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Doctoral Dissertation Review

Léo Decaux, MSc

„Functioning of Svalbard glacier drainage systems from in-situ data, remote sensing and models"

written at the Institute of Earth Sciences, Faculty of Natural Sciences, University of Silesia in Katowice under the academic supervision of Associate Professor Mariusz Grabiec

The formal basis for this review is the letter of the Ewa Łupikasza, PhD, Assoc. Professor and Director of the Institute of Earth Sciences, Faculty of Natural Sciences, University of Silesia, dated 18 July 2023, pursuant to the resolution of the Scientific Council of the Institute of Earth Sciences, Faculty of Natural Sciences, University of Silesia of 6 July 2023. The review has been prepared according to the law of 14 March 2003 on academic degrees, academic titles and art degrees and titles (Dz. U. of 2017, Item 1789), in connection with art. 179, cl. 2 of the law of 3 July 2018 – *Regulations implementing the Law on Higher Education and Science* (Dz.U. of 2022, Item 2306).

First of all, in order to emphasize the importance of the subject of research undertaken by Léo Decaux, I wish to point out that the hydrology of contemporarily glacierized areas, and glaciers in particular, is one of the most significant disciplines, the main purpose of which is to understand water circulation on the surface, inside and under the glacier. This affects the dynamics of the glacier and changes in its mass. It can also be important for the development of its thermal structure. The problem becomes especially relevant in the light of contemporary changes in climate, which have the strongest impact on such glacierized areas as the Arctic and Svalbard. This results in a prolonged period of ablation which has a considerable importance for the supply of water to the surface and into glaciers. Furthermore, periods of winter warming are more and more frequent, also affecting the structure of glacial runoff. On the other hand, processes related to intraglacial runoff are not only a result of climate change, but they are also subject to significant transformations, which can – in turn – increase their intensity. Any disturbance in the structure of supraglacial and englacial runoff causes material changes in the storage of water inside the glacier and within its catchment area, which not only modifies the variability of runoff channels and the amount of water accumulated in them, but also plays a key role in the shaping of local hydrological conditions. It is precisely the detailed results of such research that are presented in the scientific accomplishment of the dissertation.

In the dissertation submitted for review, Mr Léo Decaux undertook a weighty task of identifying the functioning of glacier drainage systems and the relationships between their different types. It is especially important, considering that the behavior of subglacial water plays a determining role in glacier dynamics and requires particular attention, especially in the context of climate warming which intensifies ablation and leads to increased meltwater production. Moreover, there has been a limited focus on understanding the supraglacial and englacial aspects. Mr Decaux accomplished the said task mainly on the basis of the results of his own field studies, applying a number of observation and measurement methods used in this kind of research, as well as own proposed innovative ones. He primarily focused on two glaciers of the Hornsund area: Hansbreen and Werenskioldbreen.

The main objective of the thesis was to improve the understanding of the individual components that constitute the glacier hydrological system while also examining their interconnected relationships. Additionally, the study aimed to analyze the influence of meteorological conditions on the IDS and evaluate the resulting dynamic response of the glaciers.

Mr Léo Decaux's doctoral dissertation is presented in the paper entitled '*Functioning of Svalbard glacier drainage systems from in-situ data, remote sensing and models'.* It consists of an abstract, introduction, five main chapters, conclusions and a summary. It is supplemented by appendices containing additional figures and two articles closely related to the topic: the '*Role of discrete water recharge from supraglacial drainage systems in modeling patterns of subglacial conduits in Svalbard glaciers'* and the '*Sustained high winter glacier velocities from brief warm events'*, in both of which the doctoral student is the main author and which had been published in peer-reviewed journals, indexed in international databases (e.g. Journal Citation Reports).

The contents of the reviewed dissertation generally follows a logical structure required of this kind of work. I also consider the inclusion of the articles in the body matter to be relevant. As a matter of fact, these are slightly expanded parts of some chapters of the dissertation, often referred to by the author (or cited), just as it is in the case of somewhat modified figures from the articles. I understand the intention, however in my opinion it ultimately makes the perception and analysis of the work a little more difficult.

The main part of the dissertation (without appendices) is 107 pages long and comprises 27 figures and 2 tables.

In the first part, Mr Léo Decaux makes a short introduction in which he points out – by referring to quite a lot of source literature – to the contemporary importance of the influence of climate change on the global rise of sea levels. This is mainly connected with glacier melting and it makes glaciers one of the best climate indicators. He also underlines the principal motivation for the undertaken topic, stating that the connection between the supraglacial drainage system and the IDS is closely intertwined with glacier dynamics and it becomes imperative to comprehensively investigate the glacier hydrological system, encompassing both the supraglacial and IDS components. And the relationship between the supraglacial drainage system and the ice discharge is not yet well established. One has to agree, however perhaps more reference should be made to the dynamics of glacier mass change, which is also mentioned, although obviously it is not the main subject matter of the dissertation. At the end of this part, the author explains the structure of the dissertation, to which I made my comments earlier in the review.

The next part is Chapter One – Glacier hydrology in Svalbard*,* which is basically an introduction detailing the concepts necessary to understand the problem. In this chapter, the doctoral student describes the location of Svalbard, its climate and contemporary glacial status, referring to relevant source literature. However, it seems that some more recent studies could be referred to as well, especially as far as climate and glaciers are concerned. The author also states that small glaciers (below 10 km^2) are considered as cold glaciers as their entire mass is far below 0°C. I would avoid such absolute statements, because that is not entirely true. Some of such glaciers are often polythermal.

In the following paragraphs the author takes a very interesting approach to describing the hydrological system of a glacier and its influence on a number of processes that occur within the glacier and its catchment area. He also emphasizes a greater importance of the system which – through increased dynamics and runoff volume – leads to the rising of the sea level. All these observations and numerous references to source literature demonstrate the doctoral student's strong knowledge of the problem.

The geographical characteristics and climate conditions of the study area, with a focus on the Hornsund glaciers of Hansbreen and Werenskioldbreen, make an important part of the chapter. It must be underlined that Hornsund is one of the best researched and described regions of Svalbard, with a lot of accessible databases, which is crucial when carrying out various detailed analyses. The author provides a sound justification of the choice of the glaciers, stating that – among other things – they are characterized by two different dynamics that have a direct impact on changes in both the surface topography and the drainage system. The description complies with the requirements for this type of dissertations. However, it seems to me that the figures representing glacier areas should be more up to date, even though I understand that it is difficult to keep up with the rapid changes in recent years. On the other hand, given the availability of latest remote sensing technologies the doctoral student must be well aware of, it should not be a problem.

Moreover, a number of passages, the titles of certain chapters and sub-chapters, and even the title of the dissertation may lead the reader to understand that it applies to the whole of Svalbard. To avoid such a misunderstanding, perhaps it would be better to specify the names of the two relevant glaciers where the research was conducted, especially as the author himself often claims that glacier drainage systems are very complex and different. Therefore, a more specific identification (in chapter and sub-chapter titles, and the main title in particular) would provide the reader with a more transparent understanding. This comment aims to improve the clarity, not to criticize, as I understand that the dissertation concerns the selected glaciers of Svalbard.

Mr Léo Decaux describes in great detail four englacial systems, selected to implement sensors, one cave (CC) and three moulins (M1, M2 and M3), and covered the whole watersheds of the glacier. He considers them to be representative of the entire Hansbreen's hydrological system. This section is very important and makes it much easier to identify the analyzed forms, however some photographs would be welcome.

The author takes a scientifically mature approach to present some gaps in the knowledge of the undertaken matter. First of all, he makes a valid observation that nowadays several models of subglacial conduits do not take the supraglacial drainage system into account. A lot of authors consider a spatial recharge meaning that the water recharge is homogeneous or with some local water values over the entire surface of the glacier, which is one of the biggest assumptions that leads to inaccurate modelling of the locations of subglacial channels. He makes an especially significant observation that due to their direct impact on the englacial and subglacial drainage system, studying supraglacial drainage systems is vital. I think that it would be interesting to have a more elaborated discussion of the stability and recurrence of supraglacial drainage channels (however, the author mentions the problem in some other parts of the paper). This can have a substantial impact on the development of englacial drainage systems. I absolutely agree with the author stating that despite a great number of techniques, many aspects of this system are still not investigated. In particular, I appreciate the author's observation that typically glacier studies of speed are reported for summer months, since this is when most speed-up events occur, but there is an increasing body of literature highlighting the importance of variability in winter motion. I will revert to this further in this review.

It should be noted that the objectives are presented clearly and in line with the requirements for such papers. Above all, the objectives are preceded by the above-mentioned knowledge gaps, which further emphasized their validity and necessity. I especially refer here to the lack of consideration of the supraglacial drainage system when studying the IDS. Based on this, the author lists the specific objectives with a high degree of scientific maturity: to characterize the permanency of the supraglacial drainage system; to determine the influence of the supraglacial drainage system on the subglacial system; to continuously measure in-situ englacial channel water fluctuations for at least one hydrological year; to comprehend the englacial channel water fluctuations over the entire hydrological year; to establish direct connections between observations of englacial water fluctuations within the channelized system and the speed of the glacier; and to identify the effect of warm winter events on the IDS and its impact on glacier speed.

The chapter ends with a strategy to address the gaps, in which the author credibly summarizes the content of subsequent chapters. It is an interesting approach, however some of it is repeated at the beginning of individual chapters further on.

The doctoral student takes a compelling and comprehensive approach to presenting research methods and data, dividing them into two main groups. In the first one, '*Modeling patterns of subglacial conduits with a discrete water recharge'* he provides a detailed description of the datasets and methods employed for mapping the supraglacial drainage system of Hansbreen and Werenskioldbreen. Additionally, these datasets and methods were utilized to calculate their respective WIAs in conjunction with their corresponding catchment areas and volume of water runoff drained during the year 2015. The author relied on high-resolution satellite imaging and existing maps of the supraglacial drainage system, but he also generated a few maps of the supraglacial drainage system of Werenskioldbreen and Hansbreen himself.

The sub-chapter entitled '*Link between meteorological conditions, internal drainage system and glacier speed'* provides a detailed presentation of the methods employed to obtain crucial datasets that enable the linkage between the IDS and meteorological conditions, as well as the speed of Hansbreen. To achieve this, specific methods were utilized to gather the necessary data, facilitating a comprehensive understanding of the interplay between the IDS, meteorological factors, and the dynamics of this glacier. The method of modelling water level in moulins seems especially interesting.

It should be pointed out that the author analyzes all the research methods with considerable scientific caution, being aware that some of them can be problematic and often burdened with errors, as it is for example in the case of rainfall measurements. He understands the limitations, such as related with the modelling of subglacial channels and various correlations between meteorological conditions and internal drainage systems, or the limitations of englacial water pressure monitoring systems.

There are also some debatable assumptions, however they are not necessarily wrong. For example, the claim that all snow deposited during the ablation period will melt due to positive average temperature over this season. I am not convinced that a single ablation stake is enough to determine the snow level. I also wish there were some references to the latest research related to intraglacial runoff, e.g. the Latvian-Polish research conducted in NW Spitsbergen in 2019-21. Moreover, understanding the author's rationale, I experience a sort of perceptive-cognitive discomfort as the author very often underlines and refers to the fact that certain calculations and models related to his dissertation have been made by other researchers, quite abundantly mentioned. I am not sure there is a need for that and it would be enough to include them in the acknowledgments. However, I would like to stress that such minor remarks do not affect my high opinion of the presented methods, especially those of the author's himself. Their number evidently demonstrates how important they are for the dissertation and their exhaustive character.

The chapter entitled '*Role of discrete water recharge from supraglacial drainage systems in modelling patterns of subglacial conduits in Svalbard glaciers'* focuses on the evolution of the supraglacial drainage system, of a land-terminating glacier and a tidewater glacier, through time, and also discusses the role of its discrete water recharge in modeling patterns of subglacial conduits. It is a very important and interesting part of the dissertation, in which the author analyzes in detail the temporal changes in the supraglacial drainage system, mainly on Werenskioldbreen at two different timescales, annual (2010-2011) and decadal (1990-2010), and presents maps of the whole supraglacial drainage system (including surface streams) for different years.

Using own and available third-party studies, the author also developed two simulation scenarios to take some glaciological and meteorological components into account. I appreciate the really detailed and complete explanation of the components of the proposed model of the theoretical pattern of subglacial channels in the study area, which – compared with previous models – is not only qualitative but also quantitative. On this basis, the author developed very interesting maps of the theoretical pattern of subglacial channels of Hansbreen and Werenskioldbreen, improving our knowledge in this respect.

He also estimated the contribution of water entering Hansbreen and Werenskioldbreen over the whole 2015 melt season. Even though the observations concern just one year and the obtained ratios of melt and precipitation are quite expected, it still is a valuable achievement as it provides information about the dynamics and supply of internal drainage. Therefore it is true that the supply of water from surface melt is the most influential runoff component, confirmed by the difference of a factor of 3 in the amount of water provided by melt (72.5%) and precipitation (27.5%) during the 2015 melt season. I wish to add that the doctoral student logically explained the differences in his results as compared with other runoff models for the same area, and justified with clear understanding why he did not include or omitted sources of water other than melting and precipitation in the first place.

He concludes that considering discrete water recharge makes it impossible to form subglacial channels in most of the accumulation area formed by surface water supply which is consistent with previous theoretical studies. And in any case, considering a discrete water recharge when modeling patterns of theoretical subglacial channels makes it possible to achieve more realistic results. One should also agree with the author's statement that contrasting model results with spatial and discrete water recharge enable a better understanding of the influence of this parameter for all glaciers and can be particularly valuable to improve glacial hydrological models.

Some other conclusions related to this problem include rather obvious observations, e.g. '*...the weak dynamics of the front and the fact that the longer a stream remains active and the deeper it carves into the glacier's surface, the more likely it is to survive'; 'supraglacial drainage patterns are relatively persistent on an annual timescale' or 'higher elevations are supplied by more precipitation than meltwater, contrary to the moulins located at lower elevations'.* I understand that these should be considered as supplementary.

I share the author's view that the proposed new way of modeling the pattern of subglacial conduits of glaciers which includes a discrete water recharge, based on a precise mapping of the entire glacier surface, and the volume of water runoff specific to all observed WIAs, produces more realistic results than was previously possible. Despite Mr Decaux's indisputable scientific maturity as regards caution in jumping to conclusions, it would be interesting to find out if and how similar modelling can be applied, considering the high dynamics and fluctuations in glacier stability, and opening and closing of existing crevasses. Perhaps more emphasis could be put on tracer studies which show the time and course of intraglacial runoff. What will be the impact of more and more frequent precipitation and ROS events in winter, also in the accumulation zones of glaciers, on the supply of the glacier with water in its various parts? Of course, I am aware that these problems are often complex and many of them require more investigation. Yet seeing the scientific passion and commitment of Mr. Decaux I trust this is not the end of his research in this respect.

In the next chapter, the author presents and interprets the englacial water pressure measurements in relation to the meteorological conditions observed over two hydrological years on Hansbreen.

In its first part, he describes in detail the englacial water fluctuations in response to meteorological conditions. The author's analysis of wintertime water fluctuations seems especially important, in the light of contemporary climate change. He observes that the two winters under study exhibit several warm events. In total, there were 11 short events lasting less than one day with an average temperature below 1°C, and 3 longer events lasting more than one day, with an average temperature above 1°C. However, during the winter period, there was no consistent rise in water level within the englacial system in response to these warm events. The winter warm events that did cause a visible response in the englacial water levels last for at least one day, with a minimum average temperature of 1°C. These are essential observations, indicating the role of winter snow cover in the shaping of runoff, and not only internal drainage system. Glaciologists increasingly indicate that in their studies and the results obtained by the doctoral student clearly substantiate it. On the other hand, we know that short warm spells in winter, often combined with rainfall, contribute to the development of numerous icings with various thickness. It seems that they can also affect the supply of englacial drainage with water, restricting its flow/percolation from time to time. I would love to know Mr Decaux's opinion on that, especially considering that the increase in ROS events is accompanied by a decrease in snow density on glaciers, which undeniably also contributes to changes in the water volume retained in the snow.

The characteristics of water fluctuations in an englacial system while snow cover persists is a notable accomplishment and it indicates a number of interesting correlations. It can be also observed that in summer these correlations are quite obvious, as the author confirms in the text: '*Throughout the summer season, when the glacier surface was free of snow, the water level inside the englacial system exhibited synchronized rises with positive peaks of air temperature and rainfall events'*; '*While there is still some snow present on the glacier surface during the summer, the start of water level rise inside the englacial system exhibits a delayed response to the positive peaks of air temperature and rainfall events.'*

Mr Leo Decaux analyzes water fluctuations in the winter and the summer season, winter-summer transitions, and summer-winter transitions. Although the periods are correctly proposed, I am not sure if the transitional periods and their names are relevant. Perhaps these are just spring and winter periods, however short ones? The author himself uses the terms, too.

In the second part, the author describes the annual cycle of englacial and subglacial drainage systems dynamics, to comprehensively analyze the dynamics of englacial and subglacial channels, and he has chosen to divide the hydrological year into four distinct periods: winter period with air temperature below 0°C plus brief; winter period with air temperature above 1°C for more than 1 day warm events; winter-summer transition period and summer period. It is a very important approach the purpose of which was to evaluate the relationship between water level fluctuations and meteorological conditions. Thus the author considerably enriched the data on englacial and subglacial channels. All the analyzed periods are documented with very interesting graphics with models which clearly and precisely show the water motions and channels dynamics within the IDS of the glacier in specific periods and thermal and hydrological situations, respectively affecting the supply of water, mainly from melting. I think that what is also meaningful in these analyzes is the fact that the author again pointed out the role of snow and winter events connected with temporary warming and periods when air temperature exceeds 0°C in the shaping of internal drainage runoff. It seems that the importance of the conclusions should be corroborated through research conducted during a greater number of seasons, especially winter ones. I would like to stress that this is not a critical comment, but a suggestion to carry out similar research in the future, and I have no doubt that Mr Léo Decaux can do it correctly in his future scientific work.

I find the author's drawing attention to the role of rainfall events, which – according to him - play a crucial role in the dynamics of the IDS, and observing that unlike the gradual variation of meltwater discharge, rainfall events are sudden and have a significant impact and each rainfall event triggers an englacial flooding event within, really valuable, although it could seem a little obvious. Yet, it has been demonstrated by very detailed research. In this part, the author also happens to draw some obvious conclusions, e.g. *'The hydraulic capacity of the subglacial drainage system is directly influenced by its water recharge history',* however this does not affect my positive assessment.

It is worth mentioning that such research is very uncommon, and Hansbreen is the first and only glacier where continuous measurement of englacial water fluctuations has been carried out within the channelized system for such an extended duration. So, I agree with Mr Decaux, who claims that it is also a first necessary step towards future studies based on this dataset, and it holds significant values, particularly for enhancing glacial hydrological models and better comprehend relationships between IDS water fluctuations and glacier dynamics, also as far as other Svalbard glaciers are concerned.

The last part of the dissertation presents the dynamic response of Hansbreen to a hydrological forcing by exploring the relationship between the fluctuations in englacial water level in glacier and flow speed measured by a GNSS monitoring of stake network on the glacier surface. For this, the author carefully selected input data for modelling and reasonably chosen the most appropriate time for the analysis. He also prudently observes that if a similar study is made for another glacier, it is most likely that different parameter values will be required.

He also analyzed series of correlations between hydrological and dynamic events for the most relevant combinations of variables, assuming the correlation limit of 0.60. Here, he demonstrates his scientific maturity again, being aware that his statistical data sample size is small. And even if his correlations are high and show a physical relationship between these variables, more data are needed to have more robust relationships. So, it requires a larger dataset to have generic relationships and not over-interpret his correlations. This can certainly lead to reservations, but I believe that given the complexity of the problem, where sourcing data can pose a number of issues, the analysis enables correct presentation, confirmation and understanding of the described processes.

This part of the dissertation contains also an especially important analysis of the influence of a so-called 'warm event' in winter on the glacier dynamics. The author chose the longest warm event that happened at the beginning of February 2017, when the rain fell over the entire glacier surface. He draws a number of interesting conclusions there, for example that the warm event increased glacier speed more than 250% over the baseline speed for several months but it occurs during the hydrological year with the highest PDD since 1980. He also proposes a hypothesis that the volume of meltwater generated by the warm event was large enough to briefly reopen the IDS, and – if so – then some water likely evacuated out the glacier front, after which the remaining water was captured within in the IDS due to creep-closure of subglacial channels. Consequently, a question arises where the water was evacuated and whether icing fields can be observed in the forefield of the glacier in question. The author also states that the great amount of meltwater due to high PDD in autumn maintain the IDS efficient and allows it to drain a larger part of the water from the melt season before the winter. Therefore, the amount of winter trapped water is considerably reduced. I think that it could be very interesting to examine, in the future, icing fields observed or not in various hydrological situations. Especially that the author himself states that his data suggest that winter warm events may fill the system and could be the cause of winter discharge. This is particularly important in the aspect of glacier movement, but also considering the winter runoff of Svalbard glaciers, which is still not fully understood.

In my opinion, the last chapter is very important, especially where it explains the role of temporary warm events (in winter in particular). The author concludes that Arctic melt season tends to last longer and the occurrence of autumns with abnormally high PDD could increase in the future and cause some glaciers to stop. Therefore, further investigations of the influence of a glacier stopped episode on the glacier dynamic for the rest of the year are needed, particularly in a context of increasing frequency of warm winter events. And it is therefore crucial to study the englacial water fluctuation at a high temporal resolution in order to fully comprehend its dynamic. On the other hand, I think that the processes are extremely complex and require further research, not only in seasons with different weather, but also on different glaciers.

The doctoral student finishes the dissertation by providing an exhaustive summary, in which he presents the key conclusions from his studies and analyzes.

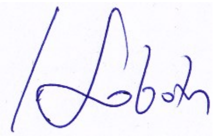
My comments, most of which are procedural, explanatory or even debatable, do not diminish the value of the reviewed dissertation and have no effect on its unequivocally positive and very high assessment.

I wish to note that in the case of a doctoral dissertation in the form of a series of multi-authored publications the reviewer is expected – according to the Regulation of the Minister of Science and Higher Education – to also evaluate the doctoral student's individual contribution to any collective work. Although the appended publications are merely a part of the presented scientific accomplishment, it should be underlined that the documents submitted by the doctoral student for review included – as an integral part – statements by the co-authors, specifying the scope of individual contribution of each of them to the publications. Accordingly, on the basis of the statements I can confirm that Mr Léo Decaux contributed more than 80% and played a leading role in the research, analyzes, conceptual work and preparation of the manuscripts for publishing, and as such is authorized to present them as a basis for applying for the award of a doctoral degree.

I can ascertain that Mr Léo Decaux undertook a very difficult task of a comprehensive description and analysis of hydrological systems of glaciers with particular focus on the conditions shaping supraglacial and englacial drainage and their relationships, the annual cycle of internal drainage system and its correlations with the glacier dynamics. The study substantially complements the state of knowledge in this respect. The underlying research is important for today's evaluation of changes in glaciers that are occurring so intensively as a result of climate change. This contributes to increasingly frequent events, such as winter-time warm spells or Rain-On-Snow events, which not only affect glacier drainage systems but also intensify changes in the glacier mass balance. A comprehensive scope of field work and models enabled the doctoral student to perform a spatio-temporal analysis of the variability of the said hydrological systems of the glaciers, making the dissertation highly valuable from the scientific point of view, as required of such papers. The subject matter of the dissertation fits well with the trends in current cryology and glaciology. The broad range of research methods used by the author is admirable and testifies to his solid understanding of the undertaken problems, whereas the reasoning demonstrates his scientific maturity.

Summing up, I am positive that the doctoral dissertation entitled '*Functioning of Svalbard glacier drainage systems from in-situ data, remote sensing and models'*, fully meets the requirements of relevant legislation for doctoral dissertations and I apply to the High Scientific Council of the Institute of Earth Sciences, University of Silesia, to admit Mr Léo Decaux to the further stages of the doctoral degree award procedure.

At the same time, I wish to point out to the great scientific value of the analysis and the exemplary preparation of the subject-related articles, addressing the research hypothesis. The doctoral student presented innovative models for the difficult and complex problem of glacier drainage systems, and provided a mature interpretation thereof. It is particularly valuable that the student has developed his own research methodology to carry out measurements in this exceptionally difficult matter and the methods can be well used by other researchers. Their importance is all the more pertinent as the number of studies in this area still seems insufficient, and the presented methods, models and analyzes essentially supplement the knowledge of the complex relationships that occur in internal drainage system and surface runoff systems within glaciers. The accomplishment is significant as it advances the current state of knowledge of glacier hydrology of polar areas. Therefore, I would like to ask the High Council to commend the presented dissertation for the award.



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