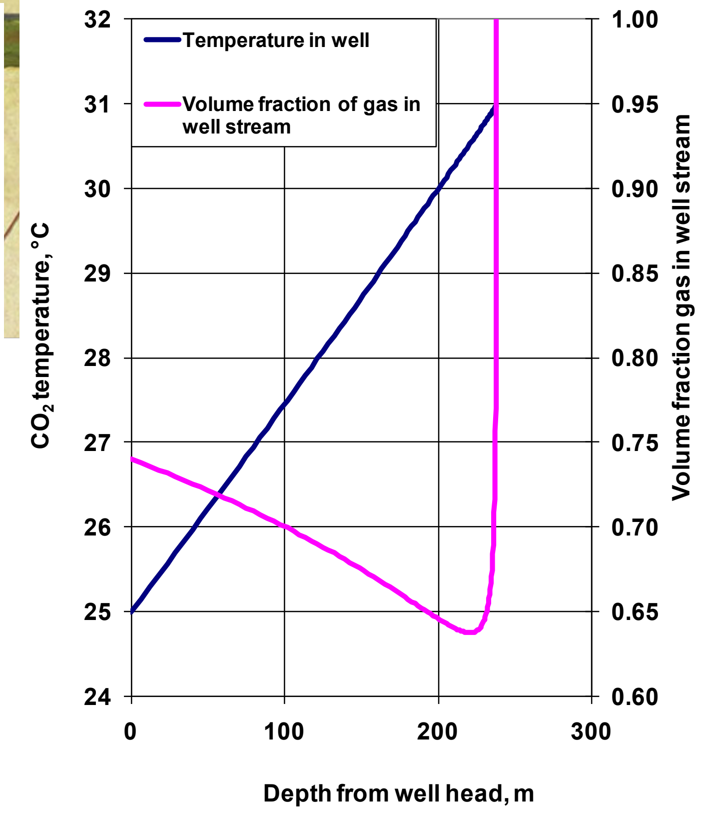
Objective

- To model multi-phase CO_2 flow in a blow-out situation taking into account
  - Phase changes occur along the well
  - Heat is exchanged between the rock and the flowing CO_2
  - Accurate modelling of the strong adiabatic cooling due to expansion (while reservoir condition has been simplified)
  - Suggest possible experiments that could verify modelling

Application on the Sleipner CO_2 injection well 15/9-A16







Two phase flow at the well head is the typical injection situation

Basic equations

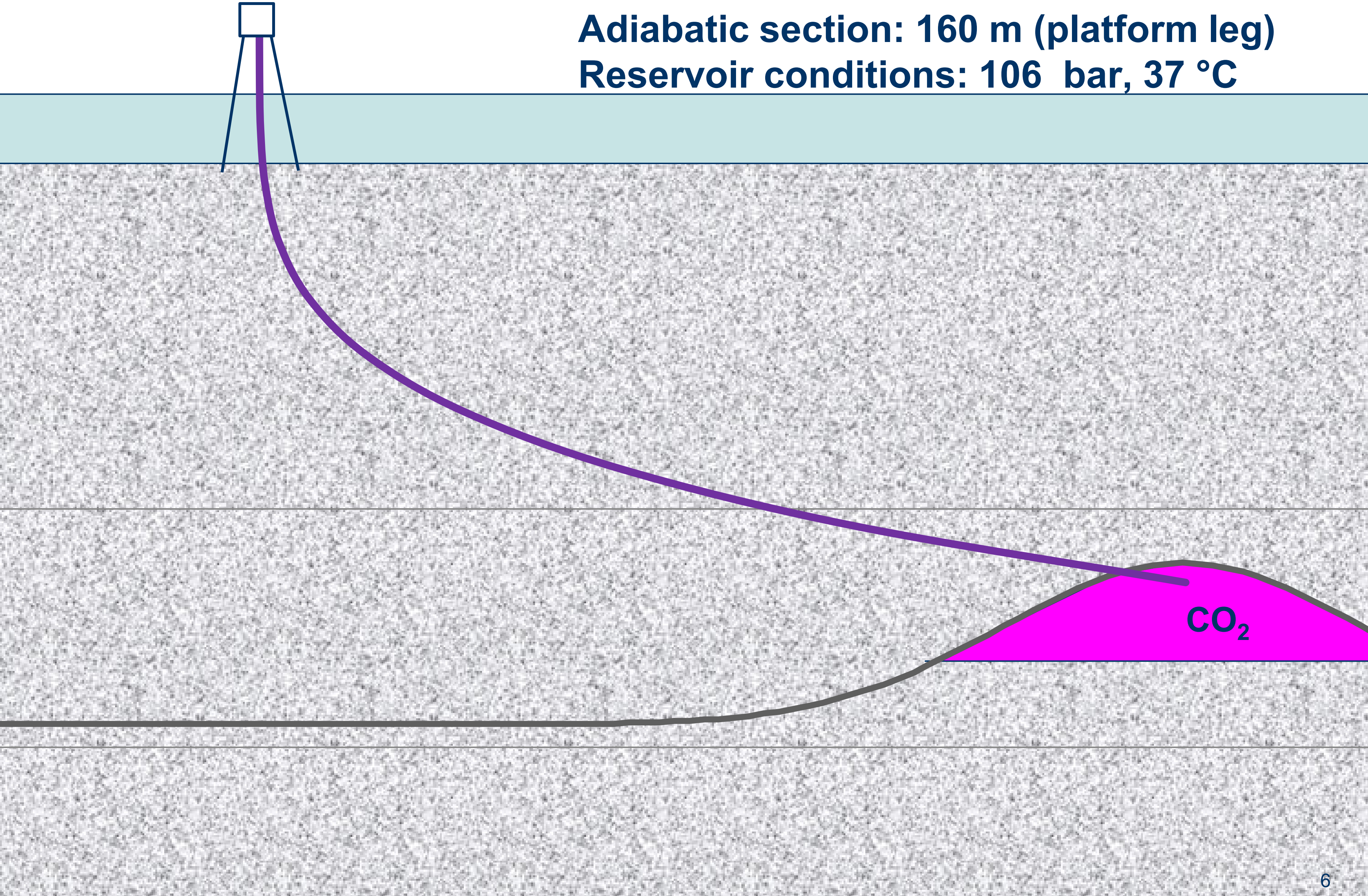
- Bernoulli equation: $$\frac{dp}{dz} = g\rho \sin\alpha + \rho v \frac{dv}{dz} + f\frac{\rho v^2}{4r}$$
- Energy balance in the fluid: $$\frac{dH}{dz} + v\frac{dv}{dz} + g\sin\alpha + \frac{Q}{dm/dt} = 0$$
- Heat flow: $$Q = KF\tau, \quad F = F(D,t,r)$$
- Combining heat flow and the adiabatic contribution
  - $$\frac{d\tau}{dz} = s - \frac{KF\tau}{\left(dm/dt\right)c_p} = s - b\tau, \quad where \;\; b = \frac{KF}{\left(dm/dt\right)c_p} \quad and \;\; s = \frac{\left(\sigma - \frac{dT_{ad}}{dz}\right)}{b\,dl}$$
  - Integrating along direction of flow: $$\tau = \left(\tau_0 - s\right)e^{bdl} + s$$
  - Boldizar (1958) : $$F \approx 4\pi / \ln\left(\frac{4Dt\gamma}{r^2}\right), \quad \gamma = 0.5772..\text{ (Eulers const.)}$$

Solution method

- Numerical solution by discretizing the well into length steps (typically < 1000). At each step the flow equation is solved analytically
- A rate is applied at the perforation and the corresponding pressure is calculated at the well head
- Phase regimes has to be located to avoid a single step to cross the phase boundary.
- The rate is iteratively altered until the desired blow-out pressure is reached (typically 1 atmosphere)

Well features

Perforation depth: 1092 m (from well head)
Length: 3100 m
Radius: 0.1 m
Adiabatic section: 160 m (platform leg)
Reservoir conditions: 106 bar, 37 °C



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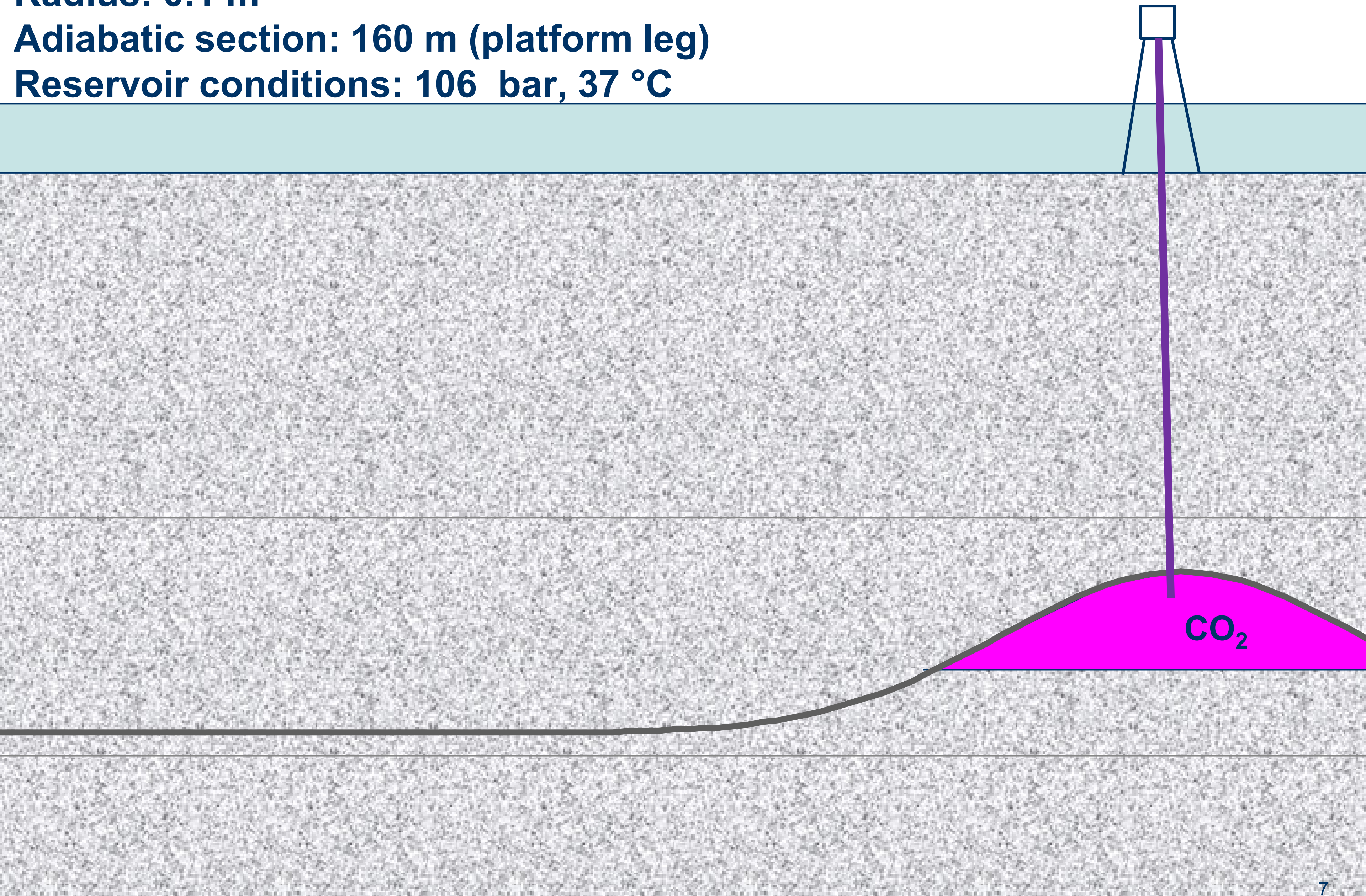
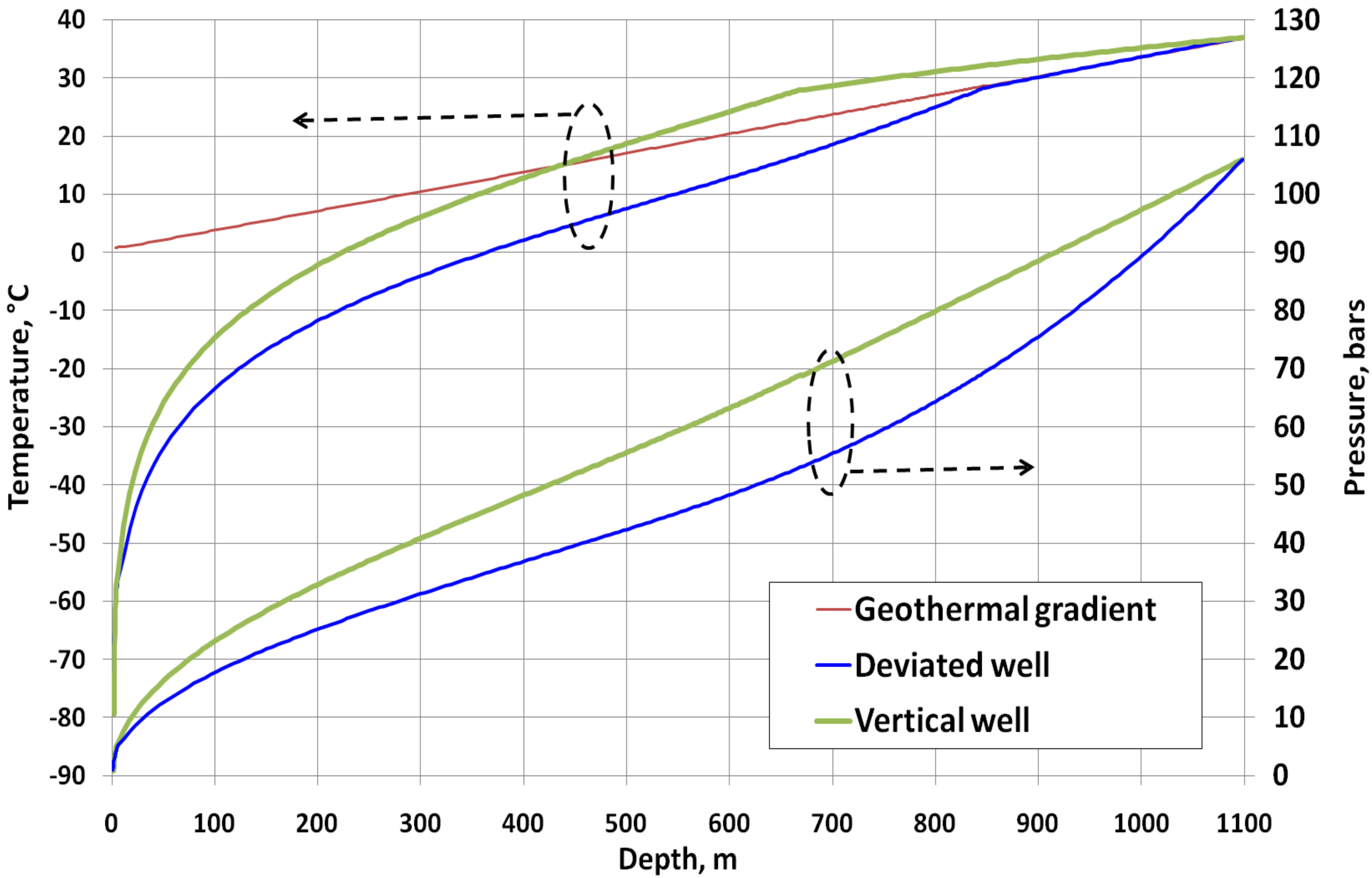
Well features

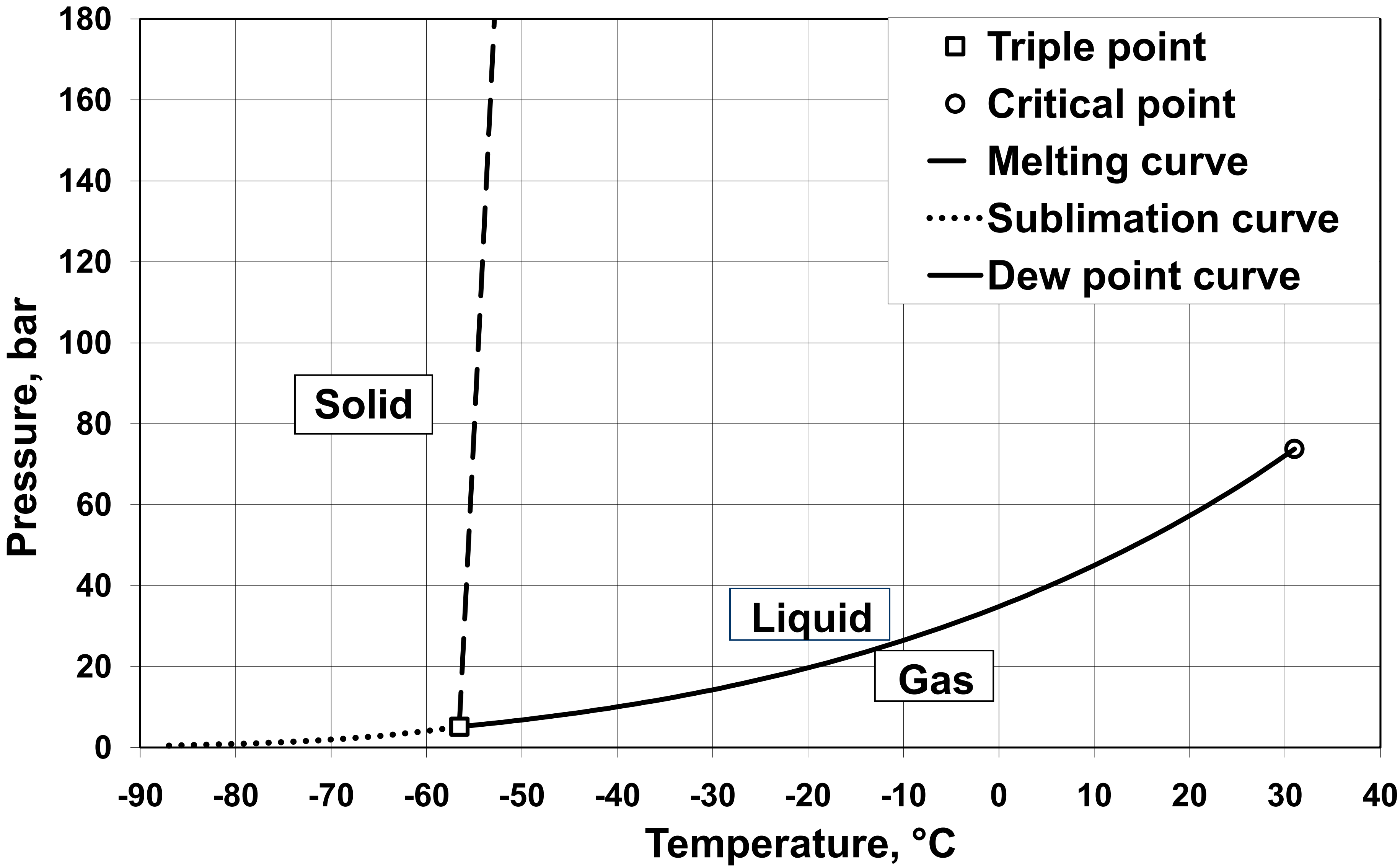
Vertical well



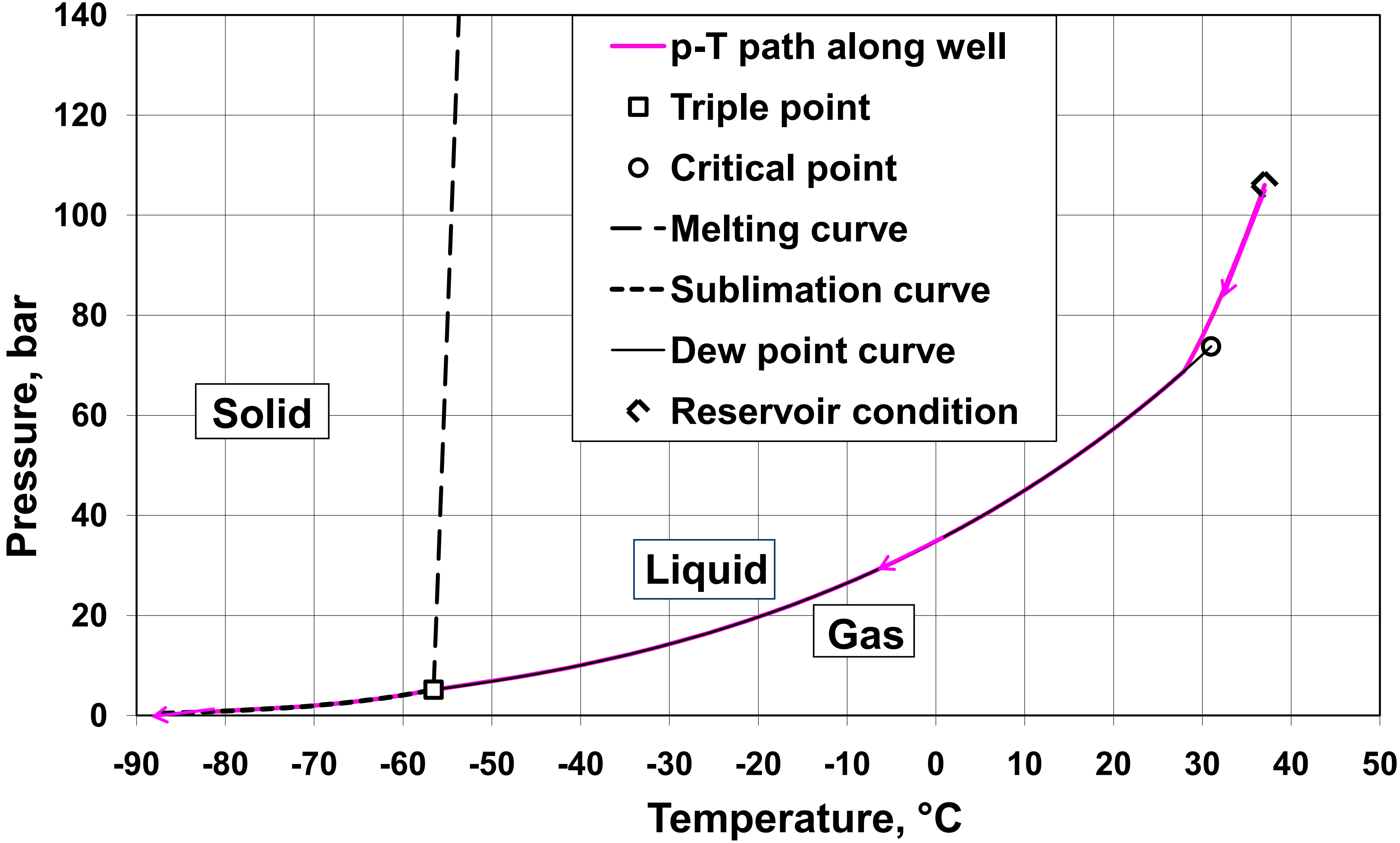
Temperature and pressure profiles



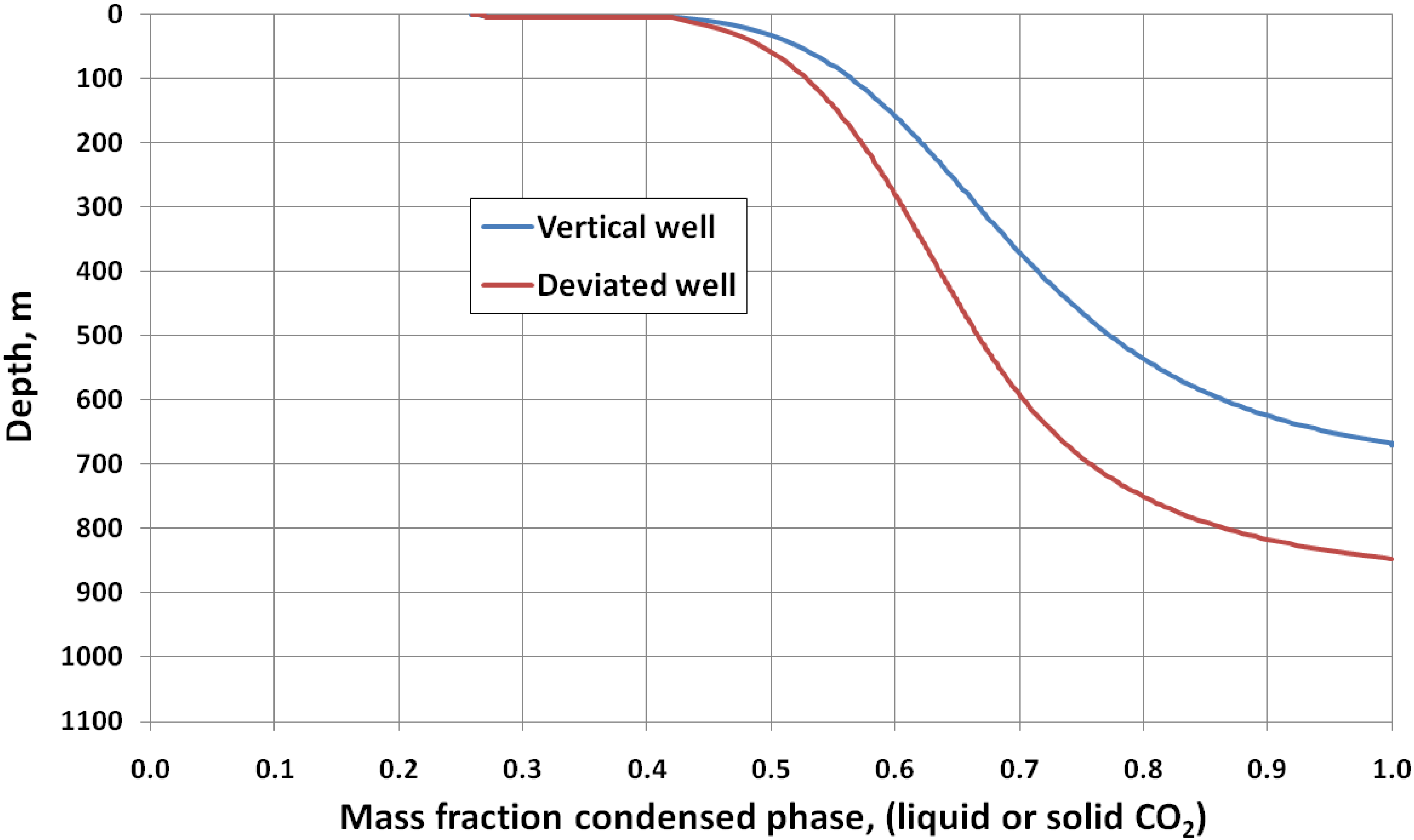
Phase diagram for CO_2 in the p and T space



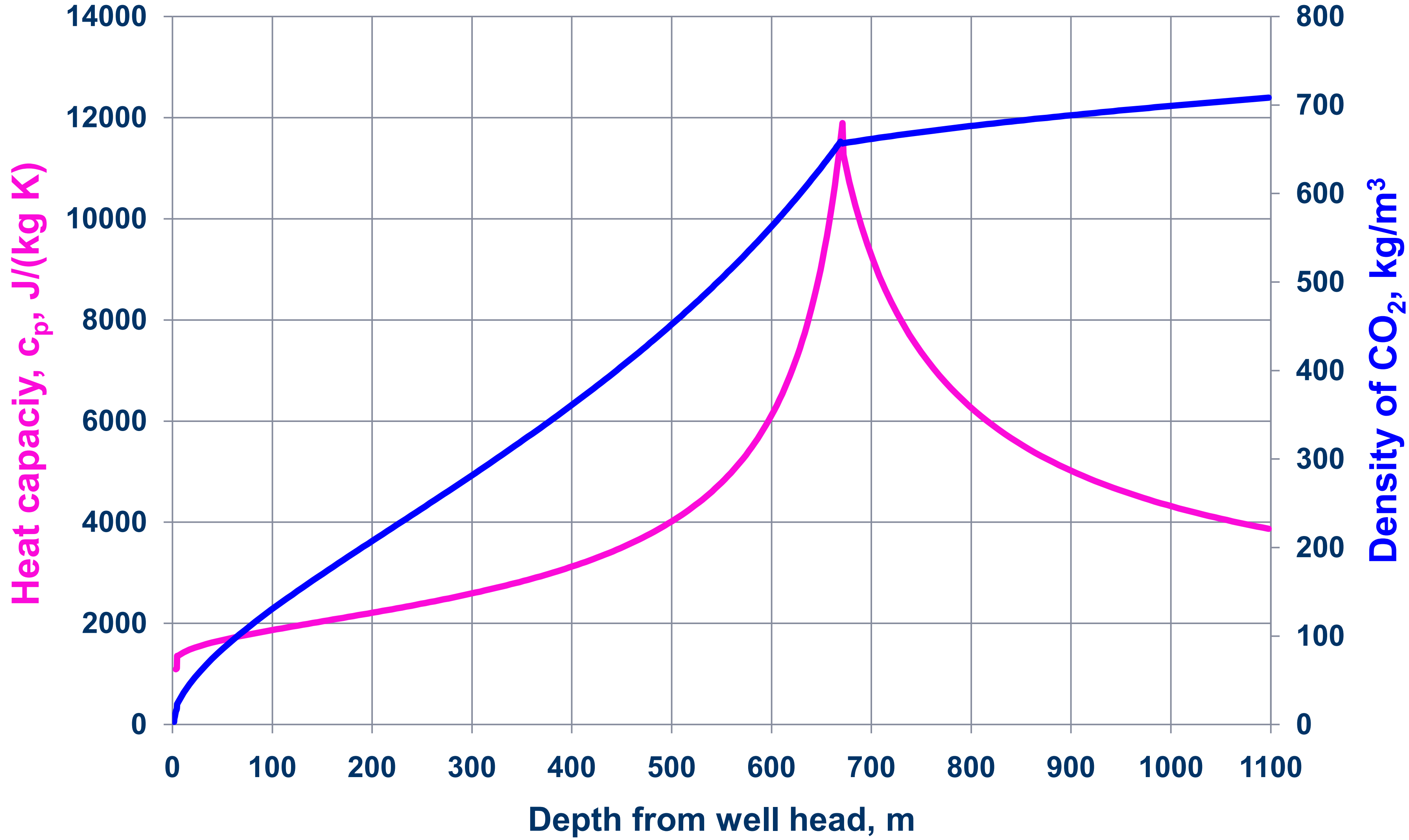
p-T path along deviated well



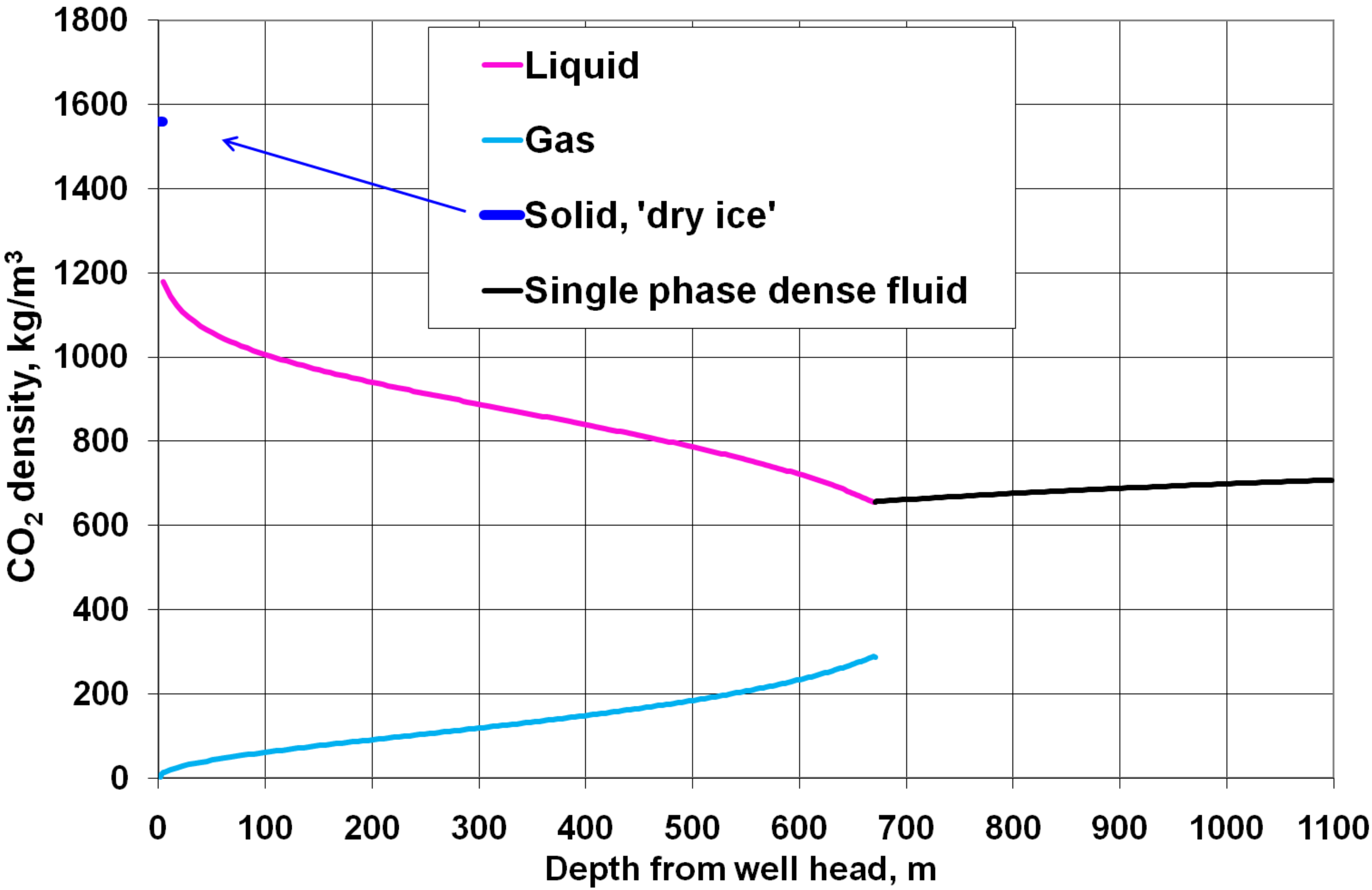
Condensed phase fraction in well



CO_2 heat capacity, c_p, and total density of as function of depth

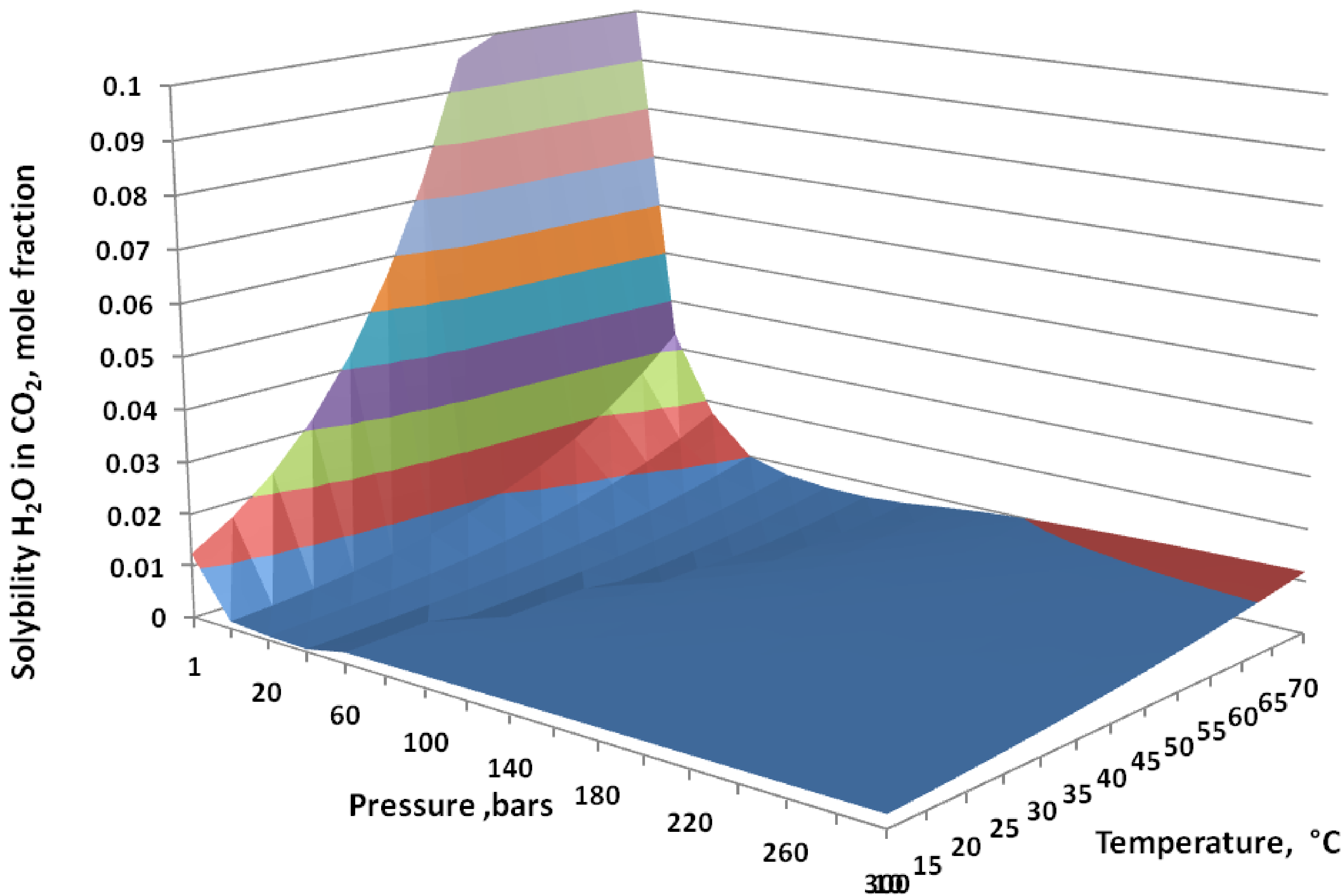


CO_2 densities along the well



Solubility of H_2O in CO_2

If CO_2 is saturated at reservoir conditions - free water will be present in the well



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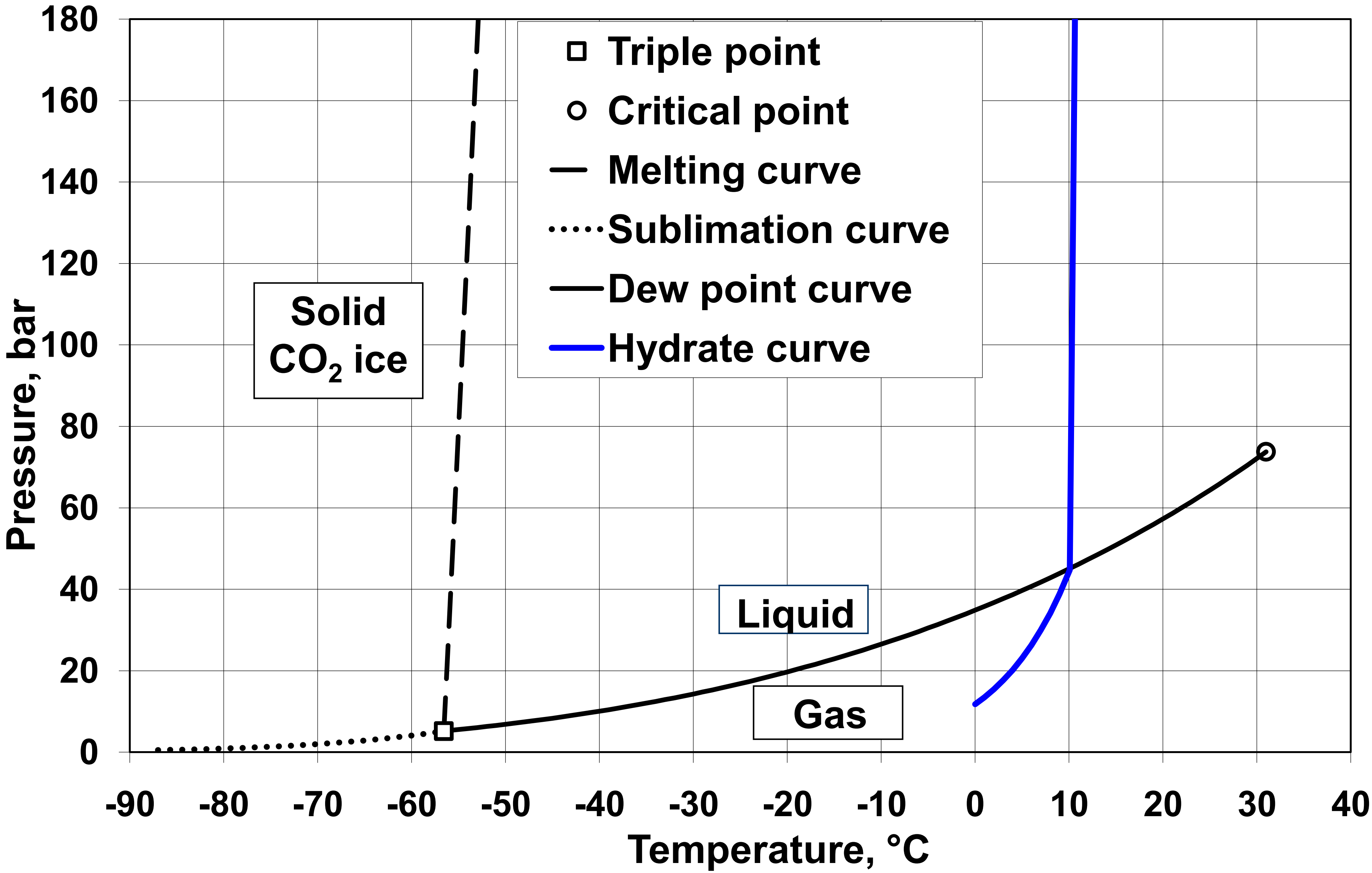
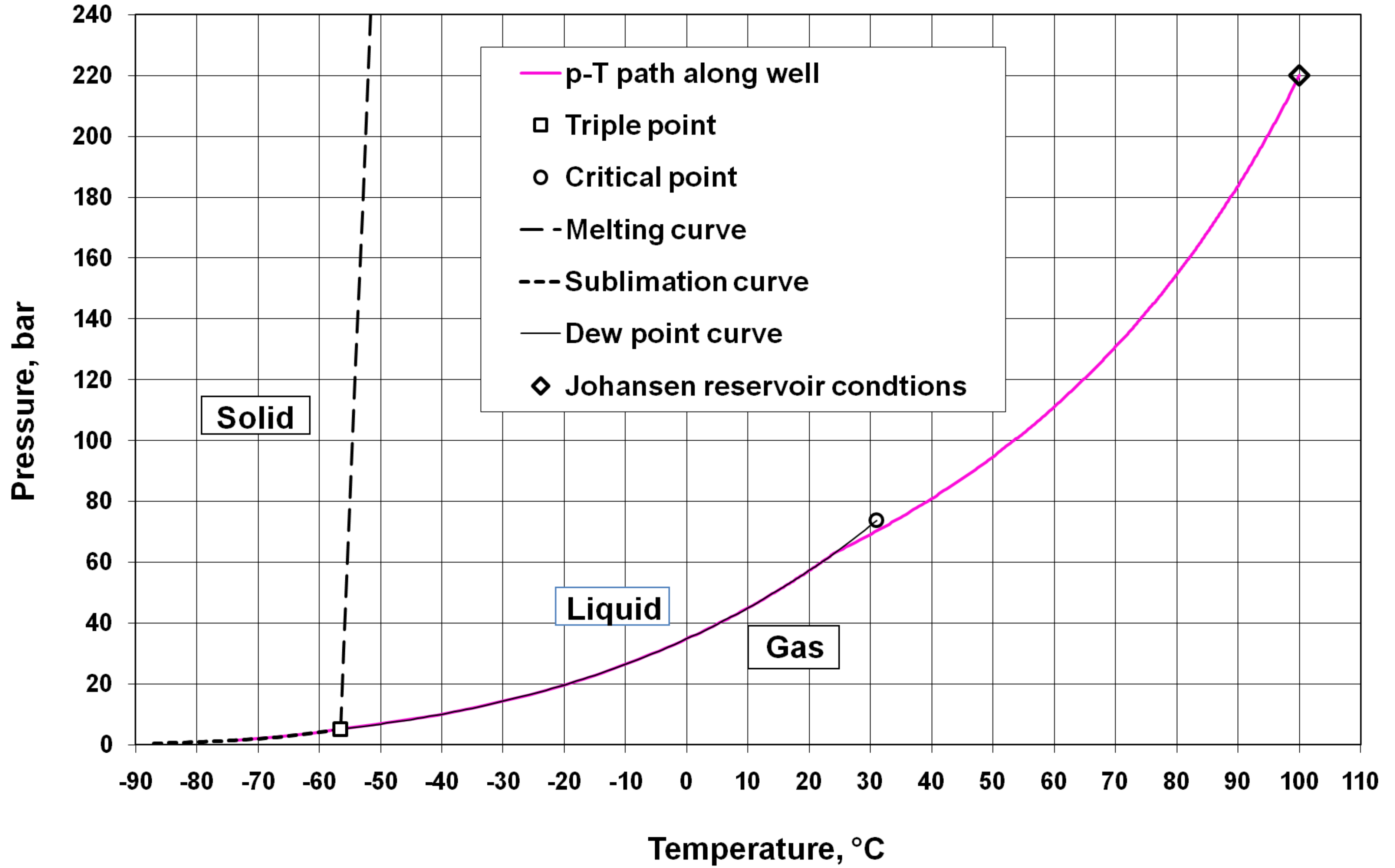


Summary of some cases

Well	Reservoir conditions		Blow out	Mass rate	Blow out speed	Blow out temp.	Depth sublimation	Depth gas+liquid	Depth hydrate
	bars	°C		kg/s	m/s	°C	m	m	m
Vertical	106	37	Well head	244	1165	-81.2	4.7	671	356
Deviated	106	37	Well head	181	935	-79.3	5.8	848	544
Vertical	106	37	Sea floor[1)]	284	183	-45.8		704	428
Deviated	106	37	Sea floor[1)]	195	150	-47.5		874	620
Vertical	130	37	Well head	313	1586	-97.1	3.7	465	252
Deviated	130	37	Well head	225	1374	-96.1	26.2	698	440
Johansen	220	100	Well head	268	1232	-74.8	2.2	389	205

[1)] Sea depth 82 m giving a blow out pressure of ~ 8.2 bars

p-T path along deviated well “Johansen”



Conclusions

- The injection well approaches adiabatic conditions relatively fast, *i.e*. the transient heat effect can then be neglected
- Stored CO_2 will be water saturated (0.01 – 0.02 mole fraction H_2O) and solubility will decrease up along the well.
- At clogging due to hydrates (or unlikely dry ice) heat transfer from the rock will melt the plugs and cause the release pulse step release.
- The recent fast CO_2 release tests in Germany from a pipe
  - 10 000 tonne per 10 hours = 278 kg/s are in the range of typical blow-out rate from wells
  - This test lack the gravity effect
  - Are approximately adiabatic
  - This suggest similar tests to be performed on an abounded well