FROZEN WATERFALLS:
HOW THEY DEVELOPE
HOW THEY COLLAPSE

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1 FROZEN WATERFALLS

Thanks to the survey, sponsored by the IFMGA, of the Waterfall Degli Specchi (Chiesa Valmalenco, Italy) during the winter seasons 2000-01 and 2001-02 (Figure 1.1 and Figure 1.2), now we know something more about the frozen waterfalls and the ice climbing safety.

Figure 1.1: the waterfall Degli Specchi in January 2001

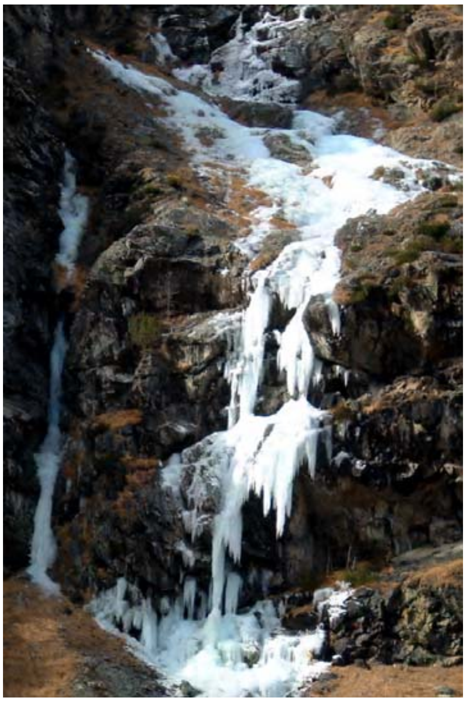


Figure 1.2: the waterfall Degli Specchi in January 2002

The frozen waterfalls can be classified according to a hydrological criterion as:

- frozen waterfalls with flow, if they originate from a real waterfall, so they exist also as liquid,
- ghost frozen waterfalls, if they don't exist as liquid waterfall except as temporary runoff after heavy rainfall.

From a static point of view the frozen waterfalls can be classified, according to the position of the vertical projection of their centre of gravity (G) respect the base of the waterfall and of its supporting wall, as (Figure 1.3):

- frozen waterfalls with this projection falling into the supporting wall,
- frozen waterfalls with this projection falling into their base.

The hanging ones are the most dangerous from the point of view of possible collapses. This kind of structure grows along overhanging rock walls and is formed by groups of stalagmites. The frozen waterfalls are composed of three different kinds of ice:

. ice produced by the congelation of liquid water,

. ice derived from snow metamorphosis,

. ice generated from the waterfall spray due to the wind (splash concretions).

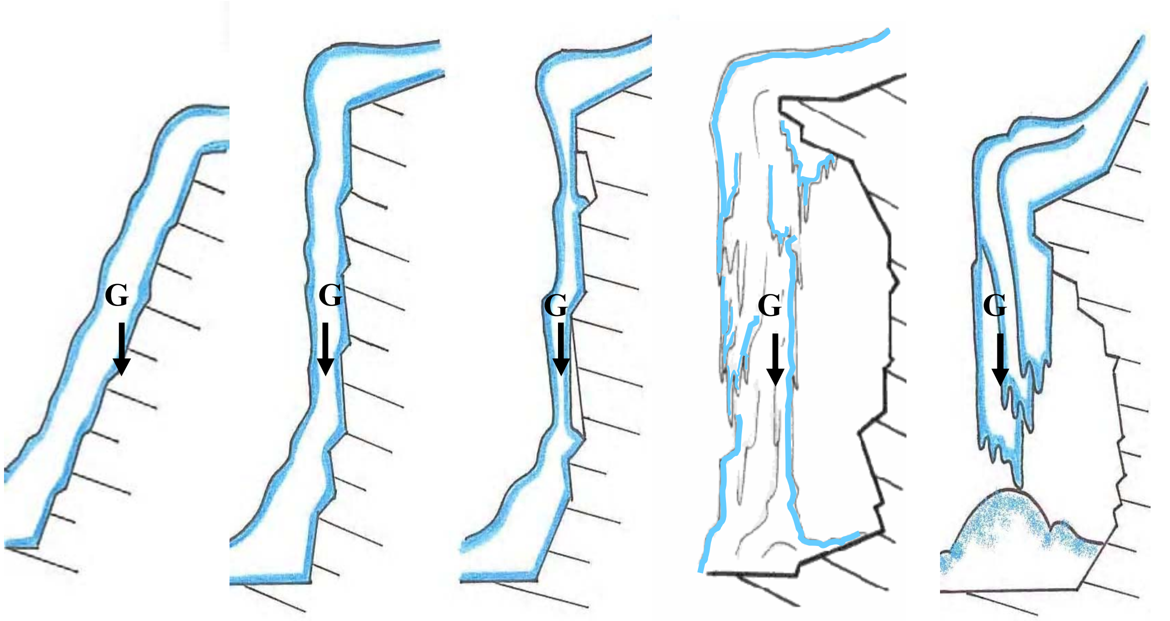
G in to the supporting wall	G into the base of the frozen waterfall			
Wall with low inclination	Sub vertical or vertical wall		Overhanging wall	
				
Hanging	*Completely adherent*	*Partially adherent*	*Column*	*Hanging*

Figure 1.3: statical classification of the frozen waterfalls

First of all the evolution of the volume of the ice of the whole frozen waterfall in winters 2000-2001 and 2001-2002 has been calculated (Figure 1.4, Figure 1.5 and Figure 1.6).

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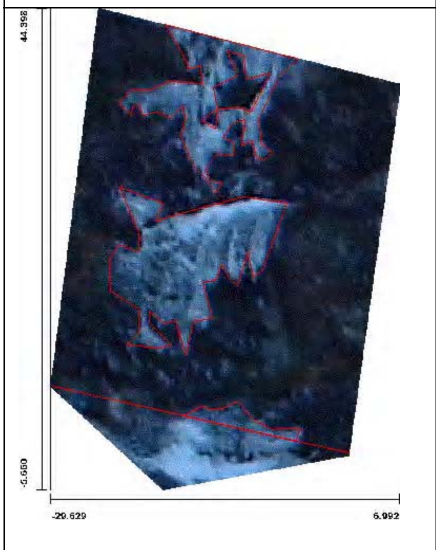	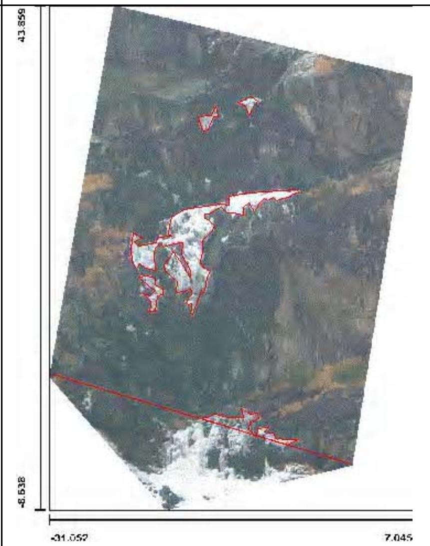	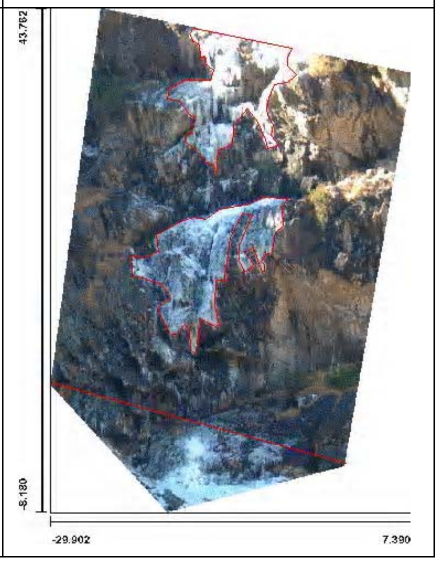

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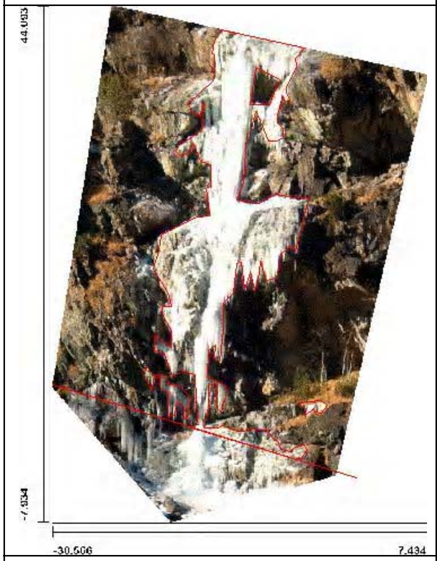
15.12.2001



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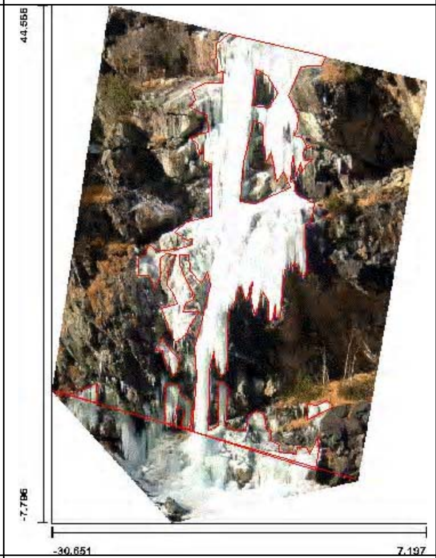

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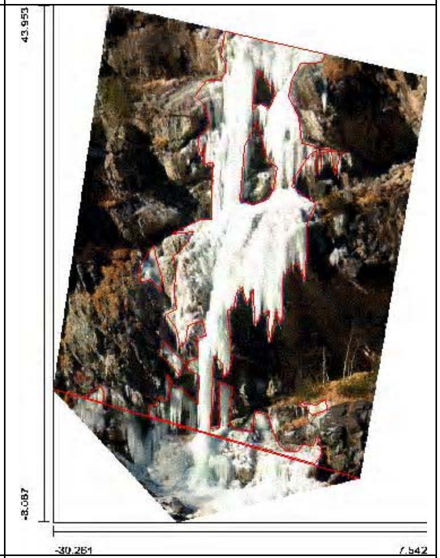

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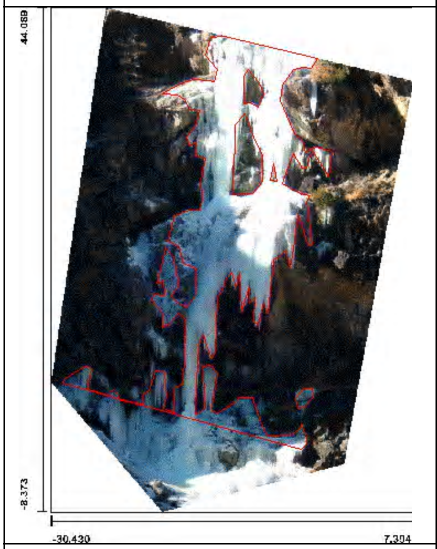
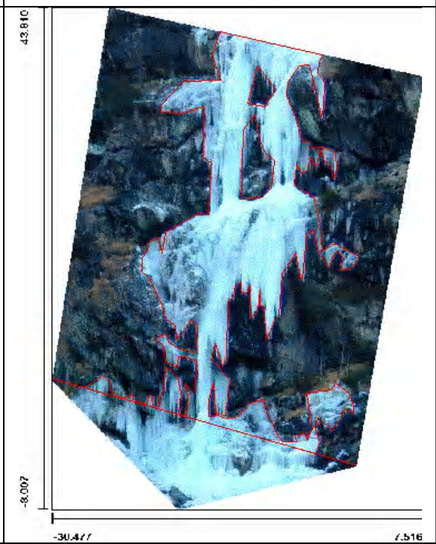
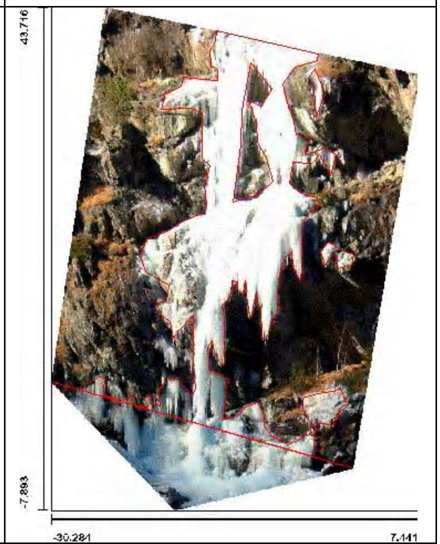


31.12.2001



03.01.2002



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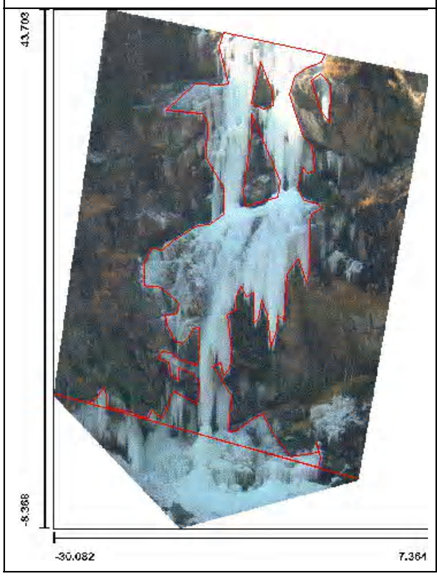
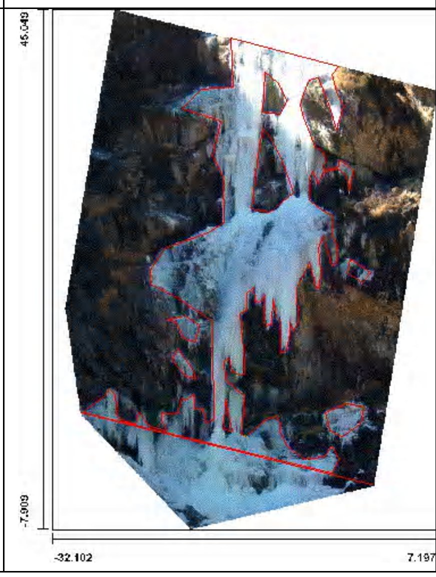
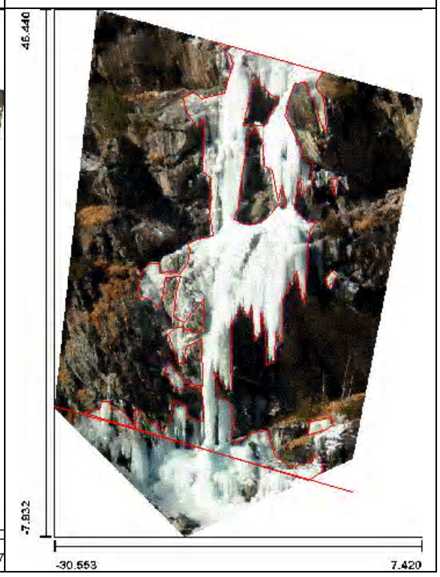


06.01.2002



19.01.2002



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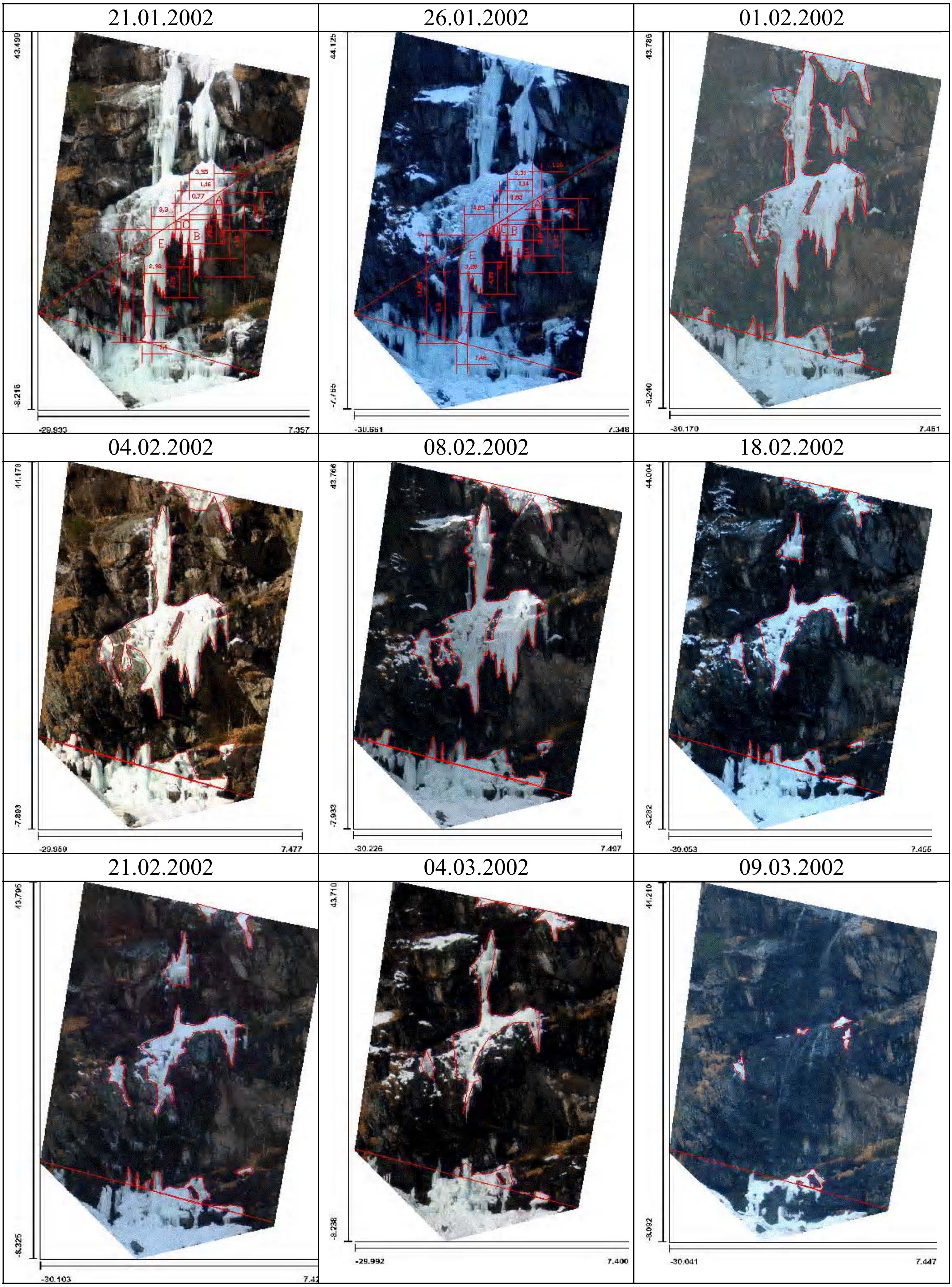

Figure 1.4: evolution of frozen waterfall in the winter season 2000-2001

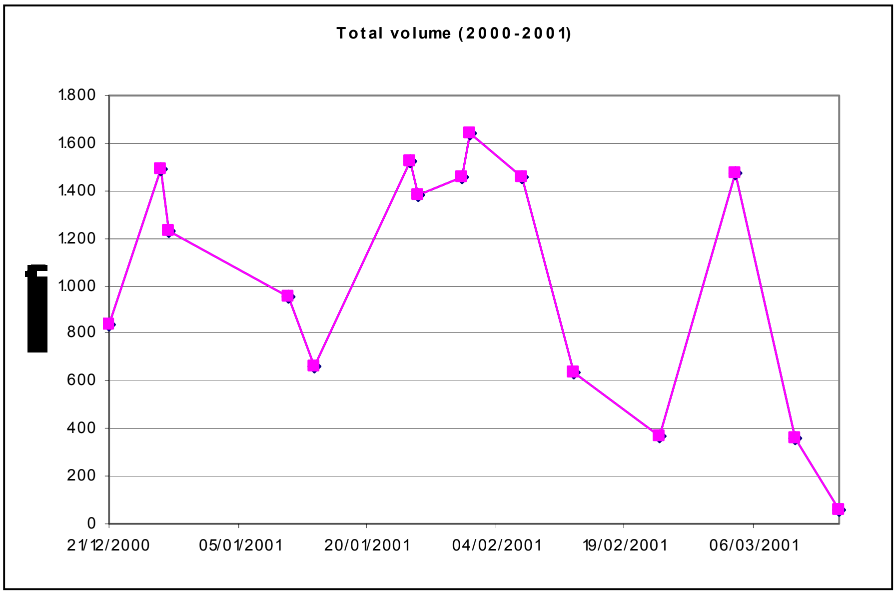

Figure 1.5: evolution of the volume of ice of the whole frozen waterfall in the winter season 2000-2001

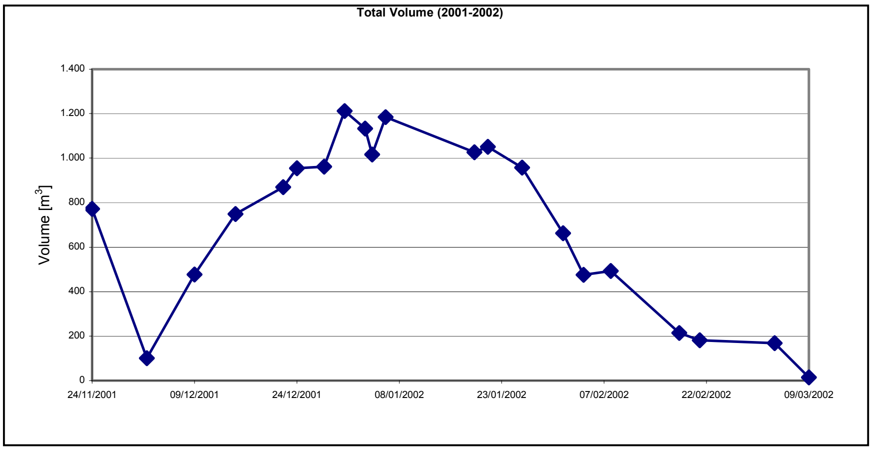

Figure 1.6: evolution of the volume of ice of the whole frozen waterfall in the winter season 2001-2002

While the growth of the frozen waterfall can proceed only gradually, even if with different velocity, for progressive freezing of the flowing water, the decrease can happen in two ways. The first gradually reduces the mass by melting the ice, while the second has instantaneous character and coincides with sudden partial or total collapse of icy structures.
A patent example of collapse happened the day of 03/02/02 when the principal structure of the frozen waterfall, a column attached to the rock in the upper part and sitting on an ice cone, fell down.

2 Factors of evolution and their internal relationships

The factors that effect the frozen waterfall evolution and their interactions are shown in Figure 2.1.

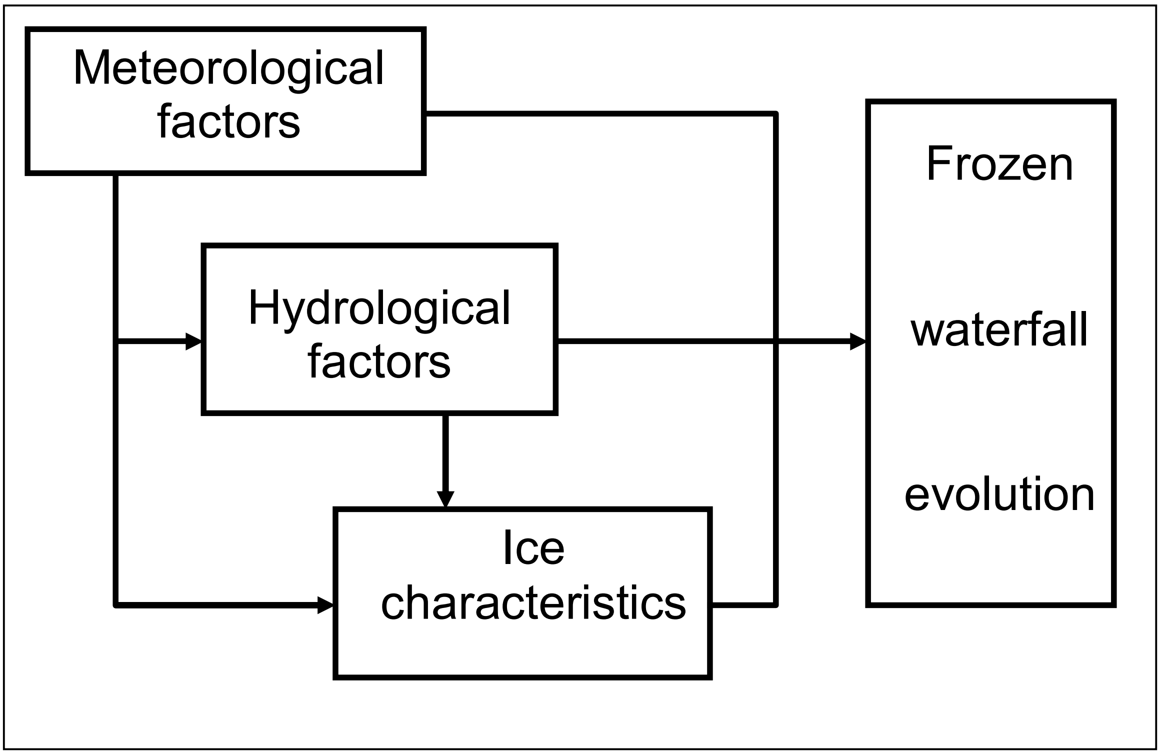

Figure 2.1: the factors that effect the evolution of frozen waterfall

2.1 The weather

The climatical factors effecting the evolution of a frozen waterfall are: precipitation, air temperature and humidity, wind speed and direction and solar radiation in the direct vicinity of the waterfall.
Singular measures of temperature at the waterfall site have been done during the stay at the waterfall, which happened nearly once a week and in the central hours of the day.
Besides this, the half-hourly data of four other stations have been used to calculate the unknown temperature values at the waterfall during the whole period.

2.2 The water

A main factor for the evolution of a frozen waterfall is, of course, the water flow that forms the waterfall and especially its hydrological regime.
The hydrological regime has been calculated by means of the PRMS rainfall-runoff mathematical model. The final simulation, shown in Figure 2.2, matches very well the estimated and measured values of flow rate.

2.3 The ice

2.3.1 Ice strength and its determination

Many bending tests have been performed at the waterfall site to determine the strength in the ice of the frozen waterfall at its breaking point. The bending test on little icicles seemed to be the only one possible due to the many local, logistic and practical problems.
According with theory, the selected icicles were little stalactites with a three-dimensional narrow and long shape as similar as possible to a cylinder and with vertical axis, while columns or more complex structures have been excluded (Figure 2.3).

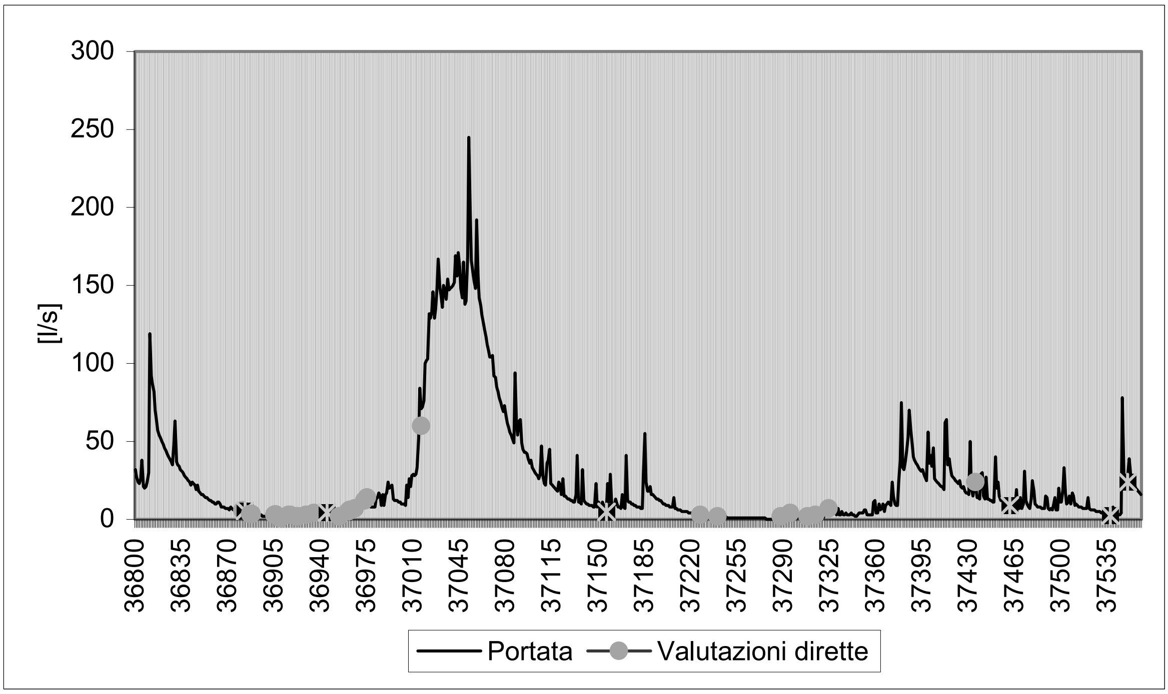

Figure 2.2: final PRMS calculated (—) and measured (x) or estimated (•) values of flow rate

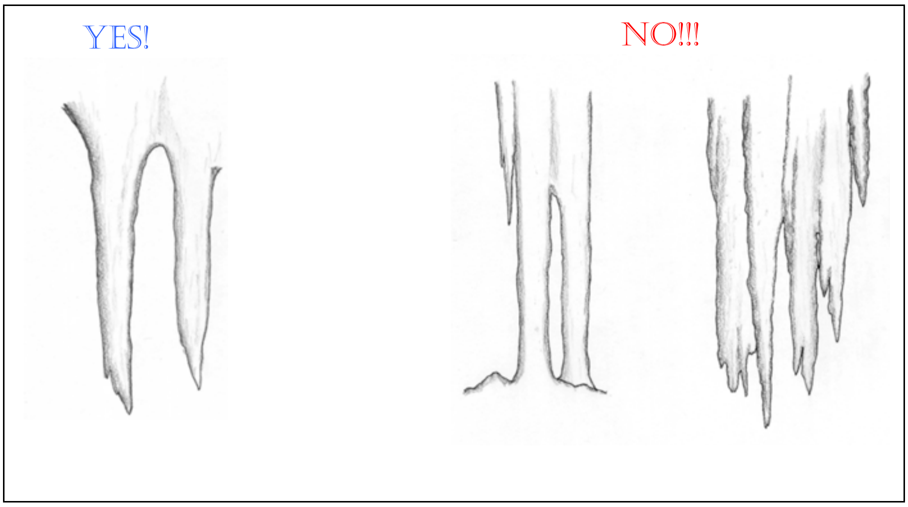

Figure 2.3: examples of selected (left) and rejected (right) structure for the bending test

The necessary data for calculating the strength at the breaking point are:

- the breaking force and its arm,
- the direction of the breaking force,
- the geometry of the breaking section.

After selecting the stalactite, a rope sling has been put around the icicle and a dynamometer hooked to the sling (Figure 2.4). Then one person pulls the dynamometer until the stalactite breaks and recorded the breaking force, a second one catches the stalactite before it falls to the ground and measures the distance from the pulling to the breaking section.

Figure 2.4: preparing a bending test

2.3.2 Index of strength of the ice

Since the calculation of the exact strength of the ice is pretty complex, two indexes of the strength of the ice has been stressed out which could be easily calculated and, at the mean time, were sufficiently close to the real strength (Figure 2.5). A comparison of the two indexes and the real strength vs. time, where you can notice that generally P_A underestimates and P_B overestimates the real value of the breaking strength, while P_B is a better estimation of the real breaking strength.

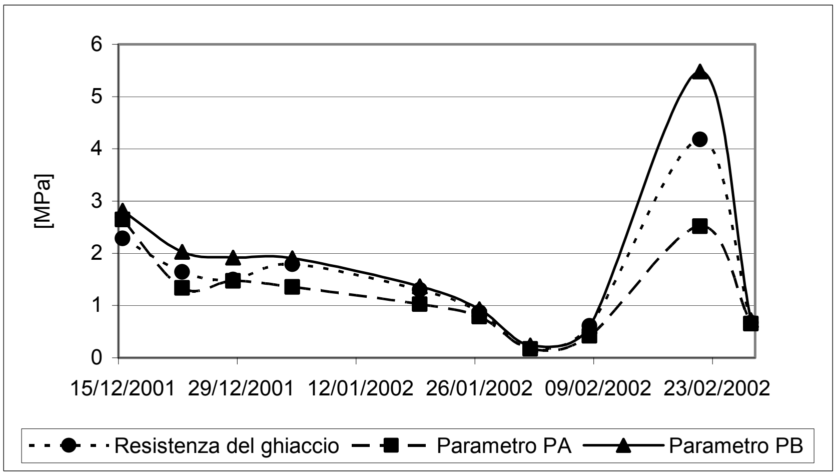

Figure 2.5: strength indexes and real breaking strength vs. time

Then the strength, if you select circular icicles, can be evaluated through the strength indexes:

$$P_B = 30.95 \cdot \frac{F \cdot b}{(2p)^3} \qquad [MPa]$$

by measuring the force (F) in kg with a dynamometer, the arm (b) in cm and the perimeter (2p) also in cm (Figure 2.6).

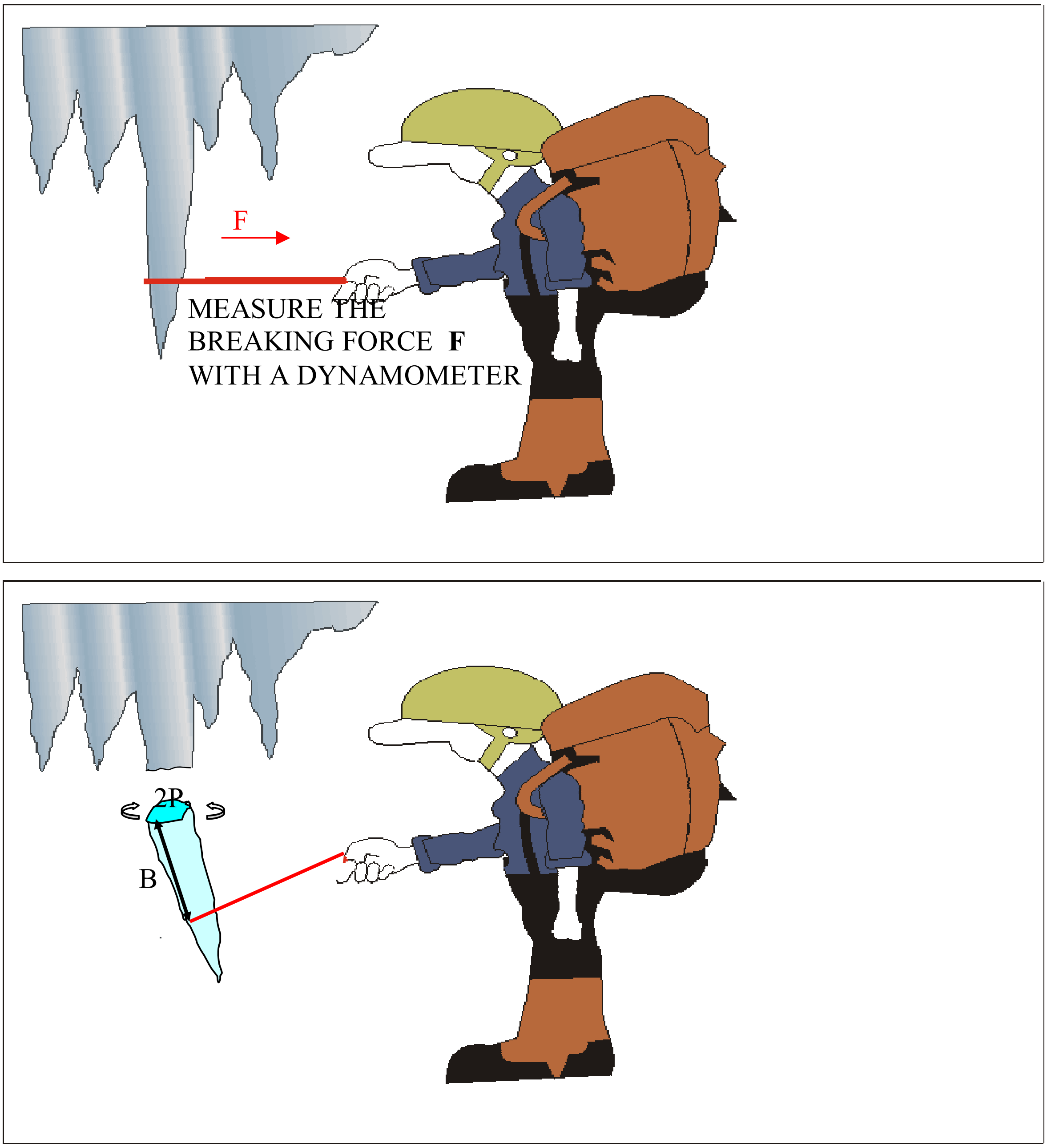

Figure 2.6: bending test for calculating the strength index

2.3.3 Ice density

During the study, measurements of the ice density have been performed. Figure 2.7 shows the whole set of measurements.

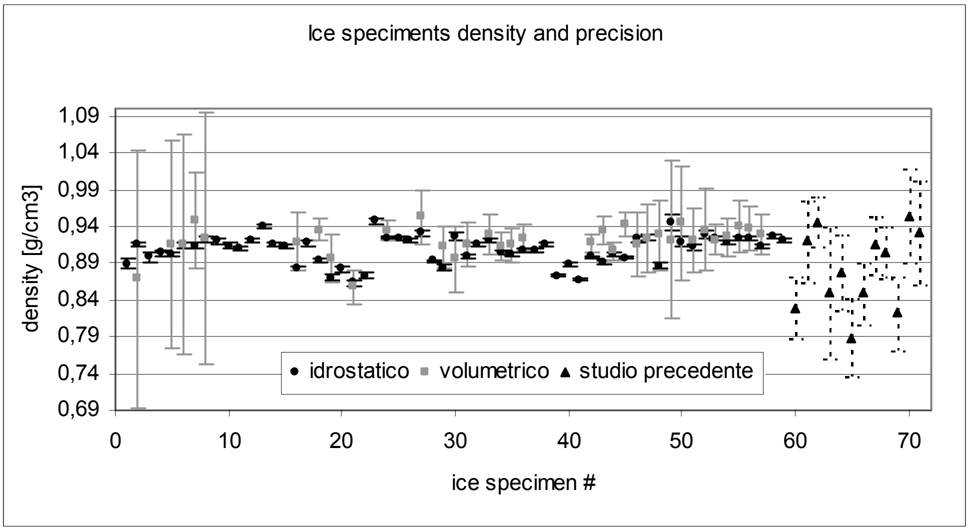

Figure 2.7: ice specimens density and precision for the set of data including those of the first phase of the study (bars represent the precision of each measurement)

2.3.4 Colour and texture of the ice

Structure, colour, texture and air bubbles and other inclusions of each ice specimen has been described.
Specimens have been classified with regard to their transparency in a scale from very transparent to white (Table 2.1).

Table 2.1: ice specimens classification according to their colour

MTr	Very transparent
Tr	Transparent
TpB	Transparent – little white
TB	Transparent – white
BpT	White – little white
To	Turbid
B	White

In a similar way they have been classified with regard to their compactness in a scale from compact to granular (Table 2.2).

Table 2.2: ice specimens classification according to their texture

C	Compact
CP	Compact – with plate
AC	Fairly compact
Po	Porous
G	Granular

2.4 Internal relationships among factors of evolution

Since one of the goals of this study is to find out the climatic and hydrological factors that mostly effect the mechanical characteristics of the ice, diagrams have been draw that represent ice strength vs. temperature, air humidity, sky coverage and flow rate.
Figure 2.8 shows the course of the ice strength and its average value during the winter season 2001-02.

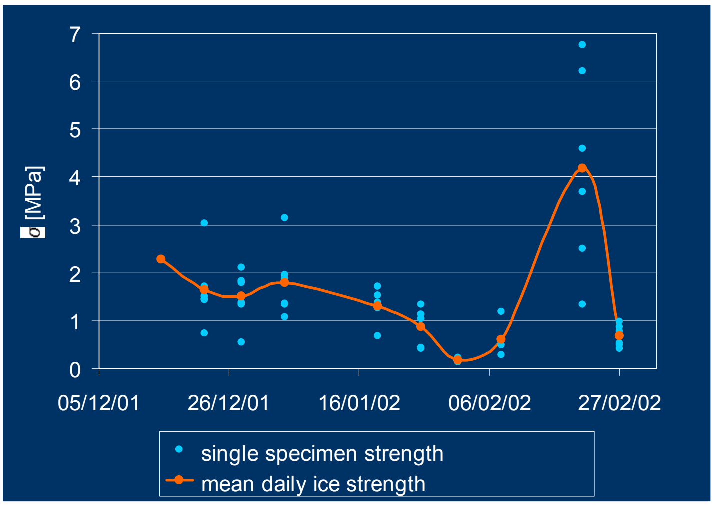

Figure 2.8: ice strength vs. time

2.4.1 Relationship between ice strength and air temperature

The temperature is surely the factor that mostly effects the ice formation process. Congelation occurs in different ways depending if there are or not sudden drops in temperature or phenomena of melting and re-congelation due to the temperature variation in time.
Thus the calculated strength has been plotted not only vs. the temperature at the test moment but also vs. mean temperature of different lag of time before the test.

2.4.1.1 Air temperature during test

From graphic of Figure 2.9 you can notice that the strength of the ice is tightly related to the temperature at the test moment as the two curves are opposite in phase: when the temperature falls the strength rises and vice versa.
From the graphic of strength vs. air temperature at the test moment (Figure 2.10) a trend can be noticed where strength is higher with lower temperature and decreases while temperature increases with the exception of the data of the 21st of February.

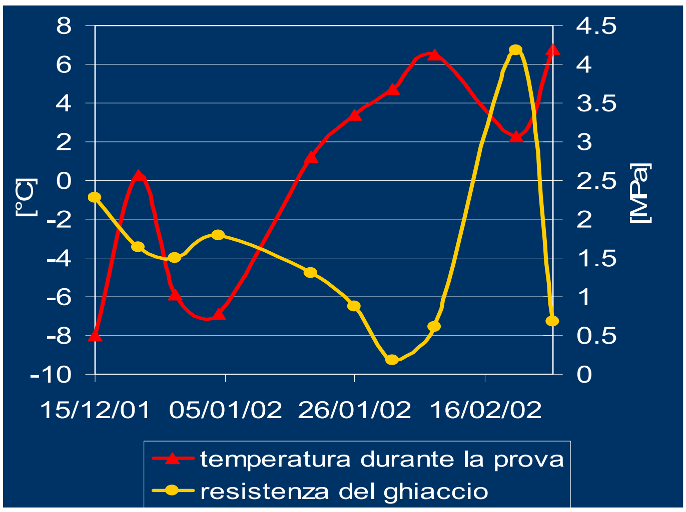

Figure 2.9: ice strength and temperature at the test moment vs. time

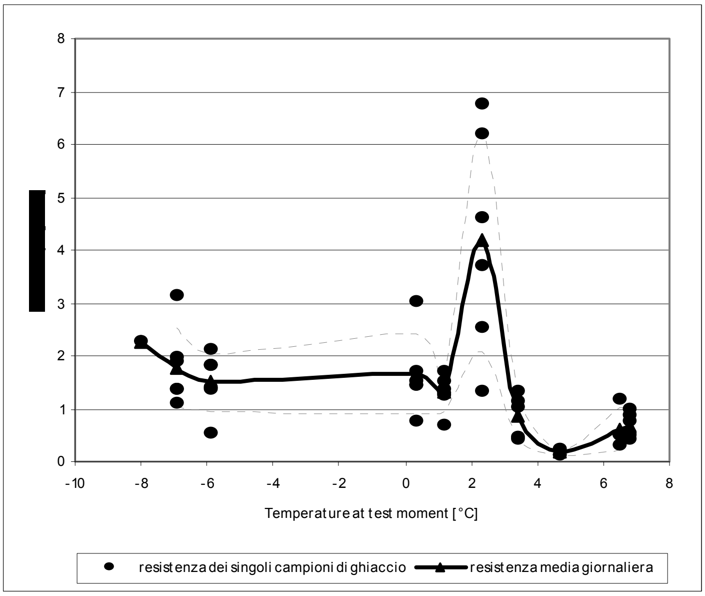

Figure 2.10: ice strength vs. air temperature at the moment of the test (dotted lines represent the standard deviation wide band)

2.4.1.2 Maximum, minimum and average daily temperature

In Figure 2.11 the course of ice strength and maximum, minimum and average daily temperature are plotted.

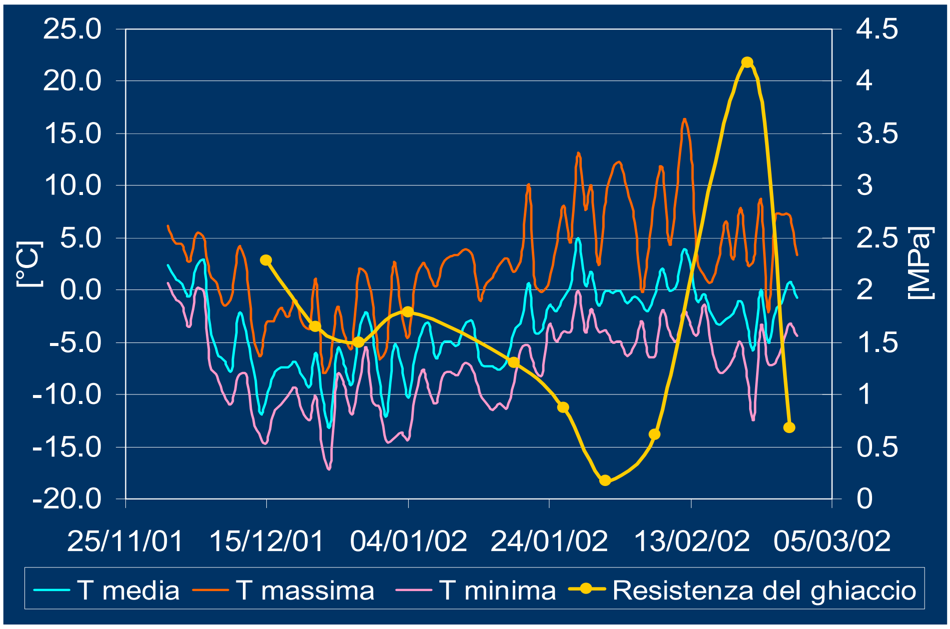

Figure 2.11: ice strength, maximum, minimum and average daily temperature vs. time

Following the evolution of the phenomena, you can notice:

- the sudden drop in minimum temperature between December 10 and 15 produces a highly resistant ice,
- then, in the last days of December, strength decreased because of the rising minimum daily temperature and the very small variation of the temperature during the day,

- at the beginning of January 2003 a new sudden drop in minimum temperature and bigger variation of the temperature during the day caused a process of melting and solidifying that increased the crystalline structure of the ice,
- then after, maximum temperature became steady above 0° C and also the minimum temperature weren't as cold as before. This produced a slow decreasing of the strength,
- from the end of January to the beginning of February, the temperature sudden increased and mean daily value became steady above zero or lightly below, while minimum temperature never went below –5° C. This produced diffused melting processes and a drop in ice strength which reached the minimum at the beginning of February,
- after this relatively warm period, the temperature dropped suddenly again below zero and the minimum temperature became very cold again. The ice started growing again and thanks to the process of melting an solidifying it was very resistant and that could explain the apparently exceptional values of February 21,
- at the end the temperature rised again and the few structures still existing at that point were little resistant.

You can carry out that the 'history' of the temperature strongly effect the strength of the ice and especially important are the processes of melting and solidifying that occur when, after increased maximum temperature, more or less rapid drop in minimum temperature happen.
These processes can change the crystalline structure of the ice which can become more resistant.

2.4.1.3 Daily temperature variation

Big and quick variation of the temperature during the day, represented by the difference between the maximum and minimum daily temperatures, can effect negatively the structure of the ice and reduce its strength. Figure 2.12 makes evident these phenomena.

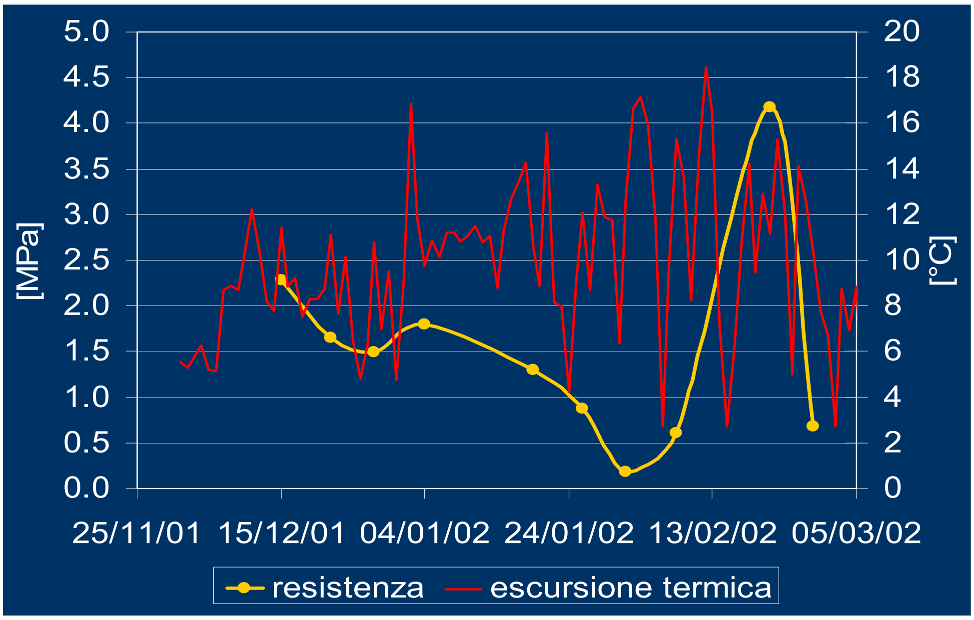

Figure 2.12: ice strength and daily temperature variation vs. time

You can notice that from the beginning of January the variation of the temperature during the day increases and the strength of the ice gradually decreases until it reaches its minimum on February 2 with a variation of 15° C.
On the contrary the high strength on February 21 depends on the low temperature during the night.

2.4.1.4 Average temperature in many days

Since the temperature in the days before the strength test is important too, the strength data have been plotted together with the average temperatures in some days before the test.

In Figure 2.13 ice strength and:

- Tr_1: average temperature of the day of the test,
- Tr_3: average temperature in 3 days before the test (including the day of the test),
- Tr_7: average temperature in 7 days before the test (including the day of the test)

are plotted vs. time.

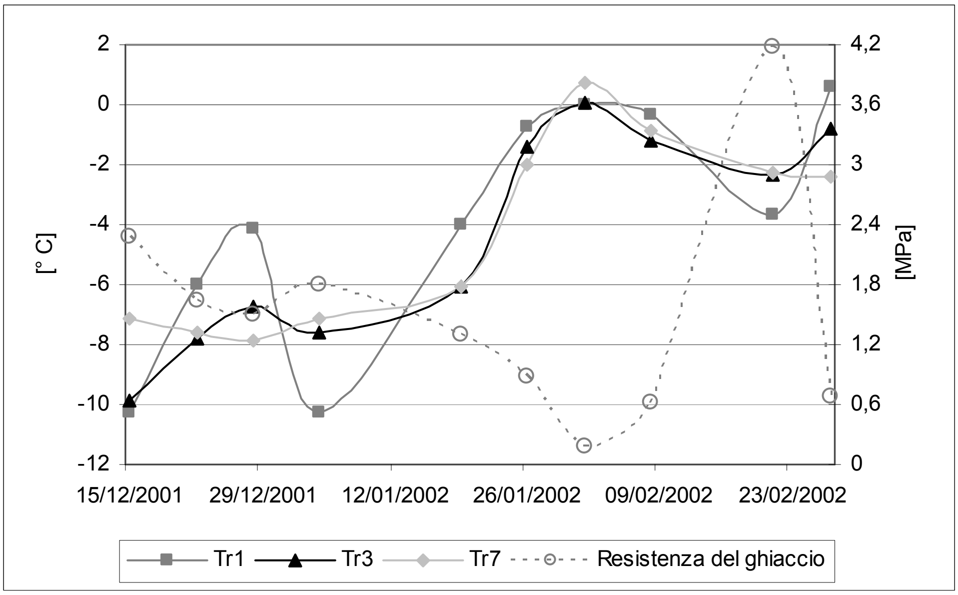

Figure 2.13: strength and temperatures Tr_1, Tr_3 e Tr_7 vs. time

You can notice that also in this case the strength and the average temperature are still opposite in phase. The curve that seems to better fit this rule is the 3 days average temperature (Tr_3, Figure 2.14). Thus it seems that the structure of the ice and its strength are mostly effected by the average temperature of a few days before the test, while longer periods do not effect it so much.

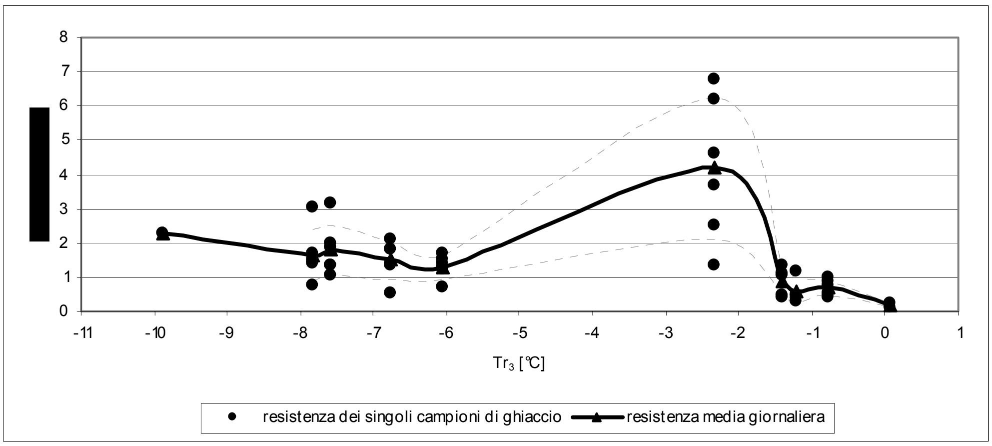

Figure 2.14: ice strength vs. Tr_3 (dotted lines represent the standard deviation wide band)

In any case the strength decreases with the increasing temperature. But there is a maximum of strength around a few degrees below zero, This fact is confirmed by many ice climbers which have noticed that the strength of the ice is high when the air temperature is about -2° C ÷ -4° C.
Finally, at very low temperature, the ice, though still resistant, become fragile and thus dangerous for the climbers.

2.4.1.5 Temperature variation in two days

Also the difference ΔT between the mean daily temperature of the day of the test and the one of the preceding day has been plotted together with the strength of the ice (Figure 2.15).

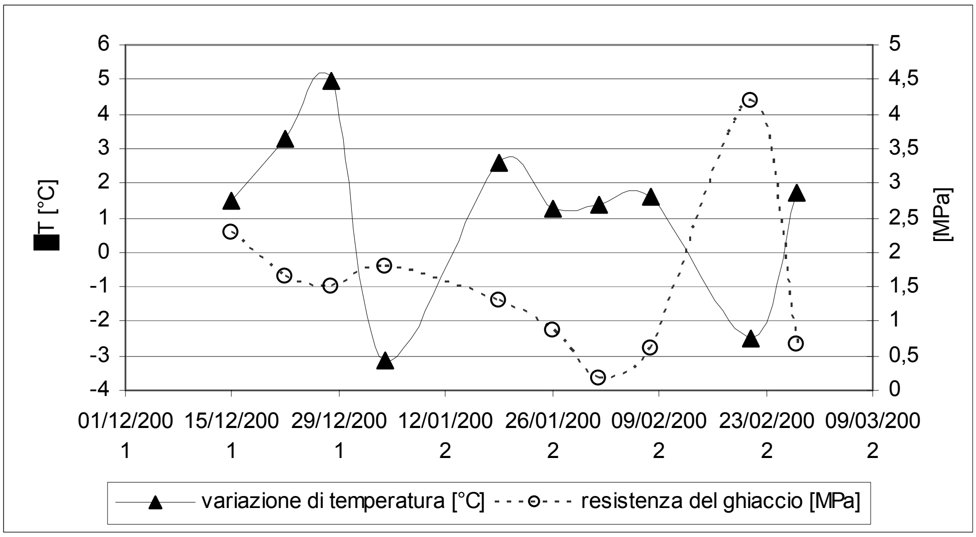

Figure 2.15: strength of the ice and temperature difference in two days vs. time

2.4.2 Relationship between ice strength and air humidity

Also air humidity effects the process of ice formation and a relationship between air humidity and ice strength has also been tried (Figure 2.16 and Figure 2.17).

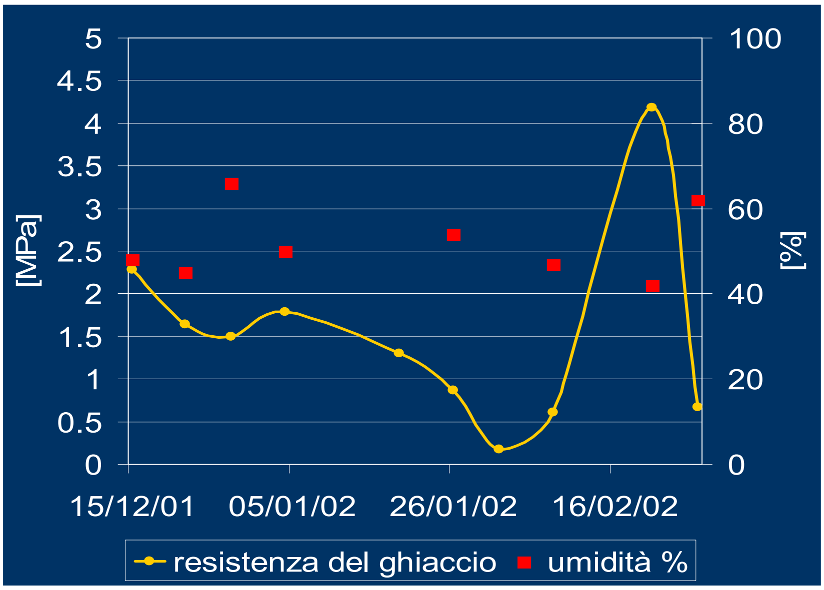

Figure 2.16: air humidity and ice strength vs. time

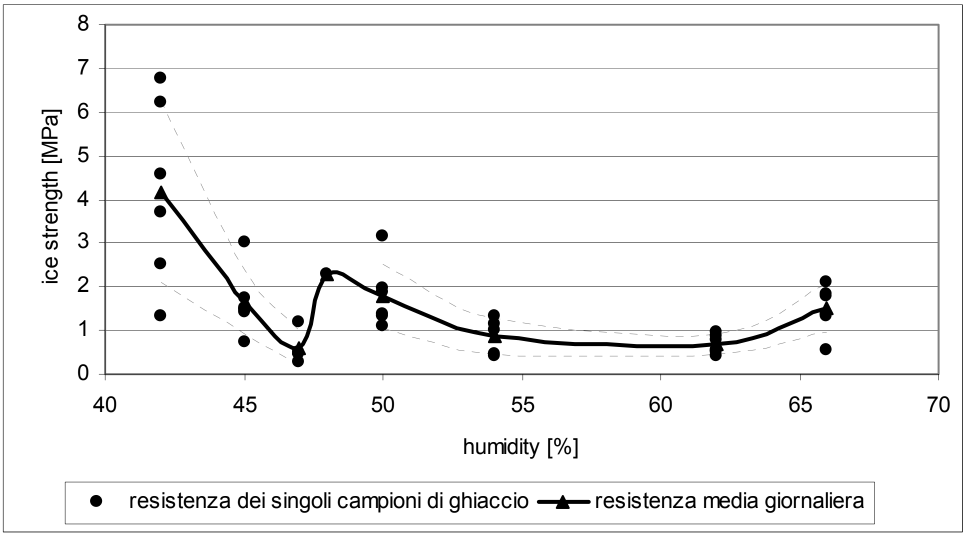

Figure 2.17: ice strength vs. air humidity (dotted lines represent the standard deviation wide band)

You can notice, how the ice seems to be stronger at lower air humidity value; but there is too little data to be sure about this.

2.4.3 Relationship between ice strength and sky coverage

Sky coverage has been observed in substitution of the solar radiation which can strongly effect the stability of the ice structures, but, due to the lack of measurements, any relationship couldn't be found between ice strength and sky coverage.
Besides this you must keep in mind that the heat exchange phenomena by radiation of the frozen waterfall are very little due to its nearly white colour.

2.4.4 Relationship between ice strength and flow rate

Since the flow rate during the whole period of study was nearly constant and very low, it was impossible to find out any relationship with the strength of the ice.

2.4.5 Relationships between ice density and strength

It was impossible to find out any relationship between these two characteristics of the frozen waterfall ice although a kind of relationship should exist.

2.4.6 Relationships between ice density and climatic factors

We tried to find out some relationship also between the ice density and the climatic factors; but we weren't able to find out any significant relationships between density and the considered climatic factors.

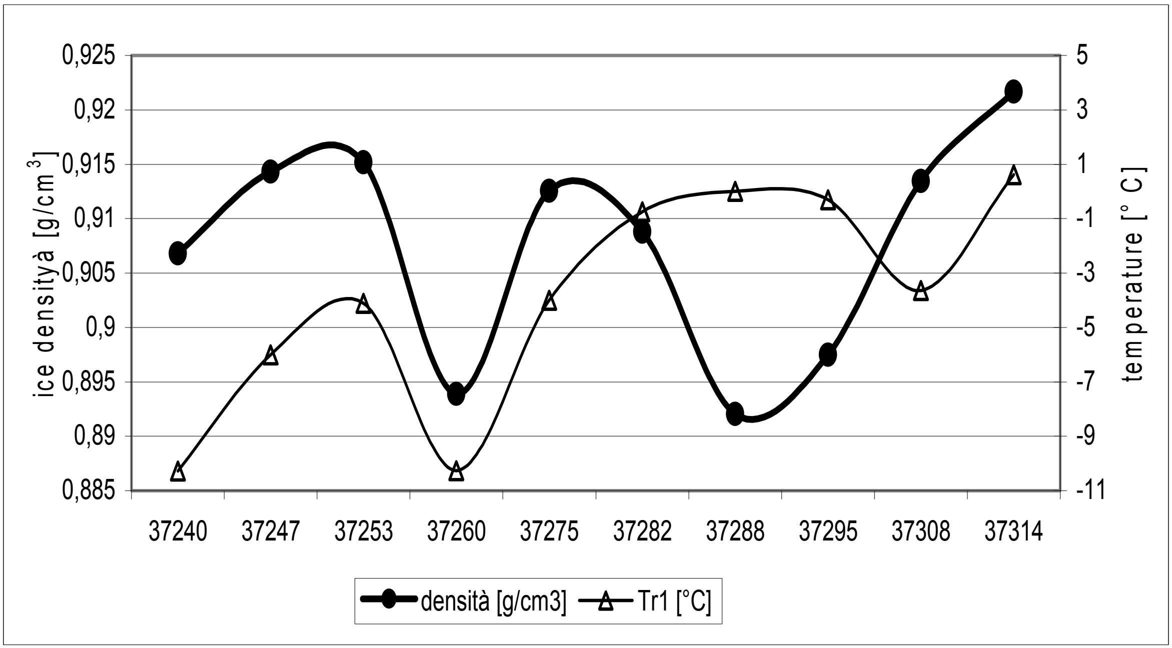

Figure 2.18: ice density and Tr_1 vs. time

Only for Tr_1 (Figure 2.18: ice density and Tr_1 vs. time) you can notice that to the lowest temperatures correspond the lowest densities while in less cold condition density is higher, probably because a fast congelation causes a noticeable air inclusion, but, when the temperature rises around zero, melting and congelation cycles occur and that is not true anymore.
About air humidity you can only say that generally the higher density values have been found in the more humid days.

2.4.7 Relationships among ice colour and texture and its strength

Relationship has been stressed out between the strength and the colour of the ice specimens. Figure 2.19 shows that actually a relationship exists between the transparency and the strength of a stalactite: the clearer and more transparent is the stalactite the stronger it is.

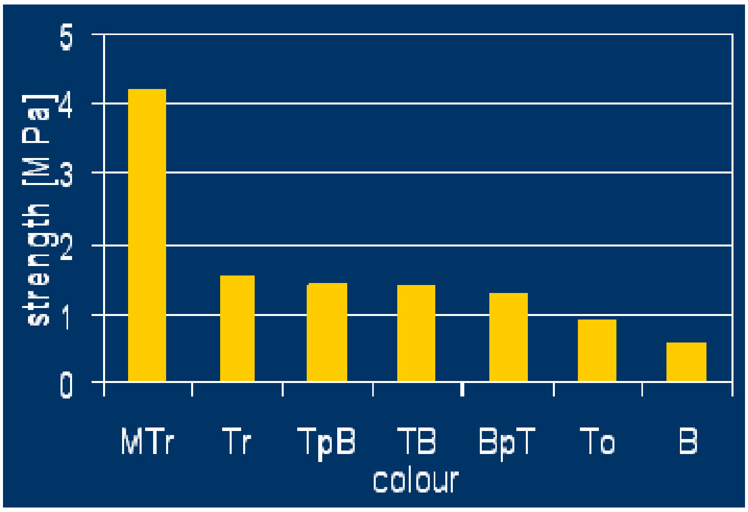

Figure 2.19: average strength of ice specimens of the same colour class

Figure 2.20 shows that the stronger stalactites are those of compact ice with a smooth and polished surface.

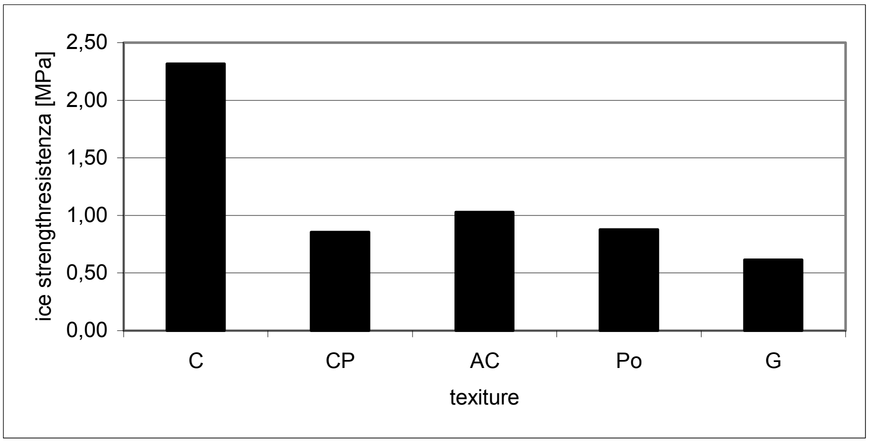

Figure 2.20: average strength of ice specimens of the same texture class

The connection indexes confirm the presence of a certain degree of dependence of the mechanical characteristics of ice and its aspect. This connection is rather low, but this fact depends on the many other factors that can effect its strength. In any case seems that the strength of the ice depends more on its colour than on its texture.

3 WHEN AND WHY FROZEN WATERFALL DEVELOP AND COLLAPSE

3.1 Effect of the climate

Temperature and flow rate are very effective factors of the evolution of the frozen waterfall. Graphics of Figure 3.1, Figure 3.2 and Figure 3.3 show the evolution of the ice volume with those of:

- T_{max}, T_{min}, T_{med} that are the daily maximum, minimum and mean air temperature,
- T_{max} - T_{min} that is the daily variation of the air temperature and
- Q_{PRMS} that is the flow rate calculated with the PRMS rainfall-runoff mathematical model.

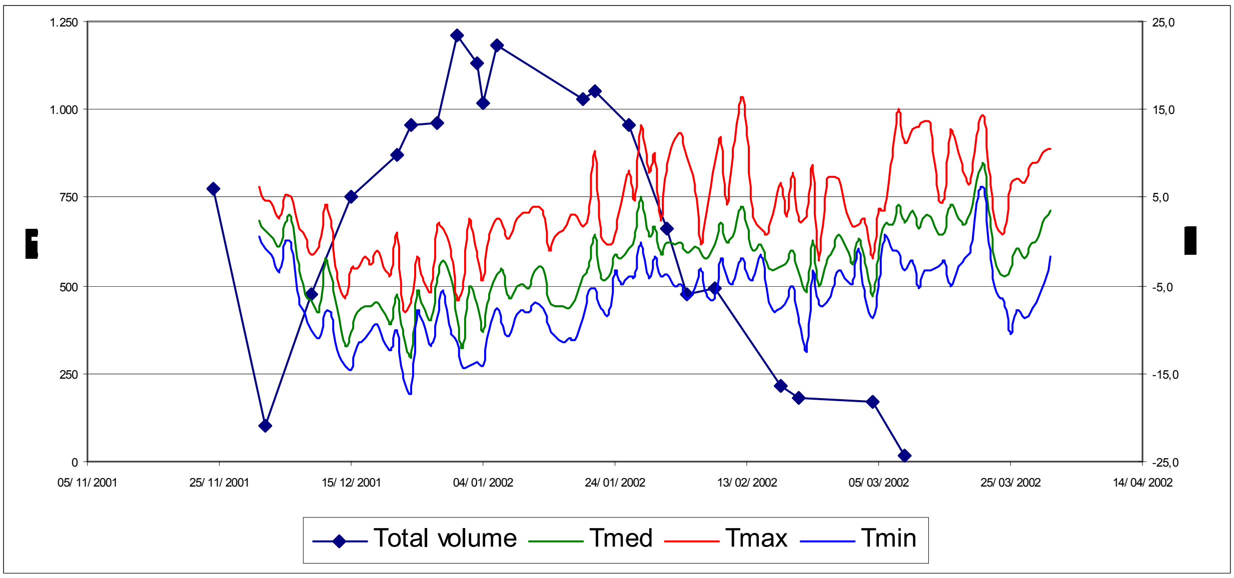

Figure 3.1: total ice volume, maximum, minimum and mean daily temperature vs. time

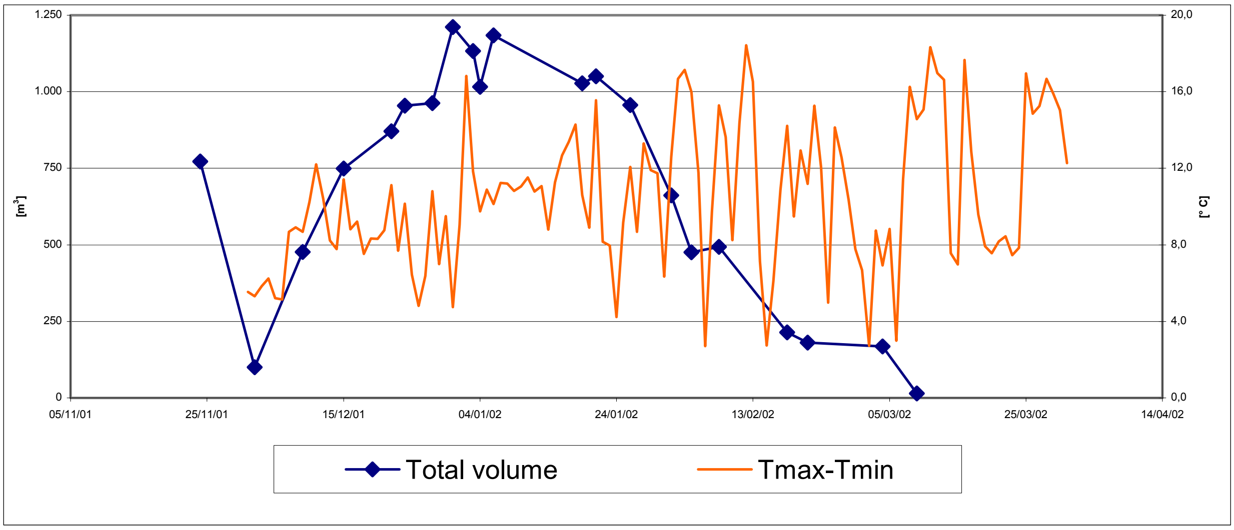

Figure 3.2: total ice volume and daily temperature difference vs. time

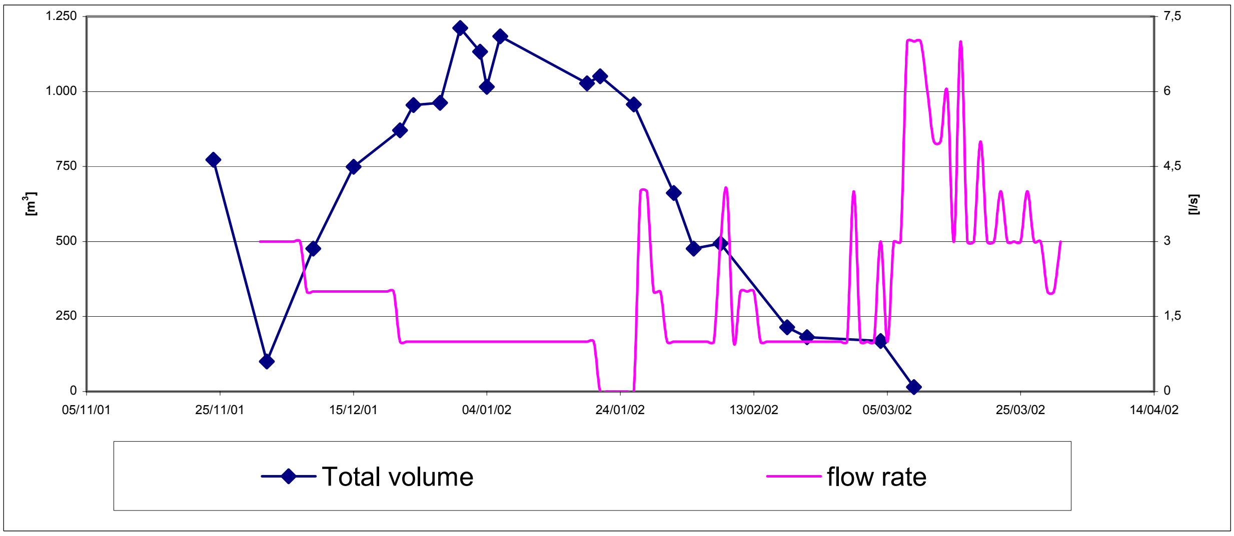

Figure 3.3: total ice volume and flow rate calculated with PRMS hydrological model vs. time

Situations that most probably can produce collapses are:
- very high maximum temperatures or, in any case, sudden increases of temperature,
- intensive solar radiation that act more indirectly by warming the surrounding air, and eventually rocks,
- wide ranges of daily temperature,
- sudden increases of the flow rate.

Finally, also the sudden drops of temperature can produce collapses, but in the period of study none of these phenomena have been observed.

3.2 Relationship between the volume of the frozen waterfall and the strength of the ice

A relationship between the volume of the frozen waterfall and the strength of the ice has been stressed out (Figure 3.4).

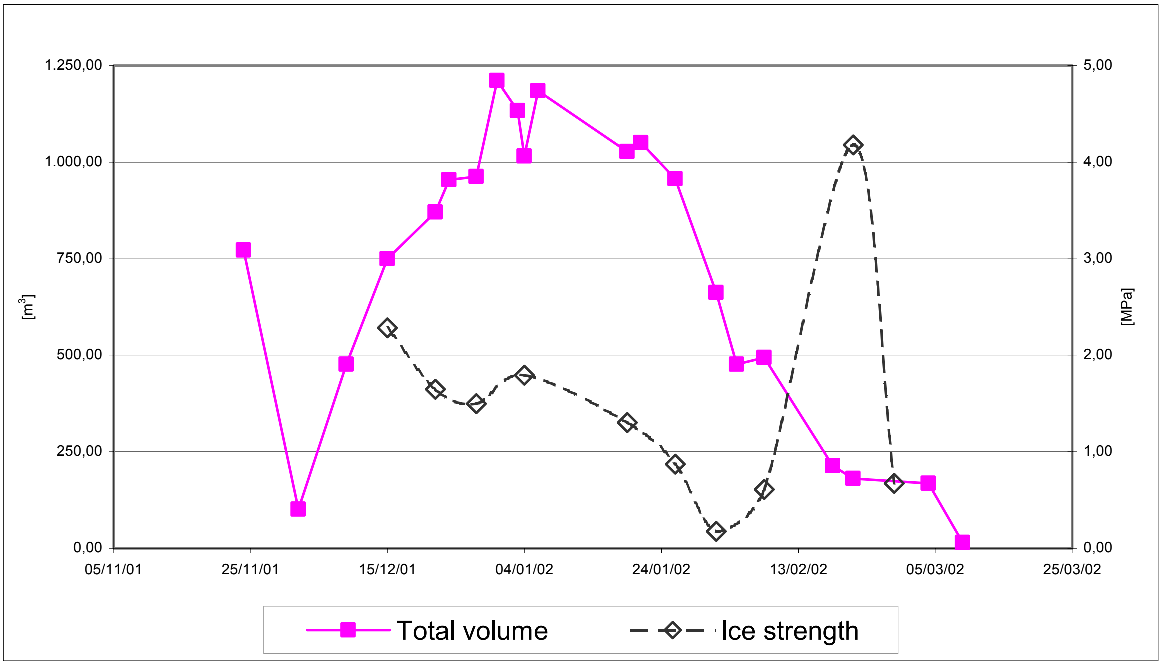

Figure 3.4: volume vs. ice strength

You can notice that the period, where the majority of the collapses occurred, thus there is a rapid diminution of the volume (from 26/01/02 to 10/02/02), correspond to the period where the minimum strength of the ice was measured. In particular, the absolute minimum of strength occurred on February 1, two days before the collapse of the main column of the frozen waterfall.
Then (the 21.02) a noticeable increase in the ice strength was measured to exactly coincide with a general interruption of collapses and melting. This confirms the temporary improvement of the ice quality.
A frozen waterfall is a dynamic structure and its making is strongly different year by year; but the ice mass reacts always in the same way to the climatic variations.
Adding the flow rate calculated with the hydrological model to the ice volume and temperature evolution, you can recognize the main rule that lead these processes (Figure 3.5).

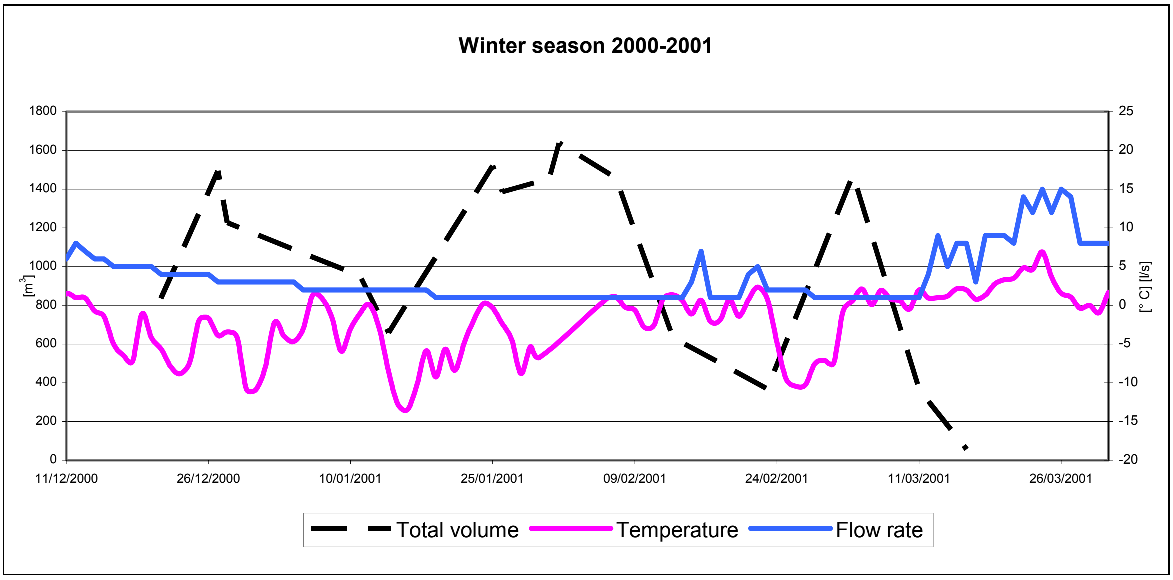

Figure 3.5: total ice volume, mean temperature and flow rate vs. time in winter season 2000-2001

You can notice how, also in this case, the increases generally occurred in periods of rather low temperature, while decreases, due to collapses and melting, were caused by more or less rapid rises of air temperature and water flow rate.

4 CONCLUSIONS

As a result, the air temperature is the most effective factor of the evolution of a frozen waterfall; also important is the story of the air temperature in the last few days.
Air humidity certainly acts in the process; but too few measurements have been made and the only thing that can be said is that for middle values of humidity the ice strength is higher while, if the air is very humid or too dry, the ice is less strong.
The solar radiation acts mainly indirectly by warming up the air and the rocks.
An other very important factor is the flow rate of the water that feed the waterfall. In fact, too little flow rate hinders the growth of the ice mass, but the turbulence of a too big flow can produce erosion and collapses.
Nothing can be said about the relationship between ice density and ice strength or the evolution of the whole structure.
Finally, important are the qualitative characteristics of the ice, which seems to be stronger if its texture is compact, its surface smooth and its colour transparent.

Table 4.1: pros and cons to evaluate the frozen waterfall ice climbing risk

PROS	CONS
- $T_{climbing}$ = -4° C ÷-3° C	- $T_{climbing}$ high or very low
- Tr_3 = -4° C ÷-2° C	- Tr_3 > 0° C
- T settled	- T highly ranging
- little daily thermical range	- warm wind
- H = 40%÷50%	- H too dry or too humid
- Q low	- Q high
- high ice strength	- low ice strength
- semitransparent ice	- white or transparent ice
- compact and homogeneous ice	- granular or disomogeneous ice
- no collapses	- frequent collapses

On the base of the previous observations, the pros and cons conditions table for ice climbing has been put together (Table 4.1) where the strength of the ice can be evaluated with the procedure described in 2.3.2.