Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences
(KB GS RAS)

Hydrogeochemical Precursors of Earthquakes : Data Analysis from Four Rregions

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September 2020

What are hydrogeochemical precursors and why should they be studied?

<u>Hydrogeochemical precursors (HGCP)</u> *- anomalous changes in the ion-salt and gas composition of groundwater before earthquakes, discovered during long-term regular observations on flowing wells in seismically active regions.*

HGHP are one of the components of <u>geochemical precursors</u>, combining a set of changes in the chemical composition of water and gases in the atmosphere, surface and ground waters during the preparation of earthquakes.

Studying the spatio-temporal patterns of HGCP manifestation and their relationship with the parameters of subsequent earthquakes allows:
(1) ***to determine the significance of the hydrogeochemical method for predicting strong earthquakes;***
(2) ***to consider the processes of HGCP formation in groundwater systems (conceptual models).***

The report examines HGCP data *from four regions (Kamchatka Peninsula, Uzbekistan, Japan, and Iceland) from a unified point of view on observation conditions (full observation period - years, observation frequency - at least one per week) in comparison with the updated parameters of subsequent earthquakes according to the USGS catalog [https://earthquake.usgs.gov/earthquakes/search].*
HGCP data *were taken into account from 10 regime vents - 9 wells and one source, in connection with 11 earthquakes with* M_w *= 5.3 - 7.8.*

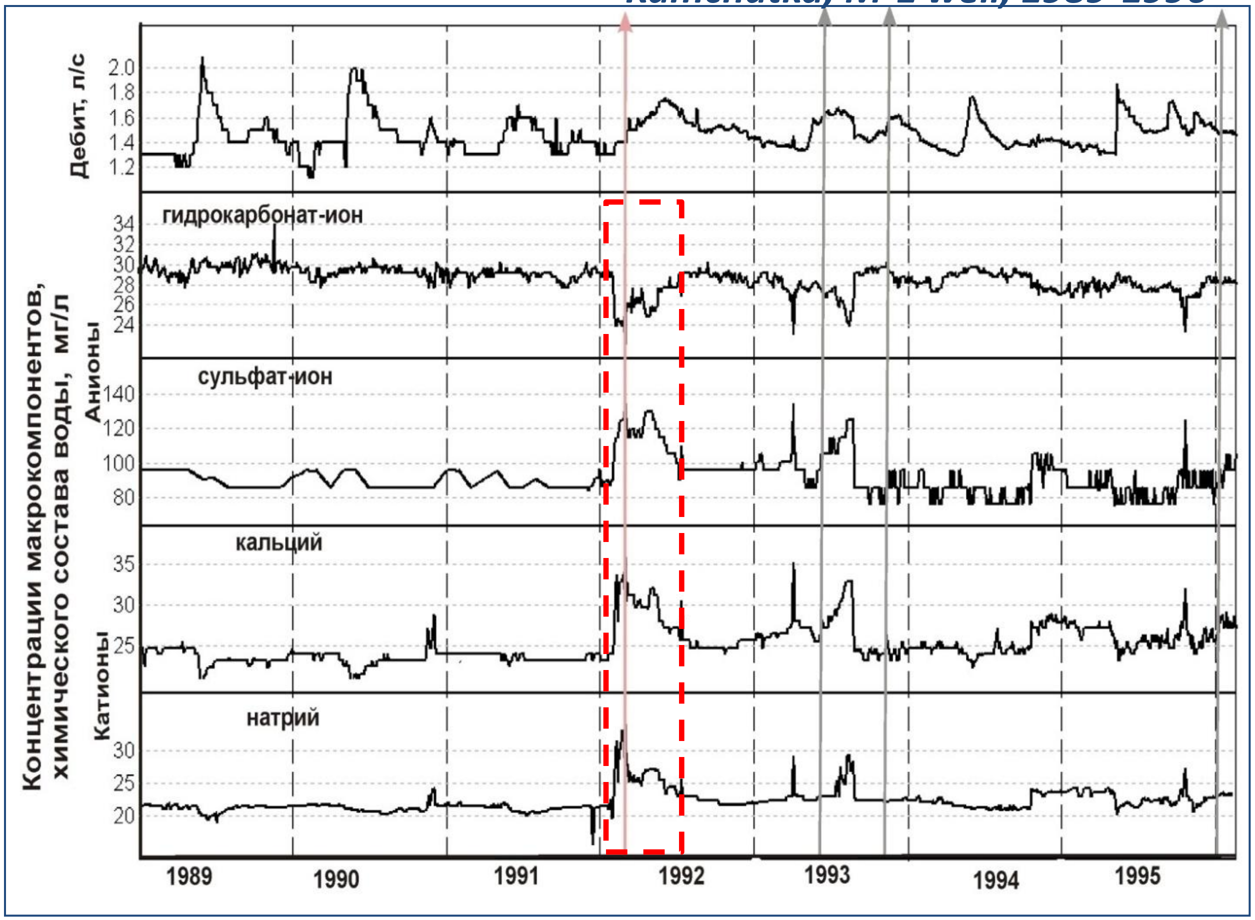
Hydrogeochemical observation technique: water sampling from flowing wells, chemical analysis of water and gas composition, time series construction, highlighting anomalies, comparison of anomalies with earthquakes

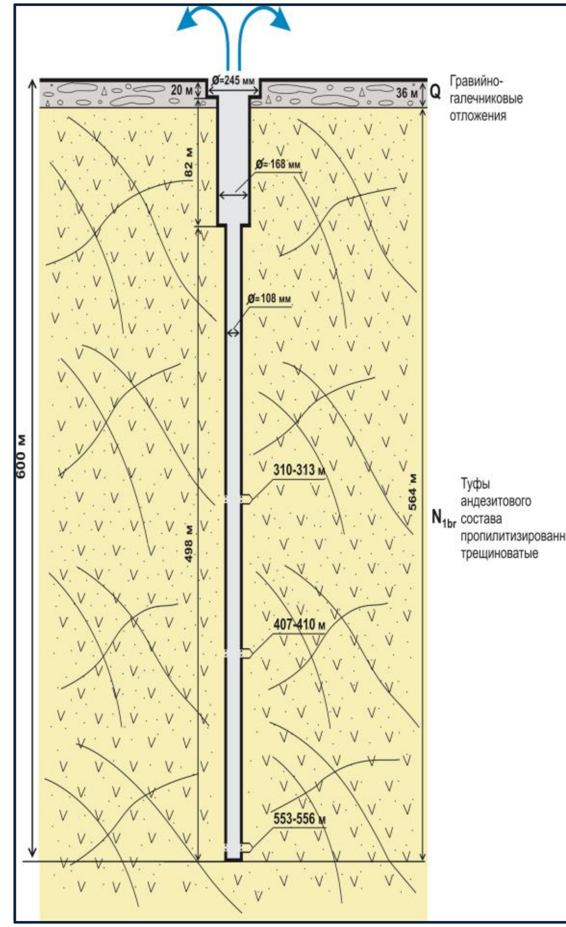
Flow rate and water temperature measurements

Sampling of water and gas

Photos provided by V.A. Poletaev

Time series of hydrogeochemical observations and hydrogeochemical precursor, Kamchatka, M-1 well, 1989-1996





$M_{0.19}$ ($SO_4$78 $HCO_3$20)/(Ca56 Na44)- *in the background*

$M_{0.25}$ ($SO_4$87 $HCO_3$11)/(Ca55 Na45)- *at the stage of HGCP formation*

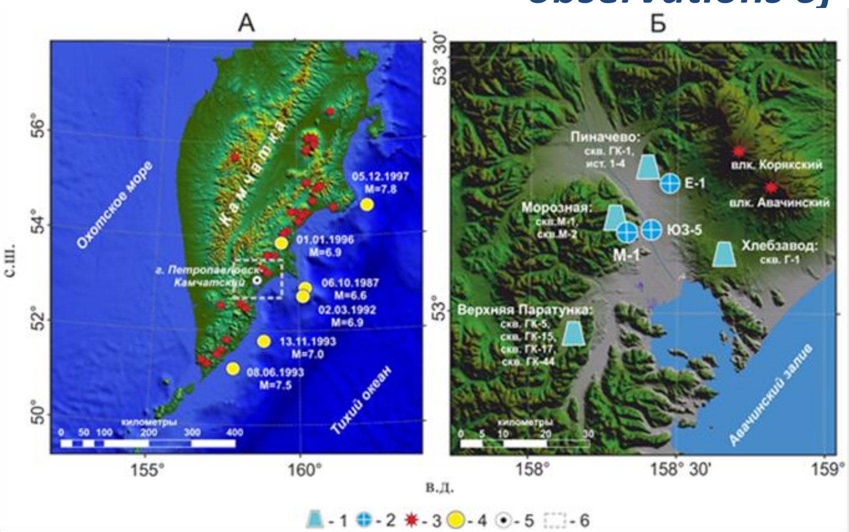
V=7.3 м^3,
Q=1.5-1.3 дм^3/с,
T=1.0-1.6 ч,
Δt=3 сут
Δ_i=2-10%
O= 1-6%

***HGCP before the 02.03.1992 EQ, M = 6.9, de = 135 km*:**

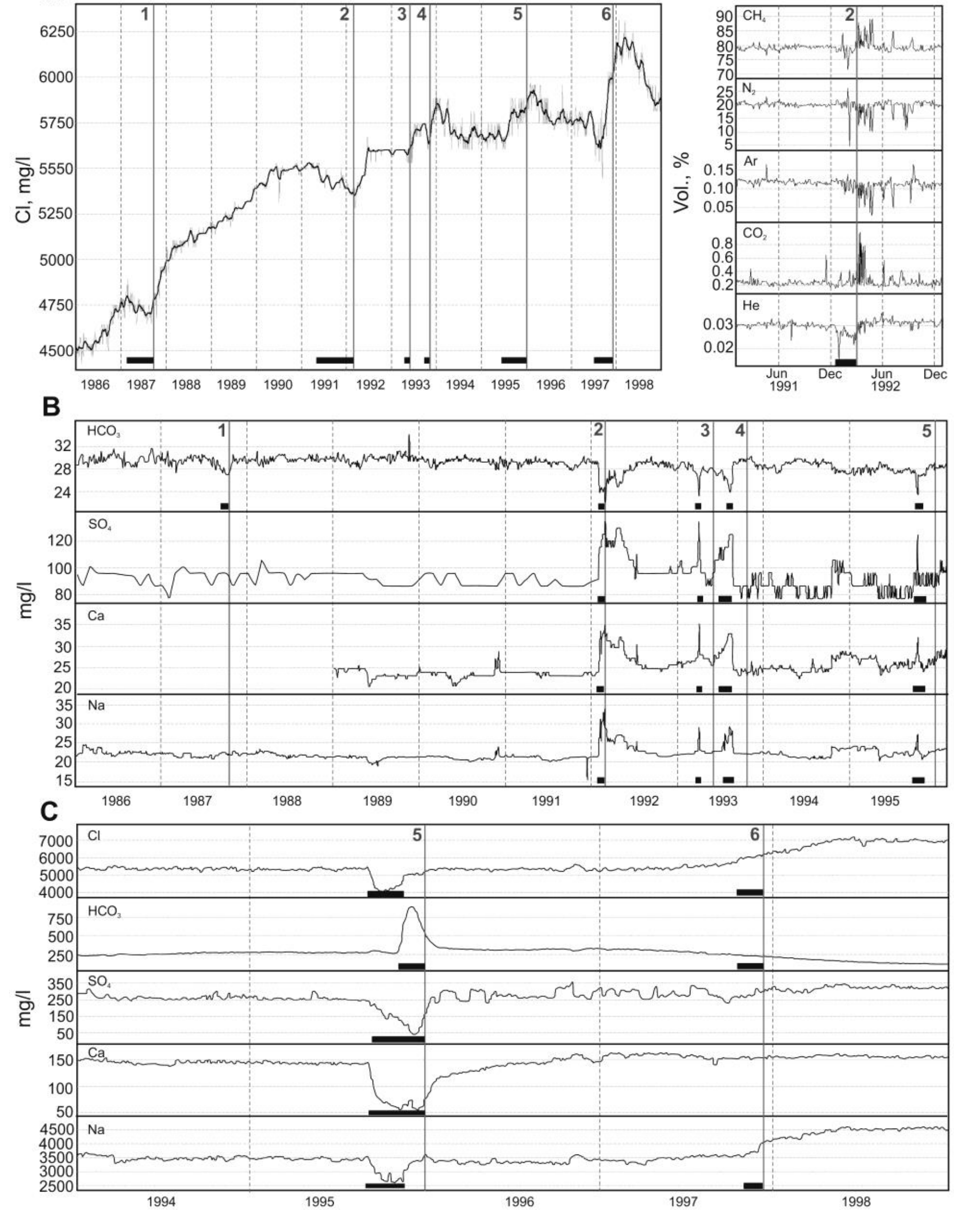
- increase in water mineralization by 30% ,

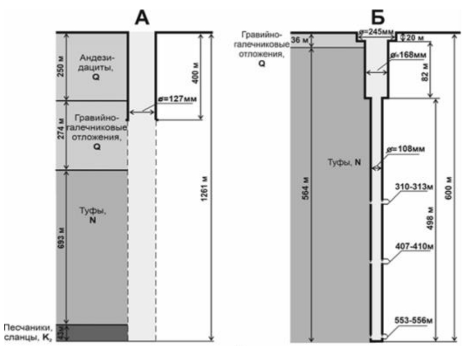
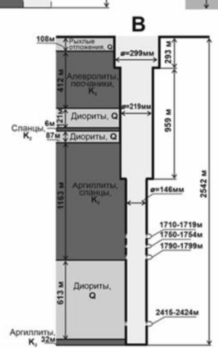
- change in the hydrogeochemical type of water due to a relative increase in sulfate ion and a decrease in bicarbonate ion.

Kamchatka Peninsula, Petropavlovsk-Kamchatsky test site, wells GK-1, M-1 and G-1, observations of the KB GS RAS, 1987-1998

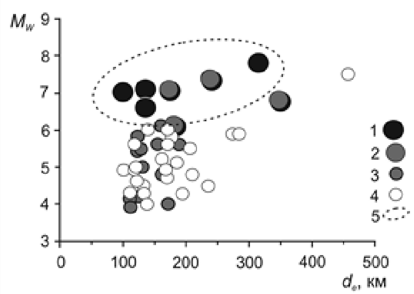


Data: A)- GK-1, B) - M-1, C) - G-1



Well structure



Kopylova, Boldina, 2019

HGCP manifested themselves in changes in the chemical composition of groundwater and gas before six earthquakes with Mw = 6.5-7.8 at distances of de=95-308 km.
The time of HGCP manifestation before earthquakes is 1-9 months (thick horizontal lines).

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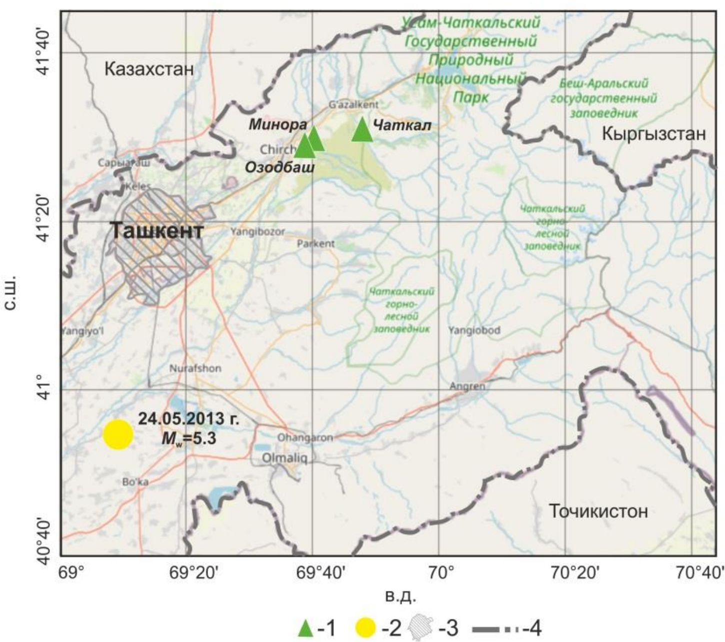
Laboratory of Hydrogeoseismology of the Institute of Seismology of the Academy of Sciences of the Republic of Uzbekistan, Tashkent polygon,

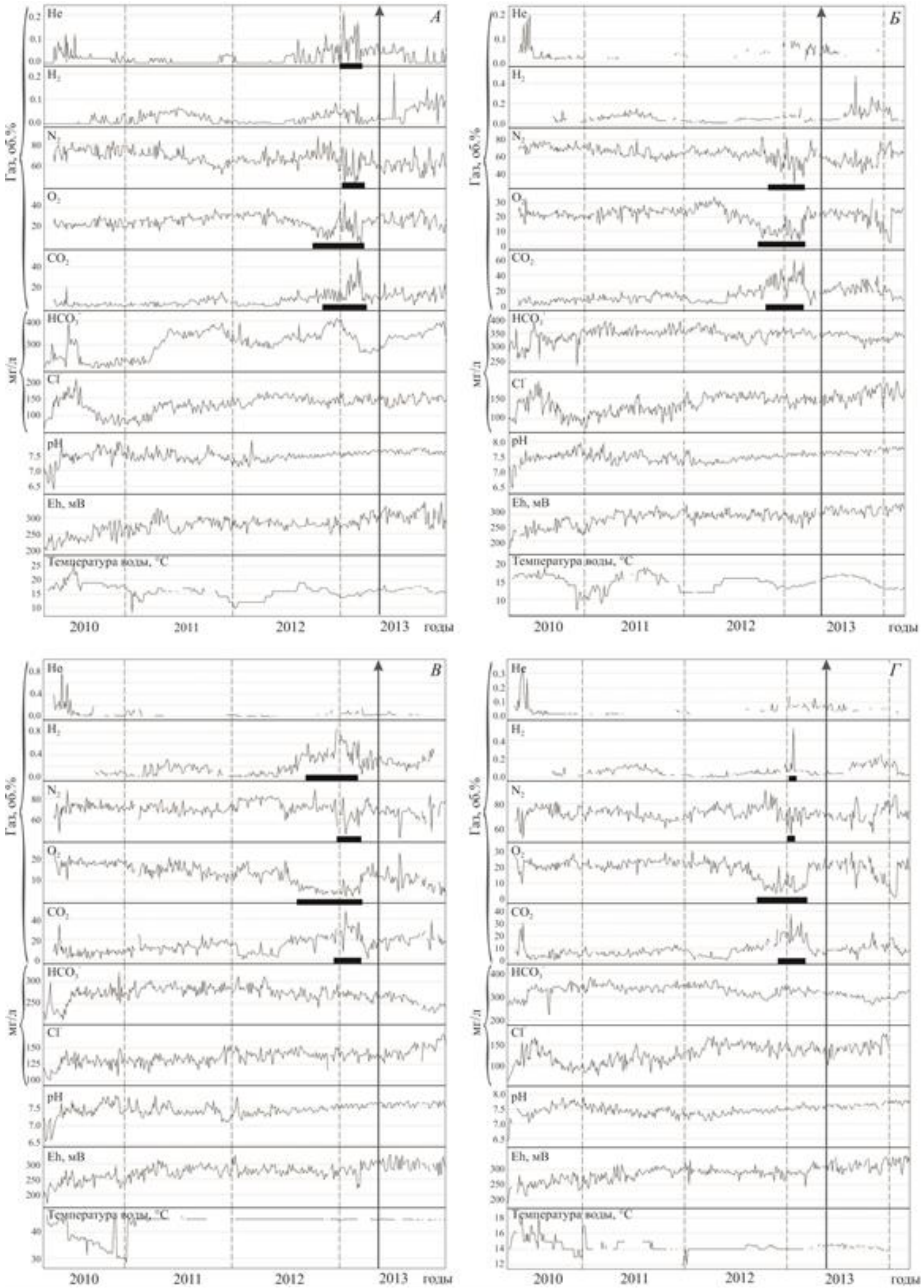


Water and gas sampling

Photo by the author

Observational data at three wells and the Ozodbash spring, 2010-2013:

EQ on May 24, 2013, M_W = 5.3, de = 80-90 km



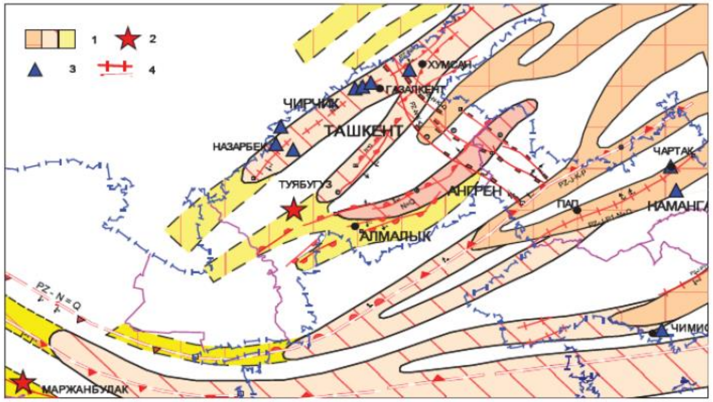
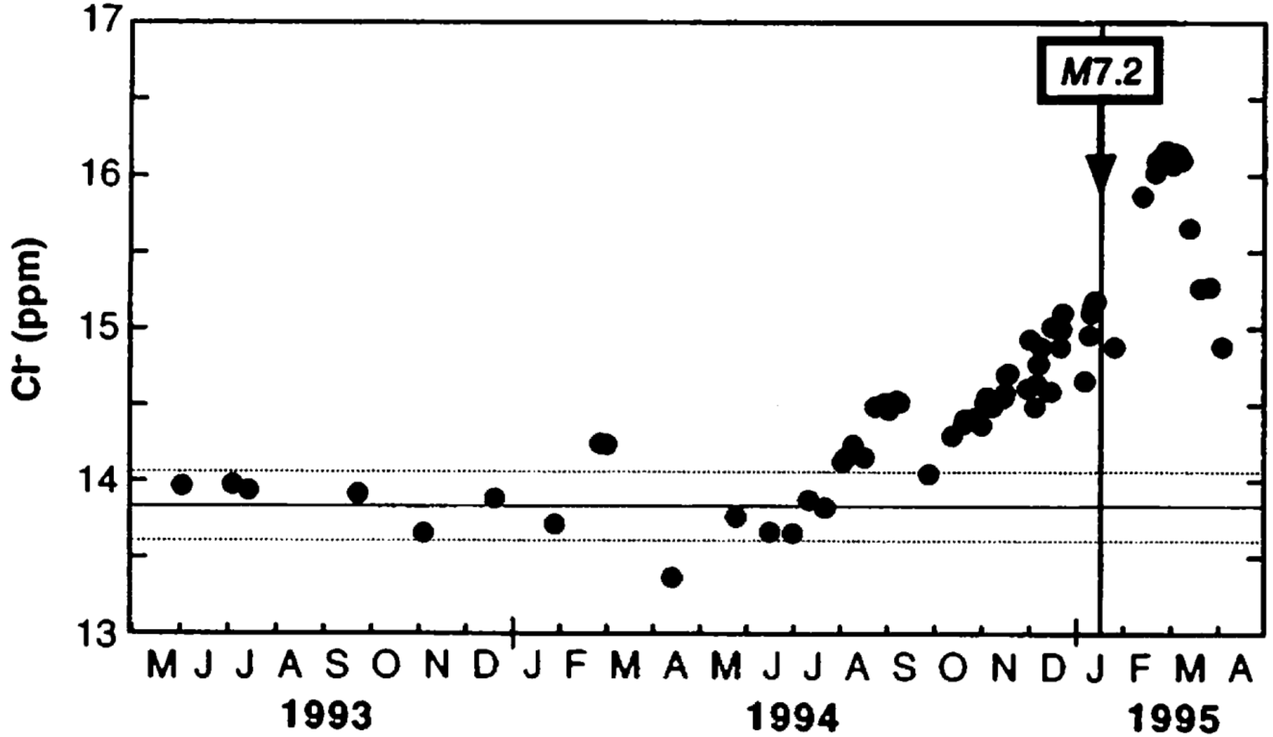


Рис. 1. Сейсмогенные зоны, активные разломы, эпицентры землетрясений и наблюдательные станции. *1* – сейсмогенные зоны; *2* – эпицентры землетрясений; *3* – прогностические станции; *4* – разломы земной коры.

HGCP in the gas composition were manifested for 5-9 months prior to EQ. An increase in the proportion of deep-seated gases (He, H2, CO2) and a decrease in the proportion of air gases (O2, N2).

Yusupov et al., 2014; Kopylova et al., 2019

Japan, EQ Kobe, 16 January 1995, Mw=6.9, ROK well, de=20 km



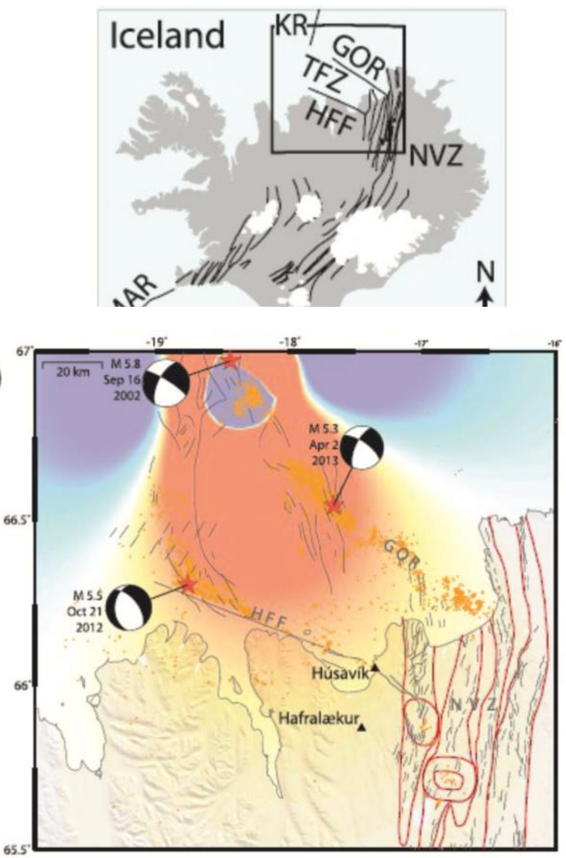
Change in chloride concentration in bottled groundwater . Time of the EQ is shown by the vertical line. Dashed horizontal lines show one standard deviation of measurements prior to July 1994 (Tsunogai and Wakita, 1995).

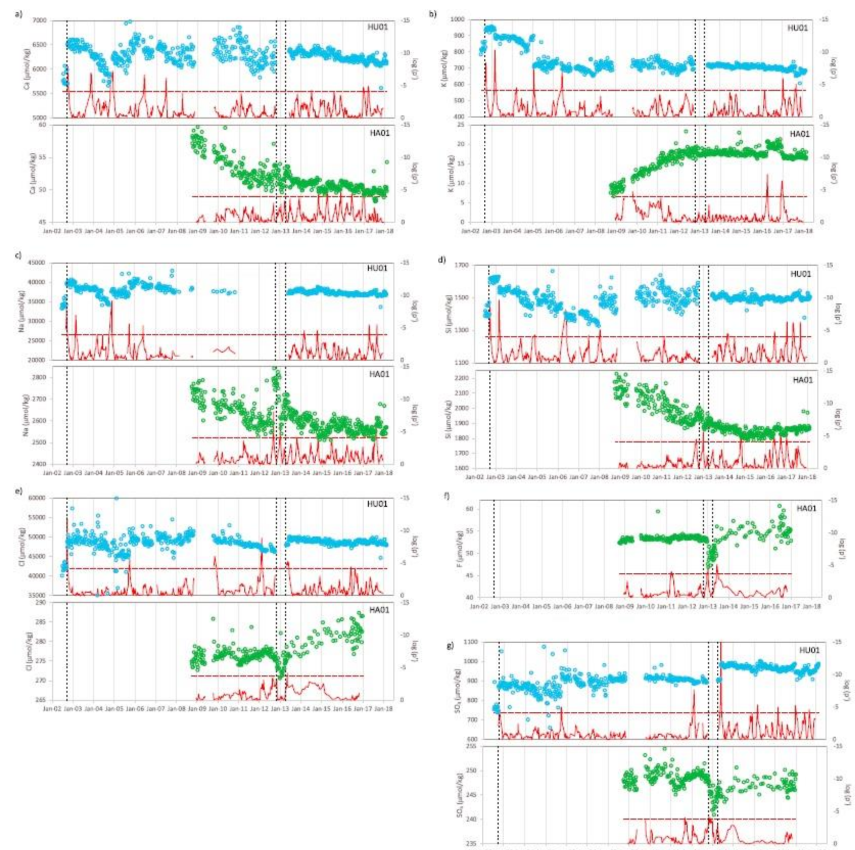
The duration of the HGCP is 5 months. Postseismic effect.

North Iceland: 2 wells, observations of 16 and 10 years, hydrogeochemical effects during three earthquakes: 1 - September 16, 2002, *Mw* = 5.8, *de*=110 km; 2 - October 21.2012, *Mw* = 5.5, *de*=66-73 km ; 3 - April 02, 2013, *Mw* = 5.3, de = 44-62 km.

Skelton, A., Liljedahl-Claesson, L., Wästeby, N., et al. (2019). Hydrochemical changes before and after earthquakes based on long-term measurements of multiple parameters at two sites in northern Iceland—A review. Journal of Geophysical Research: Solid Earth, 124. https://doi.org/10.1029/2018JB016757

Hydrogeochemical effects (shifts) were identified within 2 -6 months before earthquakes; postseismic effects (shifts) and trends. Conceptual models of the hydrogeochemical effects due to changes in the mixing conditions of groundwater of different composition and water/rock interaction are considered. The important role of fracturing of water-bearing rocks during the preparation of earthquakes and the impact of seismic waves was noted.





Analysis of the relationship between the manifestations of HGCP and:

- ***the parameters of subsequent earthquakes;***
- ***seismic impact in the observation areas.***

Used earthquake parameters:

- the ratio between $\boldsymbol{M_w}$ and the epicentral distance of EQ to the observation well, $\boldsymbol{d_e}$ (km);
- the ratio between the epicentral distance $\boldsymbol{d_e}$ and the maximum linear size of the earthquake source $\boldsymbol{L}$ (km): $\boldsymbol{d_e/L}$.

$lgL = 0.440 \cdot M_w - 1.289$ (Riznichenko, 1976):

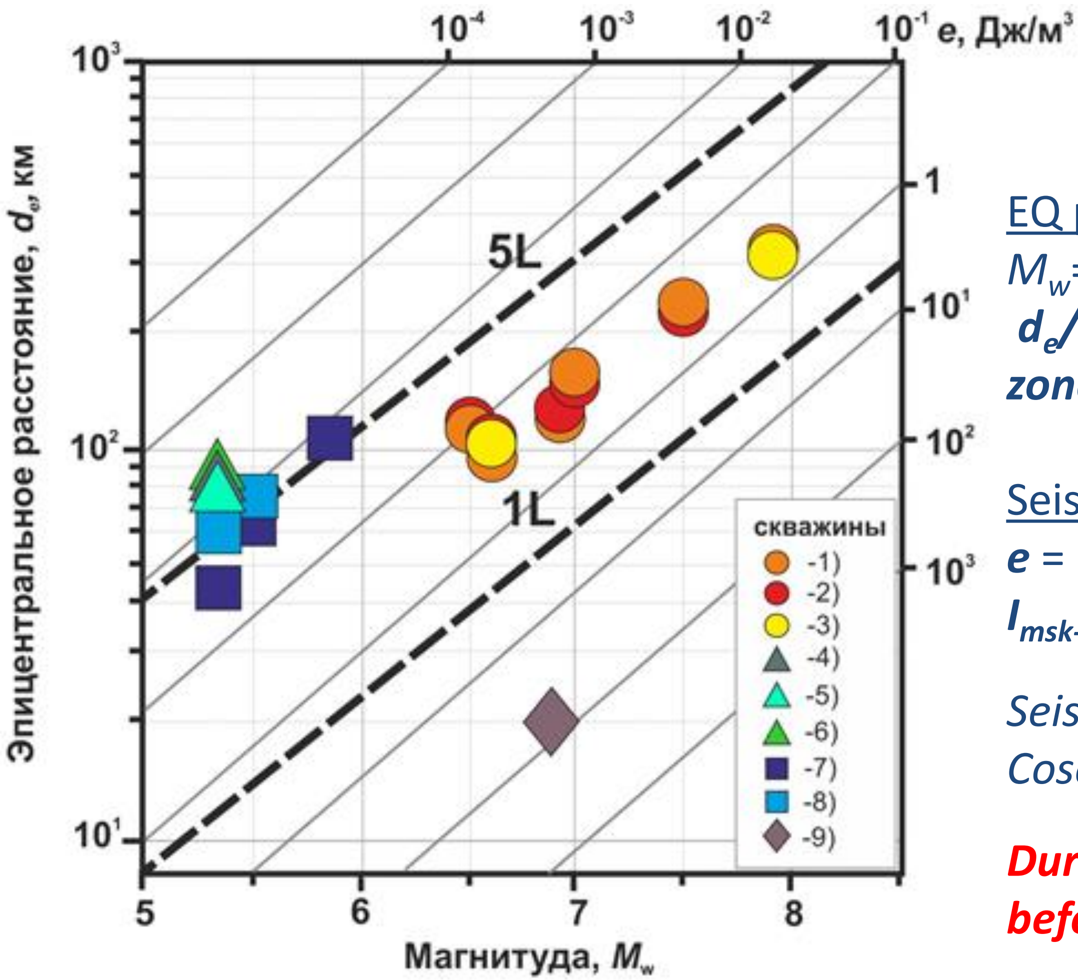
Used parameters of seismic impact of EQ in the area of the observation well:

- - specific density of seismic energy $\boldsymbol{e}$, J/m^3;
- - intensity of shaking in the observation area, points on a 12-point scale MSK-64, $\boldsymbol{I_{MSK\text{-}64}}$.

$\lg d_e = 0.48 M_W - 0.33 \lg e$ (Wang, 2007; Wang, Manga, 2010)

$$I_{MSK\_64} = bM - \nu \lg\sqrt{d_e^2 + H^2} + c,$$

H – source depth, km; b = 1.5, v = 3.5, c = 3.0 (Shebalin, 1968)



HGCP manifestations

<u>EQ parameters:</u>
M_w=5.3-7.8, *d_e* = 20-310 km,
d_e/L* = 0.7-8** (near and intermediate field zones of earthquake sources!***)

<u>Seismic impact parameters</u>:
e = (0.003 – 66) J/m^3
I_{msk-64}= 4-8 points

Seismic wave velocity ***V*** = 1-75 cm/c
Coseismic volume deformation (0.2-140)·10^{-9}.

Duration / lead time of HGCP - 1-9 months before earthquakes.

HGCP distribution depending on the magnitude M_w and the epicentral distance d_e of subsequent earthquakes:
1) - 3) - wells of the Kamchatka Peninsula: 1) - GK-1, 2) - M-1, 3) - G-1;
4) - 6) - regime vents, Uzbekistan: 4) - Ozodbash spring and DAN well, 5) - Minora well, 6) - Chatkal well;
7) - 8) - Icelandic wells: 7) - Húsavík (HU01), 8) - Hafralækur (HA01);
9) - ROK wells, Japan.
Thin gray lines - values of seismic energy density *e*. Thick dashed lines - one (***L***) and five (***5L***) maximum linear sizes of the EQ sources.

Conceptual model of hydrogeochemical precursors is a difficult task!

-- a limited set of hydrogeochemical data;

- changes in hydrodynamic parameters (pressure, discharge, water temperature, operation of observation wells) and their effect on the chemical composition of water (lack of hydrodynamic data);
- a limited set of data on hydrogeological conditions, well structure, etc.

Mixing model of two waters with different chemical composition in the zone of increased conductivity when changing hydrodynamic conditions in the aquifer [Wang et al., 2004],

$$\delta\sigma(t) = \pm\,\delta\sigma_0 \frac{e^{-t/t_0} - e^{-t/\tau_0}}{(1-\tau_0/t_0)(\tau_0/t_0)^{t_0/(t_0-\tau_0)}} + const$$

$\delta\sigma(t)$ – change in the concentrationin of idicator component IK in time t, mg/l

$\pm\delta\sigma_0$ - amplitude of the IK concentration change during the development of the anomaly, mg/l

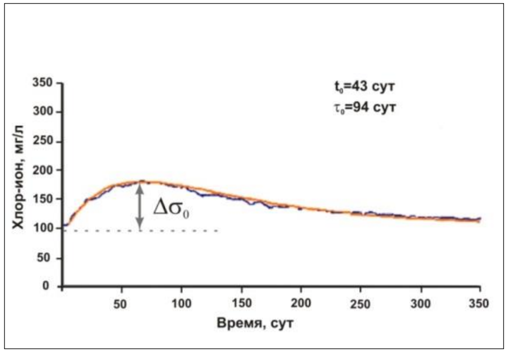
$\boldsymbol{t_0}$ – relaxation time of the pressure pulse in the aquifer, days

$\boldsymbol{\tau_0}$ – time of mixed water flow movement in the aquifer (and wellbore), days.

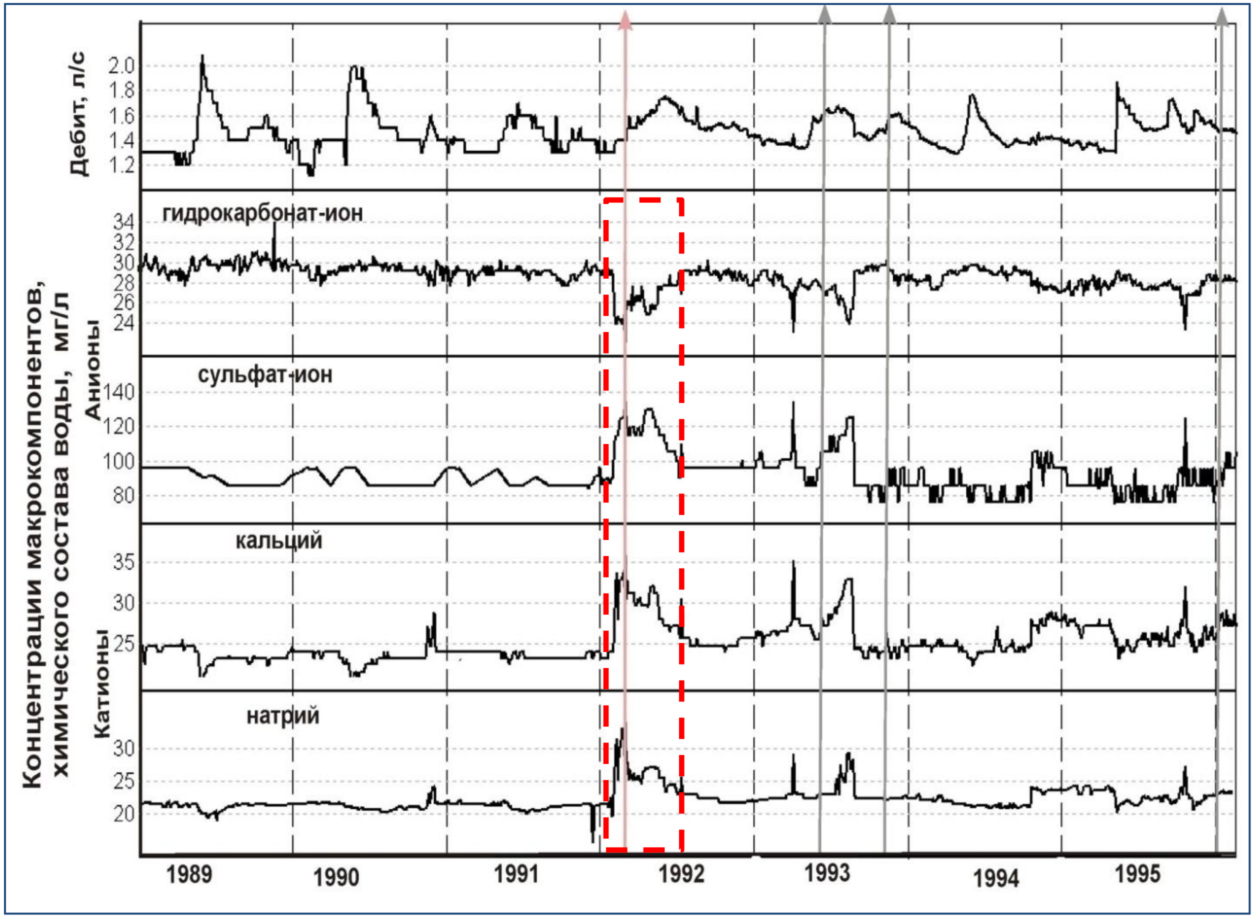
HGCP modeling :

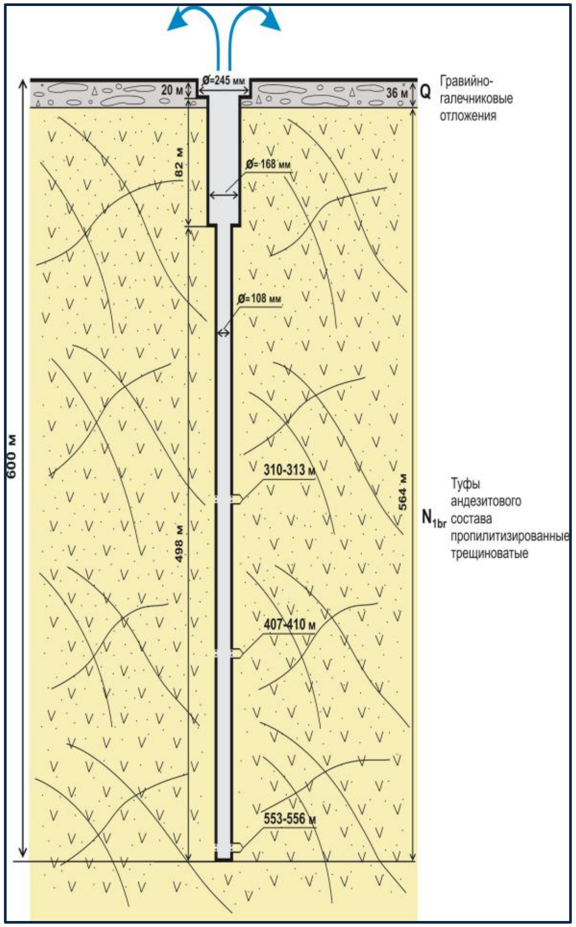
$\pm\delta\sigma_0$ estimated from the observation data as the amplitude of the anomaly in IK .

$\boldsymbol{t_0, \tau_0}$ are determined by selection with a minimum discrepancy between the model (red line) and observational data (blue line) for all components of the water composition (preferably!), or for one indicator component.



Time series of hydrogeochemical observations , Kamchatka, M-1 well, 1989-1996. Red rectangle shows background variation, precursor and postseismic variation for modeling





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HGCP before the 02.03.1992 EQ, M = 6.9, de = 135 km:

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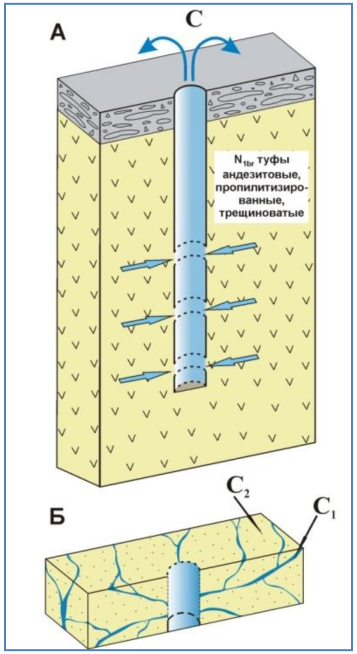
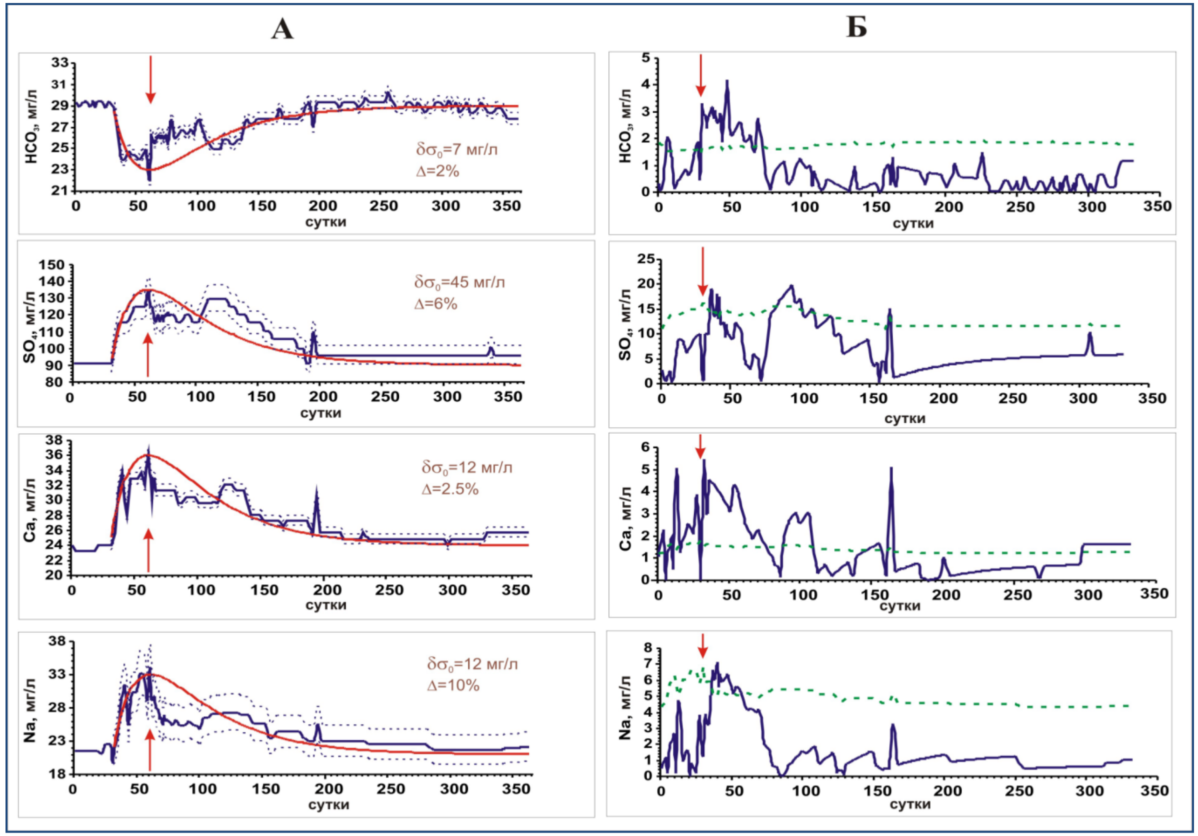
Modeling results, M-1 well *(Kopylova, Boldina, 2012, 2019)*

Aquifer model - dual porosity environment [Barenblatt, Zheltov, 1960]



C1<C2

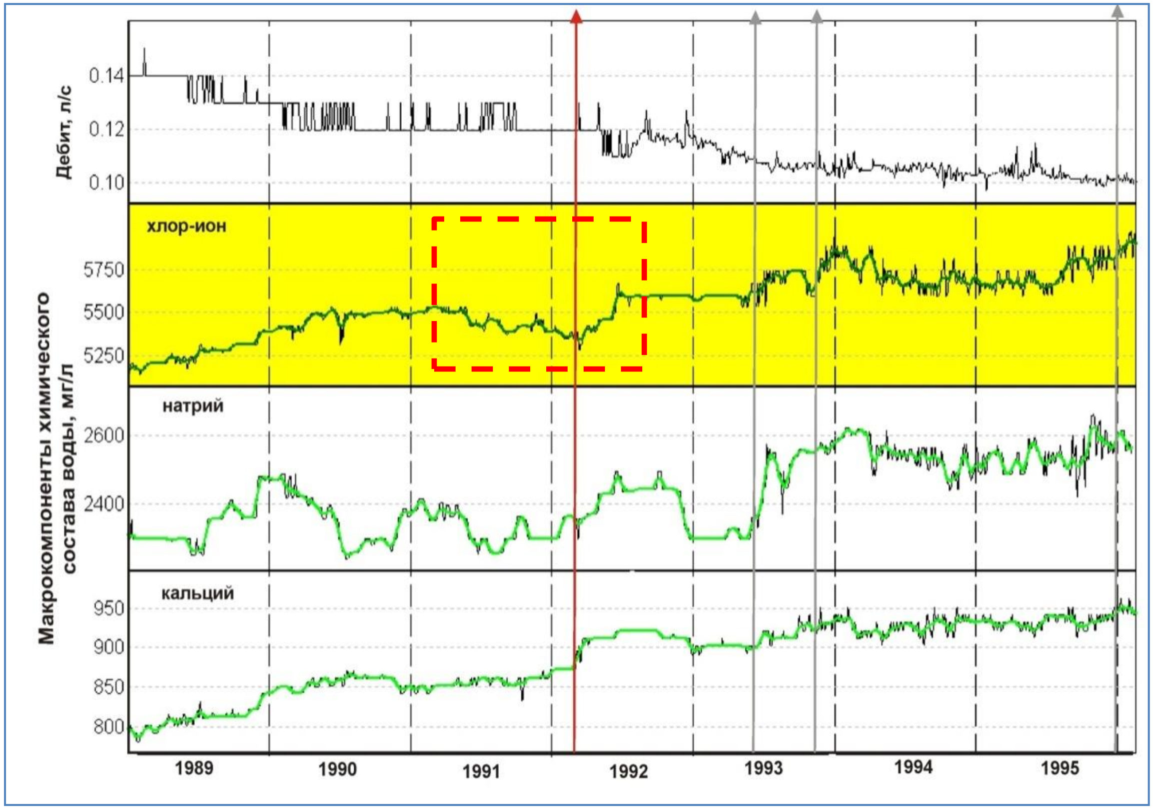


1. ***The obtained parameters characterize the hydrodynamic state of the aquifer during the formation of HGCP: relaxation time of the pressure pulse t_0 = 20 cym and the time of mixed water movement τ_0 = 50 cym.***
2. ***The compositions and fractions of two waters in mixed water from a well were estimated under background conditions and during the formation of HGCP:***

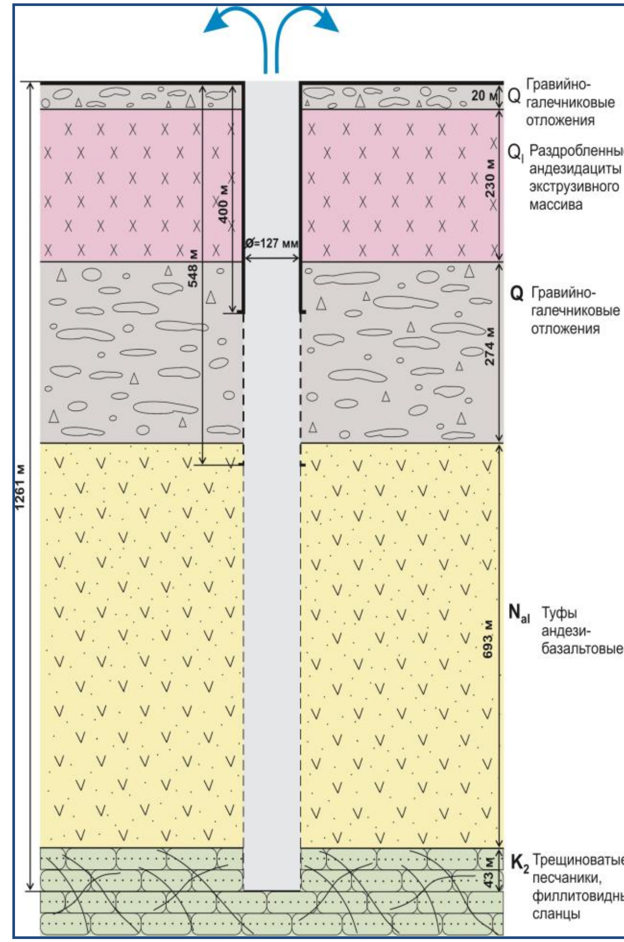
n:m	Water C_1	Water C_2	n':m'
0.9:0.1	$M_{0.17}(SO^4 72HCO^3 25)/(Ca53Na46)$	$M_{0.37}(SO^4 97HCO^3 2)/(Ca66Na34)$	0.6:0.4
0.87:0.13	$M_{0.17}(SO^4 71HCO^3 25)/(Ca57Na42)$	$M_{0.34}(SO^4 96HCO^3 3)/(Ca53Na46)$	0.5:0.5
0.8:0.2	$M_{0.16}(SO^4 71HCO^3 26)/(Ca56Na43)$	$M_{0.32}(SO^4 90HCO^3 8)/(Ca54Na45)$	0.2:0.8
0.7:0.3	$M_{0.14}(SO^4 65HCO^3 31)/(Ca56Na43)$	$M_{0.30}(SO^4 90HCO^3 8)/(Ca55Na44)$	0.2:0.8

n- water from "cracks"
m- water from "blocks"

GK-1 well



M_{10} Cl98/(Na68 Ca27)

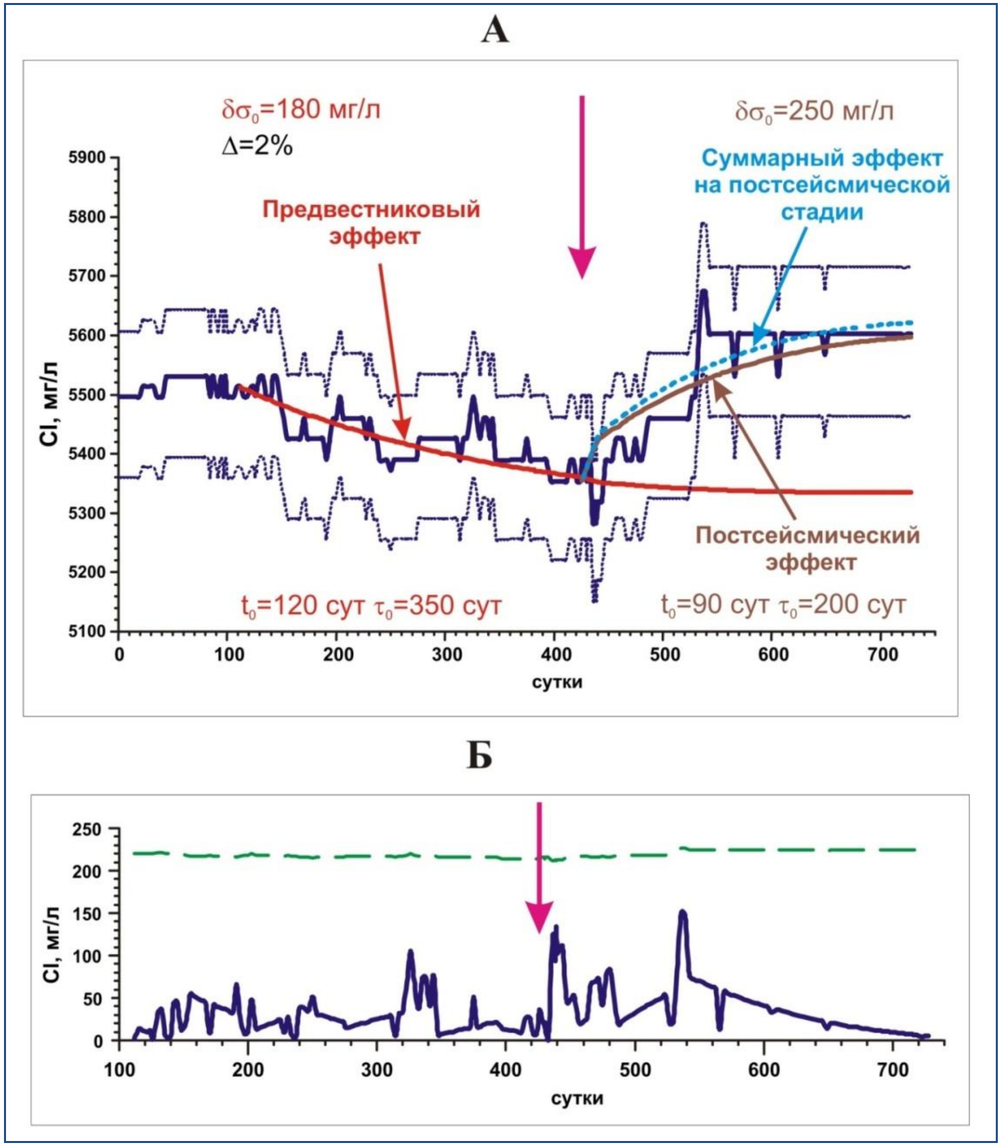


HGCP of EQ 2.03.1992, M = 6.9, de = 120 km:
relative decrease in the concentration of chlorine ion (by 180 mg/l or 3% in relation to the background, dilution) within 9 months.

Postseismic effect: an increase in the concentration of chlorine ion and other macrocomponents (solution concentration).

V=16.2 м^3
Q=0.1 дм^3/с
T=1.9 сут
Δt=3 сут
Δ_{Cl} = 2%

The results of modeling HGCP and postseismic effect, GK-1 well, Cl-ion



Theoretical modeling of the shape and duration of the HGCP according to (Wang et al., 2004) for various t_0 and τ_0 values

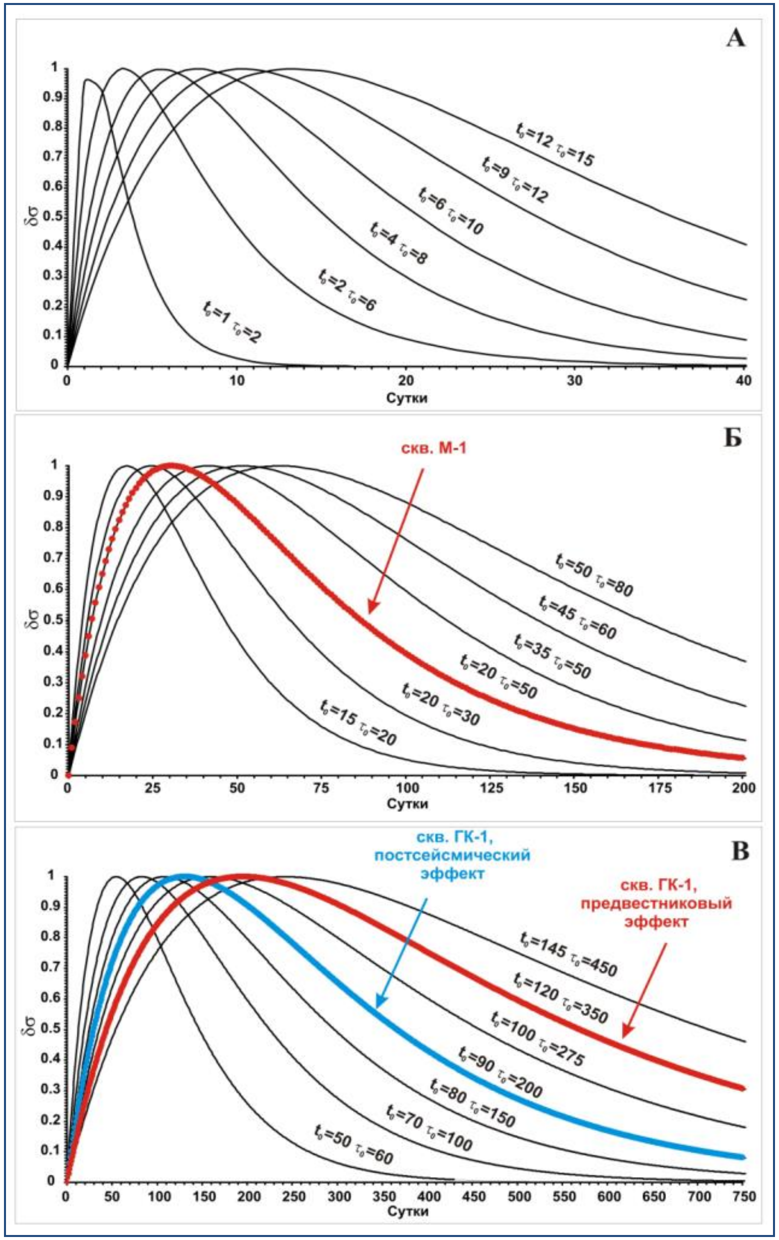
1. On the basis of reliable data on HGCP and the model [Wang et al., 2004], the parameters of the disturbed hydrodynamic state of the aquifer can be estimated: t_0 and τ_0 . **The ratio of these parameters determines the shape and duration of the HGCP.**

2. The ratio between the amplitude of the anomaly $\delta\sigma_0$ and **Δ -** the relative error of the chemical analysis of an individual component, is important for the practical determination of HGCP. If $\delta\sigma_0 \le |(\sigma_2 \pm 0.01\Delta\cdot\sigma_2)-(\sigma_1 \pm 0.01\Delta\cdot\sigma_1)|$, where σ_1 is the analytically determined background concentration of the component; σ_2 - extreme concentration at the stage of anomaly, then ***the determination of such an anomaly is impossible with relatively rare observations***.

3. If the parameters t_0 and τ_0 are small (**Fig. A**), then with a large sampling frequency, the anomaly may not stand out, or the idea of its shape will be distorted (a single "emission" of an concentration may be recorded).

For example, HGCP in the M1 well (**Fig. Б**) was previously classified as “jump-like” by morphological characteristics [*Kopylova et al., 1994; Ryabinin, Khatkevich, 2009*]. The reason for the wrong judgment is the relatively “large” periodicity of water sampling 3 days, at which the HGCP form was distorted.

The observation period of 3 days turned out to be sufficient to assess the normal “bay-like” forms of HGCP and postseismic effects in the well GK-1 (**Fig. B**) (*Kopylova, Boldina, 2012)*



Conclusion

1. ***Hydrogeochemical precursors are manifested in changes in the chemical composition of groundwater and gases in the near and intermediate zones of the strong earthquake sources.***

2. *The traditional method of HGCP searching is laborious and unreliable. The quality of the initial data depends on the "human factor". HGCP can be reliably diagnosed under very favorable combinations of natural conditions in well area and observation method:*

- the presence of waters with a contrasting chemical composition and gases of "deep" genesis in aquifers;

- favorable combinations of the aquifer structure and the natural hydrodynamic regime of observation well for the formation of contrasting and long-term (at least tens of days) anomalies in the chemical composition of mixed water;

- *qualitative analytical determination of the totality of all macro components of the chemical composition of water (anions and cations).*

3. The development of the hydrogeochemical method for the HGCP's searching is associated with the automation of the observation system at wells for the integral indicators of the chemical composition of groundwater (electrical conductivity, salinity, pH, Eh, gas content) in conjunction with observations of the water temperature and hydrodynamic parameters - pressure and discharge rate of water and gas.

4. ***The traditional method of observations at flowing wells can be used as an auxiliary one to justify the choice of objects of regime observations and obtain detailed information about the chemical composition of underground water and gas.***

Thanks for your attention!

The research was was supported by the Russian Foundation for Basic Research, project 18-05-00337