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Diskussion

Stilke, Hamburg:

Welche Gründe lagen vor, daß bei den barometrischen Höhenmessungen nicht Mikrobarometer von Askania ebenfalls eingesetzt wurden? Das Askania-Gerät ist besonders für die Höhenbestimmung bei geophysikalischen und geodätischen Messungen entwickelt worden. Es wurden Probemessungen mit mehreren Geräten im Gebirge und in Bergwerken von Askania veröffentlicht, danach sollte das Askania-Gerät solchen mit Druckdosen überlegen sein. Die Ablesegenauigkeit ist fast eine Größenordnung besser als bei den auf Grönland eingesetzten Geräten.

Gerke, Frankfurt:

Bei der Vorbereitung der Expedition ist natürlich auch die Messung des Luftdrucks und seiner Veränderung mit Askania - Mikrobarometern überlegt worden. Im Hinblick auf den auch im Vortrag kurz erläuterten Zweck der Messungen, der nicht höchste Genauigkeit erforderte, sowie auf das Expeditionsgebiet und die harte mechanische Beanspruchung der Geräte, konnten jedoch die Mikrobarometer nicht zum Einsatz kommen.

Weiter äußerten sich noch Prof. Lichte, Karlsruhe und Prof. Brockamp, Münster, mit einer Stellungnahme zu den Askania-Geräten und einem Hinweis auf den Vergleich der Barographenstreifen. Von Prof. Gerke wurde noch auf die Dissertation Wolfgang Pötzschner: „Höhenmessung mit Feinbarometern", Technische Hochschule Hannover 1955, hingewiesen.

Significance and techniques in the study of gas inclusions in glaciers ice*)

By David C. Nutt, Hanover **)

Zusammenfassung: Nach einer Definition des Begriffes Gaseinschlüsse vertritt der Verfasser die Meinung, daß solche Einschlüsse über die Bedingungen Auskunft geben können, unter denen sich das Eis gebildet hat. Er gibt einen Überblick über die technischen Forschungsverfahren, wie sie von ihm und anderen angewandt wurden. Bezüglich des Ursprunges der Einschlüsse nennt der V. zwei Quellen: 1. Luft, die zwischen den Schneeflocken eingefangen ist und 2. Ausfrieren aus Wasser. Die technischen Verfahren für das Herausziehen des Gases und seine Quantitav-Analyse werden dargelegt. Bei der Behandlung des Gasdruckes in den Einschlüssen kommt er auf zwei allgemeine Verfahren zu sprechen: das spezifische Schwere-Volumen-Verfahren und seine eigene Methode der Druckablesung mit einem Druckmesser, der an den Druckraum angeschlossen wird.

Um über die Zusammensetzung der Luft zeitlich Aufschlüsse zu erhalten, wurde ein Datierungs-Verfahren entwickelt, bei dessen Beschreibung der V. auf die beiden möglichen Fehler eingeht: 1. auf das Hinzutreten von zeitlich jüngerem CO_2 zu den Gaseinschlüssen und 2. auf die mögliche Verunreinigung während der Extraktion durch die Gegenwart von CO_2 infolge Einsickern oder Diffusion. Es folgen sodann endgültige Daten aus der Anwendung des genannten Verfahrens, die für das von den Grönland-Gletschern stammende Eis gefunden wurden.

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Abstract: After giving a definition of the term gas inclusions the author states that such inclusions can provide information about the conditions under which the ice was formed. He gives a survey of the techniques of investigation as found by himself and others as well as of their significance. As to the origin of gas inclusions he mentions two sources viz.: 1) air. trappel between snowflakes and 2) they may be frozen out by air equilibrated water. Techniques of the extraction of the gas and its quantitative analysis are given. Speaking of the pressure in gas inclusions he mentions two general techniques for their determination: specific gravity-volume technique and his own method allowing to take pressure reading directly from a pressure gauge attached to the pressure chamber.

To know the composition of the ancient air in relation to time a dating technique was developed which he describes mentioning the two possible errors: 1) addition of new atmosphere CO_2 to the gas inclusions 2) possible contamination during extraction by present day CO_2 through leak or diffusion. There follows the application of this technique on the expedition to Greenland and final dates found in the ice discharging from the Greenland glaciers.

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Introduction

Gas inclusions are a very conspicuous admixture or impurity in glacier ice. Closely spaced inclusions, often hairlike and containing gas under considerable pressure, account for the characteristic white appearance of icebergs. Gas inclusions also contribute to the gray or cloudy appearance of other forms of ice. Only rarely, and then under special conditions, does one find ice which is entirely gas free.

Until recently the study of gas inclusions has attracted only little and sporadic attention, due largely to the lack of adequate techniques and the preoccupation of glaciologists with other aspects. The principal

*) Summary of an informal lecture delivered atthe Symposium on the Geophysics of Greenland, Münster, Westf., 11—14 Mai 1961.

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earlier contributions to the study of gas in ice have been made by Steenstrup, 1893; Hamberg, 1895; Bernard, 1922; Barnes 1927, 1928; Koch & Wegener, 1930. More recent work has been undertaken by Bader, 1950; Shumskii, 1954; Nakaya, 1956; and Langway, 1958.

Although merely an impurity or admixture gas inclusions can provide information about the conditions under which the ice was formed and about the life history of the ice, and can lend themselves to radio carbon dating of the ice because of their content of atmospheric carbon dioxide. The results of our studies during recent years have been reported in detail elsewhere, and only the salient points will be covered in this present consideration of the significance and techniques in the studies of gas inclusions.

Our study began in 1954 with a random investigation of icebergs along the Labrador Coast (Scholander, et. al. 1956). From this preliminary investigation it became apparent that new and special techniques were needed. These were developed from 1955 to 1957 at the University of Oslo, and a study of the temperate Storbreen glacier was undertaken (Coachman, et. al. 1956; Coachman, et. al. 1958a; Coachman, et. al 1958b). As a result, techniques were available for the extraction of the gas from ice and accurate composition analysis; and a feasible though cumbersome technique for radio carbon dating of the ice through extraction and analysis of the carbon dioxide contained in the inclusions had been developed.

Before further consideration is given to our subject, it might be well to mention briefly a few specific points about gas in ice. So far as is known gas is insoluble in ice, although what may occur under the great pressures of 100 to 200 atmospheres deep within an inland ice mass is at present a matter of conjecture. Ice was known to be largely diffusion tight (Scholander, et. al., 1953). Hemmingsen (1959) has shown that practically no diffusion takes place in ice below 2 ° C, while, as the temperature of ice approaches its melting point at 0 ° C., diffusion and migration of gas does occur. Our pressure measurements showed variations of two to five atmospheres in closely spaced bubbles which further argues for the diffusion tightness and integrity of individual bubbles over long periods of time.

Composition of gas inclusions

The origin of gas inclusions may be from two principal sources. Either they may be atmosphere trapped between the snowflakes, compressed and sealed off as the snow changes to ice under the weight of the accumulating overburden (or air mechanically trapped by meltwater); aor they may be frozen out of airequilibrated water as happens in the case of an ice cube in the refrigerator. When air dissolves in water its components dissolve in proportions different from those originally present in the atmosphere (Hock et. al., 1952; Handbook of Physics & Chemistry, 1954—55). Thus we have

	O_2	N_2	CO_2	A_2
Air, volume percent	20.94	78.09	.03	.94
Air Equilibrated water volume percent	34.91	61.48	1.75	1.86

Thus composition analysis could tell us whether ice was formed under high polar conditions, by the freezing of water, or to what degree each process was involved. Also in the temperate glacier Storbreen composition analysis of gas inclusions showed a progressive loss by leaching of the preferentially soluable components, CO_2, O_2, and A_2, during the life history of the ice from the area of formation toward the terminal part of the glacier (Coachman, et. al. 1958a).

Determination of the composition of the gas inclusions involves first erxtraction of the gas from ice and then its quantative analysis. Gas may be extracted by using the cold technique developed by Coachman, et. al. (1956) in which a cylindrical piece of ice is shaved down under vacuum and the gas removed with a mercury extractor. Gas may be extracted also by melting ice under vacuum and boiling the gas off through a reflux condenser which keeps the water back; the gas is then removed by a mercury extractor (Scholander, et. al 1961). By using a 5 liter pot this latter method has the advantage of providing a larger sample than would be feasible by shaving cold ice. In our work the ½ cc gas analyzer (Scholander, 1947) was used for composition analysis of carbon dioxide, oxygen, and atmospheric nitrogen. The argon content was determined by mass spectrometer.

When larger gas bubbles containing a few cubic millimeters or more of gas occur, it is possible to extract the gas from individual bubbles by use of a mercury filled micro syringe (Scholander, et. al. 1961) for analysis with the micro-gas analyzer (Scholander et. al. 1955). In cases where less than a few cubic millimeters are available, the micro technique of Scholander and Evans (1947) may be used.

Pressure in gas inclusions

In a continental ice cap one might expect the included gas to be at ambient atmospheric pressure when the spaces are sealed off as the nevé is transformed to ice, and that this pressure would increase as the ice became more dense with accumulating overburden. This essentially was found by Langway (1958), except that the gas pressure was some three to four atmospheres less than expected from the glaciostatic load. He also found that ice from a deep core in Greenland with pressures greater than 13 atmospheres relaxed after a year's storage, but ice with pressures of less than 13 atmospheres was unaffected.

Our pressure measurements on icebergs showed pressure ranges from 2 to 20 atmospheres. The important feature noted was the considerable variation of from 2 to 5 atmospheres in closely spaced bubbles, which, as mentioned above, argues for the integrity of the individual bubble over long periods of time (Scholander & Nutt, 1960).

Since comparatively little work has been done with pressure measurements of gas inclusions contained in glacier ice, the full implication of their study is not yet apparent.

There are two general techniques for the determination of gas pressure in ice. The traditional specific gravity-volume technique will give an average value for all inclusions within a block of ice. It requires very accurate weighing and temperature control; and it is not suitable for high pressure ice where many of the gas inclusions may be cut by fine cracks, which means that values obtained will always be too low, and where the requirements for accuracy are more stringent. The ice is usually melted under kerosene, which involves some changes in temperature and an unknown factor of changing solubility in the kerosene. However when carfully done, as demonstrated by Langway (1958), good results can be obtained and the method method can be particularly useful when the pressures are close to atmospheric.

On the Arctic Institute Greenland Expedition of 1958 we developed a simple new technique for the direct measurement of the gas pressures in individual bubbles (Scholander & Nutt, 1960). Cold ice was placed in a pressure chamber filled with a cold glycerine solution which would effect a progressive surface melting while the ice remained cold. The ice was observed through a window with a microscope, and the pressure adjusted by a screw activated piston to match the breakthrough pressure of the bubbles as the surface eroded. Pressure readings are taken directly from a pressure guage attached to the chamber. This is a simple field method which can be mastered with a little practice.

Radio carbon dating of glacier ice

In view of the diffusion tightness of cold ice, the large diffusion distances involved, and the well known retention of the gas under considerable pressure, it was thought that the composition of the gas contained in high polar ice would remain unchanged over long periods of time. Thus analysis of such gas from high polar ice might give information as to the composition of ancient atmosphere.

Because of the desirability to know this composition in relation to time a dating technique was needed. The principle is simple: ice is melted under vacuum, the included gas is boiled off through a reflux condenser, which holds back the steam, and pumped through an alkali solution where the CO_2 is absorbed. The carbon from this

CO_2 is then radio carbon dated. Since Dr. H. DeVries at the Physical Laboratory of University of Gronningen could date a sample containing 0.2 grams of carbon, which in turn would require an ice sample of some 10 to 20 tons, this method was considered feasible. The technique was developed through a trial dating of Storbreen in the Jotenheim district of Norway where the terminal ice was shown to be some 700 years old (Coachman, et. al. 1958b).

There are two possible sources of error. First is the addition of new atmospheric CO_2 to the gas inclusions at some time during the life history of the ice after the original trapped air had been sealed off. From the known conditions and processes this would seem to be unlikely. If throughout its life history the ice remained cold, there would be little chance for diffusion or change. Warming, if it had occurred, would have resulted in a loss of CO_2, rather than enrichment as was shown by the Storbreen study (Coachman, et. al. 1958a). Uniform ice (to avoid obvious crack fills of superimposed ice) with high pressures was selected to further argue for the integrity of the gas over long periods of time. Furthermore any biological activity or oxidation which might have taken place in the ice, would not significantly affect the CO_2 and dating results.

The second source of error is possible contamination during extraction by present day CO_2 through leaks or diffusion. Prevention of this involved careful engineering with rigid standards of equipment and rigid tests. These are described in detail by Scholander, et. al. (1961 b).

With the successful dating of the Storbreen ice, the stage was then set for the ensuing study made on the icebergs discharged from the glaciers of West Greenland, where it was hoped we might find undisturbed ancient atmosphere in old ice extruded from the central mass of the inland ice through these glaciers. Through dating and composition analyses past atmosphere composition in time might be determined. Further, through measurement of the O^{18} content of the ice, which has been shown to be related to the annual mean temperature for a given area, it would be possible to determine the site of ice formation on the Greenland icecap, and thus the average rate of movement of the ice throughout its life history (Dansgaard, 1961; Scholander, et. al. 1961).

Thus the 1958 expedition to Greenland was undertaken in a Norwegian sealer, which was fitted with a deck laboratory and the necessary equipment for handling and processing large quantities of ice. "Samples were obtained from 10 glaciers from Melville Bay in North Greenland (Lat 75° N.) to Brede Fjord South Greenland (Lat. 61° N). Our efforts to obtain undisturbed ancient atmosphere were thwarted as in no case was the test of uniform composition within the same block of ice met. The composition measurements showed the gas to be close to that of present day atmosphere but with slightly elevated CO_2 values which ranged from .02 to .10 volume percent and oxygen values which ranged from 20.5 to 21.0 volume percent (Scholander et. al, 1961a). Whatever process caused these small and irregular variations is not clearly understood but could scarcely have greatly affected the CO_2 and the datings obtained. The ice discharging from these West Greenland glaciers was found to be surprisingly low with all but two samples less than 1000 years and the oldest sample from Uperniviks Isfjord 3100 qears old. The O^{18} determination by Dansgaard showed the sites of origin to be from 60 to 460 km from the coast with the older ice originating further inland. Calculated rates of movement ranged from 110 to 270 meters per year, which is in accord with earlier estimates by Hess (1904), and the recent calculations by Bauer (1960) for the Jakobshavn glacier. With due regard to possible errors, all of which would tend to increase the C^{14} content of the gas inclusions, the generally low ages are significant and furnish positive information as to the general extent of the life span of this ice. That the ice discharging from these glaciers, which are in most cases ice streams within the inland ice mass, is comparatively young does not, however, exclude the reasonable assumption that much older ice must exist at great depth and in other areas of the icecap.

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This talk has been an attempt to review the principal points in regard to the significance and techniques in the study of gas inclusions in glacier ice which have resulted from our investigations during the past several years. The reader is referred to the individual references cited above for amplification of specific points. In conclusion, it is believed that useful contributions to our knowledge and understanding of glaciological phenomena can be made through the study of gas inclusions, and further investigation along this line is desirable.

Acknowledgment

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Diskussion

Dr. Hans Stauber: Sind bei den neuen Untersuchungen auch Beobachtungen von Erdgas- oder Vulkangas-Einschlüssen im Inlandeis oder in Eisbergen gemacht worden? Vom geologischen Standpunkt wäre es durchaus möglich, daß sich unter der riesigen und dicken Inlandeisdecke stellenweis große Gasansammlungen — als sogenannte ‚Gaskissen' — unter kuppelförmigen Eiswölbungen im Laufe der vielen Jahrtausende haben bilden können, welche unter gewaltigem Druck stehen würden. Hingewiesen sei auf Erdgas- und Erdöl-Lagerstätten unter mehrere tausend Meter mächtigen abdichtenden Sedimentdecken.

Solche Gaslager wären insbesondere dort möglich, wo unter den Inlandeisdecken mächtige Sedimente mit Erdgas, Erdöl oder Kohlenschichten oder vulkanische Gesteine mit Schloten, Verwerfungen und Klüften oder junge Intrusiva oder Extrusiva mit heißen Gas- oder

Wasserquellen als Überreste des früheren aktiven Vulkanismus vorkommen. Sowohl in Grönland wie in der Antarktis sind solche Untergrundverhältnisse zu erwarten. Es sei hier auf die sogen. ‚Koch'sche Linie' hingewiesen, d. i. die markante Störungslinie, welche von den aktiven Vulkanen Islands quer durch Grönland — also unter dem Inlandeis — an die Westküste und weiter nach Kanada zu verfolgen ist. Es sind also bei den geplanten Inlandeis-Tiefbohrungen Vorsicht, Vorstudien und Sicherheitsmaßnahmen wegen der Eruptionsgefahr notwendig. Es ist wahrscheinlich, daß sich die Gas- und Wasserlager in geologisch abgeschlossenen inneren Gebirgssenken von Grönland mit seismischen Reflexions- und Laufzeitkurven feststellen lassen. Vermutlich sind sie in der 100 bis 200 m mächtigen sogen. ‚Zwischenschicht' zwischen Felsgrund und Eispanzer enthalten. Direkte Gas-Entweichungen an Fels-Eis- Kontaktgrenzen bei Nunatakern wären als Ventilöffnungen im Eispanzer denkbar und sollten überprüft werden. Ebenso sollten in den Randzonen des Inlandeises entsprechende systematische Beobachtungen gemacht werden.

Prof. Bauer: Ich schließe mich ganz den Ausführungen von Dr. B. Fristrup an, um die Wichtigkeit der Arbeiten von Commander Nutt und Kollegen zu betonen. Diese Untersuchungen sind sicher die originellsten u. wissenschaftlich bahnbrechendsten der glaziologischen Arbeiten während des Internationalen Geophysikalischen Jahres.

Prof. Brockamp hat in der Begrüßungsansprache gesagt, daß das grönländische Inlandeis ein Relikt der Eiszeit sei. Das ist insofern richtig, als das Inlandeis sich heute wahrscheinlich nicht mehr bilden würde, wenn man das Eis wegnehmen könnte. Andererseits ist aber das Eis des Inlandeises nicht ein Relikt der Eiszeit, da es, wie die Arbeiten von Nutt und Kollegen ergeben, maximal 3000 Jahre alt ist. Dieses hat schon Hess 1902 formuliert, und man kann seine Überschlagsrechnung mit den heutigen Zahlen wiederholen:

Volumen des Inlandeises $\sim 2{,}6 : 10^6$ km^3
Jährlich Akkumulation ~ 500 km^3

Mittleres Alter des Eises

$$\frac{2{,}6 : 10^6 \text{ p}}{500} \sim 5000 \text{ Jahre}$$

Dies will natürlich nicht sagen, daß an einigen Stellen noch älteres Eis existiert. Nur kann man sagen, daß **im Mittel** das Eis von Grönland nicht etwa 100 000 Jahre oder mehr alt sein kann.

Seismische Eisdickenmessungen auf Nowaja Semlja 1932/33

Von K. Wölcken, Buenos Aires *)

Zusammenfassung: Das sogenannte „Inlandeis" von Nowaja Semlja hat keine „mathematische" Form der Oberfläche; Gletscherspalten kommen auch im Zentralgebiet vor. Die Eisoberfläche ist überall „bewegt" und läßt auf einen gebirgigen Untergrund schließen mit nicht weniger Relief als die sichtbaren Küstengebirge. Das ist zum Teil seismisch bestätigt worden.

Die Längs-Achse des „Inlandeises" ist klar ausgeprägt, obwohl auch mehrere Quertäler deutlich sichtbar sind. Es ist durchaus wahrscheinlich, daß, wenn man sich das Eis fortdenkt, die Quertäler das Karische Meer mit der Barents-See verbinden würden, so wie es die Meeresstraße von Matotschkin Schar bereits tut. Die Eisdickenmessungen ergaben, daß in 15 km Küstenabstand der Untergrund tatsächlich unter dem Meeresniveau liegt.

In altem Gletschereis (Tschajew-Gletscher), dessen Temperatur auf — 11° C geschätzt wurde, beträgt die Geschwindigkeit der Longitudinalwellen recht genau 3800 m/s und die der Transversalwellen, weniger genau, zwischen 1760 und 1770 m/s.

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Abstract: The-called „inland-ice" of Novaja Semlja has no "mathematical" form of the surface and crevices also occur in the central part. The surface of the ice is everywhere „agitated" and allows to infer a mountainous underground with as much relief as the visible coast-mountains. That has partly been affirmed seismographically.

The longitudinal axis of the „inland ice" is clearly marked, although some cross-valleys are distinctly visible, too. It is, by no means, improbable that, under the presumption of the ice not being existent, the cross-valleys would join the Kar-Sea with the Barents-Sea just as it is already the case with the Straits of Matotschkin Schar. The measurement of the thickness of the ice resulted in the statement that, at a distance of 15 klm off the coast, the underground lies in fact under the level of the sea.

In the old glacier-ice (Tchajev glacier), the temperature of which was estimated at — 11° C, the velocity of the longitudinal waves is quite exactly 3800 m/s and that of the transversal waves, less exactly, from 1760 to 1770 m/s.

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Obgleich die Meßverfahren in den letzten 30 Jahren sehr verbessert sind, möchte Verf. die damals erhaltenen Ergebnisse kurz mitteilen, weil eine Veröffentlichung in englischen oder deutschen Fachzeitschriften bisher nicht erfolgt ist, und weil das seinerzeit in Rußland abgegebene Material während des Krieges verlorenging. Es handelt sich um eine Fortführung der auf der Deutschen Grönland-Expedition Alfred Wegener 1930/1931 ausgeführten seismischen Arbeiten, diesmal im Rahmen des 2. Internationalen Polarjahres und ebenfalls unterstützt von der Deutschen Forschungsgemeinschaft. Die Instrumente und Methoden sind die auf der Wegener-Expedition verwendeten. Die Ergebnisse sind nicht voll ausgeschöpft worden,

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