REPORT

ON

THE GEOLOGICAL STRUCTURE AND STABILITY

OF

THE HILL SLOPES AROUND NAINI TAL.

BY

T. H. HOLLAND, A.R.C.S., F.G.S.,

OFFICIATING SUPERINTENDENT, GEOLOGICAL SURVEY OF INDIA.

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CONTENTS.

INTRODUCTION.

The following precis of the history of the investigation whose results are contained in the report will explain how it came to be prepared.

1. Whilst Mr. Holland was on his way to report on the Gohna landslip, which was the centre of so much interest in 1894, his attention was called, whilst passing through Naini Tal, to the state of the hill underneath East Laggan on the south-western side of the lake. As a result of his examination of the peculiar conditions which caused the instability of the hill slopes in that particular section of the station, he suggested that an investigation along similar lines of the remaining portions of the hills around Naini Tal would afford data for determining, within a somewhat limited range of accuracy, the extent of other insecure sites, and form also a basis for an examination of the possibility of improvement, or condemnation as unsafe for building purposes, of the portions in which the cost of the cure would be greater than the value of the property saved. Dr. W. King, then Director of the Geological Survey of India, in forwarding this report to the Government of the North-West Provinces and Oudh, supported the suggestions made, and offered to render all possible assistance in carrying out the proposed investigation of the hills.[1]

2. The proposals having received the approval of the Government of the North-West Provinces,[2] Mr. Holland was deputed to Naini Tal at the end of April 1894, to take up the work. In reply to an enquiry from the Chief Engineer, he gave[3] the

[1] Dated Calcutta, 7th March 1894.

[2] Demi-official from Secretary to Government, North-West Provinces, Public Works Department, to Director, Geological Survey of India, dated 27th March 1894.

[3] Demi-official, dated 5th May 1894.

following summary of the method which he proposed to adopt for the purpose of ascertaining the safety of the slopes around the lake :—

(1) On a large scale, contoured map to insert details of—

(*a*) the petrological characters and distribution of the different rocks;

(*b*) the specific gravity of average specimens of each kind of rock;

(*c*) the variations in dip and strike of the divisional planes.

(2) In consultation with the Engineers, to determine values for the coefficients of friction of each kind of rock, wet and dry, and thence the angle of repose when well stratified, and when jointed and cleaved.

(3) On a series of vertical sections constructed from the contoured map—

(*a*) to insert the data obtained according to 1*a*, *b* and *c*;

(*b*) from the data so recorded to draw a theoretical line of safety for each slope when damp and when wet;

(*c*) to calculate the dimensions, and thence the weight of all portions lying outside the theoretical lines of safety, and thus obtain the necessary data for determining the size of a possible landslip; for determining the feasibility of preventing such by revetment, etc., and for the purpose of indicating the most advisable direction of drainage.

3. As every calculation depended, in some factor, upon the map, the first thing necessary was to obtain an accurate contoured survey of the station. At that time the only map giving topographical details was one published by the Survey of India Department in 1872-73, on a scale of 10 inches to a mile, indicating the slopes by shading and the positions of numerous bench marks. Besides being out of date in the matter of roads and buildings, and without instrumental contours, the map was on a scale too small for recording the geological details required, whilst the complete obliteration of the bench marks in the station removed even the faint possibility of utilizing

these means for the construction of cross sections through the suspected slopes.

4. As the result of a consultation with the Chief Engineer and Mr. Holland, His Honour Sir Charles Crosthwaite, then Lieutenant-Governor of the North-West Provinces, was pleased to approve of a contoured survey being undertaken by the Survey of India Department; and accordingly, arrangements were made for the work to be taken up by Mr. T. F. Freeman, Extra Assistant Superintendent, Survey of India. As the rains had commenced before the work had far progressed, the contouring was continued into the following year under the superintendence of Mr. G. B. Scott, Superintendent, Land Records Survey.

5. On the 8th June 1895 the Secretary to Government, North-West Provinces, Public Works Department, reported that the survey was sufficiently far advanced to admit of a number of the required cross sections being readily constructed, and the deputation of an officer of this department was requested for the purpose of carrying out the investigations on the lines suggested by Mr. Holland in May 1894. On account of the approach of the rainy season, however, the Director of the Geological Survey of India considered that the work should be postponed until the middle of September,[1] when Mr. Holland and myself were deputed to take up the work in co-operation with Mr. H. S. Wildeblood, Executive Engineer. We found, however, that the map of the station, referred to in the letter from the Chief Engineer of the previous June, was not then completed, nor had it been sent to be printed. Although it was impossible, for want of printed copies of the map, to work out the geological characters in great detail, we collected as many data, by the aid of the partial tracings supplied by the Public Works Department, as the time at our disposal permitted. As there was no possibility of our receiving the map for two or three months, I was ordered to take charge of the work appointed to me in Rewah, and accordingly left about the middle of October, whilst, after inspection by the

[1] No. 1215, dated Calcutta, 14th June 1895, to the Secretary to Government, North-West Provinces, Public Works Department.

Director, Mr. Holland received permission to return to Calcutta on the 12th November to resume his proper work at headquarters.

6. On receipt in Calcutta of the printed copies of the map of Naini Tal, at the beginning of February last, all the details collected during the previous year were entered on it, and the following report prepared. Finally, Mr. Holland was deputed in June of this year to revisit Naini Tal in order to finally revise the observations and check them with the published map previous to the final issue of his report.

7. It is, perhaps, advisable to point out that the report as now submitted differs in scope from that contemplated in the scheme detailed in para. 2 above. No engineer was associated with Mr. Holland in the preparation of the report, and consequently the safety or otherwise of particular sites and the advisability or otherwise of particular methods of treatment has not been entered into. Such specific cases must be dealt with individually on their merits, and all that has been attempted by this department is the collection of those facts and the explanation of those principles which must be considered, but which lie outside the ordinary knowledge or experience of the engineers to whom the execution of the necessary works must be entrusted.

8. It will probably be expected that, as I have been personally acquainted with Naini Tal since 1880, and have at different times been deputed to advise the Government on matters connected with the safety of that station, I should make such comments on the report as may seem necessary. Little, however, is needed. Based on more detailed surveys than were previously accessible, it bears out the previously expressed opinions of the Geological Survey in greater detail, without changing them in any essential point ; and where it goes beyond these is based on such satisfactory data and is worked out with such care that the results may be implicitly accepted. Practically there are only two passages which I should personally be inclined to modify, and there the modification would only be of degree.

9. The first of these is in regard to adit drainage. It must be distinctly understood that the calculated length of the tunnel re-

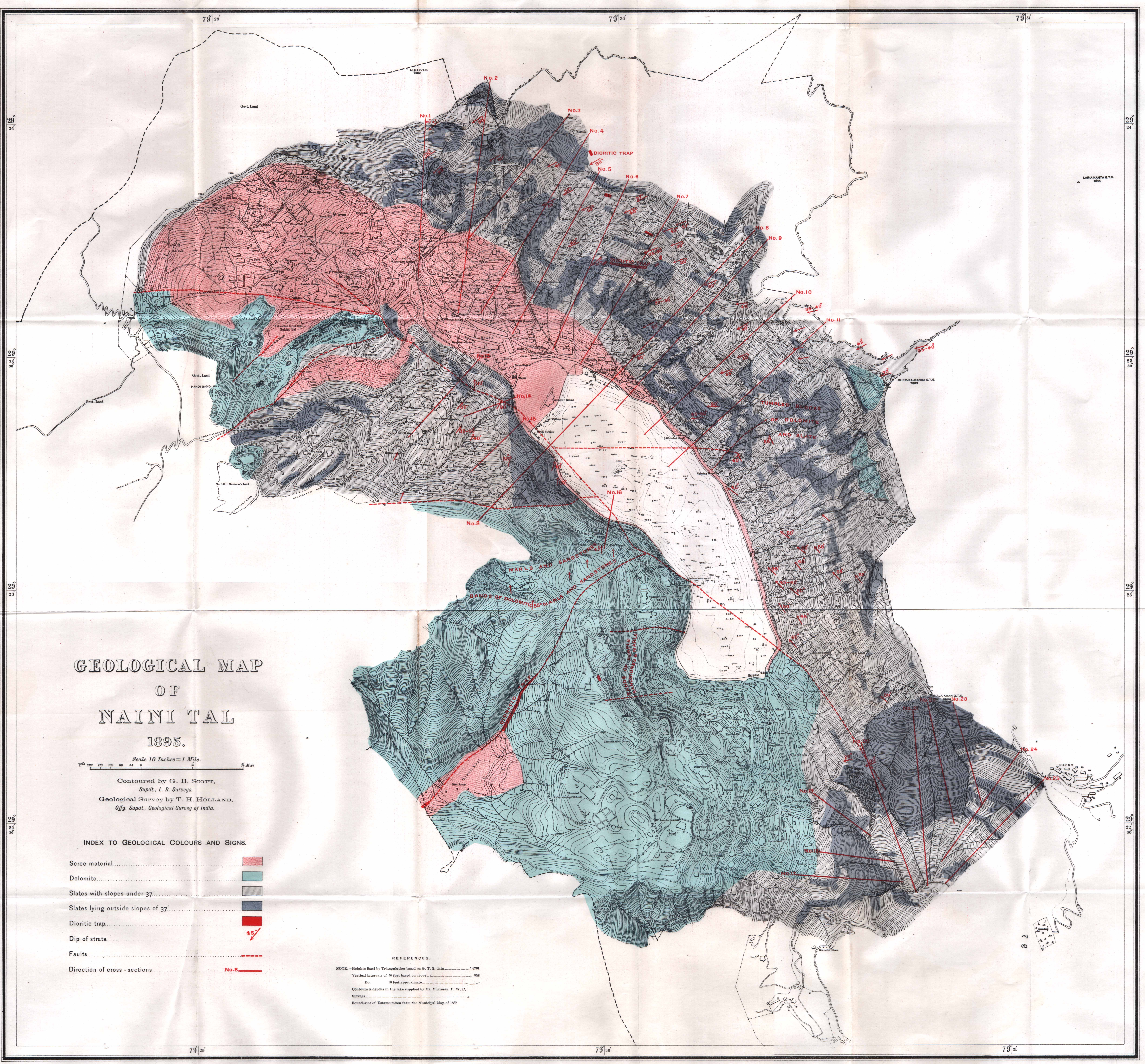
quired to drain the spur on which Charlton Lodge stands (see para. 114) is based on the supposition that the water percolates only along the bedding planes of the slates. Such is not, however, altogether the case; besides the bedding planes there are numerous joints and fractures along which water can percolate, and consequently the protective action of a tunnel would, where the dip is high, extend to some degree beyond the limits defined by the method of calculation adopted by Mr. Holland. I am besides doubtful of the advisability, under any circumstances, of making so long a tunnel. For the prevention of landslips or settlement of the hill side it is only necessary to prevent the accumulation of water in the soilcap—with which I include what would ordinarily be called solid rock, so far as it has been affected by chemical change and movements of the nature of those described in para. 91 of the report. How deep this extends it is not possible to say with precision, but to judge from the data available it probably seldom extends beyond 50 feet and never beyond 100, measured at right angles to the surface of the hill. In the unaltered rock below, the circulation of water will be much slower than in this outer skin, from which alone is danger to be looked for, and I opine that a much greater protective effect is to be anticipated from three suitably placed tunnels of 100 to 150 feet long than from a single one of 383. With the main conclusion regarding the difficulty of protecting the Charlton House and Ravenswood Spurs in this manner, and the certainty of good effects resulting on the Sher ka Danda Hill below Government House, I am in perfect agreement with Mr. Holland.

10. The second passage is in para. 120 which might be misread to produce a false feeling of security. It is true that landslips starting from the crest of a hill, such as the Sher ka Danda, are exceptional, but they do occur and, within my own experience, I have seen more than one in other parts of the Himalayas. In the present case the natural conditions have been modified by extensive cutting away of the top of the hill, and the symptoms it shows are those which are recognized as premonitory of a free landslip. In these circum-

stances it is, to say the least, wiser to adopt those curative measures indicated by the symptoms rather than await the fatal termination of the disease under a suspicion that it may have been wrongly diagnosed.

CALCUTTA,
The 12th December 1896.

R. D. OLDHAM,
Offg. Director, Geological Survey of India.



Reg. No. 388, Geol. Sur.—Nov. 96.—520.

Litho., S. I. O., Calcutta.

MEMOIRS

OF

THE GEOLOGICAL SURVEY OF INDIA.

The Geological Structure and Stability of the Hill-Slopes around Naini Tal, *by* Thomas H. Holland, A. R. C. S., F.G.S., *Officiating Superintendent, Geological Survey of India.*

I. SUMMARY OF PREVIOUS INVESTIGATIONS.

1. In summarizing the results of previous investigations concerning the subjects treated in this report, it is intended to call attention only to such reports as deal with the geological aspects of the case. I have nothing to do with the structural stability of the houses themselves, and the nature of the cracks which they show will only be considered as part of the evidence which may indicate movements of a more deep-seated nature in the rocks upon which they are founded.

2. With the exception of the Geological Sketch of Naini Tal by Mr. Middlemiss, which is of a general character, all previous reports can be divided into those which treat of the slopes on the north-eastern shores of the lake, the Sher-ka-danda side, and those which relate to the slopes on the south-western shores, the Ayarpatha side.

1. General.

3. The papers published by General R. Strachey,[1] Dr. Ball[2] and Mr. Theobald,[3] which will be referred to in another section of this

[1] *Quart. Journ. Geol. Soc.*, Vol. VII, p. 298 (1851).
[2] *Records, Geol. Surv., India*, Vol. XI, p. 174 (1878).
[3] *Ibid.*, Vol. XIII, p. 161 (1880).

report, although dealing with matters of geological interest relating, amongst other places, to Naini Tal, have only an indirect bearing on the subject of the present investigation.

C. S. Middlemiss, 1890.

4. In 1890, Mr. C. S. Middlemiss[1] published an interesting geological sketch of Naini Tal in which he indicated some of the conditions governing mountain slopes. Although Mr. Middlemiss, for very obvious reasons, did not feel justified in "naming" particular sites as dangerous it would be an easy matter to apply the principles clearly explained by him to the Naini Tal slopes, and as I am disposed to accept these general principles, they are embodied in this report together with such extensions and modifications as appear desirable in special cases.

2. *Sher-ka-danda Side.*

Committee on the Landslip of 1867.

5. According to the report of a Committee, dated 12th October 1867, the so-called landslip of 1867, above the western bazaar, appeared to be more of the nature of a rapid scour of a pre-existing ravine than a real landslip. The Upper Mall may be said to have formed the head of this ravine, and used to be annually made by building a rubble wall. No provision was made for drainage, and the road was consequently breached after every heavy rainfall, whilst springs issued at numerous points along the sides of the ravine. At that time very little provision had been made for surface drainage, and so after a long-continued heavy rain, culminating in an 8-inch fall on the night of August 1st, the ravine, which had been gradually enlarging, was rapidly scoured out to its subsequent vast dimensions in a few hours.

1873.

6. This locality was reported on again by a Committee in 1873 with a view to making arrangements to prevent further damage from landslips. They recommended the building of strong cross retaining walls, and the making

[1] *Records, Geol. Surv., India*, Vol. XXIII, p. 213 (1890).

of a masonry channel. In a note on this report, dated 13th June 1873, Colonel Brownlow pointed out the value of improving the surface drainage, and so increase the frictional stability of the hill by preventing the water from soaking into it.

7. The earliest paper which dealt in a scientific manner with the stability of the hills around the lake was by Mr. R. D. Oldham, who made a report on the landslip of 1880.[1] Besides describing the slip itself, Mr. Oldham pointed out the essential differences between the south-eastern and the north-western portions of the Sher-ka-danda slopes. His statement concerning the bulged appearance of the north-western portions—stretching from Fairlight Hall to the Bank House—when seen in profile, has been abundantly confirmed by the contoured survey recently made, and an analysis of the cross sections which accompany this report shows that even in small local bulges there is the same tendency to a steeper slope near the foot of the bulge.

R. D. Oldham, 1880.

8. The cause of this peculiar profile was explained by Mr. Oldham as follows:—

By the action of the weather the face of the hill gets covered with a greater or less thickness of decomposed rock, which weathers into a mass of small fragments. The rain-water, which obtains access to the interior of the hill, for the most part keeps in this decomposed layer and flows down at a short distance from the surface, passing out again lower down in the springs which exist in numbers over this hill, and a large part doubtless percolating downwards reaches the lake without coming to the surface. The presence of large quantities of water among this decomposed rock must, by making it more mobile, assist in producing that phenomenon which is seen in any mass of *débris* lying at a slope, whether it be wet or dry, namely, the gradual passage of such *débris* down the slope under the influence of gravity; that some movement of the *débris* down the slope takes place after heavy rains seems certain, as is shown by cracks appearing in the surface of the hillside, the lower side of which subsides slightly. Now, on a level surface the action of gravity can have no effect in producing any motion, while on a slope the force tending to produce such motion varies directly as the resultant of the vertical force of gravity acting directly down the slope that is, it varies as the sine of the angle of inclination. Suppose, then, an even slope passing near its base into level ground, and that slope covered with *débris*; the *débris* slides slowly down the hill, but on the steeper parts of the slope i must do so

[1] *Records, Geol. Surv., India*, Vol. XIII, p. 277 (1880).

faster than near the bottom, where the slope is less and there is the resistance of the *débris* lying on the level to be overcome, which can only be done by a *vis a tergo*, an impulse from behind. The *débris* coming slowly down from above and meeting with this obstacle gradually accumulates till it causes a bulging of the slope towards its base, which goes on increasing till the lower part of the hill is so steep that, to use a colloquial phrase, "it is touch and go" whether the hill can stand or not; then a burst of rain heavier than usual comes, the head of water is increased, the force of the water flowing out near the bottom is increased, it begins to wash away the *débris* near the bottom till the support being removed from below small slips begin to fall; then a few larger, and finally comes the great slip which brings down the outer crust of half the hillside, leaving a precipitous border round that part from which it has come; finally, the great slip is followed by smaller ones, which leave the hill with a pretty uniform slope from top to bottom for the whole process to begin again. Such I believe to be the history of one of these landslips where there is no stream cutting at the base of the hill; where that is the case, slips may be formed at any time by the cutting away of the foot of the slope.

Although it may be possible to extend in detail the causes contributing to this gradual creep, it may as well be stated at once that I entirely agree with Mr. Oldham as to the existence of this creep, and would follow him further in considering, as he has done in subsequent years, this action to be more deep-seated than that indicated in the paper just quoted. To whatever depth this gradual lakeward movement may extend in the slates of Sher-ka-danda (and this depth will vary for reasons explained below), there is no doubt that subaërial water is the prime agent in the mischief, and its removal must be the leading, almost the only, consideration in framing remedial measures.

Ramsay Committee, 1880.

9. By a Resolution of the Government of the North-West Provinces and Oudh, dated 22nd September 1880, a Committee, under the presidency of Lieutenant-General Sir H. Ramsay, was appointed to ascertain, after the landslip of the 18th September, the real condition of the hill, and to frame protective measures for future safety.

10. The Ramsay Committee concluded that at that time no danger of further settlement existed west of Cheena Lodge, or east of Melville Hall; but that within these limits the hill-side was liable to slip where the slope was greater than 35°. These limits include

an area approximately coincident with the portions indicated as dangerous in the paper by Mr. Oldham already quoted.

11. From the evidence collected by the Committee, it was concluded that the introduction of rain-water into the hill had been greatly facilitated by the destruction of the natural grassy covering of the slopes by the formation of roads, sites for houses, gardens and tennis courts, and by neglect in directing the course of drainage. That these had facilitated the introduction of water into the hills was shown by the increase in the volume of the springs. They concluded also, that whilst the action of water had produced numerous cracks and slips so extensive and far-reaching as to lead to the impression of a general and connected movement of the whole hillside, no such general subsidence had really occurred; and there was, therefore, no insuperable difficulty in framing remedial measures for dealing with such a series of disconnected slips. The following are the remedial measures which they suggested:—

(1) All important ravines should be revetted at intervals by strong cross walls curved in plan, with well guarded flanks (or wing walls) built into the rock on either side. These walls should have considerable batter on the face, the courses being laid at right angles to the batter.

(2) All ravines should be lined where necessary with side walls and strongly paved flooring laid in lime mortar, the channels being made large enough to carry at least double the maximum flood volume which has been known to flow down them up to date.

(3) The cracks and fissures in the hillside should be carefully searched for, dug out as far as they can be traced, and refilled with well rammed clay.

(4) The platforms round every house within the limits specified as dangerous (or wherever the civil officer in charge of the station thinks necessary) should be covered with a six inch layer of well rammed clay, or other material impervious to water (when houses have been destroyed and abandoned, this might be done at the expense of the public, and not at that of the proprietor).

(5) Gardens and cultivated terraces should be absolutely prohibited. Those that exist should be covered with clay and turf immediately, and existing lawn tennis grounds should only be permitted to remain on condition that similar precautions are taken to prevent the percolation of water into the hillside.

(6) The further erection of houses or other buildings, quarrying of stone, and the excavation of terraces or platforms for any purposes whatever, should be absolutely prohibited in the southern slope of the Sher-ka-danda hill within the limits specified as dangerous.

(7) Special care should be taken to prevent injury from house drainage. Every house should have a gutter under the eaves and a catch-water drain round its base. The water from these should be carried in a masonry channel to the most suitable ravine, in which provision should be made for its reception.

(8) House proprietors should be compelled to restore in an efficient manner all retaining walls which are bulged or cracked; and further, to build such walls where they do not exist, and where their absence has caused, or may hereafter cause, slips in the hill above. Also, where there is any tendency to slip, to slope off the hill immediately above all retaining walls to an angle of 40°. This order should be binding on all proprietors, whether the houses on their estates are occupied by tenants or not.

(9) The civil officer in charge of the station should be responsible for the maintenance in proper order of all watercourses in ravines and of all roadside drains. Special gangs should be employed during the rains to keep the drains free from obstruction and to repair damage immediately it occurs.

(10) An honest, efficient, and trustworthy subordinate should be appointed as Inspector of buildings and drains, who should be under the sole orders of, and responsible only to, the civil officer in charge of the station.

(11) All the arrangements for drainage of houses, roads, and property, and the building of all revetment walls, and in short all operations which affect the safety of the station, should be carried out by order of the civil officer in charge through the agency of this Inspector. Where these necessary improvements are executed on private property, the house or land-owner should be made to pay the cost. Private individuals should not be allowed to construct any drains, walls, or buildings without the written permission of the civil officer and the supervision of the Inspector.

(12) All steep slopes should be turfed and planted. Grass cutting and grazing on the southern slopes of Sher-ka-danda and Cheena should be strictly prohibited.

(13) The civil officer should have power to carry out the above and other measures for the safety of the station without reference to the Municipal Committee.

(14) And, finally, whatever sums are set aside by Government or the Municipality for the maintenance and improvement of drains and roads should be at the disposal of the civil officer, to be expended by him, without reference to the Municipality, in a regular and systematic plan, with the advice, when necessary, of the Superintending Engineer of the Provincial Circle.

The Committee further specified sites which they considered to be unsafe.

Forbes Committee, 1882.

12. On the 25th September 1882, a second committee, with Colonel Forbes, R.E., President, was appointed to report upon the character and stability of the protective works, and their probable effect in ensuring the

safety of the various properties which were considered unsafe by the former Committee, and also upon the general safety of the settlement and necessity for further protective works.

13. The Forbes Committee found that the measures proposed by the previous Committee had been carried out, with the exception of No. (4), which was only partially observed, and No. (5). They were also of opinion that the remedial and protective works, which were made in 1881, had rendered the houses, specified as unsafe by the Ramsay Committee, decidedly safer than before the works were constructed. The report of this Committee also embodied the results of the examination of 23 sites. They were of opinion that the general protection of the ravines and hillsides between the limits reported upon in 1880 appeared to have been very efficiently carried out, and this portion of the station was in all probability as safe as, or safer than, it ever was.

Henslowe Committee, 1883.

14. Under G.O., dated 17th March 1883, a Committee under Mr. Henslowe, was convened to enquire into the condition of Government House and to suggest remedies for the prevention of future mischief. In their preliminary report, dated 11th April 1883, the Henslowe Committee detailed the cracks in Government House, which were marked on a plan prepared by Mr. L. B. Simeon. They were unanimously of opinion that these cracks, which were all longitudinal, were consequent upon the general disturbance of the hill during the cyclone of September 1880. Although Mr. J. S. Beresford differed from the other two members of the Committee, who considered that unequal consistency in the subsoil under the foundations had tended to increase the cracks, the Committee were unanimous in considering that in the absence of any violent and abnormal disturbance, such as a considerable slip in the vicinity of the building, no material extension of the damage need be apprehended.

Besides recommending that the cracked arches be rebuilt, the remedial measures proposed by the Commitee included improvements in the maintenance of the approach roads, and in the drainage system.

R. D. Oldham, 1889.

15. In 1889, amongst other questions relating to Naini Tal, which are referred to in their proper places below, the Government of the North-West Provinces in an office memorandum (No. 3633, B.R., dated 14th September) requested Mr. Oldham's opinion as to the subsidence that appeared to be going on slowly along the Government House ridge. To this question Mr. Oldham gave the following reply:—

This is no doubt a serious matter; I can recollect that my attention was called to, and opinion asked on, this subject in 1880, since which date I find there has been a distinct further settlement of the hillside the cause and nature of which are obscure. From the facts, that there is a distinct line along one side of which subsidence takes place, that a considerable part of the subsiding portion is rock and not soil-cap, and that the subsidence happens not during but about a month after the cessation of the rains, I conclude that the movement takes place along some fault or fissure which runs at a considerable depth through the solid rock.

There can be no doubt that this is a serious matter, and will ultimately be a source of danger; but no immediate apprehension need be felt, which is fortunate as, owing to the enormous mass which is moving, and the obscurity of the cause to which its movement is due, I can see no prospect of dealing with it successfully.

J. B. Henslowe, 1889.

16. In a letter to the Superintending Engineer, dated 17th December 1889, Mr. J. B. Henslowe, Executive Engineer, Kumaun Division, referred to the great fissure under Government House as being due to no movement of the soil-cap overlying the rocky matrix, but to a distinct separation through the axis of the hill itself. The fissure could be traced from Government House, through St. Cloud, to Snow View. Judging from the separation in the tiled flooring of the corridor and conservatory, and gauged by the deviation of the outer pillars of the conservatory from the vertical, it would appear that since the erection of the house in 1880 the forward movement had not exceeded 3 to 3½ inches.

17. In Mr. Henslowe's opinion, the opening of the crack month or so after the rain ceases has no connection with the "movement" in the hill as Mr. Oldham supposed, but is due merely to the

shrinkage of the materials as the temperature rises under the warm sun of September and October, an is and incident of no significance. Mr. Henslowe continues:—

I am also inclined to think that at present there is little, if any, movement going on: the fissure is a very large one, and extends to a great depth into the mountain; it has never been filled in to the bottom, and I believe that the periodical opening out of cracks in the corridor, conservatory, garden, and in the adjacent compounds is due to the shrinkage and breaking up of the materials with which the upper portion of the chasm has been stuffed and their falling down in small particles.

I have had a portion of the tiled floor in the conservatory taken up when a slight new crack appeared, and this has disclosed a fissure four inches to six inches in width immediately beneath the tile down which a stick four or five feet long can be thrust: this is no *new* opening, or the arches and floor would have shown cracks of the same width: it simply serves, I think, to bear out my theory.

It certainly is an unusual occurrence for materials to shrink under rise of temperature; but Mr. Henslowe probably refers to the desiccation which follows the rainy season. As this desiccation extends for some distance into the soil cap, and as there is practically no water supplied to the still deeper parts of the hill after the rains, Mr. Henslowe's criticism does not affect Mr. Oldham's contention; and in another section of this report I have given my reasons in detail for agreeing with Mr. Oldham in attributing the opening of cracks after the rains to a deep-seated movement in the hill, and have given reasons also for estimating the depth to which this fissure extends.

C. H. Holme, 1890.

18. A report by Mr. C. H. Holme, Executive Engineer, dated 3rd December 1890, showed that the back verandah floor of Murray's shop was "about one foot higher than the rest of the floors, apparently forced up by the pressure of water below." Murray's shop is situated at the foot of the ridge on which Government House stands.

Corbett Committee, 1895.

19. In a report, dated 27th March 1895, Colonels Corbett and Pulford showed that a portion of the plinth of Government House had settled down as much as 7 to 10 inches and that the settlement was accompanied by an

outward movement of separation, as shown by measurements taken periodically between the wall of the drawing room and the outer wall of the conservatory. Between July 1890 and January 1895 the total increase in these measurements was 2½ inches.

20. According to a report by Mr. F. O. Oertel, District Engineer of Naini Tal, the records showed a considerable movement in the larger longitudinal cracks during the years 1890—94. A trench dug on the west side of the house, near the billiard room, touched solid limestone rock, in which gaping fissures 9 inches wide were exposed. The depth of the fissures could not be ascertained, but a stone dropped down could be heard to strike the sides for some seconds.

Beresford Committee, 1895.

21. Mr. J. S. Beresford, who had been a member of the Committees of 1880, 1882 and 1883, presided over a Committee which was convened under G. O., dated 22nd April 1895, to consider the safety of Government House. In a report, dated 11th May 1895, the Committee gave their reasons for considering Government House and its site to be at that time safe ; and, with a view to protect the house from further deterioration,and to minimize the effect of the injury already caused, they proposed certain measures, which, besides dealing with the drainage system and structure of the house itself, included a system of measurement for the accurate determination of further subsidence which might take place.

Mr. Oldham, however, disagreeing with the other members of the Committee, considered that the site of Government House, apart from the question of the stability of the structure, must already be regarded as unsafe during the rains; and considered that matters had developed so far that the proposals of the Committee, though without objection in themselves, were merely palliative and not curative. He proposed that an adit should be driven into the southern face of the hill at a spot not less than 75 or more than 100 feet directly below Government House.

22. Mr. C. L. Griesbach, Director, Geological Survey of India, on being asked to give an independent opinion agreed with Mr. Oldham in recognising the probability of landslips occurring on the slopes of the hill under Government House; but, in the absence of conclusive data, could not say whether such catastrophes may be looked for within a measureable time or not.

C. L. Griesbach, 1895.

Many of the points of evidence, upon which the foregoing general conclusions are based, will be discussed in another section of this report. (Sect. VI.)

23. In a letter, dated 26th January 1895, to the Commissioner of Kumaun, Mr. F. Giles, as President of the Naini Tal Municipal Committee, reported on the condition of the hillside between the Grand Hotel, the Allahabad Bank premises, and Ravenswood. The hillside had been examined by the President with Messrs. Matthews, Banyard, Wildeblood, Oertel and Orchard, who found cracks in the retaining walls behind the Grand Hotel, and found the Bank premises to be settling in all directions, whilst the hillside appeared to be in a more or less unstable condition.

Ravenswood spur, 1895.

24. Colonel Pulford, R.E., Superintending Engineer, subsequently examined this portion of the hillside, at the request of the Government of the North-Western Provinces, and considered that the cracks and settlement of walls in the Allahabad Bank were due to faulty construction of the foundations at the back of the house, where, also, no provision had been made for carrying off the water from a spring which issued from the hillside. He considered that the retaining walls of the Grand Hotel were at that time in a satisfactory condition, and gave his reasons for considering the slight settlement in the front portion of the Ravenswood site to be of no serious import.

25. In 1888, a very interesting report on the southern slope of Sher-ka-danda hill was published by Mr. F. E. G. Matthews, whose long residence in the

F. E. G. Mathews, 1888.

station, and necessarily intimate knowledge of the place as house agent, should enhance the value of his opinion. Mr. Matthews' report describes the condition of a large number of sites on the southern face of Sher-ka-danda, where he shows the movement to be not directly towards the lake, but in a more westerly direction following the dip of the stratification planes of the slates. As I hope to show in the sequel, this is a most important consideration in dealing with the question of the safety of special sites, and one which, so far as I can find from the records, has been practically overlooked, or at least not mentioned in the same precise form in previous reports on this hillside.

3. Ayarpatha Side.

R. D. Oldham, 1889.

26. In answer to questions addressed to him by the Government of the North-West Provinces, Mr. Oldham gave his opinion (dated 21st September 1889) on the condition of the Ayarpatha hill between the slip of 1888 above the Hindu temple and East Laggan. Referring to the northern part of this section of the hill, which is composed of slate, he was of opinion that the slopes under Galloway House were decidedly dangerous, and recommended the more complete drainage of the higher portion of the hill, where the gentler slope facilitated the introduction of water.

T. H. Holland, 1893.

27. In February 1893 my attention was called to the state of the slopes under East Laggan, and in a report to the Director, Geological Survey of India, I gave a description of the slips which had taken place, together with an account of the causes to which the slips were due. In consequence of the peculiar and interesting circumstances which gave rise to these slips, I was of opinion, as stated more fully in para. 122, that the slope was dangerous back to the house, and that any attempts to mend the roads along their original alignment could only be attended with temporary success.

28. After remaining closed for more than a year attempts were made in 1895 to reopen these roads along their original lines; but before the commencement of the rains further portions fell into the lake and the roads were left in a worse state than before. In September of the same year Mr. H. S. Wildeblood, in a report to the local Government considered that I had exaggerated the extent of the dangerous portions of the slope, and was of opinion that the roads might be opened along their old lines.

H. S. Wildeblood, 1895.

29. In the following October Mr. Oldham was asked to make a report with reference to Mr. Wildeblood's proposals, and confirmed my original conclusion that any road carried across the face of the slips must be of a purely temporary nature, liable to repeated interruptions, and a source of danger in itself, as well as to the hill above and below.

R. D. Oldham, 1895.

Casual rock falls from the dolomitic cliffs near East Laggan and at Smuggler's Rock have also been made the subject of reports at different times.

4. *Rock-falls from Cheena.*

30. Mr. Oakshott, Assistant Commissioner, reported (11th September 1889) that on the 28th of the previous August, some rocks fell from the face of Cheena, and some 12 or 14 good sized blocks reached the Mall. One stone went through the back of the outhouses of Melrose. It was recommended to make a plateau 55 feet broad, stretching from the gate of Balmoral to the branch road leading to Tonnochy's. Mr. Oldham, in a note, dated 21st September 1889, considered the proposal to make a series of terraces the best that could be adopted, as periodical rock-falls must always be expected from such an extremely steep scarp.

II. GEOLOGICAL STRUCTURE OF THE HILLS.

31. Although the new map enables us to record additional details, the general geological characters of the hills around Naini Tal,

described in the paper by Mr. Middlemiss, require very few additions and still fewer corrections.

For convenience of reference with regard to the main object of this report, the geological features are described separately under the heads of petrological, stratigraphical and physical characters in order.

a.—PETROLOGICAL CHARACTERS.

32. The rocks of Naini Tal are :—

(1) Argillaceous.

(2) Dolomitic.

(3) Dolomitic sandstones.

(4) Purple sandstones and quartzites.

(5) Dioritic traps.

(6) Gypsum.

1. Slates and Shales.

33. The *argillaceous rocks* of Naini Tal consist of slates and shales, which vary in colour from green to purple and various shades of grey and black. The green and grey-tinted varieties are seen especially in the hill under Government House and near Glenlee. The grey, hard types are often impregnated with carbonate of lime and are really hardened marls. The purple types are well displayed further to the south-east on the Sher-ka-danda side, and further north-west on the other side, as, for instance, under Snowdon and in the Aubrey road above Pope's villa, at the junction with the Ayarpatha Upper Mall. Black, carbonaceous slates, which contain large quantities of carbonates and pyrites, occur in various places, as for instance near Aberfoyle.

Mechanical changes in the shales.

34. By *pressure* the argillaceous rocks have developed a decided *cleavage*, which is often across the original bedding planes, but in some cases has accentuated the bedding planes by coincidence of cleavage and stratification. In addition to the cleavage produced by pressure, the slates of Naini

Tal have been *crumpled* and *sheared* by earth movements, and it is to this shearing that the splintery character of the slates is due, a circumstance which has rendered them useless for roofing purposes.

Chemical changes in the shales.

35. The mechanical changes which have accompanied the pressure to which the argillaceous rocks have been subjected, has been accompanied by the chemical changes of dehydration, and simultaneous molecular rearrangements to form new minerals on a microscopic scale. Near the intrusions of trap, where the rocks have been submitted to a rise of temperature other than that due to the heat which arose from, and accompanied, the mechanical deformation during earth movements, the results of contact metamorphism are often noticeable. The slates are here often penetrated by veins of quartz.

Specific gravity of the slates.

36. The specific gravity of the splintery grey slates is 2·76, the average of specimens determined from the following localities :—

North-west of Rolaston house	2·76
Near Buttress Castle	2·73
South of Lake view, near the spring	2·73
South of Alma Cottage	2·79
Road leading to Rohilla Lodge S. E. of Buttress Castle . .	2·78
N. W. of Sher-ka-danda peak	2·77
St. Loe gorge	2·74
Colvin road, N.-W. of Baugh Cot.	2·75
Near the trap under Staff House	2·77

Where the slates have been exposed to the weather they have absorbed water, and show, consequently, lower specific gravities, as for instance under Glenlee, where they are noticeably soft. Specimens collected on this slope range in specific gravity from 2·68 down to 2·35, and, where they become porous and spongy, to as low as 1·77 (for explanation see paragraph 81).

Carbonaceous and pyritous slates.

37. The heavy, black, carbonaceous, dolomitic slates of Aberfoyle, which are impregnated with finely divided pyrites, lose their pyrites and part of the carbonaceous matter and carbonates by exposure to the weather, leaving a

friable, porous, lighter rock with ferruginous red stains. It is the decomposition of a rock like this that gives rise to the sulphuretted hydrogen, which is unmistakeable by its smell in some of the springs, and to the gypsum deposited in various places.

2. *Dolomites.*

38. Until my visit to Naini Tal in 1894 the massive blue and grey rocks, which form for instance the conspicuous Craig Ellachie near East Laggan, were known as limestones and described as such by Mr. Middlemiss in his "Geological Sketch of Naini Tal," where he recalls their resemblance to the fossiliferous mountain-limestone of Northern England. At first sight they certainly do recall the mountain-limestones familiar to English students, but their hardness and high specific gravity aroused suspicion and led to their chemical examination. Even in making a preliminary chemical test with cold dilute acid suspicion might easily be disarmed by the freely effervescing thin films of carbonate of lime, which fill in the numerous cracks and so naturally form the more easily produced fracture-surfaces.

Similar Himalayan dolomites.

39. Dolomites have been recorded in a similar association of unfossiliferous rocks at various points in the Himalayas, for instance at Deoban, Mussoorie, Gohna and in Hazara. Mr. Oldham[1] has recorded the occurrence of dolomitic beds in the Deoban limestone formation, and chemical analysis of his specimens confirms his field determination.

40. The following analyses by Dr. H. Warth[2] of Mussoorie specimens prove the prevalence of magnesia in the massive limestones of that area :—

I. Fine grey dolomite from the top of Camel's back.
II. Dark crumbling rock near Jharipani.
III. White crystallized dolomite near Jharipani.
IV. Magnesite from near Happy Valley.
V. A mixture of 50 specimens of dolomites and limestones all over the Mussoorie range.

[1] *Rec., Geol. Surv. India.*, Vol. XVI, p. 195 (1883).
[2] *Indian Forester*, Vol. X, p. 118 (1884).

	I	II	III	IV	V
Carbonate of lime	58·9	50·4	48·8	13·5	56·7
Carbonate of magnesia	33·2	47·1	48·2	69·1	33·3
Residue of silica, alumina, etc.	4·7	0·5	0·3	13·2	6·1
Water, bituminous matter and loss	3·2	2·0	2·7	4·2	3·9

41. A chemical analysis of a specimen from Gohna, Garhwal, gave[1]:

Carbonate of lime	53·875
Carbonate of magnesia	44·780
Ferric oxide, alumina and phosphoric acid	1·225
Insoluble residue	1·355
	101·235
Specific gravity of fragment analysed	2·83

42. The determination in the Geological laboratory of magnesia in the Hazara specimens collected by Mr. Middlemiss proves the dolomitic character of similar rocks in that area, and dolomites, containing 38 per cent. of magnesic carbonate, have also been recorded by Mr. F. R. Mallet in a similar series in the Western Duars.[2]

Effects of dolomitization.

43. As carbonate of magnesia possesses a higher specific gravity than carbonate of lime the introduction of the former compound is indicated by an increase in the specific gravity of the specimens. The specific gravity of calcite (calcium carbonate) is 2·72; of normal dolomite (double carbonate of magnesia and lime), 2·85; and of magnesite (carbonate of magnesia) 3·00. The determination, therefore, of the specific gravity forms an indication of the chemical composition, which, though fairly accurate in well crystallized specimens, would be only approximate in specimens where, like the Naini Tal dolomitic rocks, small quantities of aluminous and carbonaceous foreign matters are included. Still, the

[1] Holland, Report on the Gohna Landslip, *Rec. Geol. Surv. India*, Vol. XXVII, p. 58 (1894).

[2] *Mem. Geol. Surv. India*, Vol. XI, pp. 34, 83.

results will on the average so frequently approach the truth, that the determination of the specific gravity forms a very quick and simple way of estimating the chemical constituents in a specimen, and might very well be employed by the Engineer for that purpose.[1]

44. The average specific gravity of the ordinary dark, blue-grey dolomite of Naini Tal is 2·82, which corresponds to a composition of—

Carbonate of lime	64·3
Carbonate of magnesia	35·7
	100·0

The foreign matters are often considerable in quantity as shown by the following analysis of a specimen from Ayarpatha :—

Carbonate of lime	50·13
Carbonate of magnesia	40·89
Alumina, etc.	1·63
Insoluble residue	7·71
	100·36

Characters of the dolomites.

45. The dolomitic rocks may be recognised at once by the rugged, craggy masses into which they weather. As a rule, they are divided into irregular masses by joint-planes ; but sometimes are well bedded, as shown on the road leading to the house above Smuggler's Rock. Besides the main divisional planes, the rocks are generally divided into small fragments, which are recemented by thin films of carbonate of lime, giving the weathered surfaces a characteristic roughness. This pseudo-brecciation of the rocks is in all probability the result of the contraction which accompanied the replacement of a portion of the carbonate of lime in the original limestone by carbonate of magnesia to form the dolomite, a reduction which amounts to 12·1 per cent. in volume. The real breccia, made up of fragments of the dark-coloured dolomite cemented by lighter carbonate of lime, occurs very frequently between the big blocks,

[1] Representing the percentage of magnesic carbonate as x; then—

$$\frac{3\cdot0\,x + (100-x)\ 2\cdot72}{100} = G$$

or $\cdot28x = (G - 2\cdot72)\ 100$.

and is the result of actual crushing of the rocks during earth-movements.

46. The remarkable fact about these rocks is the complete absence of fossils, a feature which is characteristic of all the similar exposures of this formation in other parts of the Himalayas, and in consequence of which it is impossible to settle the position of these rocks in the stratigraphical sequence. The nearest approach to fossils are certain structures which outwardly resemble those of organic origin, but which in section are found to be so completely altered by secondary crystallization of the carbonates that all original organic structures have been completely obliterated.

Absence of fossils.

47. The most characteristic of these pseudo-organic structures resembles the *Stromatoporoidea* of European Lower Palæozoic rocks, and has been found in the Deoban limestone in Jaunsar and Sirmur,[1] as well as in the dolomitic limestones and dolomites from Kúlú,[2] Kumaon,[3] Hazara,[4] and Gohna.[5]

Pseudo-fossil structures.

48. Another structure, which is possibly of organic origin, is that of the oolitic rock of Deopatha in Naini Tal. Sections of this rock show it to possess the typical structure of the oolites, but with the delicate internal structures destroyed by secondary crystallization. Mr. Wethered, in a series of papers contributed to the Geological Society of London,[6] has concluded, from an examination of a wide range of rocks, that the oolitic structure is of organic origin. Rarely fragments of shells are found in the Deopatha oolites.

[1] R. D. Oldham, *Rec. Geol. Surv. Ind.*, Vol. XXI, p. 133 (1888).

[2] C. D. Sherborn, *Geol. Mag.*, 3rd dec., Vol. V, p. 255 (1888). Mr. Sherborn compared the general characters of the structure with those of certain similar American specimens described under the name of *Cryptozoon proliferum*. Prof. H. A. Nicholson, who examined the Kúlú specimen, was inclined to attribute it to an organic origin, quoting a similar case described by M. Dupont from the altered Devonian lime stones of Belgium under the name *Stromatactis* (*ibid.*, p. 257).

[3] J. McClelland, *Journ. As. Soc., Beng.*, Vol. III, p. 628 (1834).

[4] Specimens collected by A. B. Wynne, G.S.I., in 1878 and preserved in the Geological Museum, Calcutta; No. 79. 118.

[5] T. H. Holland, *Rec. Geol. Surv. Ind.*, Vol. XXVII, p. 57 (1894).

[6] See especially *Quart. Journ. Geol. Soc.*, Vol. LI, p. 196, 1895.

49. In discussing the cause of this absence of fossils, Mr. Middlemiss has given as one explanation the subsequent slow chemical and mechanical changes in the rock by which the original organic structures have been destroyed.[1] The discovery of the prevalence of magnesia in these rocks, introduced as a secondary constituent and accompanied by complete metasomatic change, confirms this conclusion.

Cause of the absence of fossils.

3. Dolomitic Sandstones.

50. At East Laggan a mass of sandstone has been faulted into position in the ordinary dolomite. This sandstone is grey in colour, with carbonaceous micaceous and marly bands, and is well bedded. The flaggy character of broken fragments at once distinguishes it from the more irregular shapes of the dolomite blocks, and enhances its value for building purposes. Thin sections of this rock examined under the microscope show it to be composed of quartz, and, to a less extent plagioclase granules cemented into a compact rock by dolomite, which is very irregular in its distribution. Being well bedded, porous and jointed, water passes freely through the rock, removes the cementing carbonates in solution, oxidizes and hydrates the ferruginous materials, leaving a crumbling mass of rust-coloured sand. It is in this way that settlement occurs in inclined beds of this rock (*vide infra*, paras. 84, 123, 125).

Structure of the dolomitic sandstones.

51. This rock occurs typically developed under East Laggan house, and is found on traversing the strata on the hill above the house to be interstratified with beds of ordinary dolomite, and finally near the Upper Mall, passes into a white sandstone practically devoid of carbonates.

The specific gravity of this rock varies from 2·68 to 2·73, the

[1] *Op. cit.*, p. 218.

heavier forms containing generally more dolomite. The following analyses show the composition of two leading types :—

	No. 9,740. Sandy dolomite (East Laggan).	No. 9,741. Dolomitic sandstone (East Laggan).
Carbonate of lime	32·48	12·98
" magnesia	28·33	9·44
Ferric oxide, alumina, etc. . . .	1·78	1·88
Insoluble residue	34·86	75·76
Carbonaceous matter	2·95	...
	100·40	100·06

4. *Purple Sandstones.*

52. On the southern side of the outlet of the lake, bands of purple sandstone and grit are found interbedded with the dolomite and grey shales. The purple sandstones are especially well developed under Purbeck Lodge and Dereham House. Its position, with gentle dips towards the hill, is not likely to affect the main subject of this enquiry. It is a fine-grained, compact, well-jointed rock, with a specific gravity of 2·68. It frequently contains much mica.

5. *Dioritic traps.*

53. The dioritic rocks occurring as dykes in the dolomite, and as dykes and intrusive sheets in the slates, are probably members of one great intrusion. Originally they were composed principally of pyroxene (pale augite), plagioclase, apatite and the usual opaque iron-ores, magnetite, ilmenite and pyrite; but by secondary changes hornblende, quartz, epidote, rhombohedral carbonates, zeolites and green serpentinous and chloritic products have been produced, giving the rock a green colour.

Micrographic quartz in the diorites.

The most interesting feature in connection with these rocks is the occurrence in them of micrographic quartz, a feature which though very rare in rocks of this class I have found to be extremely common, almost characteristic in fact, in the dykes and contemporaneous traps of the Transition rocks of India, both Peninsular and Himalayan. In many cases portions at least of this micrographic quartz can be shown to be of secondary origin, and such I consider to be the origin of the micrographic quartz in the Naini Tal diorites.

54. The following determinations show the variations in specific gravity of the diorites :—

Near Tara Hall	2·94
Alma Hill	2·89
Near Himalaya House	2·88
Staff road, under Staff House	2·87

55. Very similar trap rocks are found associated with the same formations in other parts of Kumaon. At Ratighat diorite forms a wide dyke, almost boss-like in character. It is interbedded with the quartzites of the Alaknanda valley, sometimes preserving its original crystalline character, and sometimes crushed out to form a hornblende schist. About 3 miles west of Karnprayag, on the Alaknanda, a sheet of this rock in the quartzites forms a very beautiful example of the cases containing micrographic quartz. Large masses also break through the dolomitic limestones of Mussoorie.

6. *Gypsum and other secondary minerals.*

Origin of sulphuretted hydrogen.

56. Nearly all the dolomites, and some of the slates, contain pyrites and carbonaceous matter. The excess of sulphur in the pyrites combines with the hydrogen in the hydrocarbons and gives rise to the sulphuretted hydrogen, which can be so easily recognised by its disagreeable odour at the outlet of the lake, and gives the new-comer an unfavourable impression of the Lower Bazár, which he passes through on entering Naini Tal.

Origin of sulphuric acid and gypsum.

The oxidation of sulphuretted hydrogen and of the other sulphides gives rise to sulphuric acid, which converts the carbonates of lime and magnesia into sulphates. The more soluble sulphate of magnesia passes away entirely in solution, whilst the sulphate of lime is deposited in any convenient cavity as gypsum. The sulphuric acid, acting in a similar manner on the argillaceous rocks, produces sulphate of alumina, which appears during the dry season as an efflorescence at many points below Naini Tal.

57. The gypsum so formed becomes deposited in any convenient cavity in the other rocks, and especially in the scree material, forming sometimes considerable masses. When these become discovered by a road or other cutting, or in other ways become exposed to the action of circulating waters, the gypsum, being slightly soluble in water (1 in 400), becomes gradually removed in solution, and subsidence consequently takes place in the superincumbent material. The presence of this substance cannot therefore be regarded as a source of strength to the rocks, whilst the mere fact of its formation shows that the rocks from which it was derived must have contained pyrites and have been partially decomposed. Pyrites in rocks of the type found in Naini Tal are, from their liability to change, and from the nature of their secondary products, invariably the source of mischief.

58. *Calcareous tufa* is very common amongst the dolomitic rocks, and is frequently found encrusting the surfaces, lining cavities, or forming the cement of breccias and scree material. Being a cement it is generally a source of strength, and it is probably in part due to the calcareous cement that the dolomitic blocks, forming the dangerous-looking slope near the top of the hill over the Lake View Hotel, have remained so long at their present steep angle.

b.—STRATIGRAPHICAL CHARACTERS.

Stratigraphical position of the beds.

59. In the absence of fossils, it is impossible to fix with certainty the position of the slates and dolomitic limestones of Naini Tal in the stratigraphical succession. But, from general lithological resemblances, they are referred to as the equivalents of the lime-

stone series of Jaunsar to which Mr. Oldham has given the name *Deoban*, from their development in the peak of that name, north of Chakráta. The limestones of this series are frequently mephitic, dolomitic and sometimes oolitic. The general resemblances indicated by these characters are corroborated by the peculiar pseudo-organic structure already referred to (*vide supra*, para. 47).

60. The age of these beds is unknown; but they appear to be unconformable to the Jaunsar system, which exihibit certain resemblances to the Haimantas and Silurians of the Central Himalayas, and are overlaid with marked unconformity by beds which are considered to be of Carboniferous or Permian age.[1]

Should the pseudo-organic structure as already suggested (§ 47) prove to be referable to the peculiar group of *Stromatoporoidea* the age of these beds would most probably be from Silurian to Devonian and their stratigraphical relations to other Indian formations are not, so far as they go, inconsistent with this suggestion.

The fact that the intrusive traps in Naini Tal present certain peculiarities repeated in the contemporaneous traps of the Peninsular Transition rocks should not be passed unrecorded ; but it must be clearly understood that such secondary structures in igneous rocks are never to be relied on for the purposes of stratigraphical correlation.

61. From the evidence of the section about three-quarters of a mile south of the outlet of the lake, the dolomitic rocks are considered, as first pointed out by Mr. Middlemiss, to be laid down in normal succession to the slates; but slaty bands are frequently found in the dolomites, and narrow bands of dolomite are frequently exposed in the slates, as shown clearly near the faulted junction exposed on the Lower Mall and in the East Laggan road.

Direction of dip of slates.

62. Whilst the slates are sometimes crumpled locally, they present a regularity of dip over considerable areas. On the Ayarpatha side the slates dip towards the N.N.E. at angles varying from 25° to 40°

[1] Manual Geology of India, 2nd Ed. (1893), p. 1 7.

along the outer slopes; but at much higher angles as the fault-line to the south is approached. This increase in dip can easily be traced in walking along any of the roads from the Polo ground towards East Laggan, along the East Laggan road or along the Lake Mall. On the Sher-ka-danda side the dip is towards the S.W. and W.S.W., as shown on the map. Near Melville Hall, where the strata have been disturbed by a fault, the dips change suddenly to the N.W., which continues for some distance along towards the outlet of the lake, and is accompanied by the exposure of a harder and more splintery set of beds in which dolomitic bands are frequent. On the road to the Depôt, however, the softer loose slates, characteristic of the north-western portions of the Sher-ka-danda slopes, are again exposed, and there also are seen to be dipping towards the W.S.W. and S.W., at angles varying between 25° and 35°.

Dolomites.

63. The dolomites are often so massive that no direction of stratification planes can be definitely determined, and in any case the direction of dip is of less importance for the purposes of the present investigation, than in the case of the slates. Near the picnic ground on Ayarpatha there is a well-defined synclinal fold, and numerous small foldings can be observed in passing along the upper Ayarpatha Mall; but between Giwali-Khet and the Lower Bazár the beds are practically horizontal.

Dolomitic sandstones.

64. The dolomitic sandstones of East Laggan have, near the house, a well-defined dip of 47° towards N. 10° E.; but the dip increases and becomes irregular in the ground between the house and the Upper Ayarpatha Mall, which crosses the point where these sandstones become almost devoid of dolomitic cement, and where they form a faulted junction with the massive dolomite.

Dykes and sheets of trap.

65. The traps occur as distinct dykes in the dolomitic rocks; but in the slates on the Sher-ka-danda side, their distribution indicates an intrusive sheet approximately parallel to the stratification

planes. The outcrop is well displayed at the back of Alma Hill where the surface slope is across the edges of the strata; but on the southern slopes of the hill, where the dip-planes are approximately coincident with the slope, the traps are only exposed at irregular intervals where, within limited areas, the slope of the surface exceeds that of the intrusive sheet A sheet of trap will generally coincide with a water-carrying plane.

Fault-planes.

66. As might be expected in such a hill station most of the junctions exposed at the surface are traces of fault-planes. Mr. Middlemiss has recognized a system of *fold-faults* running east and west, the two most important of which he has indicated on his map, and named the Ayarpatha fold-fault and the Deopatha fold-fault. He has also marked the position of three *cross-faults*, the Sleepy Hollow fault, the Giwali-Khet fault, and the Lake-fault. To the last-named has been ascribed the broken character of Bleak House Spur, which was the subject of concern for some years to the authorities in charge of the approach roads; the falls of stones and general crushed appearance of Smuggler's Rock, and probably the steep angle of the slope along the south shore of the lake from East Laggan up to Pendennis is due also to this fault. Soundings show that the same steep slope continues below the surface of the lake, in spite of the considerable amount of silt which has been deposited. It is possible, therefore, that movement along this fault has gone on within recent times and so preserved the steep angle of slope below the surface of the lake. In discussing the nature of the Lake-fault Mr. Middlemiss refers to a similar great lateral fault running down the Balia ravine and cutting the Gola river at Ranibágh, which he regards as part of the effect of the same great movement, and connected with the upheaval of the Nahan zone of rocks at a later epoch than that at which the other faults were produced[1] (*vide infra*, para. 97).

On the new map I have indicated the position of some minor

[1] *Op. cit.*, p. 227, and *Mem. Geol. Surv. Ind.*, Vol. XXIV, Part 2 (map).

faults by which the dolomitic sandstone has been let into position amongst the dolomite. Local minor faults are also produced in the dolomites and dolomitic sandstones by subsidence resulting from the dwindling of the latter beds (*infra*, para. 126).

Thrust-plane.

67. Mr. Oldham is of opinion that the even slope on the south-eastern shore of the lake, near the Ramsay Hospital, is due to a thrust-plane, which is not an uncommon feature in highly-disturbed mountain regions, and has been recognized more definitely elsewhere in the Himalayas. The shales in this particular area are lithologically distinct from those exposed in the hill further north-west, being harder and interbedded with much dolomite, whilst the ravines are more nearly coincident with their direction of strike. Around Dunedin House, Assembly Cottage, and Kumaon Lodge may be seen large tumbled masses of purple slate and buff-coloured dolomite, which, if cleaned off, would probably be found resting on a surface like that exposed near Buttress Castle, a continuation of the same thrust-plane. This thrust-plane is cut off at Melville Hall by a continuation eastwards of the Ayarpatha fold-fault, which is a very fortunate circumstance for those who hold property on the slopes further to the north-west.

c.—PHYSICAL FEATURES.

Physical aspects of the valley.

68. In his charming "Geological Sketch" Mr. Middlemiss, after describing a section from Kathgodam to Naini Tal, says: "We have now arrived in the cool and shady valley of Naini Tal amid a keener and lighter air, amid a more temperate flora of fir, oak and rhododendron, as contrasted with the heavy, hot, sub-tropical climate of the sál-covered Sub-Himalayan tract." There is hidden between these lines a sigh of relief which recalls very vividly one's feelings on passing through the sulphuretted odours of the Lower Bazár and catching the first sudden glimpse of the little lake so prettily nestled between the well-clad dolomitic crags on one side and the grass-covered slopes on the other, with the rugged cliffs of Chína over-

hanging the cypress-covered slopes rising above the clusters of houses in the background. Whatever may be the result of stubborn facts and figures, there is no doubt that, on arriving from the steamy plains of Lower Bengal, one's sympathies are at once given as usual to the "fair culprit"; and it is not surprising to find that the intoxication of pretty scenery has drowned the warnings of 1880 concerning the hillsides, whose treachery is the outcome of their beauty.

Watershed.

69. The valley of Naini Tal runs about north-west—south-east, and, except at the outlet on the south-east, is surrounded on all sides by ridges, rising to 2,200 feet above the lake at Chína. These ridges give a very definite limit to the catchment basin, as shown in the new contoured map. The principal peaks on the surrounding ridges, which have been selected as G. T. S. points, are, commencing on the south side, Giwali Khet, 6,916·99; Ayarpatha, 7,721; Deopatha, 7,989; China, 8,568; Alma, 7,980; Sher-ka-danda, 7,869; and Kalakhan, 6,966 feet. The level of the lake, and consequently of its outlet, is 6,350 feet.

The Lake-basin.

70. The soundings of the lake show it to be divided into two distinct basins, with the deepest part about centrally situated in each basin. In the north-west basin the greatest depth is 87·3, and in the south-eastern basin 80·4 feet. The highest point of the ridge between the two basins, situated in a line between East Laggan and Melville Hall, is only 20 feet from the surface. As this measurement of the shallow part agrees with that made by Dr. Amesbury in 1871 it is probable that the soundings have been made from about the same surface-level, so his record of 93 feet, as the maximum depth in 1871, shows that the bottom has silted up in the north-western basin, by something less than 6 feet in 24 years. In all probability the principal reduction of depth occurred, Mr. Oldham suggests, at the time of the landslip of 1880, when the *débris* from the landslip invaded the north-western end of the lake, and thrust forward the previously formed delta silt. Only small quantities of silt could,

under normal circumstances, be carried out to the central portions of the lake.

71. The slopes of the hill on the southern shore of the lake are in dolomitic rocks, and present the characteristic craggy appearance of that formation. Further to the north-west, on coming to the slates, the slopes are very steep, which, as already explained, is probably due to the action of the, geologically, young Lake-fault. Passing around to Chína, the slopes, now covered with cypresses, are formed of scree-material fallen from the cliffs above, and, beyond the casual fall of loosened fragments from above, are not likely to be the source of any danger.

Southern slopes.

72. Passing around to Alma and Sher-ka-danda we find the surface-slopes to present an average inclination of about 30°. The direction of greatest slope in the western portion crosses the direction of the dip of the strata at an angle of about 45°, but, on passing eastwards, the contours curve around and bring the surface slope more nearly coincident with the direction of dip.

Northern slope.

73. On the map I have, for reasons stated in para. 88, deeply coloured the portions of the slopes in slate which lie outside a surface inclined at an angle of 37° to the horizon. On the portions of the slate formation sloping towards the lake it is found that just one-third of the entire area lies outside the surface of 37°. It will be noticed that under Government House and in the Ravenswood Spur there is a noticeably large area lying outside the 37° plane towards the lower half of the hill, in fact within what I have named in another part of this report (para. 120) the *landslip section* of the hill. A further feature of the greatest importance has been revealed by analysis of the cross sections, where it appears that in these bulges the steepest slope is generally near the foot of the bulge—a fact of the greatest significance in connection with Mr. Oldham's remarks concerning the bulging due to creep of the superficial materials in these slopes.

Angle of slopes.

The origin of the Lake.

74. As the question of the origin of Naini Tal is indirectly connected with this investigation, it seems desirable to summarize the facts bearing on the case in this section of the report dealing with the physical features of the station.

The origin of the group of lakes in Kumaon has been a subject of controversy since 1877, when the late Mr. H. F. Blanford suggested that the basin had been excavated by glacial action.[1] In the following year Dr. Ball[2] examined Naini Tal and the lakes of the adjoining area, and was unable to find any proof of the glacial theory ; but suggested that the valley had been dammed by landslip *débris*.

H. F. Blanford, 1877.

V. Ball, 1878.

In 1880 Mr. Theobald[3] criticised Dr. Ball's paper and concluded in favour of the glacial theory, that the barrier of Naini Tal was made of moraine material.

W. Theobald, 1880.

75. In his paper on the landslip of 1880, Mr. Oldham considered that the point of most scientific interest in connection with that catastrophe was its bearing on the theory of lake formation by landslips.[4] As Mr. Oldham's remarks on this question have received abundant confirmation by several cases in recent years, and especially in the well known case of Gohna, it may be well to quote that section of his paper *in extenso* :—

R. D. Oldham, 1880.

One of the principal objections raised to the supposition that the barrier at the outlet of the Naini Tal, for instance, can be formed by a landslip is, that those slips, "possessed of most mobility, from the greater fluidity of their composition are in the precise ratio of such fluidity least capable of * * * bearing upon their surface craggy masses of rock, such as I should term erratics." The examination of the landslip under consideration disposes of this objection ; for though most certainly such "craggy masses of rock" were not borne on the surface of the semi-liquid mass, yet there were numbers of such floated in its substance, many of which

[1] *Proc. As. Soc. Beng.*, January 1877, p. 3.
[2] *Rec. Geol. Surv. Ind.* Vol. XI, p. 174 (1878).
[3] *Ibid.*, Vol. XIII, p. 161 (1880).
[4] *Ibid.*, Vol. XIII, p. 270 (1880).

now show at the surface, several being 9 or 10 feet in length exposed; and I have no hesitation in saying that were this landslip on a larger scale—for it must not be forgotten that, compared with several others in the hills around, it is insignificant in size—and left untouched by the hand of man, it would, when cut into by rain and streams, show many, if not all, those features which are supposed to be especially characteristic of a moraine.

As to the question whether the barrier of the Naini Tal basin is a landslip or a moraine, I shall not here enter into its discussion; this, however, I must say, that the profile of the slope, to the east of the outlet bears every appearance indicative of a large landslip having fallen there. On the hillside there is no bulging, but a straight sweep down to a comparatively level terrace, through which the stream forming the outlet of the lake has cut down for some distance. Whether the lake was formed by the landslip, or whether this was subsequent to the formation of the lake, I am not prepared to assert dogmatically; but this I believe, that in past times there has been a great landslip from the slopes of the Kalikhan, and that on this old slip are placed the hospital and convalescent depôt.

The recent slip shows clearly that a large landslip can extend across and fill up a valley, and at the same time may show that mixture of rocks of all sizes which forms one of the chief features of a moraine; and it is not improbable that under favourable circumstances it might resist the wash of a stream over it and so form a permanent lake. In the case of Mulwa Tal, one would certainly suppose from the look of the ground, that if its existence is not due to a landslip, yet the level of the water must at one time have been raised some twenty or thirty feet higher than it now stands, by a great landslip which has undoubtedly fallen from the hills to the east of the outlet in times which may not date further back than one or two hundred years, and are certainly later than much that geologists would speak of as recent.

But if a lake is to be formed by a landslip, it must not merely be one of those which are everywhere to be seen, caused by the cuttings of a stream into the base of the slope, but rather one of those which take many years and even centuries preparing, as has been the case with this small one at Naini Tal, and which when they fall do not come down in a stream of fragments, but with one great rush, which would carry them right across the valley and raise the surface to such a height that, by the time the dammed-up water reached high enough to overflow, the *débris* would have had time for the water mixed with it to drain off somewhat, and would have settled down sufficiently to withstand the wash of the stream running over it. Such cases have been known, but the dam has always given way; yet it is not inconceivable that in some cases which have happened in that remote past, of which we have no knowledge but what is written in the rocks, some few barriers so made were able to stand and form what are now known as the Kumaon Lakes.

C. S. Middlemiss, 1890.

76. Mr. Middlemiss, in examining this question in 1890, considered the possibility of the formation of lake basins by differential earth-movements along the lines of faulting so clearly indicated in

Naini Tal, supplemented by the destruction of swallow-holes by their coalescence and collapse.[1] That numerous small depressions due to depression by solution in subaërial waters do exist around Naini Tal is beyond doubt. A good illustration of one near the junction of the sandstone and dolomite is shown on the Upper Ayarpatha Mall above the East Laggan estate. It is clearly defined on the new contoured map (sheet No. 4) where the miniature streams running into it are also indicated. It is also a well known fact that the dolomitic rocks are riddled with caverns and "swallow holes," and that a portion of the water leaving the lake is carried away through such subterranean channels. If these then become partially choked so that the influx exceeds the limits of subterranean drainage, the depression naturally fills and forms a lake, such as Naini Tal and the miniature cases in the hills around. One such small lake basin now nearly filled with silt, is exhibited at Giwali Khet.

III.—ACTION OF WATER ON THE ROCKS.

77. Water is so pre-eminently and directly the leading agent in bringing about the conditions favourable to a landslip, that it seems desirable to devote a special section of this report to an analysis of the conditions under which it affects the rocks of Naini Tal.

Absorptive powers of rocks.

All rocks within accessible portions of the earth's crust contain interstitial water (so called "quarry-water") which has simply been mechanically absorbed. Experiments made by the well known French geologist Delesse[2] show that the argillaceous are amongst the most absorbent of all rocks, taking up, under ordinary atmospheric pressure from 2·85 up to as much as 19·5 to 24·5 per cent. of their weight of water, whilst dolomites absorb only 3·29 per cent. when semicrystalline, and 12·87 when friable and oolitic. When pulverised much larger quantities of water are absorbed in all cases. Similarly Dau-

[1] *Ibid.*, Vol. XXIII, p. 228 (1890).
[2] *Bull. Soc. Geol., France*, 2nd ser., Vol. XIX, p. 65 (1861).

brée has shown that, in virtue of their capillarity and porosity, rocks absorb large quantities of water even against considerable vapour pressure, and thus accounts for the presence in part of water in deep-seated portions of the Earth's crust.[1] The intimate admixture of water and rock which is effected by such absorption prepares the way for its effective chemical action, and the chemical action, as shown below, prepares the way for its destructive mechanical action amongst the slates.

78. Nearly all, probably all, rock-constituents are appreciably soluble in pure water, and still more so in sub-aërial water which contains oxygen, carbonic acid and salts in solution.[2] As all rocks are also absorbent, as shown above (para. 77), chemical action will go on in all superficial parts of the Earth's crust as long as water is available.

Solution.

79. Whilst in the dolomites, dolomitic sandstones and gypsum the principal changes to consider are those brought about by removal of material in solution; in the slates the most dangerous change to be feared is that produced by absorption of water to form more hydrated silicates of lower specific gravity.

Hydration.

80. The slates of Naini Tal, and especially the greenish grey slates of Sher-ka-danda, have, amongst the changes which accompanied their production from the original shales, lost considerable quantities of water, which they gradually re-absorb. Natural pure clay contains 14 per cent. of chemically combined water, and larger quantities, under circumstances of ordinary atmospheric exposure, by mechanical absorption. The mechanically held water is driven off at 100° C., whilst that chemically combined with the alumina and silica is only removed completely at temperatures over 330° C. Whilst there is no doubt

Dehydration.

[1] *Cf.* Pfaff, Allgemeine Geologie, p. 141.

[2] W. B. and R. E. Rogers. "On the decomposition and partial solution of minerals, rocks, etc., by pure water, and water charged with carbonic acid." *Amer. Journ. Sci.*, 2nd ser., vol. V, p. 401 (1848).

that the slates in proximity to the sheets of intrusive trap have been raised far above this latter temperature, it is impossible to say to what temperature the slates generally have been exposed in past times. There is no doubt that they have been depressed to great depths in the Earth's crust since their original deposition, and have thus been exposed to high temperatures, and there is no doubt also that they have been exposed to pressure sufficient to produce cleavage, and movement under pressure sufficient to shear them. We know very little about the amount of heat produced in such cases, and practically nothing about the accompanying rise of temperature; but experiments by R. Mallet showed that mere crushing of slate was sufficient to produce heat enough to raise its temperature by about 140° F.[1]

At any rate, whatever may have been the vicissitudes of temperature through which the Naini Tal slates have passed, there is no doubt that they have been dehydrated and have since only partially recovered their water. Specimens dried over sulphuric acid gave the following results on ignition:—

Specimen.	Sp. Gr.	Water, per cent.
1. Greenish slate, under Tara Hall . .	2·79	3
2. Blue-grey slate, Sher-ka-danda . .	2·76	4
3. Grey slate, Alma Hill	2·76	4
4. Purple slate, near Snowdon . . .	2·74	9

Secondary hydration.

81. Like a natural anhydrite, or over-burnt gypsum, the dehydrated slates and shales gradually absorb water and form the higher hydrated silicates of alumina with simultaneous expansion of the mass. Besides the normal hydrous silicate of alumina represented in pure form by kaolin (Al_2O_3. SiO_2. $2H_2O$), which contains 14 per cent. of water and has a specific gravity of 2·6, the following hydrated clays may be produced:—

Cimolite	Sp. Gr. 2·2, with	12·7	per cent of water
Halloysite	" 2·1 "	19·6	" " "
Montmorillonite	" 2·0 "	25–38	" " "
Allophane	" 1·85 "	40	" " "

[1] *Phil. Trans.*, 1873, p.187.

There are numerous varieties of so-called clays, but these, the leading types, are sufficient to show that the increase in the water percentage is accompanied generally by decrease in specific gravity, or, in other words, expansion of the mass. In addition to this, there is a change in the manner in which the added water exists in the clay. In kaolin the water is chemically combined, and is only given off at very high temperatures, whilst in the more hydrated forms varying amounts of water are given off between 100°C. and 330°C, according to the state of hydration.

Applying these facts to the special case of the Naini Tal slates, I have made a series of determinations in the laboratory, which show beyond question that such hydration, and, consequently, attendant expansion, has been going on in the slates to which water has obtained access:—

Locality of Specimen.	Sp. Gr.	Loss at 110°C.	Loss at 300°C.	Loss at red heat.
Alma Hill	2·76	1·24	1·67	3·65
. . . .	2·69	1·74	2·03	5·23
. . . .	2·65	1·81	2·04	5·26
Near Glenlee	2·34	2·53	6·24	3·41
. . . .	2·12	2·45	6·53	3·61

82. The chemical action of water on the argillaceous rocks prepares the way for its effective mechanical action in preparing a slippery clay, and so reducing the co-efficient of friction. Ordinary rubbish piles of dry Naini Tal slate will stand at an angle of between 37° and 38° when *dry*; but when reduced to a soft clay and thoroughly *wet*, they will run down to an inclination as low as 16°. The absorption of water, therefore, produces first of all expansion of the mass and consequent creep downwards, attended, for reasons clearly explained by

Reduction of co-efficient of friction.

Expansion in direction of least resistance.

Mr. Oldham (*supra*, para. 8), with an increase in the angle of slope towards the foot of the hill. This movement being a differential one cracks are manifested in the upper portions of the slope, and in any structures built thereon. The result of the absorption of the water is a reduction in the strength of rocks forming the hill, and of larger quantities of water a very great reduction in the co-efficient of friction, by which means a warning creep, with attendant cracks is suddenly converted into a destructive landslip. The landslip of 1880 showed how a slope of probably over 35° can, by the action of water, be suddenly reduced to one of 15°, and for other reasons, in parts to even a lower angle.

Solution of dolomites.

83. The action of water on the dolomites is almost wholly chemical, but is not so uniformly destructive as in the case of the slates and shales. Whilst in some places blocks are being loosened by solution of the double carbonates, in other places cementation by the same agency is a source of strength.

The caverns and "swallow holes" so commonly found in limestone countries, and produced by removal in solution of the carbonates, are well exemplified in the dolomitic limestones of Ayarpatha, where also precisely the same agency has given rise to the irregularity of such craggy masses as Craig Ellachie and Smuggler's Rock, which give the Ayarpatha side a beauty and variety superior to the slopes of Sher-ka-danda.

It is upon this action that Mr. Middlemiss has based his theory for the deepening of the lake-basin in common with many of the minor depressions, which, during the rainy season, are submerged and become minute lakes (*vide supra*, para. 66).

Deposition of carbonates.

The cementation by deposition of the carbonates is well illustrated, especially along the traces of the fault-planes, where the rocks have been brecciated. Good examples are seen at Smuggler's Rock and near the Convalescent Depôt along the line of the Lake-fault; at Barron's

Hill and in the Upper Mall, south of Brinsop, along the small cross faults parallel to that running through the Kaladungi gorge and Sleepy Hollow.

The calcareous tufa which forms a cream-coloured crust over the surfaces of rocks in the caverns and along the faces of the great fissures is formed in a precisely similar manner by deposition of carbonates on evaporation of the water or loss of carbonic acid.

Dwindling of dolomitic sandstones.

84. The action of water on the dolomitic sandstones is one of peculiar interest, and, from the well bedded character of these rocks, simple in its results. The destruction of East Laggan house and of the slope at this point forms a very striking example of a slip directly resulting from the chemical action of water on these rocks. Blocks of this rock are light-grey in colour and compact in texture inwardly, being composed of grains of quartz and felspar cemented together with carbonates of lime and magnesia (*supra* para. 50). In the outer portions each block is reduced to a thick crust of rusty, crumbling sand, from which, by the action of circulating subaërial water, the dolomitic cement has been removed and the iron compounds oxidized and hydrated.

As the sandstones dip at East Laggan at an angle of about 47° to N. 10°E., or approximately at right angles to the adjoining lake shore, there is a tendency to slide in that direction along the bedding planes dependent on the rate of solution of the cementing material, and facilitated by the layers of loose sand formed between the blocks of hard rock. This differential movement is manifested by cracks running paralled to the strike of the formation through the compound and house at East Laggan (*vide infra*, para. 123). The band of this sandstone and marl running up from East Laggan across the Ayarpatha ridge is marked by a depression caused in part by such settlement along the bedding planes (paras. 125, 126).

Alteration of trap-rocks.

85. Although the action of water on the trap rock has effected the production of secondary minerals, like epidote and quartz, and the complete decomposition of some of the primary constituents, these

changes are only discoverable by the microscope, and have not reduced its toughness or produced any change in its physical characters which affects the question of the stability of the slopes in which the dykes are found. The final results of such alteration will in any case never give rise to a product weaker than the slates and shales into which they are intruded, and therefore need not be taken into consideration in determining the safety of any slope.

Transport of gypsum.

86. Gypsum, the principal amongst the secondary minerals, being soluble in water, will, wherever it occurs, be a source of trouble to any buildings above it, producing irregular settlement following its removal in solution. The distribution of this mineral, however, is too limited and too irregular to affect the general stability of any slope, although the lenticular masses exposed in the ravines between China Lodge and Rookwood show that it exists in sufficient quantities to damage the foundations of a house.

IV. CONDITIONS AFFECTING THE STABILITY OF SLOPES.

87. The stability of any slope of known inclination depends upon—

(*a*) The composition of the rocks.
(*b*) Their state of preservation.
(*c*) The direction and inclination of dip and other divisional planes.
(*d*) The variations in subaërial conditions to which they are exposed.
(*e*) The occurrence of earthquake shocks.

The rapid deepening of valleys, following the geologically-recent elevation of the Himalayas, tends to keep the slopes always near the critical angle, and the most unobservant must be aware of the great differences of slope noticeable in the different valleys, or on opposite sides of the same valley. Examination of the present state of the Himalayan slopes, therefore, affords a direct means for obtaining data concerning the conditions affecting the stability of slopes generally.

(*a*) *Composition of the rocks.*

88. The first fact that strikes the observer is the variation in slope

with the change of rock-formation. Whilst in slates and shales the slope seldom exceeds 37° for any great distance, in massive dolomite we frequently have slopes of over 45°, and in such rocks as quartzite, granite and gneiss even higher angles. The course of a long river often affords numerous illustrations of this fact. To take a case now familiar to many people in the North-West Provinces, the valley of the Alaknanda affords an example in which the variations of slope in slate, dolomite, gneiss and quartzite can be easily compared. Opposite Dangripant the slopes of slates approaching 38° in inclination show raw surfaces exposed by repeated small slips, whilst below Karnprayag, and again at Chamoli, the quartzites form perfectly stable precipices at very much higher angles, and in places even vertical (*cf.* para. 91).

Slates.

Other things being equal, slopes in dolomite are safer than those in slates, and in fact it is on account of this greater stability of *material* that the dolomitic slopes in Naini Tal are noticeably steeper, more irregular and more rugged than those in the adjacent slate. Loose blocks may occasionally be precipitated from the dolomitic crags; but where the rock is massive and without regular bedding a rock slide is impossible. Slates on the other hand which lie outside an angle of 37° are in an unstable condition, and if not relieved by continual fragmentary surface-slips may give rise to a destructive slide of considerable dimensions.

Dolomite.

Where rocks of two kinds are interbedded, the maximum angle of safety of the slope is determined by that of the weakest constituent. It is on this account that the steep dolomitic masses resting on the slates of Sher-ka-danda, like that above the Lake View Hotel and above Oak Openings, become a perpetual menace to everything below. Still more striking examples illustrating this statement are found in the Siwalik rocks on the road between Naini Tal and Kathgodam, where the comparatively stable Nahan sandstones are interbedded with soft, greasy shales, on which they slide wherever the direction of dip and surface slope coincide.

Alternating formations.

Precisely similar remarks apply to the intrusive sheets of trap.

Trap dykes and sheets.

The traps themselves are tough stable rocks, but coinciding with the stratification planes, as they do on Sher-ka-danda, they cannot be considered to increase the safety of the hill. Where, however, they occur as dykes they become ribs of strength, and so at least limit the dimensions of a slip.

Sandstone.

89. The only case where the peculiarities of a dolomitic sandstone seriously affect a slope, is at East Laggan, where its peculiar characters are manifested only on account of the direction of the stratification planes (*cf.* paras. 84, 123).

(*b*) *State of preservation.*

90. The destruction of the original characters by crushing during subsequent earth-movements reduces the stability of every kind of rock, and as all the rocks of Naini Tal have been so affected in the neighbourhood of the fault-planes, determinations of stability depending on the other conditions under consideration are valueless at those particular points. The crushing, however, has been purely local and is manifested by irregular and small rock falls of little importance. The small falls of rock from the neighbourhood of Smuggler's Rock and Bleak House spur are due to the crushing of the dolomite along the line of the comparatively young Lake-fault.

(*c*) *Direction of dip.*

91. The direction and inclination of the stratification and other great divisional planes determine more largely than any of the foregoing conditions, the slopes of surfaces, and, consequently, the extent of the more serious rock *slides*.

Dolomites and dolomitic sandstones.

Whilst in rocks which have suffered such a complete chemical re-arrangement as the dolomites, the original dip is a consideration of little importance, in the dolomitic sandstones it is, as already pointed out, the main cause of the westerly trend of the lake-shore under East Laggan, and of the hopeless instability of the outer portion of the slope up to the house.

Slates.

In the slates the simple effect of the dip-planes is complicated proportionately by the number of joint planes; and in some parts of Naini Tal the latter are so numerous and so pronounced, that the slaty rocks must be treated only as a pile of irregular rubbish; but there is, in my opinion, no question about the fact that, as a rule, the dip planes in the Naini Tal slates and shales are still sufficiently pronounced to affect very materially the stability of the slopes. This is a serious consi-

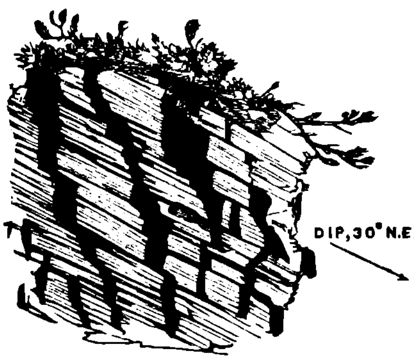


Fig. 1.—*Slate, showing the opening of joints by movement along the bedding planes. Near Fine View.* $\frac{1}{30}$ *nat. size.*

deration for such a hill as Sher-ka-danda, where, in the direction of greatest slope, the inclination of the dip planes is frequently either parallel to, or slightly less than, that of the surface.

As the result of some hundreds of determinations made on Sher-ka-danda, I find that the average dip of the slates is 40° to W.S.W., whilst the direction of greatest slope under Government House, for instance, is towards the S.W. and at the site of the landslip of 1880 towards the S.S.W. In these directions, therefore, the apparent dip of the beds will be less than the true dip, being in fact 37½° in the former and 31° in the latter case. On reference to the analyses of cross-sections, it will be seen that there are a few small portions of the Government House slope over 37½°, whilst in the case of the 1880 landslip slope the hill from a height of 250 feet above the lake to its crest averages almost 31°, and in many parts is very much over this angle. I have no doubt that it is at this upper end of the lake, where the contours curve around to the west, and so reduce the apparent dip of the rocks in the direction of the surface slope, that the danger of sliding is increased by the inclination of the dip planes being so reduced as to coincide with, or to be slightly less than, that of the surface at the same place. Mr. Middlemiss, in the paper already quoted, has shown how the stability of a slope is reduced as the angle of dip approaches the inclination of the surface, and the likelihood and magnitude of a *rock slide* are very much increased when in a steep slope the rocks dip at a slightly lower angle (see Plate XI). I have no doubt that this peculiar relation between the dip of the rocks and the direction of the surface slope, which has been brought out with the aid of the new contoured map, indicates the reason why the serious landslips of 1867 and 1880 occurred at the upper end of the lake, although the slopes under Government House and further south-east may have been quite as steep.

Comparison of dip-slope and scarp-face.

The most complete and striking proof that the direction of the stratification planes do determine the slope is obtained by a comparison of the northern with the southern slopes of Sher-ka-danda. On passing through the St. Loe gorge the comparatively gentle slope to Naini Tal, towards which the slates dip, stands in remarkable contrast to the precipitous cliffs shown by the hill at the back of Government House, where the edges of the strata are exposed. The same thing is true of the southern and northern slopes of Alma Hill.

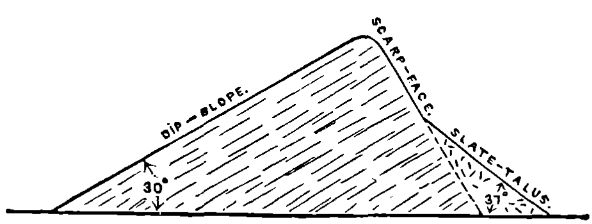


Fig. 2.

The northern slopes of Alma Hill afford an illustration of a further fact directly bearing on the question under discussion.

Where the edges of the strata are exposed by quarrying, cliffs are exposed whose high angle can be at once contrasted with that of the rubbish pile of broken slate below the quarry lying with a slope of 37° (Fig. 2). In this case we have an example of the way in which by the shattering of the rock the angle of repose is reduced to 37°.

Angle of repose of shattered slate.

In the case of Alma Hill the shattered slate is produced by artificial means; but a natural example exposed in the Kalakhan road is equally conclusive. The rocks on the Kalakhan road have been so shattered by crushing during earth-movements that it is difficult to determine the direction of the original planes of stratification. The Ballia nadi carrying the overflow from the lake is continually undermining this slope, which is kept perpetually raw by small slips, and so the slope varies very slightly from the natural angle of repose of broken slate. I have, with the aid of the contoured map, drawn six sections through these slopes from the unbroken crest of the hill to the Ballia nadi, and they give the following average inclinations:—

No. of Section.	Average slope.	Direction.
17	39°	E. 5°S.
18	35°	E. 7°S.
19	40½°	E. 37°S.
19*a*	39½°	S. 25°W.
20	32°	S. 20°E.
21	34°	S. 3°E.
Average.	36⅔°	

The average of all these determinations, 36⅔°, agrees very closely, therefore, with the artificially-made pile of broken slate at the back of Alma Hill.

Contour of oblique ravines.

Still another proof that the direction of dip influences the slope of the surface is afforded by the ravines in Naini Tal, and especially by the hollows scooped out by the landslips of 1867 and 1880. The western edges of these two last-mentioned hollows, as well as the western banks of the ravines, are steeper than those on the eastern side, the dip of the rocks being westerly.

A further fact quite as interesting and important arises, as a corollary of the same proposition. Towards the north-western corner of the valley on the Sher-ka-danda side, where, as already mentioned, the contours trend around to the west, the ravines, which, of course, approximately coincide with the direction of greatest surface-slope, cross the line of true dip at angles up to as much as 45°. As is invariably the case where a river crosses the dip of stratified rocks, we should expect the slopes on the eastern (south-eastern) banks of the ravine to be gentler than those on the western (south-western) banks. Rosamond's ravine is a very striking example of this fact. If now, as Mr. Oldham has so often stated since writing his paper in 1880, there is a continual creep down the hill-side, it naturally follows that this creep, instead of being *directly* down the slope, would take the direction of a resultant somewhere between the direction of the maximum surface-slope and that of the true dip of the stratified rocks. Consequently a house built on the western bank of a ravine might be safer than one on the eastern bank, although the latter is on a very much gentler slope. The facts relating to the houses on the Rosamond's ravine, detailed in Mr. F. E. G. Matthews' valuable Report on the southern slope of Sher-ka-danda hill, confirm this conclusion most strikingly. Alma House, built in 1864, and Alma Cottage, built in 1846, on the precipitous western bank of the ravine have only shown the usual effects of old age, whilst St. Cloud (1874), Snow View (1867), Brae House (1863), and Brae Side (1846, 1872, 1875), built on the gentler slope of the eastern bank, have been cracked and show a movement westward towards therefore the direction of dip (see Collection of papers relating to Government House, etc., P. W. D., 1895, part II, p. 14). It is interesting to note, too, that no springs are observed on the steep western bank of Rosamond's ravine; the water entering this spur evidently follows the bedding planes towards the Glenmore ravine.

In face of all these facts there can be no question about the fact that, notwithstanding the severe jointing which the slates of Naini Tal have suffered, the original bedding planes are sufficiently well pronounced to determine the direction of the sliding movement on steep slopes and the direction also of underground drainage. This being so, it is ridiculous to say that the cracks in all the structures built on Sher-ka-danda, and, for example, in Government House itself, running parallel to the strike of the rocks, are due merely to superficial settlement. They are unquestionably indications, and only partial indications, too, of movements which have been going on in the rocks themselves—movements of a decidedly serious nature.

d. *Variations in subaërial conditions.*

92. The variations in subaërial conditions to which the rocks are subjected is a point of paramount importance in Naini Tal, because it is the only one which can be materially controlled by artificial means.

93. The action of circulating subterranean water has already been described in a special section of this report (Sect. III). As this action is uniformly destructive, and the principal cause of instability in slates and shales especially, it is obviously necessary to prevent rain-water from entering the hill. The action of water running over the surface, deepening the ravines by erosion and so increasing the angle of slope locally, would, without capacious drains and artificial protective works, prepare the way for the effectual destructive action of the subterranean water (*vide infra*, paras. 108—115).

Superficial and subterranean water.

94. The results of variation in temperature, though more superficial than the action of water, are, so far as they go, supple-

mentary in effect. The expansion of the surface rocks, which follows the heat of the hot season and the warmer water circulating during the rains, is naturally manifested in the direction of least resistance, that is, down the slope; and as the warm season and rainy season are consecutive and in part coincident they combine to produce a small, but inevitable, annual movement down the hillside along the bedding planes. As the contraction which attends the following cold and dry season cannot bring the rocks back to their original places, the movement which has taken place is manifested by the production of cracks opening out at the end of the rains, and these are invariably displayed in directions parallel to the strike of the slates.

Variations in temperature.

95. The action of frost is purely superficial and practically confined in its destructive effects to the artificial protective works. The water produced by melting snow, of course, must be included with the subaërial water referred to before.

Frost.

96. The evidence concerning the action of earthquakes, in connection with the slips which have occurred in the past is very conflicting. According to Mr. H. C. Conybeare's report on the landslip of 1880, a slight earthquake shook the station on the fatal 18th September. At 10 in the morning Mr. Fleetwood Williams felt in the Assembly Rooms the nauseous sensation often excited by such convulsions. He noticed that the lake had assumed a peculiar greenish chalky hue, which was never imparted to it by mere influx of muddy water, and never seen except after earthquakes. Tremulous shocks were perceived at different hours on the same date by Major Byam, Mr. Holderness and a few others. Whilst there is no doubt that water was the chief agent in reducing the stability of the hill to a dangerous limit, it is possible, of course, that the actual slip of the weakest portion of the slope under old Government House was precipitated by the small earthquake shocks, which probably *did* occur at the time of the catastrophe.

Earthquakes.

Precisely similar evidence is obtainable in the history of East Laggan, where there is no question about the fact of the hill having been weakened by the action of water as already explained. The first cracks in the house appeared, it is stated by Major-General Thomason, R.E.,[1] after an earthquake shock on the 3rd November 1877; and further signs of settlement followed an earthquake shock in 1889 (*vide infra*, para. 122).

Direction of earthquake shocks.

97. Although of course the destructive action of earthquakes in Naini Tal can no more be foreseen or guarded against than in other hill stations, or in the plains, it goes without saying that liability to destructive effects is greater where the slopes are already near the limit of normal stability. The danger arising from earthquakes is, morever, increased by the liability to shocks progressing north-east and south-west at right angles to the strike of the slates in Sher-ka-danda, and consequently to the great fissure which is known to run through the hill on which Government House stands; at right angles, that is, to the line of folding of the Himalayan range itself, which is marked in this particular area by the N.W.—S.E. synclinal axis parallel to the greatest length of the lake and of the lake-fault, which, as I have already shown (para. 66), is geologically very young, younger than the deposition of the Nahan sandstones, connected with the folding of the Himalayas, and therefore possibly still a line of movement.

The correlation of these facts is not only of the greatest geological interest, but, as is very evident, of the greatest practical importance to those concerned with the safety of the station. The effects of earthquakes, which might be disastrous anywhere, are, from these peculiar stratigraphical and structural characters of the hills, still more likely to be attended with destructive results in those portions of Naini Tal lying on stratified rocks with a strike of N.E.—S.W.

[1] Note on the East Laggan Landslip, dated 20th Sept., 1893.

V. CLASSIFICATION OF LANDSLIPS.

98. In Switzerland, where the deep, narrow valleys are well-inhabited, investigations into the nature and causes of landslips have arisen from the necessity of devising means to avert their disastrous results. As a consequence of the systematic observations of Tscharner, Baltzer, Riedl, Heim and others, the classification adopted by Swiss geologists, as summarised by the last-named geologist, appears to include all possible cases, and is therefore universally applicable.[1]

Landslip.

99. The word *landslip*, both etymologically, and by force of common usage, may be conveniently used to include *slips*, *slides* and *falls* of all varieties, and to correspond to the French *éboulement* and to the German word *Bergsturze*, which, though more limited in meaning etymologically, has, by common usage, been made as comprehensive.

100. The different varieties of landslips have been classified by Professor Heim according to the nature of the movement, and the nature of the material put into motion, as follows :—

LANDSLIPS (*BERGSTÜRZE*).

A. Soil-cap movements	(*Schuttbewegungen*).
1. Soil-cap creeps	(*Schuttrutschungen*).
2. Soil-cap slips	(*Schuttstürze*).
B. Rock movements	(*Felsbewegungen*).
3. Rock-slides	(*Felsschlipfe*).
4. Rock-falls	(*Felsstürze*).
C. Combined and compound landslips .	(*Gemischte und zusammen gesetze*).

D. Exceptional subsidences (*Besondere*).
(Such as expressed clays (*Quetschschlammströme*), collapse of ground (*Erdfälle*) through removal of subterranean soluble materials like gypsum and rock-salt).

Strictly speaking, all landslips are combined (*gemischte*) slips ; but the movements included in classes A and B may be sufficiently predominant to warrant the grouping of known cases under these special heads, the most prominent feature being sufficient for pur-

[1] A Heim, *Ueber Bergstürze*, Zürich, 1882.

poses of practical control. Within the two classes *soil-cap movements* and *rock movements* it will be found also that landslips commence as *creeps* and *slides* and complete their history as *slips* and *falls* respectively, and thus become *compound* landslips. Like all classifications of natural phenomena, absolute lines of demarcation are impossible.

Falls and slides.

The Naini Tal landslip of 1880 commenced as a soil-cap *creep* and extended to a combined soil-cap *slip* and rock *slide*. In the Gohna landslip of 1894 the predominant features were those characterising rock *falls*, but it probably commenced as a rock *slide*. These two cases are sufficient to indicate the general points of difference between the two classes soil-cap movements and rock movements, the latter class, and especially the sub-class of rock falls, indicating movement over a steeper average slope—a necessary distinction and one of practical importance. At East Laggan a limited rock slide of dolomitic sandstone has been accompanied by small rock falls from a slope as steep as 52°. Rock *falls* of shale may occur at any angle above 37°; and rock *slides* of the same material may occur at any angle above 15°.

Falls and *slides* are moreover distinguished by the nature of the rubbish heap formed. In the former case no regularity of arrangement is recognisable, whilst in the latter the portion of the slide where the large blocks come to rest (*Blockgebiet*) can generally be distinguished from the softer muddy portions (*Schlammstrom*).

Examples of subsidences due to removal in solution of subterranean material (Class D) might very well be illustrated in Naini Tal, where

Subsidences.

beds of gypsum are found associated with the slaty rocks. Subsidences of this nature are manifested also by cracks in structures built partly on the solid rock and partly on soluble substance. A house built partly on dolomite and partly on more porous and decomposable dolomitic sandstone would, in all probability, become cracked by settlement of the portion resting on the sandstone, although the house may be well removed from any slope. The settlement consequently need not indicate any movement such as might lead to a free landslip, but might be nevertheless as destructive to structures built on the surface (see plate IX and paras. 107, 131, 132).

Premonitory symptoms of slips.

101. In every landslip there is an upper region in which the rocks are torn away from the rest of the hill, the *Abrissgebiet* of Heim; a middle portion through which the materials move down (*Sturzbahn*, *Bewegungskanal* or *Weggebiet*); and a lower portion in which the rubbish becomes heaped up (*Ablagerungsgebiet*). The commencement of a creep, or slide, is indicated by the development of certain characters especially in the upper and lower portions of the mass in motion.

Indications of creep.

102. The first indications of a *creep* consist commonly of the cracking of the upper portion of the mass (the future *Abrissgebiet* of Heim) with depression of the soil below; at the same time protuberances are gradually formed at the foot of the slope, in both cases more pronounced when the soil cap is uniform in structure, and so resembling approximately the surface phenomena presented by moving ice. With the development of the movement, the portion where the cracks are formed becomes increasingly irregular, whilst the protuberances below, rolling onwards and penetrated by a fan-like system of fissures, display their characteristic structures, repeatedly formed and destroyed, until the area of final deposition is attained. Longitudinal cracks, limiting the moving mass laterally, exhibiting a striation and even polishing of the materials remaining *in situ*, extend for great distances, but show no gaping of the fissures. These lateral lines of shearing which run down the hillside are not only much less marked than the transverse fissures above, but they are rendered less conspicuous by the ease with which they are obliterated by rain wash.

The cracks formed in the upper portions are generally gaping and curved with the convexity of the curves directed upwards; they are continued obliquely downwards, forming a fan-shaped system of shear cracks, cutting the downward-directed curves of the protuberances at right angles.

Indications of slides.

103. The commencement of a *rock slide* is indicated by a series of more or less rectilinear fissures formed in the upper portion of the slip, parallel to the strike of the beds in motion. At the same time the angle of slope increases towards the foot of the hill. In Naini Tal we have an example of this kind afforded by East Laggan, where fissures, gradually opening parallel to the strike of, and coextensive with, the sandtone appeared 7 months before the first small falls and 9 months before the main fall. A large fissure is known at present to run parallel to the strike of the slates under Government House, and to extend for some distance north-westwards through St. Cloud. The portion of the hill on the south-western side of this fissure, seems to have moved slightly over a slope of about 28°, and the cracks developed in Government House have gradually increased in width (*vide infra*, paras. 119—121).

Warnings of 1880.

104. Abundant warnings of the nature above described were given before the disastrous landslip of 1880, although they were only partially recognized and their import practically neglected. Mr. Conybeare, in his Report on the landslip, records the fact that Dr. Walker noticed that the whole hill-crust had sunk some six inches from a crack in the Upper Mall just at the upper limit (*Abrissgebiet*) of the slip. That the hill towards the foot of the slope was bulged is very evident from the contours of the portions still standing on either side of the slip. An examination of the contoured map shows how the steep portions of the slope are now further up the hill-side, and a convex slope has been converted into a concave one.

The changes in the structure of the hills are accompanied by changes in the circulation of subterranean water, and in the courses of surface streams. Springs dry up in some places and appear at new spots. The cracks formed in the upper portion of the incipient slip admit surface water and so hasten the catastrophe. Before the landslip of 1880 a tank in the compound of St. Asaph's, situated near the summit of the slope above Ravenswood, suddenly emptied into the hill, and at about the same time Braemar House, immediately below, cracked, whilst cracks extending towards St. Loe were noticed at the same time.

The most natural inference as to the origin of these serious cracks, extending for such great distances parallel to the strike of the rocks and in the upper portions of the slope, is that there has been a distinct movement towards the lake of the lower portions of the hill and, taken in connection with the undoubted bulge towards the foot of the slope, they can only be regarded as premonitory symptoms of a movement, which, if permitted to continue, will culminate in a disastrous landslip.

Lateral lines of shearing.

105. Although, for reasons already indicated, the lateral lines of shearing will be less conspicuous than the cracks which open parallel to the strike of the strata, I agree entirely with Mr. Oldham in recognising such evidence in the ravine between St. Loe and the Staff House, where the drain built in 1880 has been considerably deformed by numerous cracks, all of which show an oblique transverse shearing of the drain as a whole. In a line with the direction of dip, above this particular point, the four roads, Upper Mall, road into St. Loe grounds, St. Loe Road and the Middle Mall, show marked depressions along a line running W.S.W.; that is, parallel to direction of the dip of the slates (A, B, C, D, fig. 3).

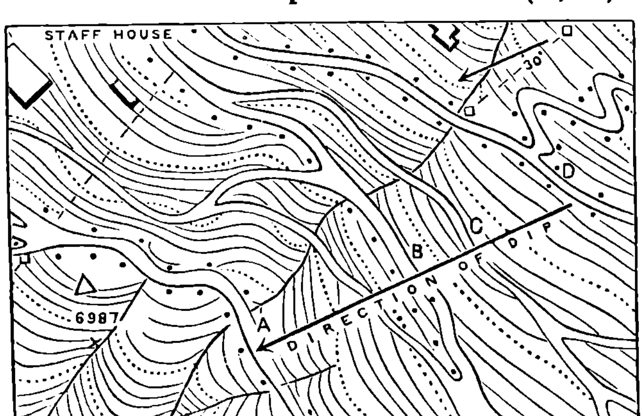


Fig. 3, Scale 10 in. = 1 Mile; contoured at 10 feet vertical intervals.

According to the evidence of Mr. Matthews these depressions did not exist when the roads were made, and being in a line with the portion of the drain referred to by Mr. Oldham as transversely sheared, may be taken as evidence of subsidence having taken place along the stratification planes of the slate.

Differential and total movements.

106. A mistake commonly made in estimating the value of the premonitory symptoms of slips is to regard the cracks formed in buildings and ground as indicative of the total amount of movement which has taken place. Most movements which precede rock slides are differential, the outer portions moving faster than those which are resting on more deep-seated rocks. The cracks, therefore, which appear at the surface only partially represent the amount of movement. The total movement of any particular portion of a slope of known angle can be indicated by obtaining the vertical component by levelling from a fixed point, or by obtaining the horizontal component by a series of marks in the same vertical plane as two marks on fixed ground. The latter method has been adopted, on the recommendation of the Beresford (1895) Committee, for the Sher-ka-danda slope in Naini Tal, by means of masonry pillars built on the face of each spur. This arrangement, however, suffers from the disadvantage of all the points being fixed on the same formation, and consequently the forward movement of any point can only be detected when the rate is different at the various points.

107. Differential movements are especially well shown in areas where there are rapid alternations of stable and unstable rocks. The band of dolomitic sandstone running across Ayarpatha forms a good example. Every cutting across the outcrop of this rock shows the more deep-seated portions to be full of large cavities, which become obliterated by falling down of the well jointed rock and consequent settlement of the surface. The mere wedging together of these blocks prevents the total loss of material being completely manifested

by the surface settlement, when the superincumbent pressure is not great; but the increase of this pressure by the weight of buildings may be sufficient to obliterate many of the cavities previously in existence and cause a depression of the foundations. If a portion of the building is resting on the more massive, solid dolomite, cracks will invariably be developed, and the structural stability of the building will consequently be impaired.

The depression on the surface which marks the limits of this band sandstone on Ayarpatha is not due to the more rapid removal of material from the surface by weathering agents, so much as to the subterranean removal in solution of the cementing carbonates by water which so easily passes through this porous rock, and the consequent settlement of the superincumbent masses. In this way houses become damaged without the occurrence of an ordinary free landslip. As secondary results of settlement of this nature the ridges of dolomite weather out above the level of the sandstones and marls, the outcrops of which become obscured by fallen blocks from the adjacent dolomitic ridges. Where strata are inclined at considerable angles the settlement caused by the dwindling of the sandstone and marls gives rise to the production of local small faults in the dolomite, giving rise to phenomena in fact precisely similar in origin to cracks in a house. Both these processes are well exemplified on Ayarpatha above the Upper Mall (see paras. 131, 132 and plate IX.

Prevention of slips.

108. Abundant evidence has been given to show that water is the chief source of mischief in landslips. Surface water may increase the average slopes beyond the angle of repose by undermining the foot of the hill; and subterranean water will simultaneously diminish the strength of the rocks, produce expansion in the direction of least resistance, and reduce the co-efficient of friction sufficiently to permit manifestation of the action of gravity. Well directed and efficient drainage must

Surface drainage.

therefore be the first means of prevention considered. The details of construction come within the province of the engineer; but it may not be out of place to briefly indicate some of the principles which should govern the direction of drains.

109. It ought to be evident to any one that drains should never be allowed to run along the line of strike further than is absolutely necessary. The continual settlement along the dip planes being a differential one, cracks are opened out along the line of strike, and in a drain these being small might very well be obscured by accumulations of leaves and other dirt.

The drain along the Braemar road, and the Upper Mall further east, is an example of this kind. This drain which, to make matters worse, is a simple, dry stone drain of low gradient, runs for a considerable distance along the strike of the rocks, at a part of the hill, too, which is most severely cracked and well above the upper limit of possible landslips. The danger of introducing water at this level is increased by the great width of the Ravenswood spur itself, and is still more aggravated by the state of the compound of St. Asaph's above.

Adit drainage.

110. No system of surface-drainage is sufficient to remove the *whole* of the rain-water which falls on a hill composed of such porous rocks as the slates of Naini Tal, and subterranean accumulations should consequently be relieved by *adits.*

The value of adits in removing the subterranean water would naturally be accentuated in wide spurs. As the dip of the strata is more westerly than the direction of greatest slope, the rocks naturally carry the water obliquely across the spur, and are relieved by springs on the eastern banks of the ravines. The narrower the spurs, therefore, the easier the internal drainage; and, other things being equal, a narrow spur such as that upon which Edgehill stands is safer than a wide one like Ravenswood.

111. The position, direction and length of adits should be decided by the relation of the stratification planes to the surface. They should

consequently on Sher-ka-danda always be at considerable distances from the eastern side of a spur, and should always be near, but not below, the base of the bulges indicated by the contoured map and cross-sections. They should run parallel to the direction of dip, and hence not necessarily parallel to the direction of maximum surface slope. Theoretically they should reach the innermost water-carrying stratification plane, but tis will not always be possible.

Springs.

112. The points at which springs issue should generally be the first localities selected for adits, the course of the main flow of water determining also the direction and length of the drive. As the most natural course for the subterranean water will be in the direction of maximum dip, such springs will be found, unless the strata are disturbed by fault planes or unusual joints, near the foot of a bulge, and on its dip-side. An inspection of the points where springs are marked on the map will bear out these remarks. Springs occur in the ravine running almost due south of Tonnochy's, tapping the narrow spur which is bounded on the east by the Glenmore ravine. The Glenmore spur is relieved in the same way by springs at the foot of the bulge in two places, one to the west and the other to the south-south-west of Glenmore house. The spur on which Springfield stands is relieved by a spring in the ravine west-south-west of the house, at the foot of a very well defined bulge. The spur on which Oak Lodge stands is drained in the same way by a spring issuing on its western side and at the foot of a well marked bulge, into the ravine whose rapid scour formed the landslip of 1867. The foot of the bulge under Edgehill forms the site of another spring, and another occurs at the foot of the mound of decomposed, broken slate just north-east of Spring Cottage. Further springs occur to the south-east on the Sher-ka-danda slopes; but they are probably of less importance where the direction of dip crosses the direction of surface slope at such wide angles. All these springs are situated at points where the deeper water-carrying strata are brought to the surface by an increase in the surface slope ; and it naturally follows that an

artificial addition to such natural relief must increase the frictional stability of the hill above, besides preventing the soaking of so much water into the portions of the hill below.

113. The adits, which are thus constructed for more effectual relief at points where the water actually makes its appearance in the form of a spring, should be supplemented by an additional number opened at points similarly situated with regard to the bulges, to which subterranean water must necessarily tend, although its quantity may be insufficient, or through some purely local cause it fails to appear at the actual surface. The importance of these increases with the width of the spur on the east-north-east and north-east side of the foot of the bulge, but decreases with the steepness of the dip.

Relief of subterranean water.

114. It is on account of the high angle of dip that adits constructed below the steep bulges on the parts of Sher-ka-danda south-east of the Edgehill spur, would be of little practical advantage in removing the water carried along the actual stratification planes of the undecomposed rock. The water circulating through the soil-cap might be relieved under any bulge, but these are generally so small that revetment effectually prevents them being a source of serious danger.

There are two striking instances illustrating the principles just stated: one is the spur on which Charlton Lodge stands, and the other is the Ravenswood spur. From the mere surface appearance, one would at once select the steep bulge west of Charlton Lodge, as the site of an efficient adit, to tap the large quantity of water which must enter the hill on the Maldon Estate and around Oak Lodge, Oak Cottage and Marshal Cottage. Taking the Maldon Estate as the principal place where water enters the hill, and the point where the 6,650 contour crosses the ravine as the steepest portion of the bulge on the dip side, we have a horizontal distance of about 800 feet in the direction of dip, and a vertical difference of 350 feet between these two points. Now, the average dip of the slates in this spur is about 40°. The strata outcropping on the Maldon

Estate would, therefore, be 800—*cotan* 40° × 350 = 800—417 = 383 feet from the surface at the level of the 6,550 contour, a distance which would clearly be an undesirably expensive length for an adit. There must be large quantities of water entering this spur, and these facts explain its non-appearance in the form of springs at the foot of the steep bulge on its south-west side. With a dip so nearly approaching 45° it may be stated generally that an adit under such circumstances can only relieve similar horizontal and vertical distances. The rocks are very much decomposed at this point, with a layer of soil-cap quite 50 feet thick. Supposing an adit were driven to a length of 100 feet, it would then only relieve the small area included by two of the 50-feet contours—an undertaking in which the results obtainable would be quite out of proportion to the cost.

The Ravenswood spur, as already remarked (para. 109), is another instance of a spur which receives a large quantity of water which, however, cannot, according to my conclusion, be relieved efficiently by adits, and for reasons similar to those stated in the previous paragraph shows no springs on its western side.

115. There is, however, one area in which adit-drainage is likely to be of very great value, and that is the area of low dips under Government House. The spot which suggests itself at once would be at the foot of the great wedge of slate upon which, as I have described below (para. 120), Government House stands. The most suitable spot appears to be where the ravine running down east of Brackenbury Hall meets the 7,200 feet contour. An adit driven east-north-east at this point for a distance of 150 feet would approach the line of shearing already referred to (para. 109) which is probably a subterranean water-course, and would relieve much of the water entering the Government House compound. The strata dip at an average angle of 30° under Government House, so the actual horizontal distance relieved by an adit driven at this point parallel to the direction of dip, will be 200 × *cotan.* 30° = 346 feet, in addition to its own length. Such an undertaking would, in my opinion, be the most

effectual means of arresting the destructive differential settlement which has been in progress at least since the construction of the plateau upon which Government House now stands (*vide infra*, paras. 119—121).

Revetments, etc.

116. Most other methods adopted for the prevention of slips, such as the construction of revetments, buttresses, and the plantation of trees, are comparatively superficial in their effects and need not be considered in a purely geological enquiry. In such a hill as Sher-ka-danda they can seldom protect more than the soil-cap. As an exception to this statement, the revetment in the road leading to Government House from the St. Loe gorge side probably props a very definite wedge of strata, whose upper margin must come near, if it is not actually underneath, the eastern end of the house.

Conclusion.

117. For the very simple reason that the hills around Naini Tal are gradually changing their structure and contour under the destructive influence of the ordinary agents of atmospheric denudation, the facts embodied in this report, and even the topographical features recorded so carefully by the Survey Department on the map which accompanies it, can only be of temporary value. The progress of events must be the subject for frequently-repeated inspection, and the accurate contoured map, prepared under the supervision of Mr. G. B. Scott, will form for this purpose the most useful supplement to the detailed records being compiled and preserved by the Public Works Department.

VI. DESCRIPTION OF SPECIAL SITES IN NAINI TAL.

118. It would obviously be inadvisable to "name" particular sites in Naini Tal; but, as illustrations of the application of the principles set forth in the preceding sections of this Report, three sites, totally different in character, have been described in detail. They are:—

(1) *Government House and the Edgehill spur*, representing the destruction of a building by movements which form

the premonitory symptoms of a free landslip in slates.

(2) *East Laggan*, an example of a rock fall and rock slide in dolomitic sandstone.

(3) *A site on Ayarpatha*, covering two different formations and liable to differential settlement *without* a free landslip.

1. Government House and the Edgehill spur.

119. Government House, St. Loe and Edgehill stand on a narrow spur which is bounded on the west by a ravine running down east of Brackenbury Hall and the Mission Sanitarium. On the east of the spur a ravine commences near the St. Loe gorge and divides the Edgehill from the Ravenswood spur.

A complete account of the construction and subsequent cracking of Government House has been issued with the report of the Beresford Committee (1895) (*vide* para. 21). A plan of the house shows that the main cracks in the building run parallel to the strike of the slates composing the hill and of a deep fissure which was known, at the time of building, to run through the site for some distance in both directions, and of course parallel also to the strike of the strata. According to the evidence of Mr. Docherty, who was a subordinate in charge of the building of Government House, this fissure sloped to the west, and a plumb bob with a line would go down 40 feet in some places, whilst in other places the crack was only one inch wide.[1] Mr. Oldham differed from the rest of the Committee in regarding this crack as part of the evidence pointing to serious movement in the rocks of the hill, and one which might culminate in a disastrous landslip. From measurements made by Mr. F. O. Oertel, District Engineer, it appeared that the plinth of the building had settled down as much as from 7 to 10 inches, and that the settlement had been accompanied by an outward movement of separation as shown by measurements taken periodically of the distance between the main wall of the dawing room and the outer wall of the conserva-

[1] Collection of papers (1895), part I, p. 65. See also pp. 31—36 and 41.

tory.[1] That this settlement and the development of cracks were due to movement of some kind was of course undoubted; but opinions differed as to whether it was attributable to defective design and faulty workmanship in the building, or to slipping of the hill itself and opening out of the main fissure known to run along the site at the top of the hill.

The facts that the fissures run parallel to the strike and the movement is in the direction of the dip of the strata, strongly support the latter conclusion, although the origin of the fissures was attributed by one member of the committee to solution of a portion of the rock[2]—an explanation which does not account for the regularity of direction of the fissures, or the movement in the outer portion of the house.

120. As, at the time of the Committee's investigation, the full stratigraphical details of the hill had not been entered on the map, one consideration, which appears to be most important, had to be left practically unconsidered. It has already been shown (para. 91) that, notwithstanding the jointed, and sometimes crushed, condition of the slates on Sher-ka-danda, the stratification-planes are still sufficiently pronounced to influence the direction of movement in the rocks. As the spur on which Government House stands runs about south-west, and the dip is to west-south-west, the movement will not be directly down the slope, but obliquely across. As a result of this fact, the movements of the rocks immediately under Government House would not necessarily be connected with the movements of those under Edgehill, and an examination of the cross-section No. 8 (plate I) confirms this view. For the first 200 feet above the lake the average slope is about 20°. For the next 650 feet the average slope is 30°, from which point to the summit, 200 feet higher, the average slope is 34°.[3] Although there are minor bulges between, the hill

[1] Collection of papers (1895), P. W. D., pp., 42 and 47.

[2] *Ibid*, p. 79.

[3] It must be understood that these slopes refer to a cross-section taken in a straight line (N.-E.—S.W.) down to the lake, and as the steepest slopes are obliquely towards the ravines, the slopes shown on this section are less than the maximum (See map).

above R. L. 6,550 may be divided into two main bulges. In the upper bulge the dip of the rocks is about 30° towards west-30°-south, whilst in the lower bulge the average dip is over 40° west-south-west. The inclination of the stratification-planes along the line of cross-section will therefore be 28° in the former case, and 37½° in the latter case.[1] That is to say, the stratification-planes immediately under Government House are inclined at a lower angle than the slope of the surface, whilst in the bulge on which Edgehill stands, the strata stand at a higher angle than the surface ; the two conditions, in fact, are similar to those shown in the appended figs. I and II taken from the paper by Mr. Middlemiss (plate XI).

There is, therefore, a moveable mass of strata under Government House, which is in the form of a 6°-wedge, having a length of 400 feet. It is the gradual creep of this wedge, from causes explained in paras. 79—82, which produces the cracks parallel to the strike of the strata through Government House, and I should expect that the large fissure known to exist under Government House extends vertically down only to this gliding plane, which cannot be more than about 50 feet below the foundations of the house. That this wedge will rapidly slide off like an ordinary landslip is not possible, as long as it is kept dry, and careful drainage might even arrest much, or practically the whole, of the creeping movement, whose differential effects are endangering the structural stability of the house above. Although rock-*falls* may occur from any part of a steep hill, a hill of slate, such as we are dealing with in this instance, would hardly, if exposed to the ordinary action of weather, give a serious rock-*slide* from near the watershed. For reasons which need not be detailed here, serious landslips occur generally near the base of the slate hills (the *landslip section*), and seldom extend more than half-way up, as was the case with the landslips of 1867 and 1880 in Naini Tal.

As to the stability of Government House *per se*, the Engineers, who are acquainted with the history of its construction, are the only

[1] Calling the angle of apparent dip in the direction of cross-section, A; the angle of true dip of the strata, D, and difference of bearing between the direction of true dip and the direction of apparent dip, B, then $\tan A = \tan D \cos B$.

qualified judges; but with regard to the particular portion of the hill upon which it stands, there seems to me to be no possibility, as long as the drainage works are kept in order, of anything approaching a landslip. As long as Edgehill and Ravenswood stand, the hill under Government House is, I consider, absolutely safe. Even if Edgehill should slide down into the lake, the foundations of Government House will be no more affected than those of St. Cloud were by the landslip of 1880, and until that catastrophe takes place, the only source of danger will be due to the damage done to the foundations of the house by the slow differential movement that has unquestionably been going on for some time all along Sher-ka-danda.

121. In accordance with suggestions made by the Committee of 1895 periodical measurements have been made between points fixed on opposite sides of cracks and of the levels of several points in Government House.

The weekly reports on the state of the house show that since the commencement of the rains of 1895 new cracks have appeared, and the distances between most of the points on opposite sides of the old cracks have increased, whilst the levels taken towards the end of September showed a slight subsidence, principally near the south-east corner of the building, which amounted to nearly half an inch from the commencement of the rains. On the 30th November the subsidence was reported to be steadily continuing in the south wall of the conservatory (south-east corner of the house), and as a result, a large number of the panes of glass in that side cracked, whilst the framing was perceptibly bulged. This very evident movement occurred about the time when the old breast wall under the flag-staff on the approach road from St. Loe gorge was removed for the purpose of building a stronger structure. As this wall is below the house in the direction of the dip of the strata, it is evident that the cracks are due to movements of the rocks and not to faulty foundations.

Settlement was reported to be still in progress on the 4th January 1896.

2. *East Laggan.*

122. The site of East Laggan house is situated at a horizontal distance of 310 feet from the western shore, and at a height of 350 feet above the surface of the lake. The average slope from the house to the foot of the cliff is therefore the angle whose *cotan.* is $\frac{310}{350}$ = ·886 = *cotan.* $48\frac{1}{2}°$ (see section 16, plate VII).

The house was built in 1863-64 under the supervision of General J. Fisher, and since 1864 has been in the possession of Major-General C. S. Thomason, R.E., who has, in a note to the Municipality, given a history of the house up to September 1893.

The first cracks in the house were noticed after a severe earthquake shock on November 3rd, 1877. Between 1880 and 1888 further cracks developed in the concrete verandah floor, after which date they were noticed to steadily increase, and subsidence of the verandah plinth was found about the same time to have occurred. A slight earthquake shock in 1889 brought down a revetment wall in the compound, and severely damaged a masonry pillar in the verandah. The badminton ground also showed distinct signs of subsidence, but this was at the time attributed to shrinking of the made soil. During the years 1889-90 rocks fell on to the Mall and into the lake at the foot of the cliff. From 1890 to 1892 the symptoms of differential subsidence became gradually aggravated.

In January 1893 a fissure was noticed running from the retaining wall below East Laggan across the road leading to Ivanhoe on the south-east. In April, as soon as the melting of the snow rendered observations possible, Mr. C. H. Holme found this fissure to be 9 inches wide at the widest place and about 1 inch wide near the Ivanhoe entrance. In the early part of July 1893 several small boulders mixed with earth fell at different dates on the road running along the Ayarpatha side of the lake, the greater part falling from a part of the hill immediately under East Laggan.

At the same time several cracks were noticed in the East Laggan building itself. The cracks developed as more slips occurred, and Major-General Thomason, R.E., the owner, vacated the house on the morning of the 27th July, moving his goods into the small building on the north-west side, which showed no signs of cracking and appeared to be safe. On this date, according to Mr. W. G. Wood, then District Engineer, Public Works Department, the highest crack appeared on the north side, at about 120 feet from the huge boulder overhanging the road leading up to East Laggan, which forms a prominent feature of the hill when viewed from the lake. Running up the hill-side the crack appeared again in front of the small dwelling-house attached to East Laggan, running through the plot of ground in front of this house and up through the retaining wall on to the higher level of East Laggan itself. It was then traced across the ground between the two buildings and through the centre of East Laggan, being 2 inches wide on the 27th and 3 inches in places on the 30th. From the house it ran through the steps leading up to the servants' quarters, through the plot of ground in front of the retaining wall below the quarters, then across the public road below the house, and the road leading to Ivanhoe, ending up in the *khad* below Ivanhoe. Below this crack the retaining walls and drains showed numerous cracks, which increased steadily up to the 30th July, when, at 5 P.M., a large portion of the hill, extending nearly up to the public road running under East Laggan, fell into the lake.

During the season there were unusual falls of stone on the Ayarpatha side of the lake, and at 11 A.M. on the 19th of October, after three days of very heavy rain (about 30 inches), another slip further to the north-west occurred, the fall of rocks and trees into the lake raising a wave which swamped the Mall on the opposite side.

Between the sites of these two slips there was built in 1888-89, on the road beside the lake, a buttress of solid masonry 100 feet high, and above this point the rocks have remained undisturbed. The support rendered by this revetment may have been just sufficient to prevent a coalescence of the two slips; but if my interpretation of the geological structure is correct, that portion of the slope is now in a condition of decidedly unstable equilibrium, as such a slender piece of masonry would be quite insufficient when, by further depression, the weight of the rocks in the steep cliff above comes to bear on it.

123. *Cause of the slip.*—The sketch (plate X) made in February 1894 shows the house in a tottering condition. The verandah facing the lake had sunk, and numerous cracks through the front half of the house, the verandah, terraces and garden, showed a general parallelism to the shore of the lake, which is the direction also of the strike of the dolomitic sandstone upon which the house was situated, and which outcrops for some distance on the face of the hill rising behind. The house and compound therefore clearly indicated the upper region of a landslip—the *Abrissgebiet* of Heim (see § 101), where cracks were produced by differential settlement of the outer portions of the slope.

The dip of this sandstone (obtained as an average of various determinations made at the back of the house, under the floors of the two front rooms, and on the Upper Mall) is 47° N. 10° E., or in a direction almost at right angles to the shore of the lake at this point. It can be traced beyond the cottage beside East Laggan to a gully bounded on the north-west side by massive dolomite, and in the other direction half way down the entrance to Ivanhoe, where it is again limited by black, massive dolomite. The large crack traced by Mr. Wood on the 27th July occurs within these limits, and is very nearly co-extensive with the sandstone. The slip has, therefore, been confined to this sandstone and has taken place in the direction of dip. To small falls of stones, and large slips at odd times in the past, may be ascribed the westerly trend which characterises the shore of the lake at this point.

The sandstone consists of grains of quartz and felspar cemented by carbonates of lime and magnesia (see § 50). Blocks of the rock examined, for example, under East Laggan, are of light-grey colour and compact texture inwardly, but each piece has been decomposed in the outer portions, and is surrounded by a thick crust of rusty, crumbling sand, from which the carbonates of lime and magnesia have been removed and the iron compounds oxidised and hydrated by the atmospheric waters sinking through the soil and percolating through the rocks below. Action of this kind has taken place along all the joint planes, but naturally has received greatest facility for decomposition along the more perfectly developed bedding-planes, the residue of crumbling sand acting as a lubricant between adjacent faces of compact rock. Any slope, therefore, in this formation having a greater inclination to the horizontal than the dip of the sandstone, will be liable to slips, until the surface-slope and the bedding-planes coincide. In the case of East Laggan the dip of the sandstone is about 47°, and the outer slope of the cliff 52°. There is, therefore, as shown in the section (No. 16, plate VII), a wedge of rock ready at any time to slide off towards the lake, and whenever settlement occurs cracks parallel to the strike of the sandstone will appear at the surface. I should have no hesitation in condemning as unsafe the whole of the ground between the broken lines in the section. Any house built within this area will never stand long without being cracked by differential settlement, and will be liable at any time to be carried away altogether by a sudden landslip. The circulation of rain-water along the bedding and joint-planes of this sandstone will continually make it unsafe, and an earthquake (not unfrequent in this area), or heavy rain, may at any time carry the whole of the ground into the lake. It may be mentioned that East Laggan is not far removed from the place marked by Mr. Middlemiss as the point where three faults cross, and in their vicinity the rocks have been crushed, and so rendered less stable; but this fact, though complicating possibly the nature of the movement, does not affect the conclusions stated above concerning the instability of the ground under East Laggan (for opinions of Messrs. Wildeblood and Oldham see paras. 28 and 29).

There is no question about the fact that subaërial water is the principal cause of the mischief in this interesting case, and if marked symptoms of settlement appeared after earthquake-shocks they were only rendered possible by the rocks having already been weakened by removal in solution of the dolomitic cement.

130. In face of the facts stated above, I think it would be useless to attempt repairing the two roads which have been broken down by the slip. If possible, the Upper Mall might be carried along the ground at the back of East Laggan, and even there may be subject to settlement, but of no very serious nature. Whilst a *road* may be allowable on the lake side of the rock behind East Laggan, any *building* on that side should most certainly be prohibited.

As long as the steep cliff in front of East Laggan remains, it will always be a source of danger to the road around the lake below; and unless the cost be considered prohibitive, it should even be helped down as soon as possible, a much more satisfactory and less expensive operation than propping it up by masonry on an insecure foundation. The prop now existing between the two slips is highly dangerous, because it is deceptive, and totally inadequate to prevent any settlement in the cliff above.

3. Site on Ayarpatha.

131. The ground near the site selected for the news chool on Ayarpatha, west of Ayarpatha House, forms an interesting illustration of a case where, without the possibility of a free landslip, any house built on the site would most certainly be seriously damaged by settlement of the rocks.

This ground was at first selected as a site for the new Boys' School; but to be quite certain as to its nature, His Honour Sir Antony MacDonnell ordered the hill to be cut down at different points for the purpose of ascertaining its geological structure—a precaution which has been well justified by the results. It was found that the site was situated along the line of junction between the massive dolomite and the dolomitic sandstones and marls which form a continuation of the East Laggan band of rocks.

132. The distribution of these rocks is shown by a contoured map and section (plate IX), from which it will be seen that the sandstone and marl beds include a band of dolomite, and dip northwards at angles between 48° and 60°. The beds being inclined, the

surface outcrop naturally appears further south at higher levels, as shown on the map.

By the action of rain-water, which obtains easy access through the well-bedded rocks, the cementing double carbonates of lime and magnesia are removed in solution, and the rock reduced to a friable, crumbling mass. The residue being of less volume than the original rock, surface settlement follows the natural collapse of the rocks on themselves, a collapse especially facilitated by the high angle at which the strata are inclined. That this conclusion from theoretical considerations is correct was verified by the exposure of fissures in the trenches cut across the strike.

Any sufficient addition to the superincumbent pressure on the rotten rock of this area naturally produces settlement by obliteration of the cavities already formed, and a building partly on the firm dolomite and partly on the yielding sandy beds would most certainly suffer from such differential subsidence of the foundations.

The effect of this settlement on a building will be precisely similar to that on the dolomite bands interstratified with the sandstones. The dwindling of the sandstone by removal of its dolomitic cement produces dislocation of the narrow, weak bands of dolomite, and, where larger masses rest on these strata, very definite local faultings are produced, as shown in the diagrammatic section (Fig. 1, plate IX). For the same reason also, the dolomitic bands, resisting the action of weather more effectually than the sandstone and marls, stand out as ridges from which the falling blocks partly obscure the outcrops of the latter rocks, as shown in the same diagram.

The steep angle of the adjoining cliff on the north side of the site which was formerly such a dolomite band as just described, allows of free subterranean circulation of the rain-water which enters the site, and so helps to accelerate the destruction of the sandy beds. It would be a difficult matter to devise a drainage system sufficiently complete for the protection of such porous strata.

The noticeable depression which coincides with this sandstone band and runs across the ridge of Ayarpatha is due, not so much to more rapid removal of material from the surface by the ordinary processes of rock denudation, as to the dwindling of the dolomitic sandstones and marls by subterranean solution of the carbonates —a point of practical importance, and, from its exceptional nature, one of great geological interest.

VII.—EXPLANATION OF MAP AND PLATES.

THE MAP.

The survey was commenced by Mr. T. F. Freeman in May 1894, and completed under the supervision of Mr. G. B. Scott in the following year, when the geological details were entered as far as possible on the partial tracings supplied before the map was printed. The map was originally printed in five sheets on a scale of 20 inches to the mile, but has been reduced for convenience of publication to one sheet by reduction to a scale of 10″ to a mile. The geological colouring shows the distribution of the slates, dolomites, dolomitic and purple sandstones and marls, dioritic traps and scree-material, the main faults, dip of the beds, and lines of cross sections. The areas in slate lying outside a surface inclined at an angle of 37° have been deeply coloured. This angle is found to be the angle of repose of dry slate, and any portions presenting a steeper slope must consequently be exposed to risk (*cf.* paras 88, 91 ; fig. 2).

THE CROSS SECTIONS (Plates I—VIII).

With the aid of the 20-inch map 25 cross sections have been drawn through the slopes in slate. Fifteen of these have been reproduced on the same scale (horizontal and vertical) showing the principal geological features and the angle of slope between each pair of 50-feet contours. The dips given are the average *apparent* dips along the direction of section (see para. 45). The average *true* dip of each case is given in the analyses below. The datum line selected for the fifteen cross sections reproduced full size is R. L. 6,000 feet. Section No. 12 has not been reproduced.

In addition to these, cross sections Nos. 17—25, drawn down to the Ballia nadi on the Kalakhan side, have been reproduced one-quarter of the original size, and show the variations in slope where the slates are so shattered that the directions of the original stratification planes have been obscured. Datum line, R. L. 5,000.

Cross Section No. 8 (Plate I).

(Through Government House, the Lake, and Ayarpatha.)

Direction of section, N.-W.—S.-E.

Rocks.—Slates under Government House dipping 30° towards 240°, separated probably by a fault from the lower portion of the hill where the slates dip at an angle of 40° towards W. S. W. (245°). The Lake fault is shown at the foot of Ayarpatha in which the slates increase in dip and form a sharp syncline before reaching the reversed, fault, separating the slates from the dolomite. Further details are shown in the index.

Sher-ka-danda Side.

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of slope.	Remarks.
					°	
7350	7400	65	50	1·3	37	Northern Scarp-face.
7400	7450	255	50	5·1	11	
7450	7450	125	0	...	0	Government House plateau.
7450	7400	280	50	5·6	10	
7400	7350	60	50	1·2	40	Southern dip-slope begins.
7350	7300	85	50	1·7	30	
7300	7250	80	50	1·6	32	
7250	7200	110	50	2·2	24	
7200	7150	115	50	2·3	23	
7150	7100	120	50	2·4	22	St. Loe.
7100	7050	105	50	2·1	25	
7050	7000	75	50	1·5	34	
7000	6950	60	50	1·2	40	
6950	6900	55	50	1·1	42	
6900	6850	80	50	1·6	32	
6850	6800	60	50	1·2	40	

CROSS SECTION No. 8 (Plate I).—*contd.*

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of slope.	REMARKS.
					°	
6800	6750	75	50	1·5	34	
6750	6700	95	50	1·9	28	
6700	6650	80	50	1·6	32	
6650	6600	75	50	1·5	34	
6600	6550	75	50	1·5	34	
6550	6500	80	50	1·6	32	
6500	6450	125	50	2·5	22	
6450	6400	55	50	1·1	42	
6400	6350	255	50	5·1	11	Scree-material, Lake Mall.

The Lake, 1,200 feet wide.

Ayarpatha Side.

6350	6400	55	50	1·1	42	Lake Mall.
6400	6450	65	50	1·3	37	
6450	6500	70	50	1·4	35	
6500	6550	40	50	0·8	51	
6550	6600	70	50	1·4	35	
6600	6650	55	50	1·1	42	
6650	6700	60	50	1·2	40	
6700	6750	75	50	1·5	34	
6750	6800	115	50	2 3	23	
6800	6850	125	50	2·5	22	Galloway House.
6850	6900	90	50	1·8	29	
6900	6940	240	40	6·0	9	Dolomite, St. Andrews.

CROSS SECTION NO. 1 (Plate II).

(East of China Lodge.)

Bearing of section, 183° (S. 3° W.) and 3° (N. 3° E.).
Rocks, Slates dipping 30° towards 229°.
Apparent dip in direction of section 21°.

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of slope.	REMARKS.
					°	
7350	7300	75	50	1·5	33	
7300	7250	80	50	1·6	32	
7250	7200	80	50	1·6	32	
7200	7150	100	50	2·0	27	
7150	7100	65	50	1·3	38	
7100	7050	85	50	1·7	30	
7050	7000	70	50	1·4	36	
7000	6950	75	50	1·5	33	
6950	6900	70	50	1·4	36	
6900	6850	110	50	2·2	24	
6850	6800	40	50	0·8	51	Steepest slope.
6800	6750	145	50	2·9	19	
6750	6700	90	50	1·8	29	
6700	6650	250	50	5·0	11	} In scree-material.
6650	6600	290	50	5·8	10	} In scree-material.
7350	6700	1085	650	1·67	31	Average slope in slate.

Cross Section No. 2 (Plate II).

(Through Tonnochy's.)

Bearing of section, 188° —— 8° (S. 8° W. —— N. 8° E.).
Rocks, Slates with an average dip of 30° towards 243°.
Apparent dip in direction of section, 18°.

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of slope.	Remarks.
					°	
7350	7500	120	150	0·8	51	Northern Scarp-face of hill.
7500	7530	110	30	3·73	15	Summit of hill.
7530	7500	145	30	4·83	12	Commencement of southern dip-slope.
7500	7450	120	50	2·4	23	
7450	7400	175	50	3·5	16	Tonnochy's.
7400	7350	45	50	0·9	48	Steepest slope.
7350	7300	60	50	1·2	40	
7300	7250	75	50	1·5	33	
7250	7200	60	50	1·2	40	
7200	7150	85	50	1·7	30	
7150	7050	160	100	1·6	32	
7050	7000	80	50	1·6	32	
7000	6950	105	50	2·1	25	St. Helens.
6950	6900	90	50	1·8	29	
6900	6850	95	50	1·9	28	
6850	6800	80	50	1·6	32	
6800	6750	65	50	1·3	38	
6750	6700	60	50	1·2	40	
6700	6650	330	50	6·6	9	Scree-material.
6650	6600	295	50	5·9	10	
7530	6700	1500	830	1·8	29	Average southern slope in slate.

CROSS SECTION NO. 3 (Plate III).

(Through Alma Hill and Glenmore.)

Bearing of section, 218° —— 38° (S.W. —— N.E.).
Rocks, Slates with an average dip of 45° towards 251°.
Apparent dip in direction of section, 40°.

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of Slope.	REMARKS.
					°	
7792	7750	75	42	1·78	29	From summit of Alma Hill.
7750	7700	80	50	1·6	32	
7700	7650	75	50	1·5	33	
7650	7600	75	50	1·5	33	
7600	7550	55	50	1·1	42	
7550	7500	75	50	1·5	33	
7500	7450	60	50	1·2	40	
7450	7400	40	50	0·8	51	
7400	7350	55	50	1·1	42	
7350	7300	90	50	1·8	29	
7300	7250	100	50	2·0	27	
7250	7200	70	50	1·4	36	
7200	7150	80	50	1·6	32	
7150	7100	160	50	3·2	17	Glenmore.
7100	7050	105	50	2·1	25	
7050	7000	65	50	1·3	38	
7000	6950	75	50	1·5	33	
6950	6900	80	50	1·6	32	
6900	6850	120	50	2·4	23	
6850	6800	75	50	1·5	33	
6800	6750	215	50	4·3	13	
6750	6700	235	50	4·7	12	
6700	6685	75	15	5·0	11	Meets Cross-section No. 2.
7792	6685	2135	1107	1·93	30	Average slope.

Cross Section No. 4 (Plate III).

(Through Alma House and the Landslip of 1867.)
Bearing of section, 211°—31° (S W.—N. E.)
Rocks, Slates with an average dip of 53° towards 243°.
Apparent dip in direction of section, 48°.

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of slope.	Remarks.
					°	
7650	7600	95	50	1·9	28	
7600	7550	85	50	1·7	30	
7550	7500	75	50	1·5	33	
7500	7450	80	50	1·6	32	
7450	7400	60	50	1·2	40	
7400	7350	55	50	1·1	42	
7350	7300	120	50	2·4	23	Alma House.
7300	7250	120	50	2·4	23	
7250	7200	150	50	3·0	18	Alma Cottage.
7200	7150	105	50	2·1	25	Top of 1867, Landslip.
7150	7100	65	50	1·3	38	
7100	7050	65	50	1·3	38	
7050	7000	55	50	1·1	42	
7000	6950	75	50	1·5	33	
6950	6900	55	50	1·1	42	
6900	6850	110	50	2·2	24	
6850	6800	90	50	1·4	36	
6800	6750	55	50	1·1	42	
6750	6700	200	50	4·0	14	Scree-material.
6700	6650	2co	50	4·0	14	
6650	6600	145	50	2·9	19	
6600	6550	215	50	4·3	13	
6550	6500	335	50	6·7	8	
7650	6750	1530	900	1·70	30	Average slope in slate.

Cross Section No. 5 (Plate IV).

(Through Braeside and Alma Lodge.)

Bearing of section, 209°—29° (S.W.—N.E.).

Rocks, Slates dipping 45° towards 245° (W.S.W.).

Outcrop of trap near Himalaya House, R.L. 7,350.

Apparent dip in direction of section, 38°.

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of slope.	Remarks.
					°	
7250	7300	45	50	0·9	48	Northern scarp-face.
7300	7350	55	50	1·1	42	
7350	7350	175	0	...	0	Watershed. Himalaya House.
7350	7300	105	50	2·1	25	Commencement of southern dip-slope.
7300	7250	105	50	2·1	25	
7250	7200	80	50	1 6	32	
7200	7150	85	50	1·7	30	Braeside.
7150	7100	105	50	2·1	25	
7100	7050	100	50	2·0	27	
7050	7000	85	50	1·7	30	
7000	6850	350	150	2·3	24	
6850	6800	65	50	1·3	38	
6800	6750	80	50	1·6	32	
6750	6700	65	50	1·3	38	
6700	6650	120	50	2·4	23	Charlton Lodge.
6650	6600	65	50	1·3	38	
6600	6550	65	50	1·3	38	
6550	6500	105	50	2·1	25	Scree-material.
6500	6450	125	0	...	0	
7350	6550	1475	800	1·84	29	Average dip-slope in slate.

CROSS SECTION No. 6 (Plate IV).

(Through St. Cloud and the Landslip of 1880.).
Bearing of section, 204°—24° (S.S.W.—N.N.E.).
Rocks, Slates dipping 40° towards 242° (W.S.W.)
Apparent dip in direction of section, 33°.

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of slope.	REMARKS.
					°	
7250	7300	95	50	1·9	28	Northern scarp-face.
7300	7350	90	50	1·8	29	Ditto.
7350	7350	205	0	...	0	Watershed, St. Cloud.
7350	7300	95	50	1·9	28	Southern dip-slope begins.
7300	7250	100	50	2·0	27	
7250	7200	100	50	2·0	27	
7200	7150	110	50	2·2	24	
7150	7100	80	50	1·6	32	
7100	7050	115	50	2·3	24	
7050	7000	115	50	2·3	24	
7000	6950	70	50	1·4	36	Top of 1880 landslip.
6950	6900	40	50	0·8	51	
6900	6850	40	50	0·8	51	
6850	6800	70	50	1·4	36	
6800	6750	70	50	1·4	36	
6750	6700	70	50	1·4	36	
6700	6650	95	50	1·9	28	
6650	6600	110	50	2·2	24	
6600	6550	150	50	3·0	19	
6550	6500	135	50	2·7	20	
6500	6450	155	50	3·1	18	Scree-material.
6450	6400	240	50	4·8	12	Ditto.
6400	6400	110	0	00	0	Ditto.
7350	6500	1530	850	1·8	29	Average slope of slate on dip-side.

Cross Section No. 7 (Plate V).

(Through Tara Hall and Staff House.)

Bearing of section, 211°—31°.
Rocks, Slates dipping 35° towards 251°.
Sheet of trap outcropping at R. L. 7,000 and 7,300.
Apparent dip in direction of section, 28.°

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of slope.	Remarks.
7250	7300	100	50	2·0	27	Northern scarp-face.
7300	7350	75	50	1·5	33	Ditto.
7350	7400	75	50	1·5	33	Ditto.
7400	7400	80	0	—	0	Watershed.
7400	7350	130	50	2·6	21	Southern dip-slope begins.
7350	7300	105	50	2·1	25	
7300	7250	105	50	2·1	25	Tara Hall.
7250	7200	80	50	1·6	32	
7200	7150	140	50	2·8	20	
7150	7100	85	50	1·7	30	
7100	7050	60	50	1·2	40	Staff House.
7050	7000	50	50	1·0	45	
7000	6950	100	50	2·0	27	
6950	6900	100	50	2·0	27	
6900	6850	100	50	2·0	27	
6850	6800	80	50	1·6	32	
6800	6750	55	50	1·1	42	
6750	6700	55	50	1·1	42	
6700	6650	45	50	0·9	48	
6650	6600	65	50	1·3	38	
6600	6550	210	50	4·2	13	
6550	6500	125	50	2·5	22	Scree-material.
6500	6450	145	50	2·9	19	Ditto.
6450	6400	160	50	3·2	17	Ditto.
7400	6550	1590	850	1·87	28	Average slope of slate on dip-side.

Cross Section No. 9 (Plate V).

(Through St.Loe and Spring Cottage.).

Bearing of section, 221°—41° (S.W.—N. E.).

Rocks, Slates dipping at an angle of 40° towards 250°.

Apparent dip in direction of section, 36°.

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of slope.	Remarks.
					°	
7350	7350	420	0	—	0	Watershed.
7350	7300	70	50	1·40	36	Southern dip-slope.
7300	7250	100	50	2·0	27	
7250	7200	155	50	3·1	18	
7200	7150	120	50	2·4	23	St. Loe.
7150	7100	80	50	1·6	32	
7100	7050	60	50	1·2	40	
7050	7000	80	50	1·6	32	
7000	6950	120	50	2·4	23	
6950	6900	65	50	1·3	38	
6900	6850	80	50	1·6	32	
6850	6800	90	50	1·8	29	
6800	6750	70	50	1·4	36	
6750	6700	75	50	1·5	33	
6700	6650	95	50	1·9	28	Spring Cottage.
6650	6600	95	50	1·9	28	
6600	6550	100	50	2·0	27	
6550	6500	120	50	2·4	23	
6500	6450	75	50	1·5	33	
6450	6400	80	50	1·6	32	
6400	6350	205	50	4·1	14	Level of the Lake.
6350	6330	80	20	4·0	14	Soundings.
6330	6310	25	20	1·25	39	Ditto.
6310	6290	35	20	1·75	30	Ditto.
6290	6280	20	10	2·0	27	Ditto.
6280	6270	80	10	8·0	7	Ditto.
7350	6400	1700	950	1·8	29	Average slope on dip-side.

CROSS SECTION No. 10 (Plate VI).

(Through the Ravenswood Spur.)

Bearing of section, S.W.—N.E.

Rocks, Slates dipping 45° W.S.W.

Apparent dip in direction of section, 43°.

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of slope.	REMARKS.
					°	
7450	7400	110	50	2·2	24	
7400	7350	140	50	2·8	20	
7350	7300	145	50	2·9	19	
7300	7250	130	50	2·6	21	
7250	7200	145	50	2·9	19	The Towers.
7200	7150	60	50	1·2	40	
7150	7100	80	50	1·6	32	
7100	7050	80	50	1·6	32	
7050	7000	65	50	1·3	38	
7000	6950	80	50	1·6	32	
6950	6900	100	50	2·0	27	
6900	6850	95	50	1·9	28	
6850	6800	150	50	3·0	18	Ravenswood.
6800	6750	50	50	1·0	45	
6750	6700	75	50	1·5	33	
6700	6650	75	50	1·5	33	
6650	6600	70	50	1·4	36	
6600	6550	70	50	1·4	36	
6550	6500	65	50	1·3	38	
6500	6450	55	50	1·1	42	Foot of bulge below Ravenswood.
6450	6400	120	50	2·4	23	
6400	6350	100	50	2·0	27	The Lake.
7450	6350	2060	1100	1·87	28	Average slope.

CROSS SECTION No. 11 (Plate VI).

(Through St. Asaph's.)

Bearing of section, S. W.—N. E.

Rocks, Slates dipping 45° to W. S. W.

Apparent dip in direction of section, 43°.

Between Contours.		Hor.	Vert.	Hor./Vert.	Angle of slope.	REMARKS.
					°	
7510	7550	90	40	2·25	24	
7550	7550	55	0	∞	0	
7550	7500	160	50	3·2	17	St. Asaph's
7500	7450	60	50	1·2	40	
7450	7400	80	50	1·6	32	
7400	7350	75	50	1·5	33	
7350	7300	105	50	2·1	25	Braemar.
7300	7300	60	0	∞	0	Braemar tennis-court.
7300	7250	60	50	1·2	40	
7250	7200	120	50	2·4	23	
7200	7150	80	50	1·6	32	
7150	7100	60	50	1·2	40	
7100	7050	95	50	1·9	28	
7050	7000	55	50	1·1	42	
7000	6950	85	50	1·7	30	
6950	6900	75	50	1·5	33	
6900	6850	100	50	2·0	27	
6850	6800	45	50	0·9	48	
6800	6750	45	50	0·9	48	
6750	6700	40	50	0·8	51	Foot of bulge.
6700	6650	90	50	1·8	29	
6650	6600	135	50	2·7	20	
6600	6550	100	50	2·0	27	
6550	6500	80	50	1·6	32	
6500	6450	80	50	1·6	32	
6450	6400	75	50	1·5	33	Allahabad Bank.
6400	6350	160	50	3·2	17	The Lake.
7550	6350	2120	1200	1·77	29	Average slope on dip-side.

Cross Section No. 13 (Plate VII).

(Through the Priory and Glenlee.)

Direction of section, S.W.—N.E.

Rocks, Slates with interbedded dolomitic bands dipping 35° to N.N.E.

Apparent dip in direction of section, 33°.

Greatest slope, 51°, forming the foot of a bulge whose base is inclined at an angle of 30° between contours 6,600 and 6,700 (Glenlee compound). The average slope from Glenlee to the foot of the slope is 32°, which so closely agrees with the apparent dip of the strata, that creeping movement must take place along the stratification planes. This will reveal itself by cracks parallel to the strike in the compound and in all revetment walls on the slope running approximately north-eastwards.

Cross Section No. 14 (Plate VIII).

(Through Raja's House and Fine view to the Polo-ground.)

Direction of section, E.-17°-N. and W.-17°-S.

Rocks, Slates dipping 30° N.N.E.

Apparent dip in direction of section, 20°.

With such a low angle of dip and an average slope of 34° from the Polo-ground up to the 6,500 contour, there is a great tendency to the formation of slips and no portion up to Fine view can be considered safe.

Cross Section No. 15 (Plate VII).

(Through Clifton to the Polo-ground.)

Direction of section, N.E.—S.W.

Rocks, Slates dipping 30° to N.N.E.

Apparent dip in direction of section, 28°.

With a low angle of dip and an average slope of 39° this slope up to the 6,650 contour must be considered unsafe. From Clifton itself to the Polo-ground the average slope is 28°, which agrees with that of the dip-planes. At this angle cracks may be opened in front of the house, but the house as a whole is on a perfectly safe site.

CROSS SECTION No. 16 (Plate VII).

(Through East Laggan.)

The peculiar characters of this section have already been described (*vide supra*, paras. 128—130).

CROSS SECTIONS Nos. 17—25 (Plate VIII.)

(Through the Kalakhan slopes to the Ballia Nadi.)

These sections are reproduced one-quarter of the original scale to show the average slope in broken slate, where the cliffs are being continually undermined by a river, and are practically free of artificial supports. The average inclination of the nine sections reproduced is 35°; but this angle is slightly lower than the normal slope on account of the inclusion of the gently sloped portions below the Goorkha barracks (No. 17), the Police station (No. 19) and at the Depôt (Nos. 24 and 25°). The average angle of the undisturbed portion approaches very nearly the angle of repose of broken slate, as already explained (§ 91).

GEOLOGICAL STRUCTURE OF A SITE ON AYARPATHA (Plate IX).

(*Scale, 1 inch=80 feet.*)

The structure of this site has already been explained (§ 131). It is an interesting case of settlement in a compound formation, where there is no possibility of a free landslip (class D, § 100). Figure 1 is a diagrammatic section showing the way in which, by the dwindling of a dolomitic sandstone, the interbedded dolomitic bands collapse and show local faulting; and by the weathering at the surface the blocks falling from the ridges of the harder dolomite obscure the outcrop of sandstone. Figure 2 is a contoured map, reduced from one prepared by the Public Works Department, on which I have entered the geological details showing massive dolomite on the south side, succeeded by a band of dolomitic sandstone and marl with an interbedded thin band of dolomite. The dolomite shown on the north side forms the top of the cliff shown in figure 3, which is a continuation of the section along the line A.B. as far as the Upper Ayarpatha Mall.

CRACKS IN MASONRY, EAST LAGGAN (Plate X).

The cracks in the house run in plan E.—W. parallel to the strike of the dolomitic sandstone. This forms a striking instance of the opening *Abrissgebiet* in a rock-slide (§ 101, 103) and its cause has already been fully explained (§ 128).

RELATION OF DIP-PLANES TO SURFACE-SLOPE (Plate XI).

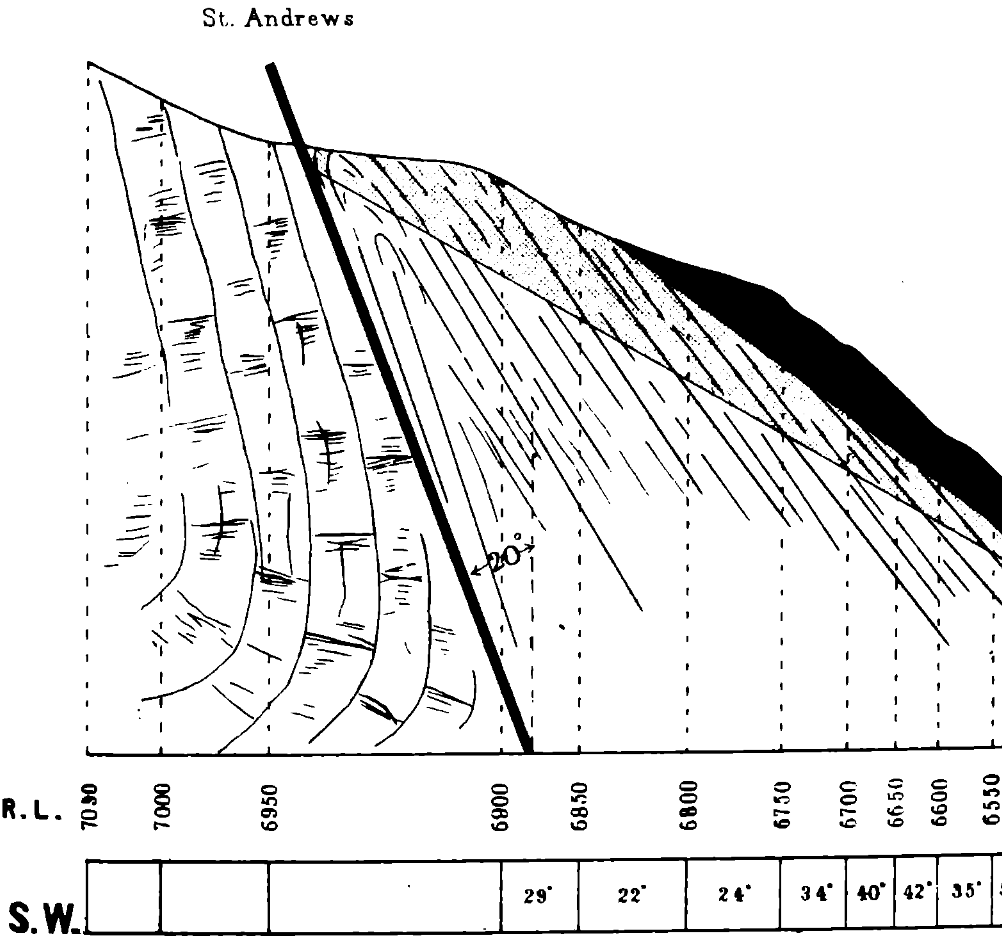
C. S. MIDDLEMISS, *Records, Geological Survey of India*, Vol. XXIII (1890), p. 233.

Figs. I, II, and III are examples of dip down the slope, and fig. IV is an example of dip in towards the hill. The two first are those to be avoided, as likely to prove unstable and prone to slip. Of the two, the combination of dip and slope as seen in fig. I where the angle of dip is slightly lower than that of the slope is the more dangerous. This is easily seen to be due to the fact that in it the beds or layers of cleaved rock are cut away below, leaving a free edge which allows an upper bed to slide down over a lower; whereas in the case depicted in fig. II, a similar set of beds is shown cut away above, leaving each bed with a firm basis of rock below it on which to rest. The third example (fig. III) shows a combination of a steep angle of dip coinciding in direction with the slope. Here the hill side may be considered structurally much safer than that of fig. II. Finally, in fig. IV, the dip is shown in the opposite direction or in towards the hill. This is the safest arrangement for all slopes fixed at the debatable angles of between 35° and 25°.

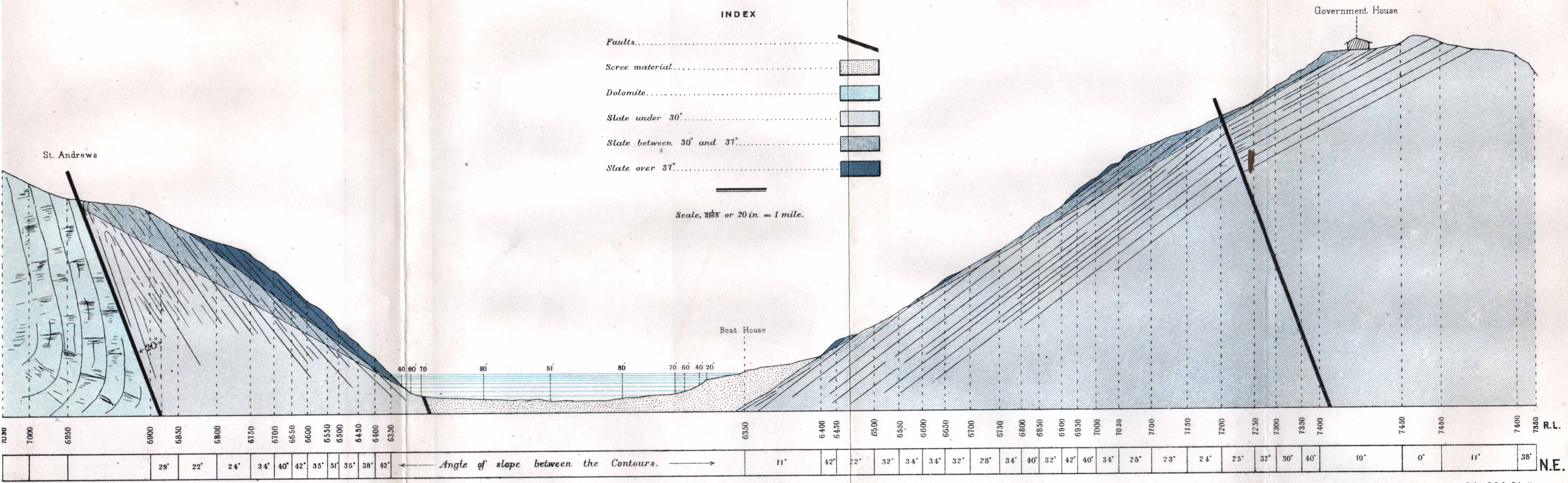
In the diagram, fig. V, *a b* represents the slope of the hill and the radiating lines represent the different angles of dip. The thin lines show the amounts of dip which in combination with the slope of the hill are dangerous, whilst the thick lines show the safe amounts.

From this we see that dips between 15° and 45° in the direction of the slope constitute an unsafe hill-side. This may be expressed differently by saying that when the dip varies within 15° on one side or other of the angle of slope (taken at 30°) it must be considered dangerous; and it is more dangerous when the angles of dip within the prescribed limits of 15° are less than those of the angle of slope, and less dangerous when they are greater.

G I C. P. O. No. 31 D. G. Survey—6 4·97.—350.



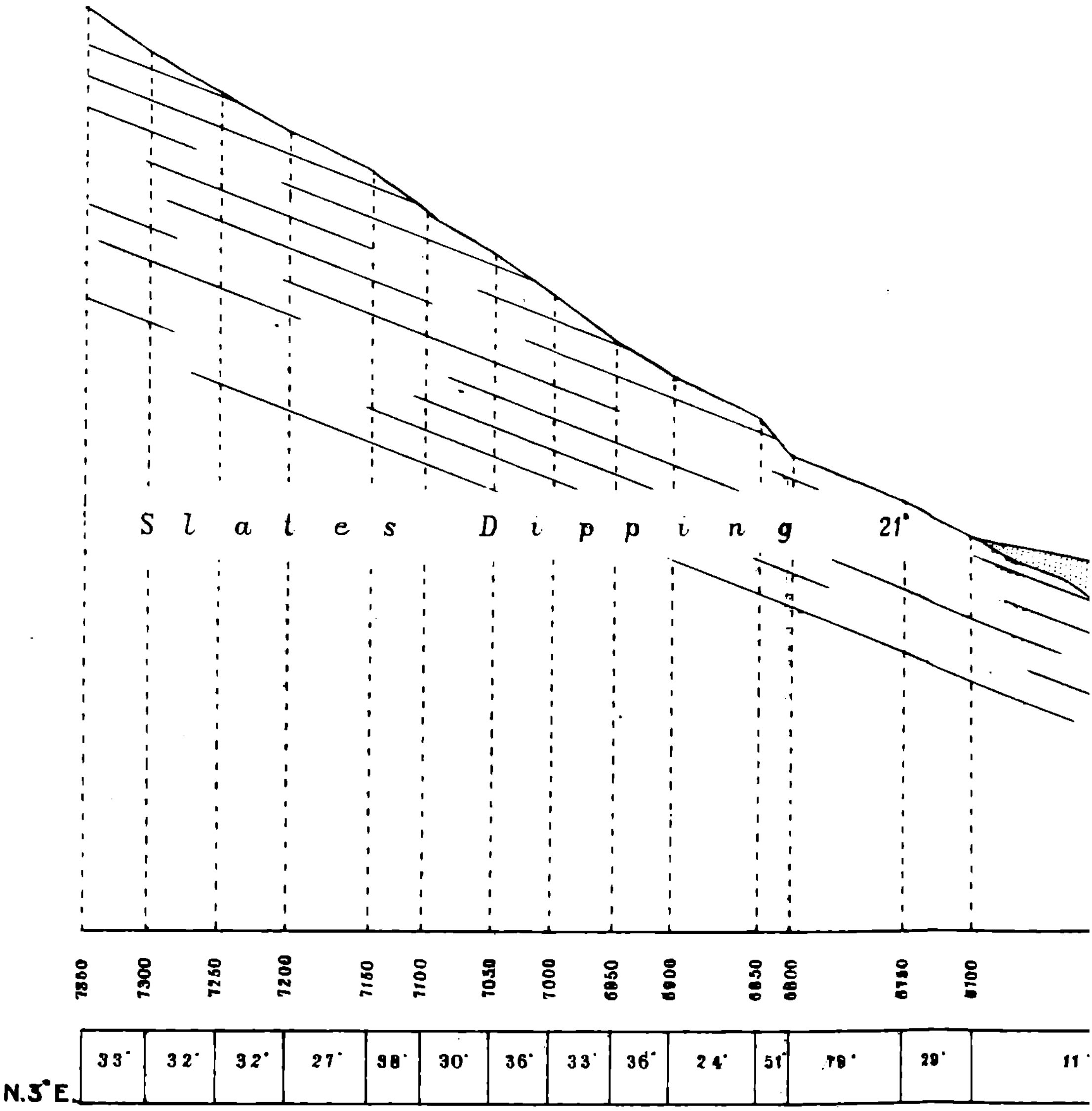
Reg. No. 399, Geol. Sur.—Aug. 06.—600.



Reg. No. 399, Geol. Sur.—Aug. 96.—600.

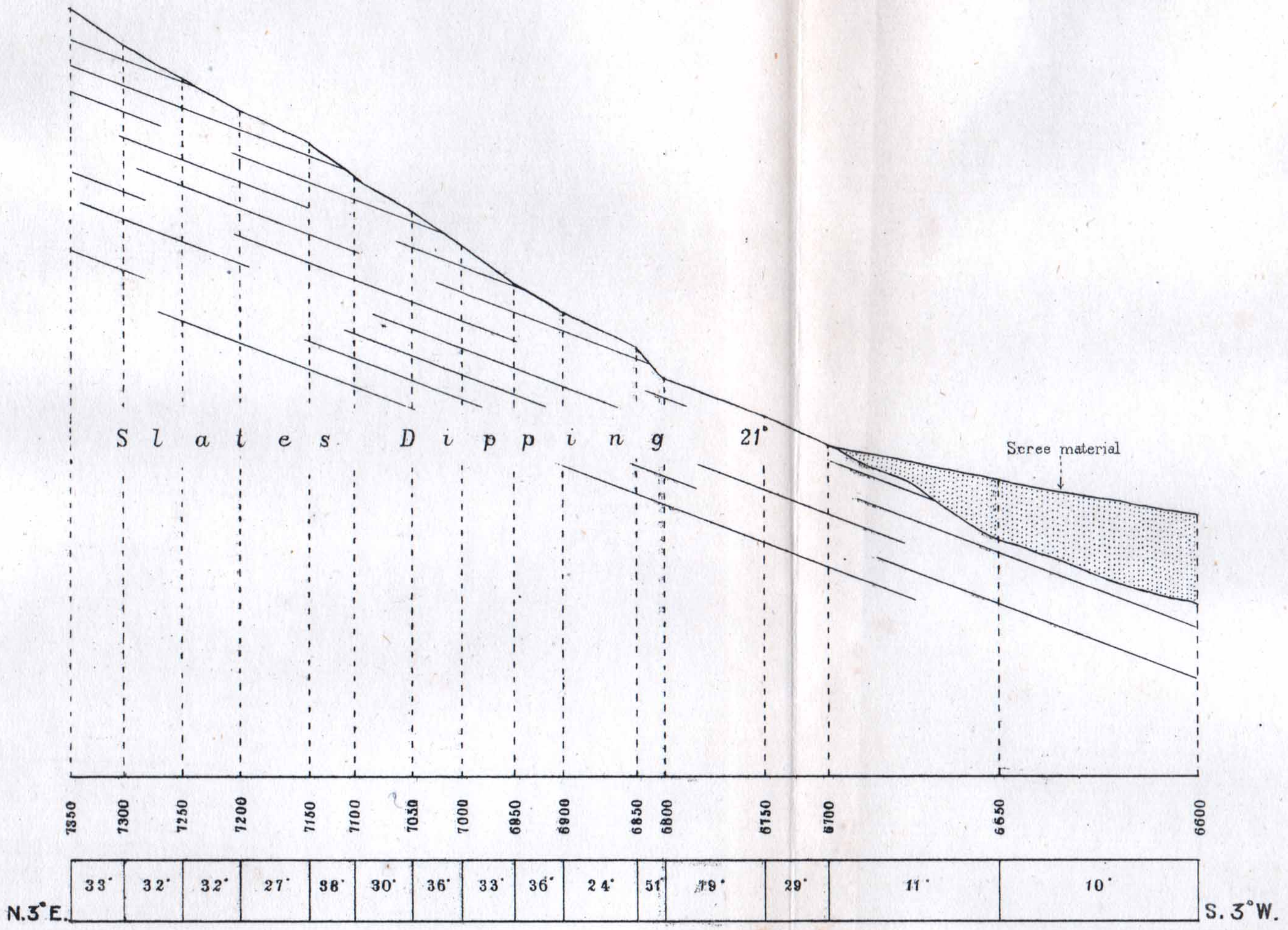
Litho., S. I. O., Calcutta.

CROSS SECTION No. 8 (NE.-SW.), THROUGH GOVERNMENT HOUSE, THE LAKE AND AYARPATA, NAINI TAL.

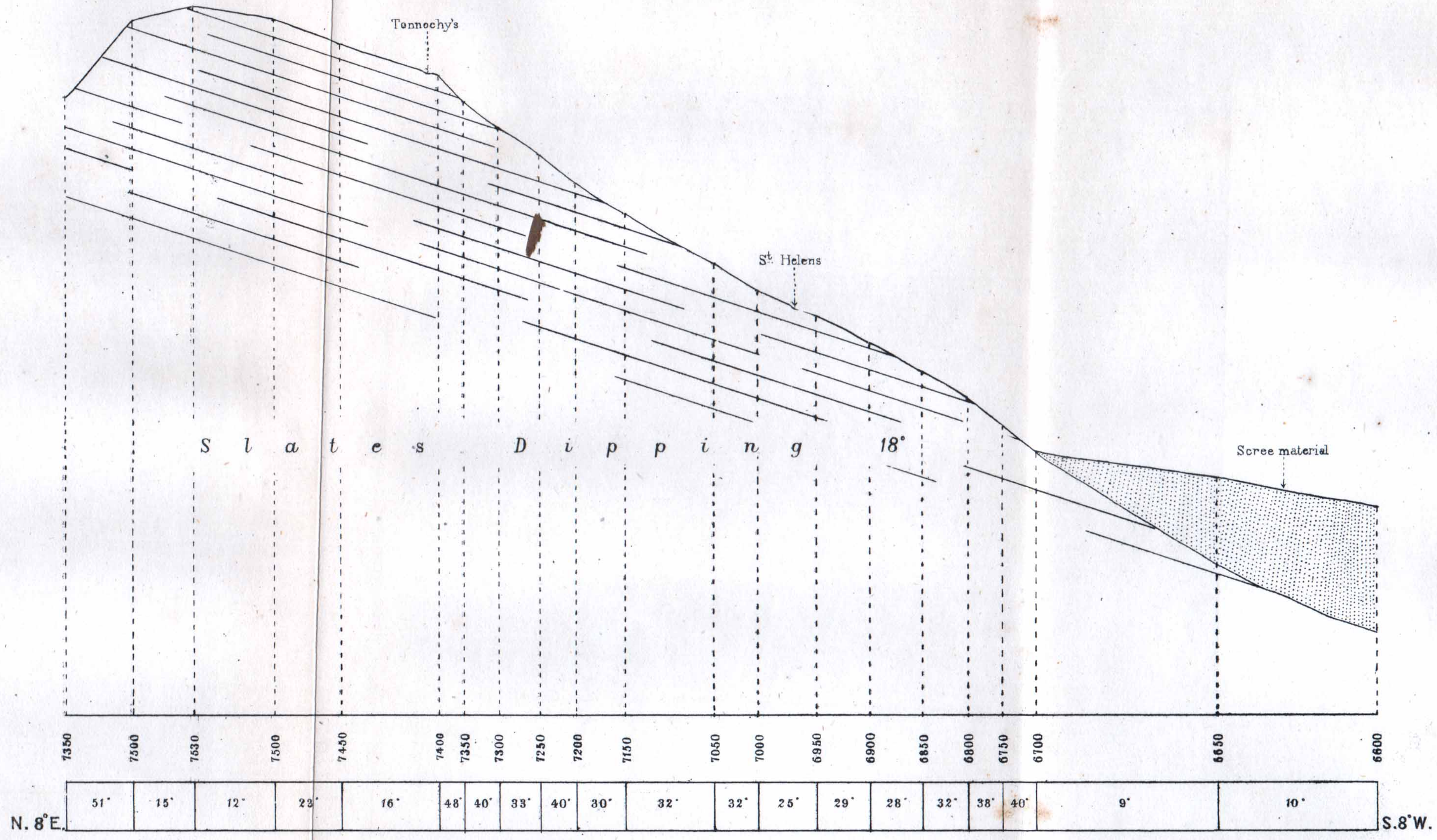


Nº 1. East of China Lodge.

C R O

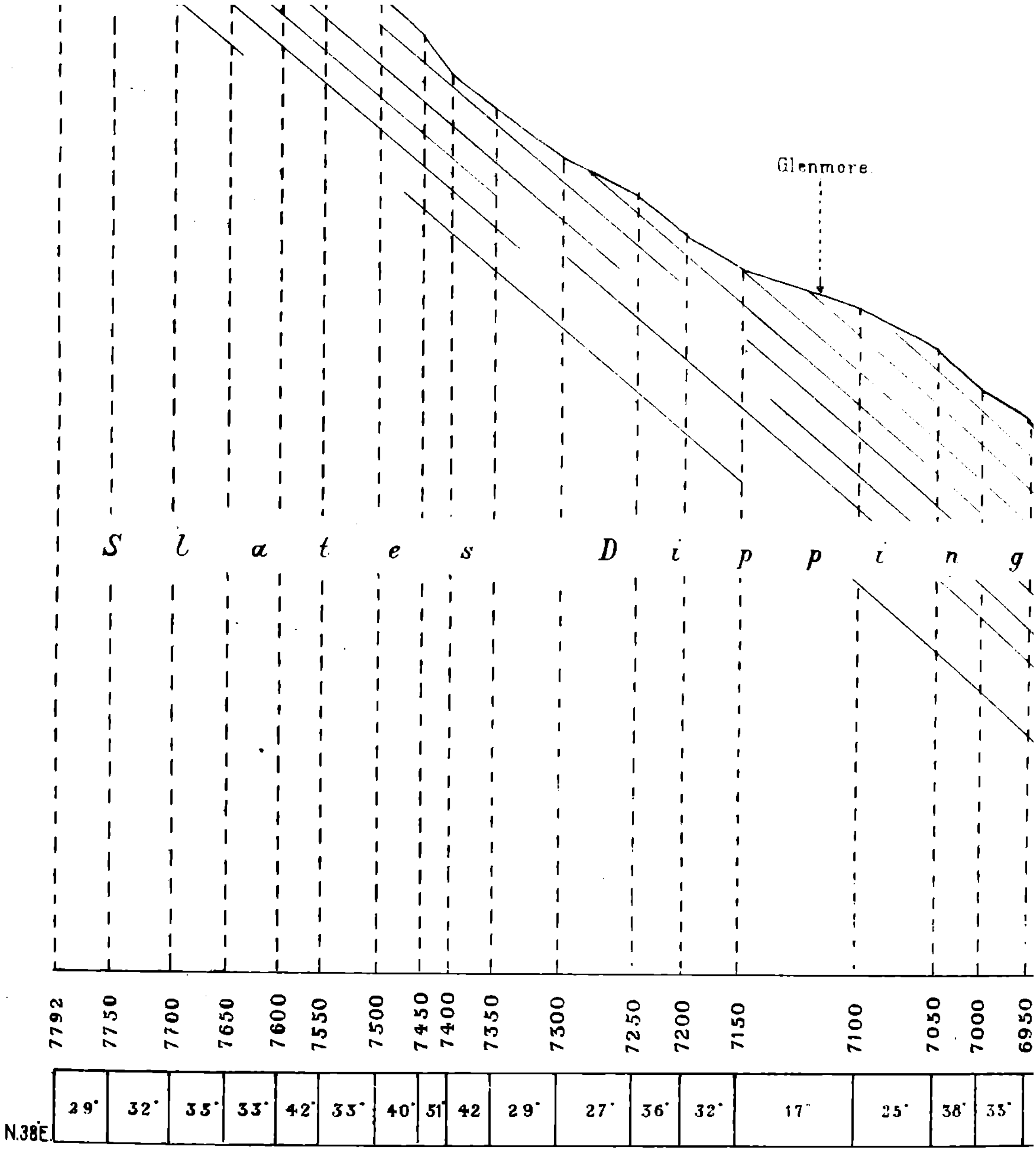


No. 1. East of China Lodge.



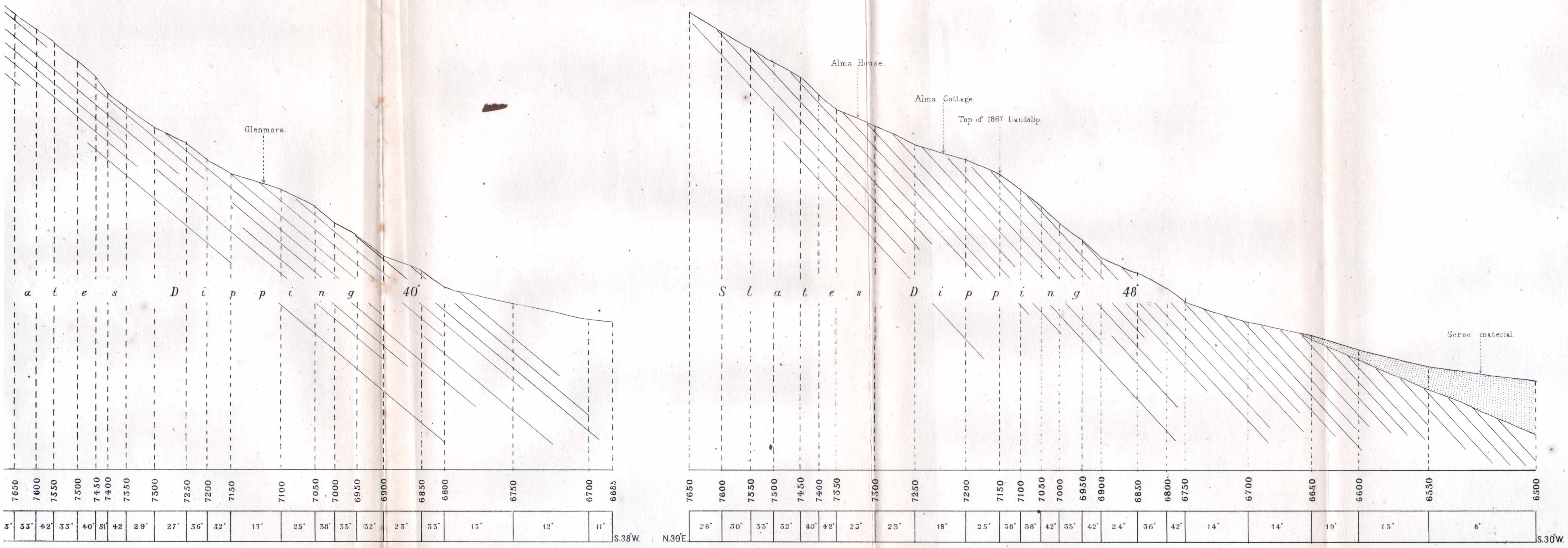
No. 2. Through Tonnochy's.

CROSS-SECTIONS Nos. 1 AND 2.



No. 3. Through Glenmore.

C

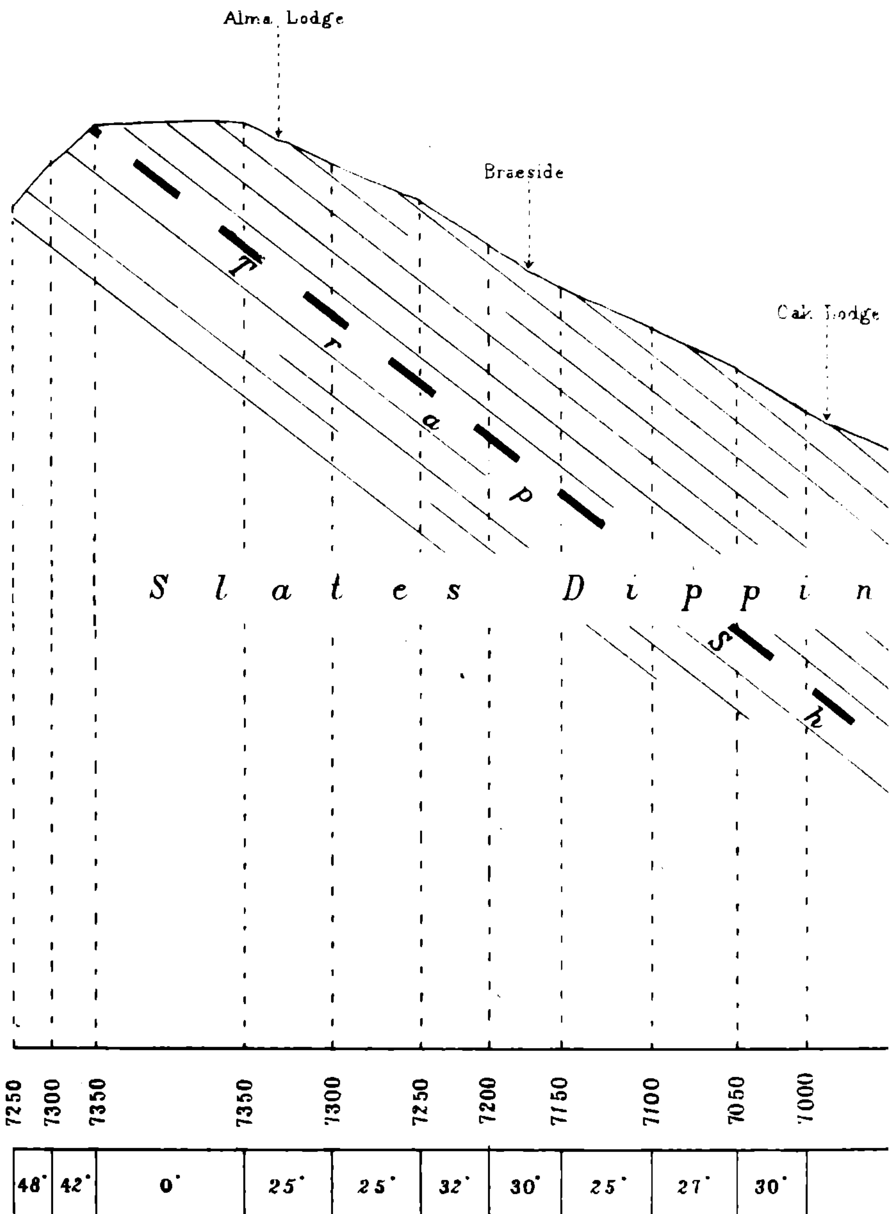


No. 3. Through Glenmore.

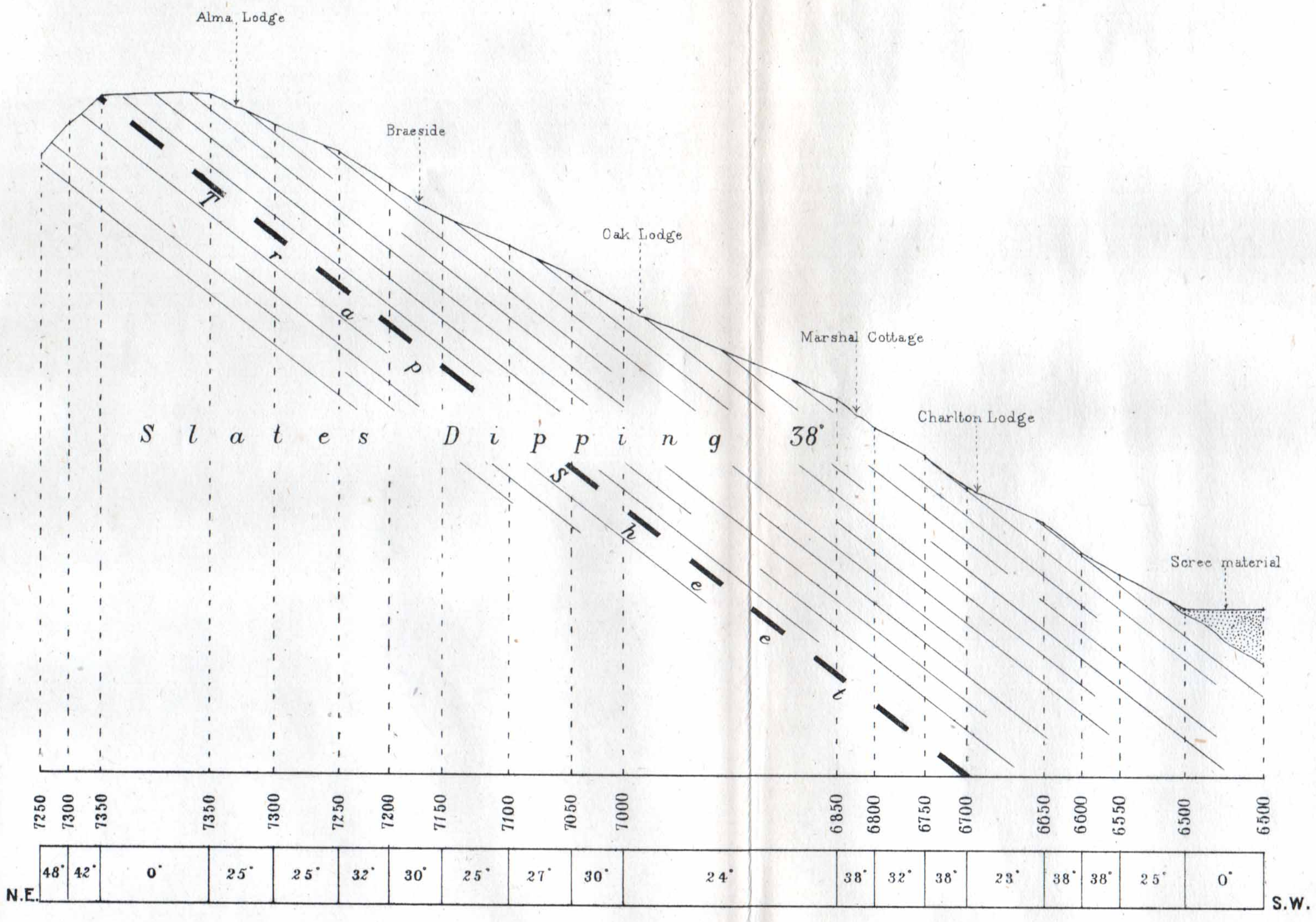
No. 4. Through Alma House.

CROSS-SECTIONS Nos 3 AND 4.

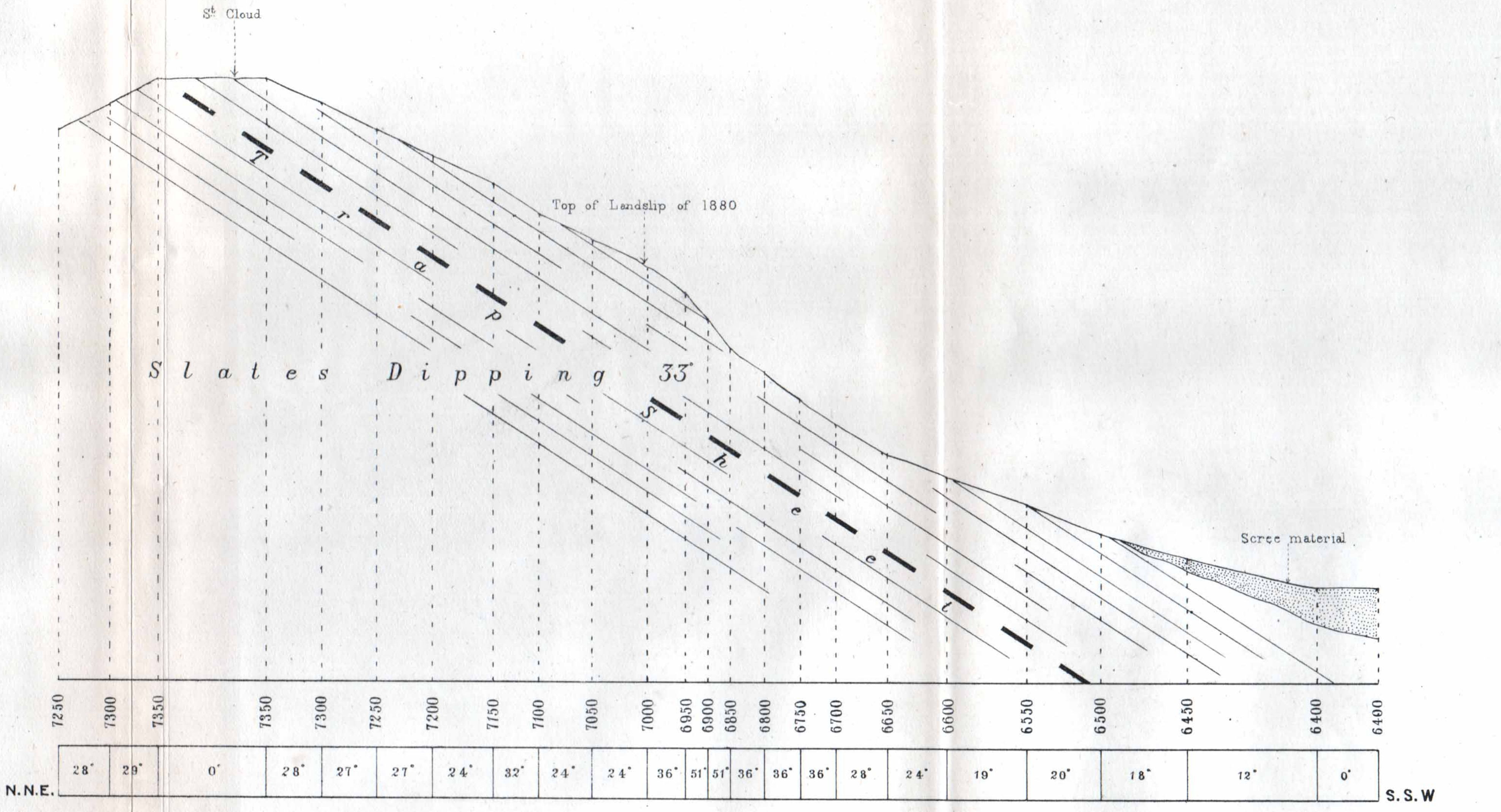
Holland.



Alma Lodge
Braeside
Oak Lodge
T r a p
S l a t e s D i p p i n g
S h
7250
7300
7350
7350
7300
7250
7200
7150
7100
7050
7000
48°
42°
0°
25°
25°
32°
30°
25°
27°
30°



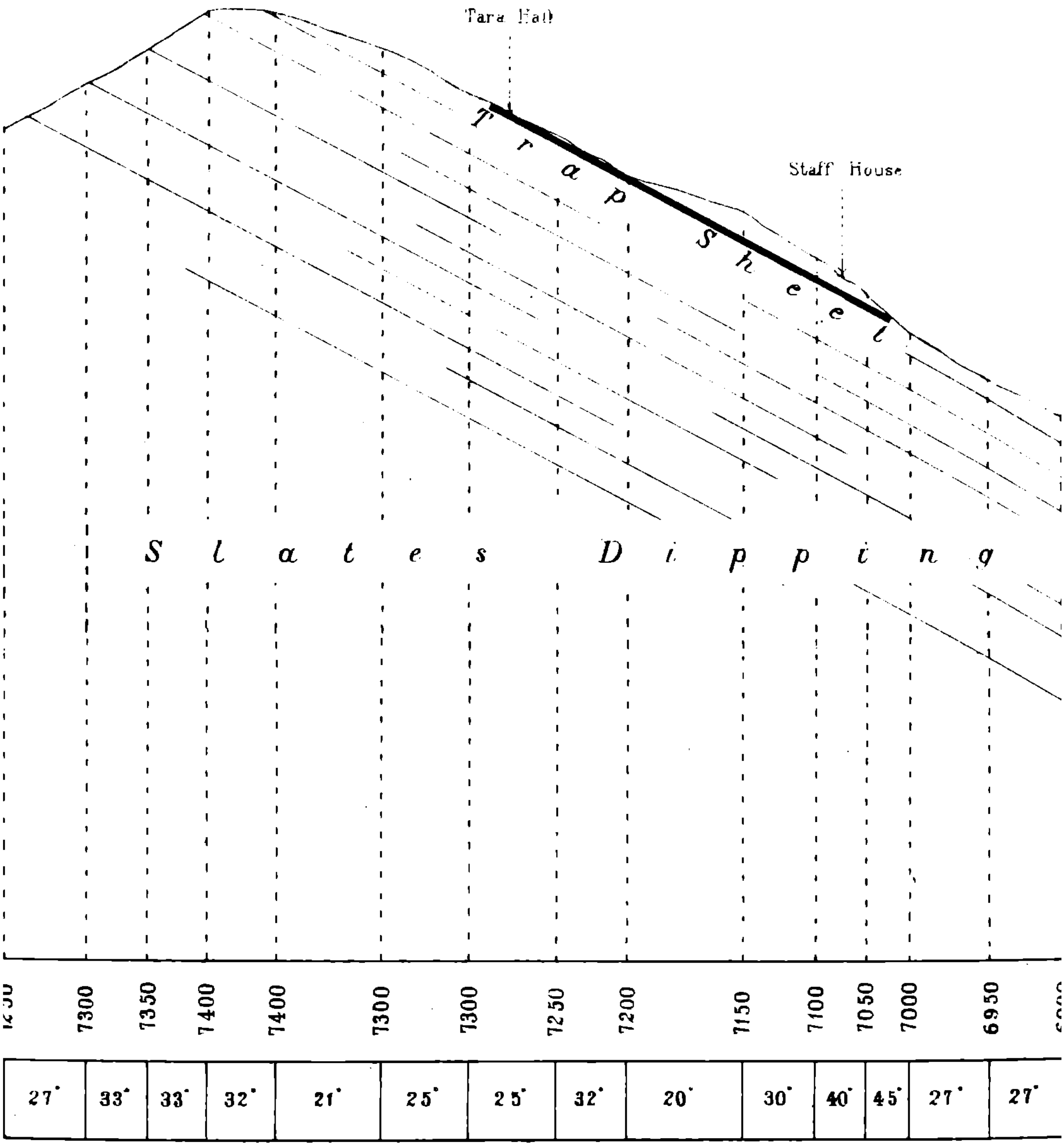
No. 5. Through Brae Side and Alma Lodge.



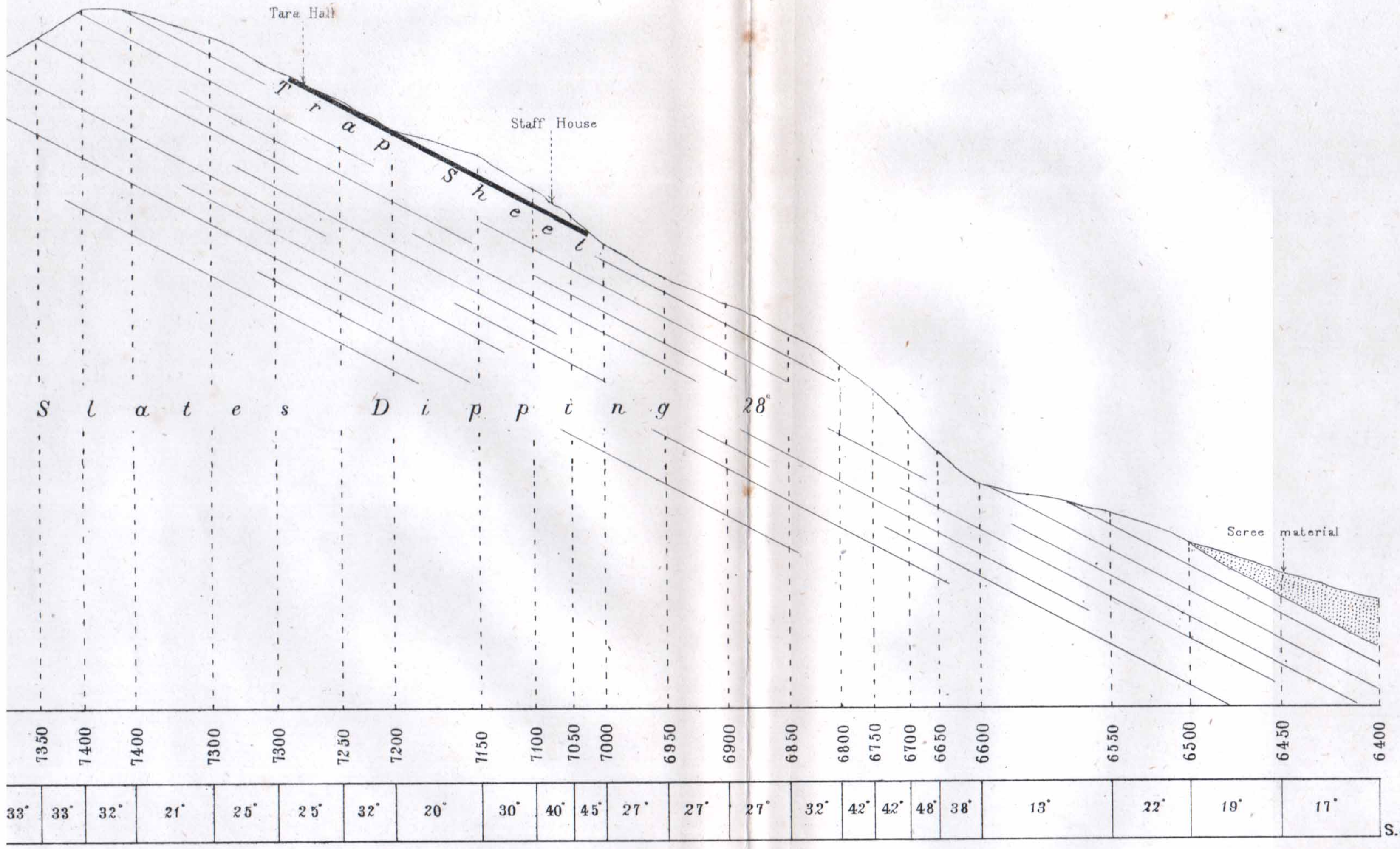
No. 6. Through St. Cloud and the Landslip of 1880.

CROSS-SECTIONS Nos. 5 AND 6.

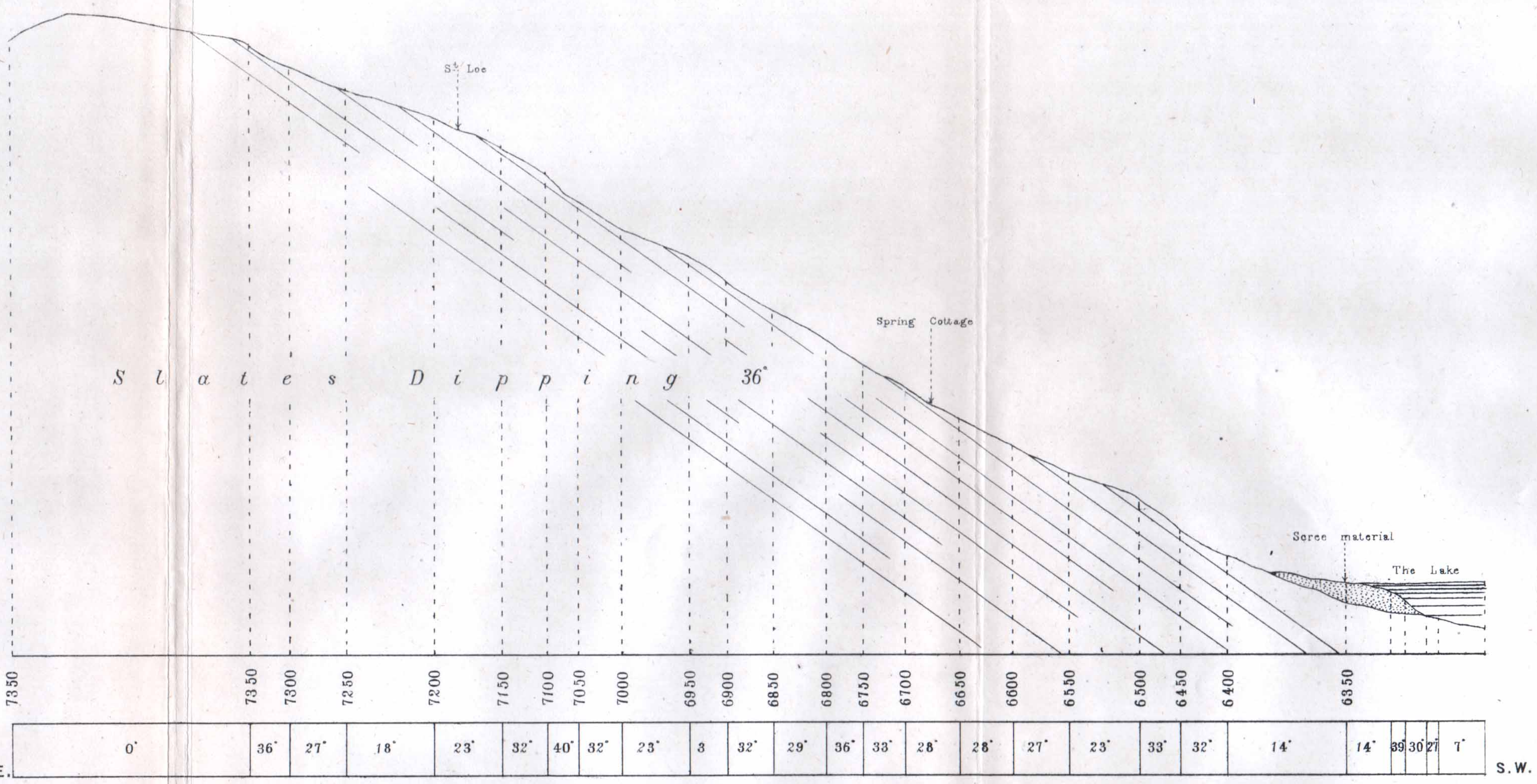
Holland.



No. 7. Through Tara Hall



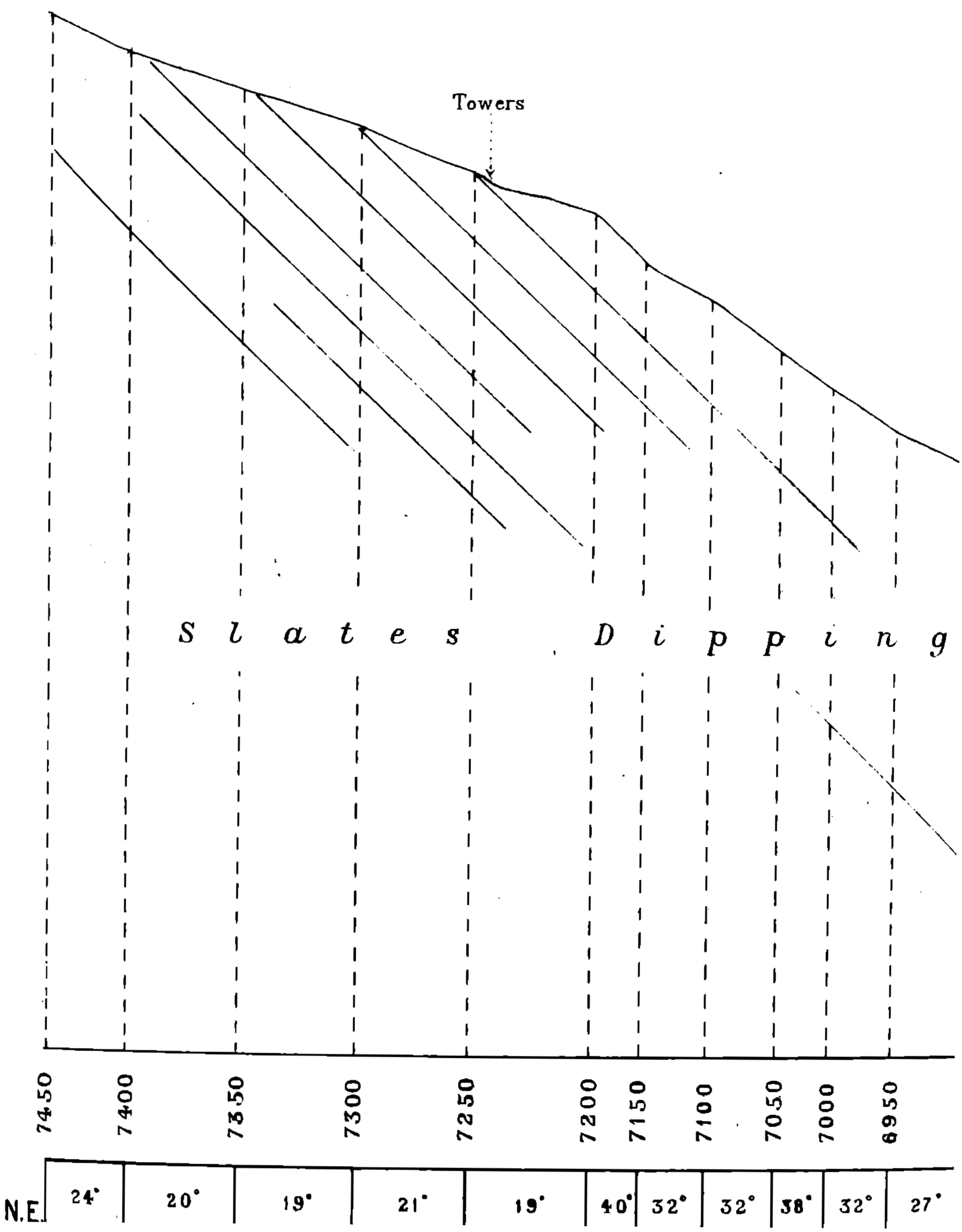
Nº 7. Through Tara Hall and Staff House.

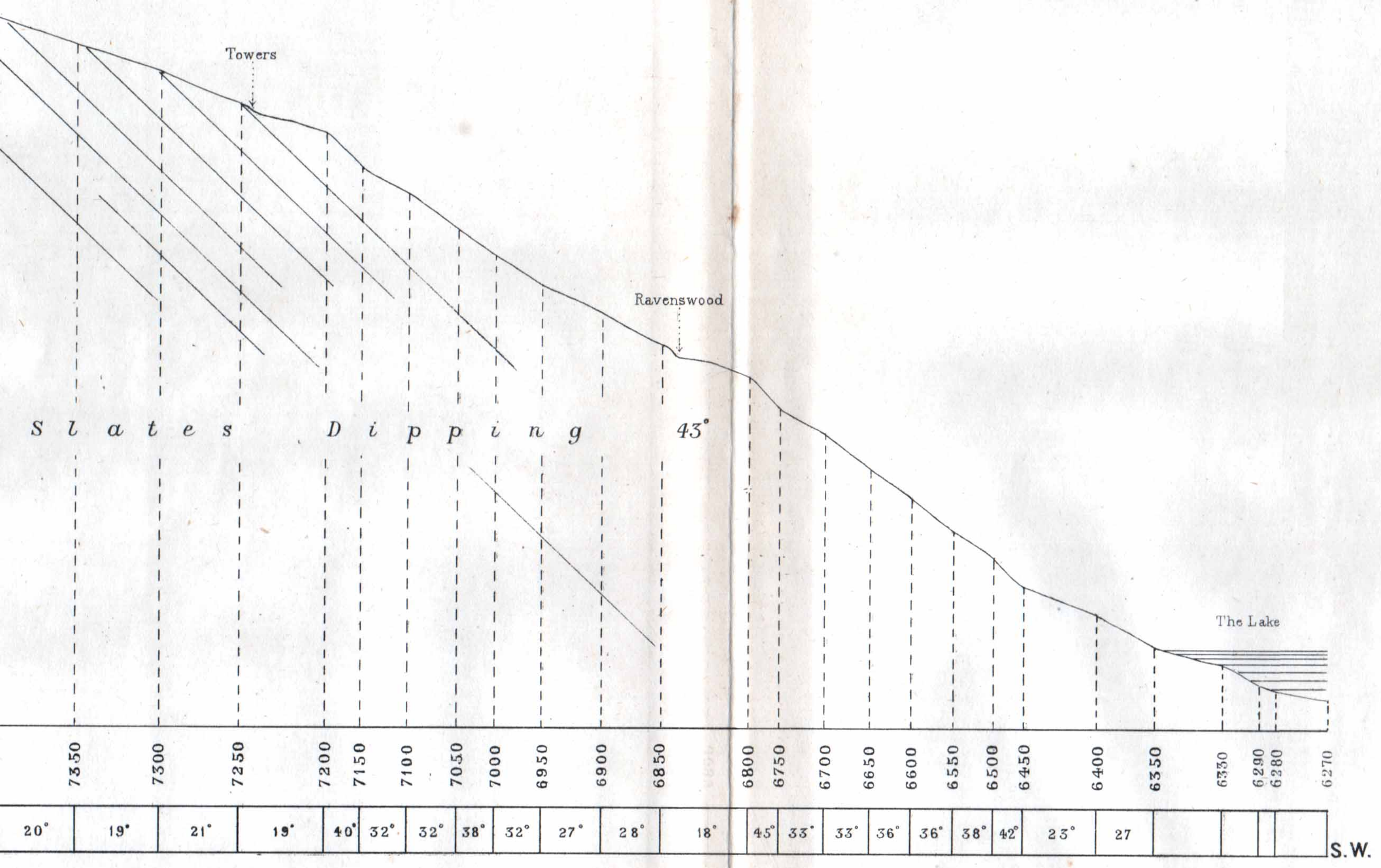


Nº 9. Through St Loe and Spring Cottage.

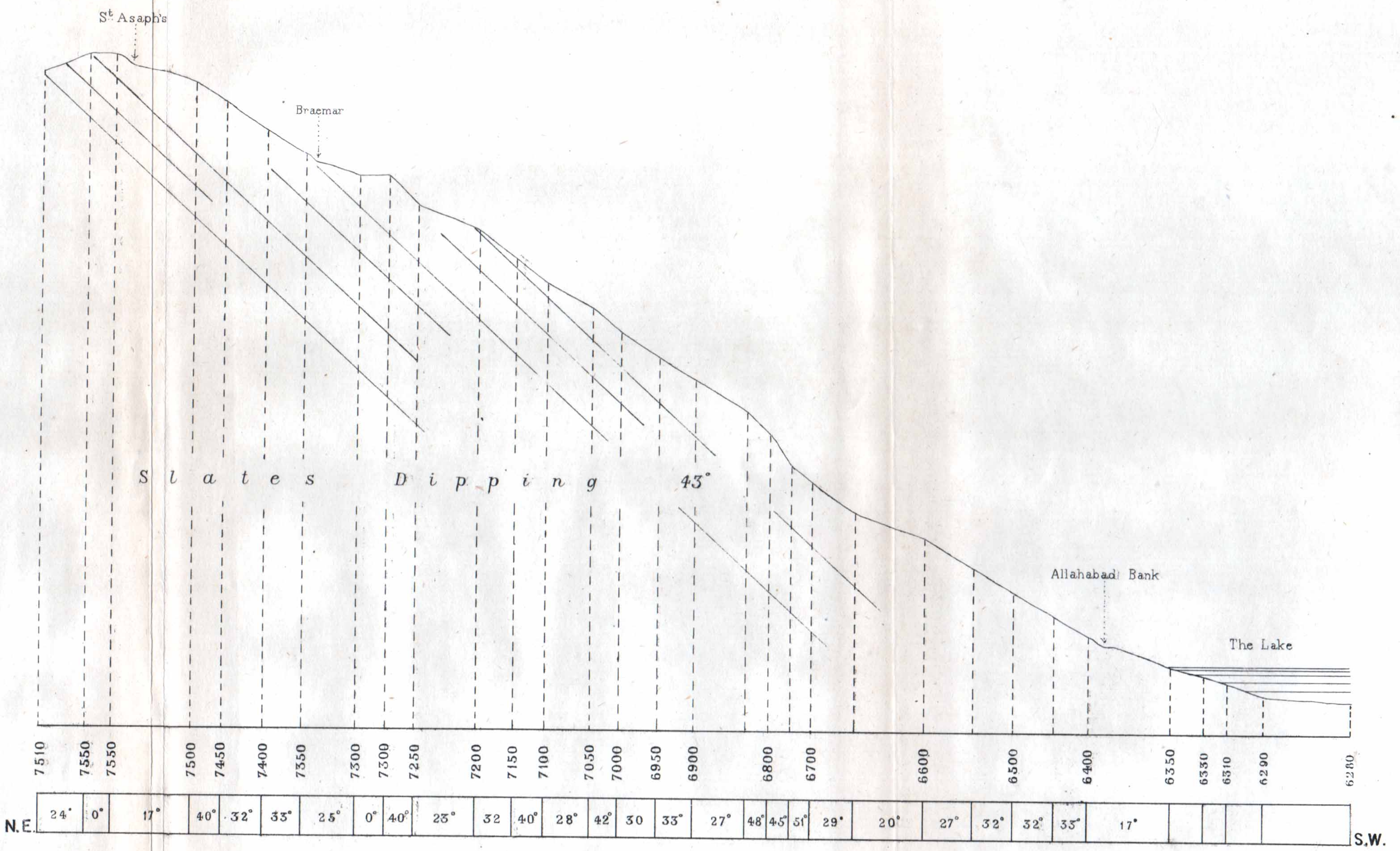
CROSS-SECTIONS Nos 7 AND 9.

Holland


Towers
Slates Dipping
7450
7400
7350
7300
7250
7200
7150
7100
7050
7000
6950
N.E.
24°
20°
19°
21°
19°
40°
32°
32°
38°
32°
27°

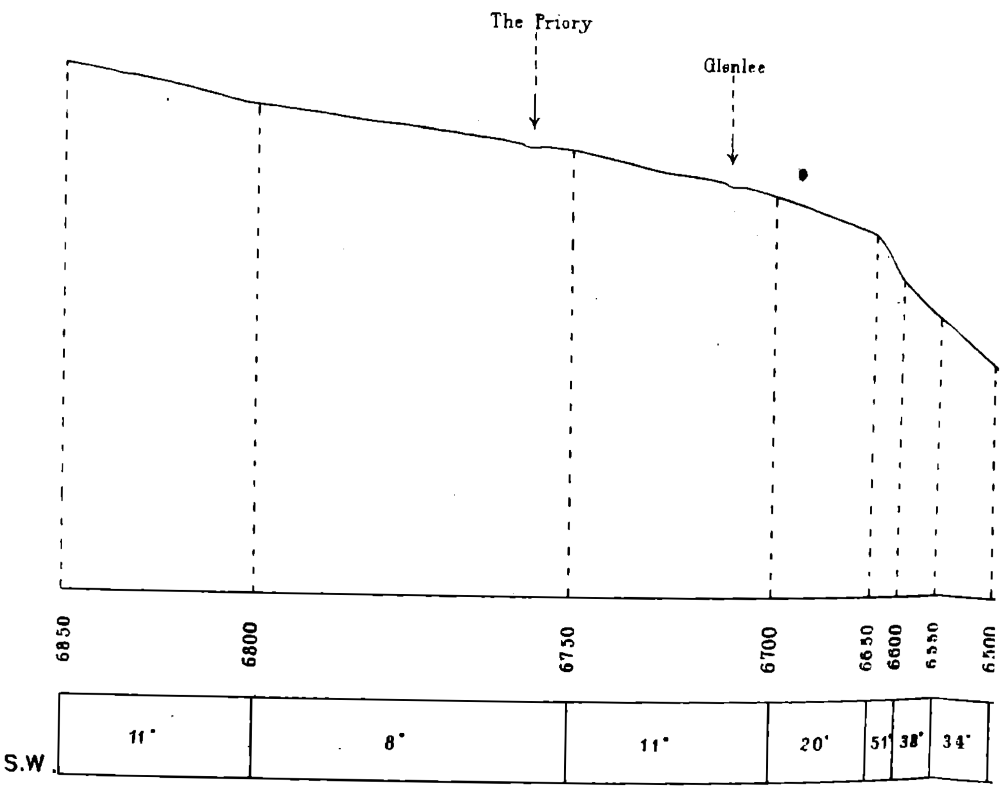


Nº 10. Through the Ravenswood Spur



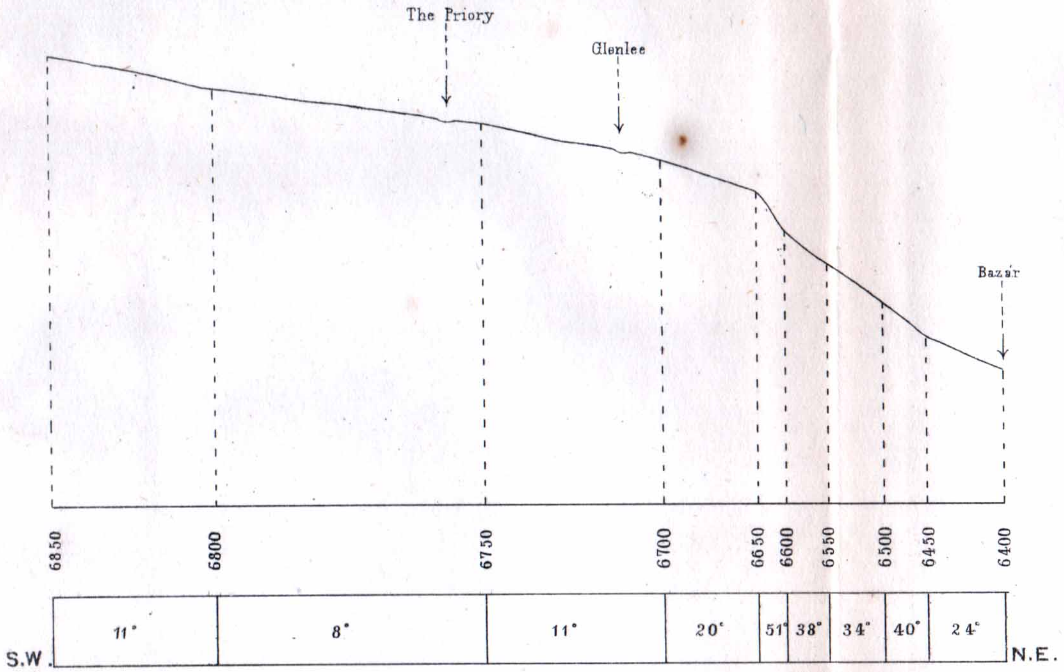
Nº 11. Through Sᵗ Asaph's

CROSS-SECTIONS Nos 10 AND 11.

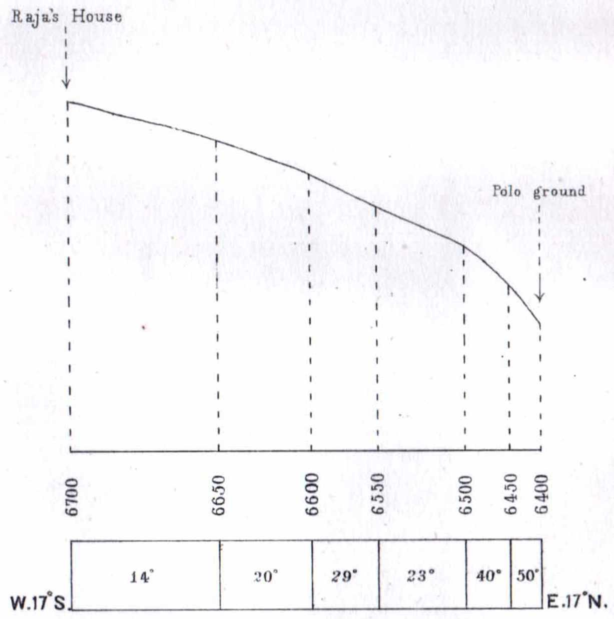


Nº 13. Through Glenlee.

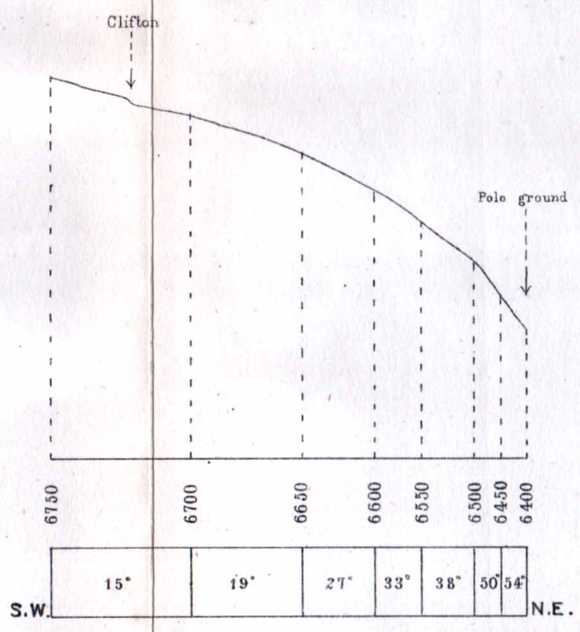
CROSS



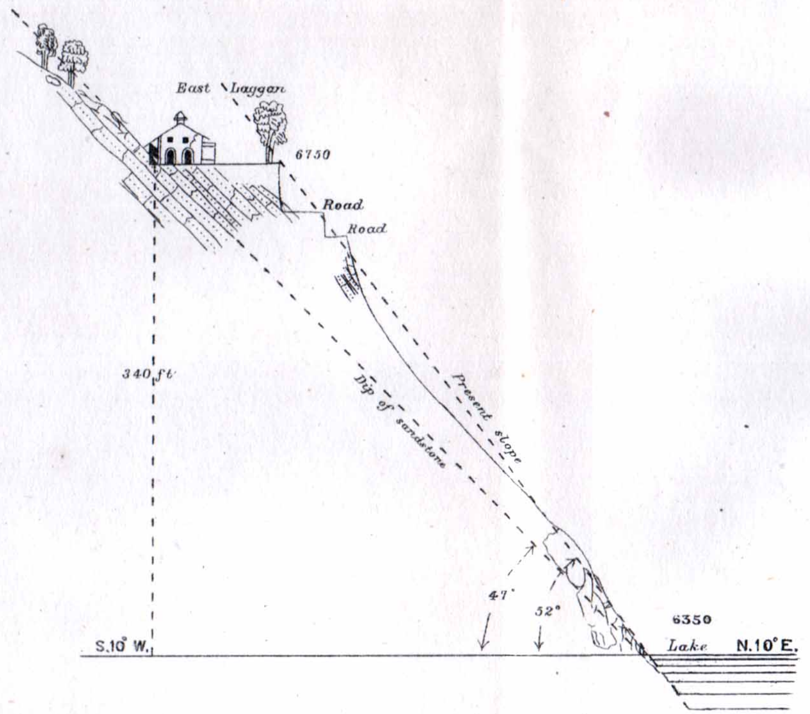
Nº 13. Through Glenlee.



Nº 14. Through Fine View.



Nº 15. Through Clifton.

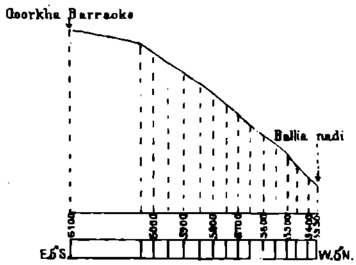


Nº 16. Through East Laggan.

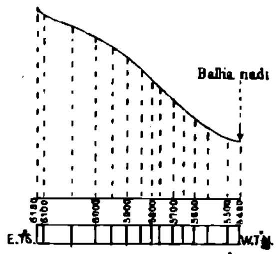
CROSS-SECTIONS Nos 13, 14, 15, AND 16.

Holland.

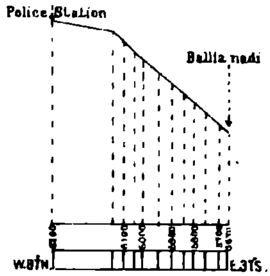
Report on Naini Tal. Pl. VIII.



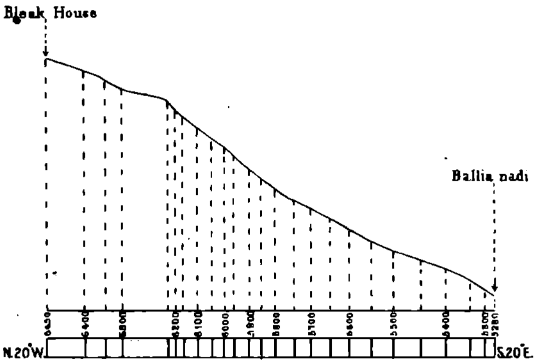
Average Slope, 39°
Nº 17.
Goorkha Barracks to Ballia nadi.



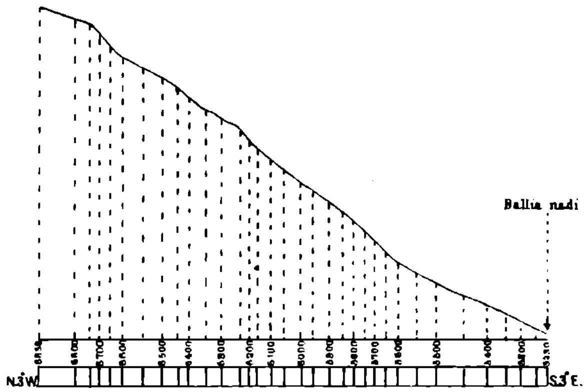
Average Slope, 35°
Nº 18.
To the Ballia nadi.



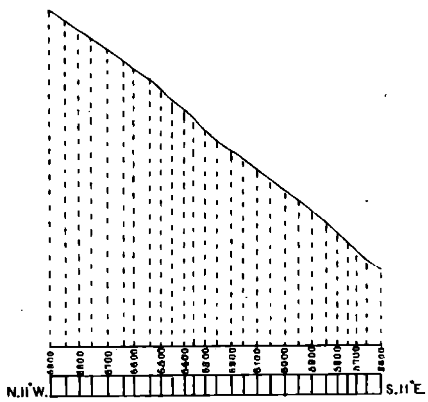
Average Slope, 40 ½°
Nº 19.
Police Station to Ballia nadi.



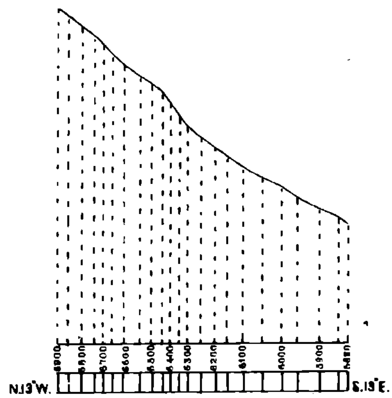
Average Slope, 32°
Nº 20.
Bleak House to Ballia nadi.



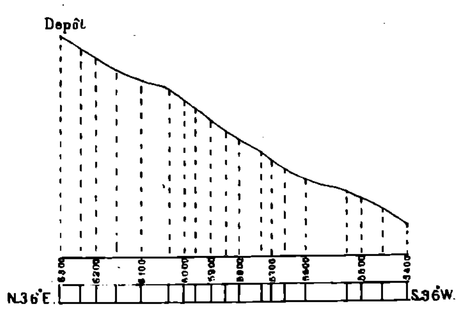
Average Slope, 34°
Nº 21.
Kalakhan to Ballia nadi.



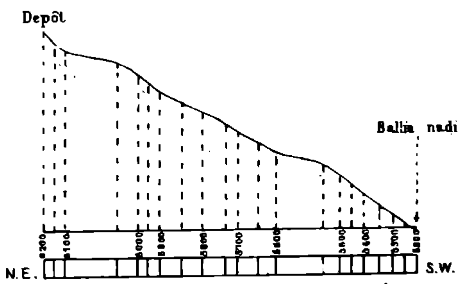
Average Slope, 39°
Nº 22. Kalakhan.



Average Slope, 37°
Nº 23. Kalakhan.



Average Slope, 28°
Nº 24. Kalakhan Depôt.



Average Slope, 28°
Nº 25. Kalakhan Depôt.

CROSS-SECTIONS Nos. 17 – 25.

Scale 1/12672 or 5 in. = 1 mile.

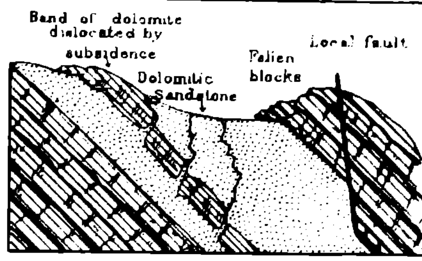


Fig 1 Collapse of strata by solution of carbonates from dolomitic sandstones

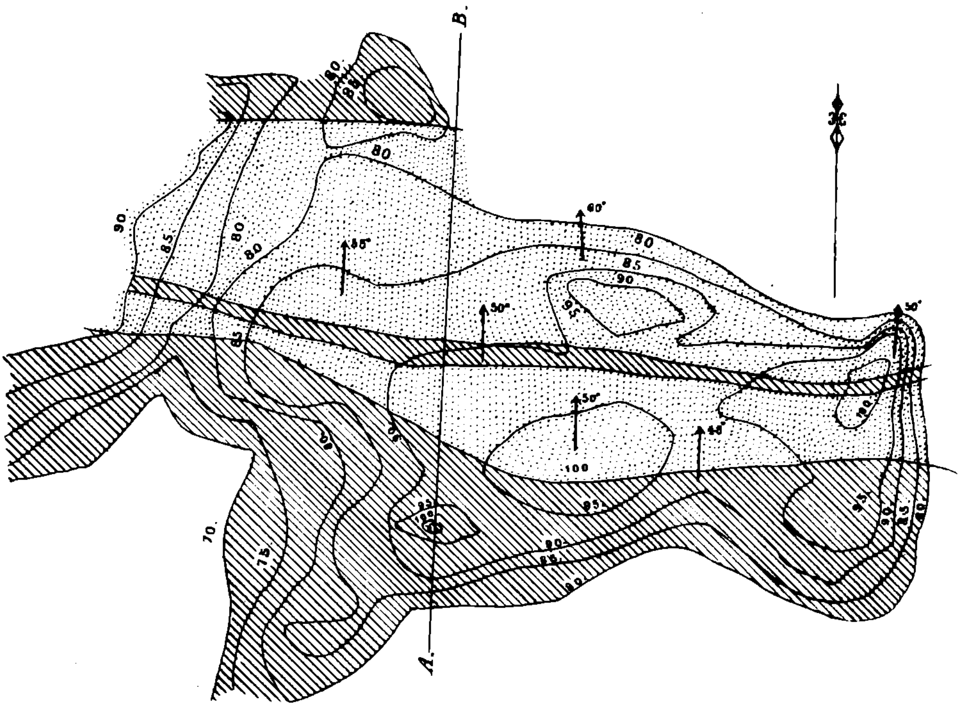


Fig. 2 Contoured Map showing Geological features.
Contoured at 5 feet vertical intervals. Scale 80 ft = 1 in.

1, 3 & 5, Dolomite ....

2, 4 & 6, Dolomitic sandstones and marls ....

Dips in sandstones and marls .... 50°

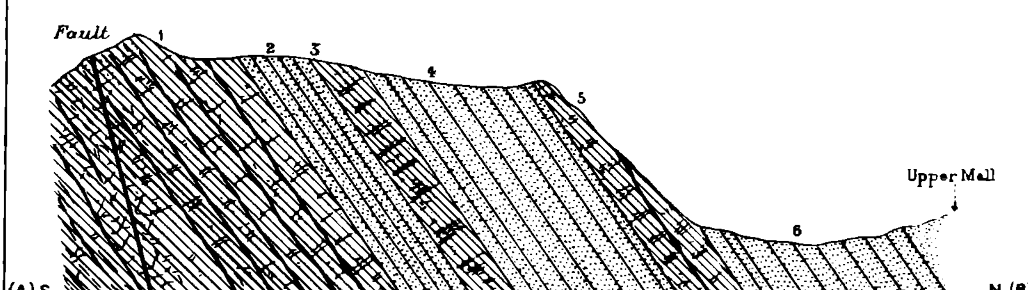
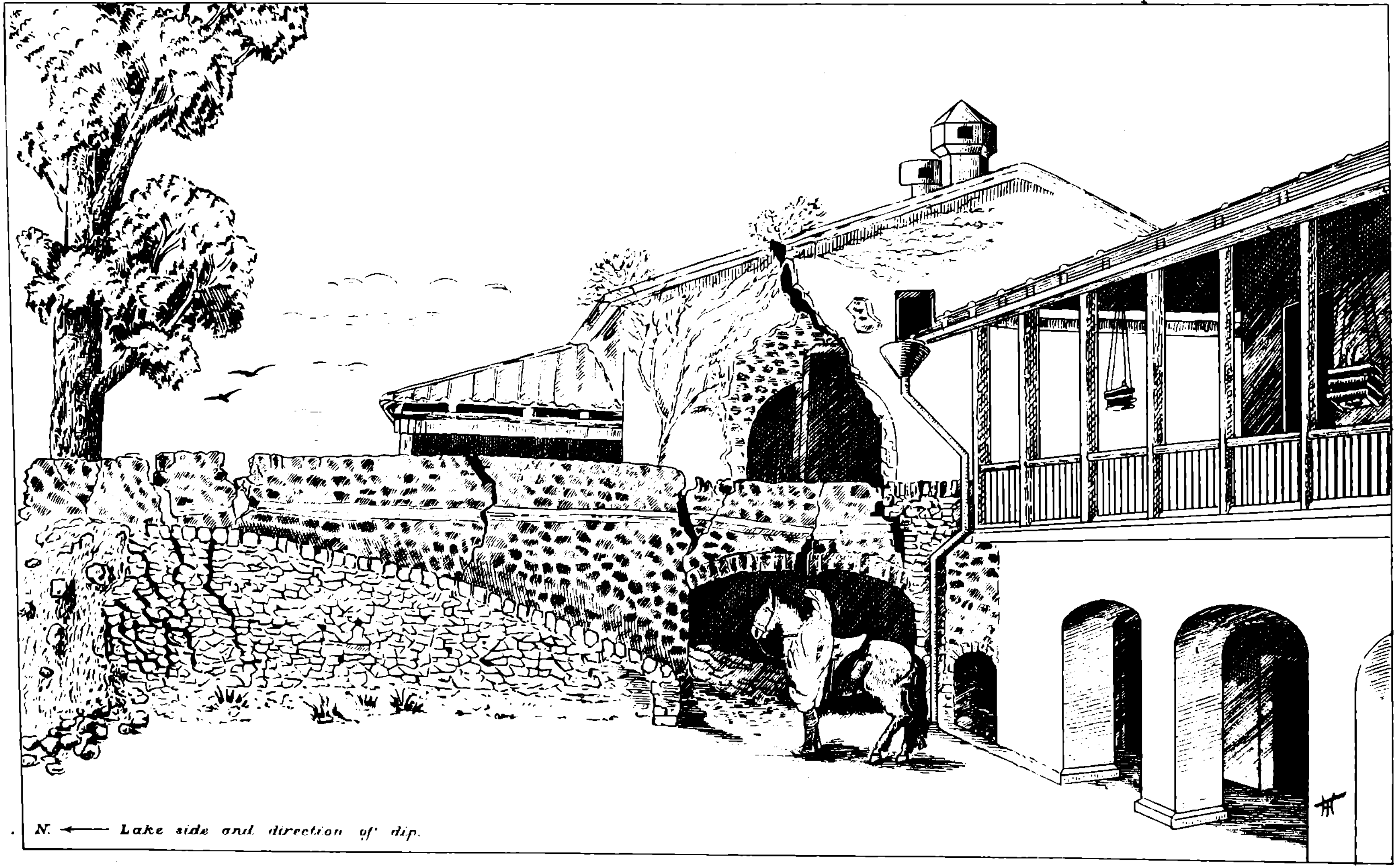


Fig. 3. Section along A.B.

GEOLOGICAL STRUCTURE OF A SITE ON AYARPATA HILL.



CRACKS IN MASONRY, EAST LAGGAN.

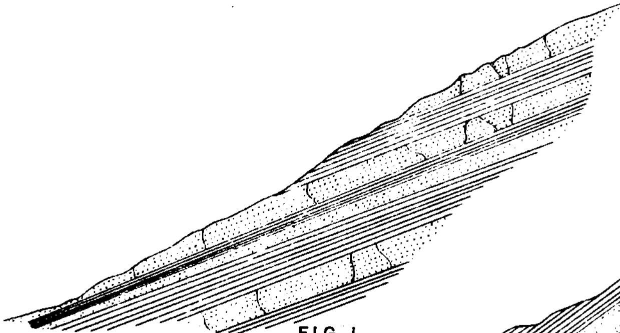


FIG. I.

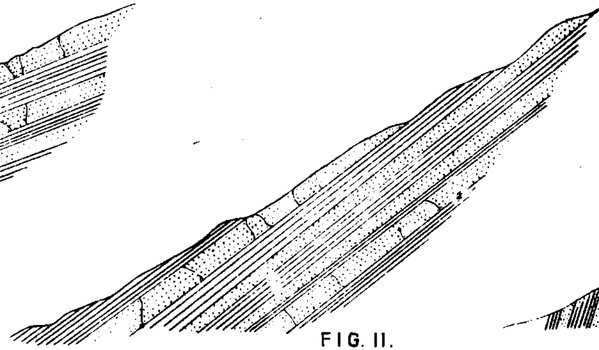


FIG. II.

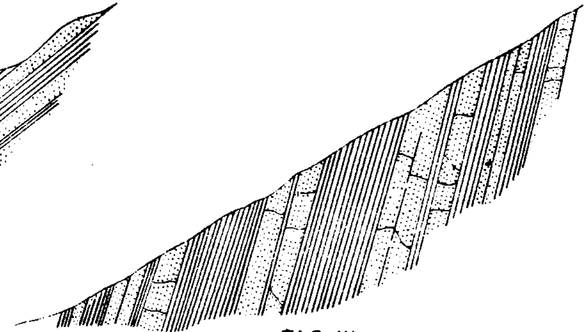


FIG. III.

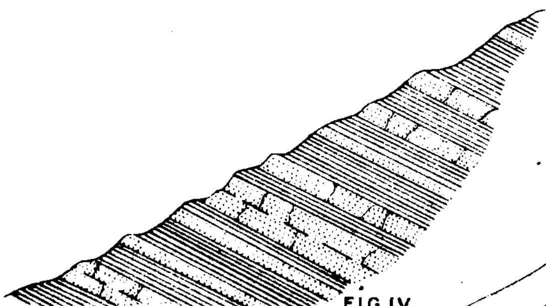


FIG. IV.

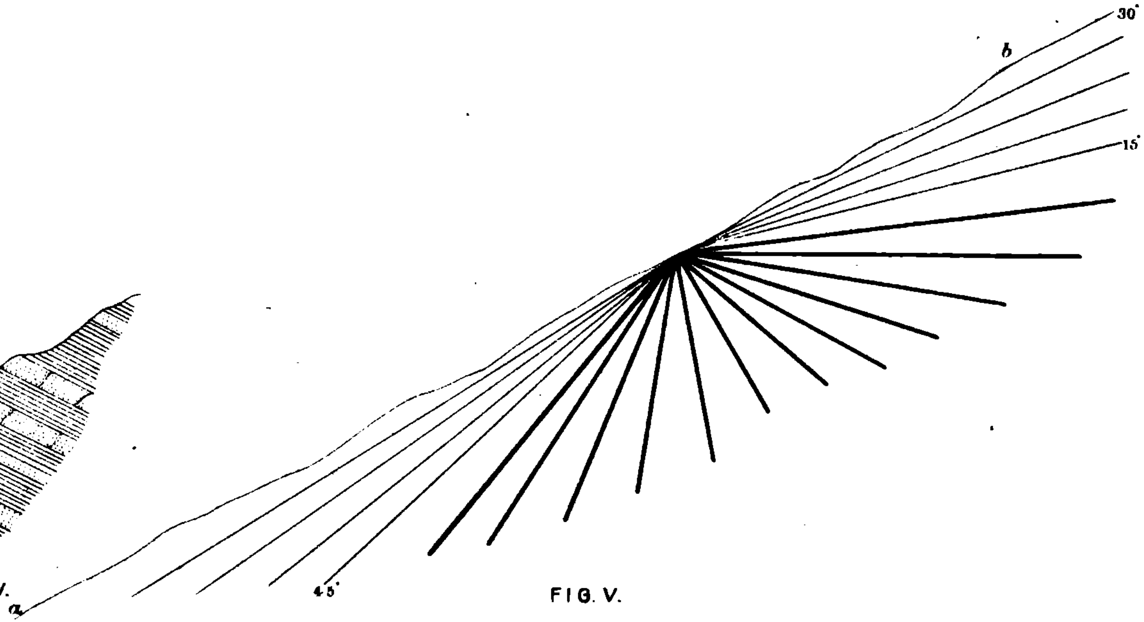


FIG. V.

RELATION OF DIP-PLANES TO SURFACE-SLOPE.

(after Middlemiss)