Airborne multispectral scanning of subsidence caused by Permian gypsum dissolution at Ripon, North Yorkshire

A. H. Cooper

British Geological Survey, Windsor Court, Windsor Terrace, Newcastle upon Tyne NE2 4HB, UK.

Abstract

Around Ripon, North Yorkshire, catastrophic subsidence locally occurs because of natural underground dissolution in the Permian gypsum. This airborne study assesses the merits of multispectral scanning (MSS) as a method of detecting incipient subsidence areas and as an aid to geological mapping. The multispectral method indicates subsidence areas by vegetation, soil colour and temperature variations. Computer enhancement of the multispectral images allow some subsidence details not seen by conventional photography to be delineated. The MSS images are two-dimensional and even the most detailed ones have a fairly coarse resolution (1.5–2.0 m). Because of this, conventional 3D interpretation of stereo air photographs better indicates the morphology of the subsidence hollows and the geology.

Introduction

Natural catastrophic subsidences, caused by the dissolution of Permian gypsum, occur in an area about 100 km long and 3 km wide. This area extends from Bedale in the north to near Doncaster in the south. The worst affected area is Ripon (Fig. 1) where more than 40 instances of subsidence have occurred in the past 150 years. The subsidence hollows which can be up to 20 m deep by 30 m in diameter can form suddenly (Fig. 2). Several buildings around Ripon have been demolished as a result of this subsidence and further development is difficult to plan.

A geological survey of the area was carried out in 1980–81 for the British Geological Survey (funded by the Department of the Environment) and defined the extent, cause and nature of the subsidence (Cooper 1986). It showed the subsidence resulted from underground dissolution of Permian gypsum and that the subsidence hollows occur in a roughly rectilinear pattern, but that prediction of future subsidence areas was not possible.

The Natural Environment Research Council (NERC) requested research programmes to evaluate the Daedalus 1268 airborne multispectral scanner (MSS) as a survey tool. This present work assesses its usefulness as a mechanism for locating incipient subsidence features, which may develop into major collapses, and as a survey tool for both geological mapping and the study of more general subsidence problems.

Geology

In the Ripon district the four formations of the Permian sequence strike approximately north–south and dip gently eastwards at between one and two degrees (Smith 1974a, b). The nomenclature of these rocks has recently been formalized (Smith, Harwood, Pattison & Pettigrew 1986), but to allow comparison with previous and future works, both old and new names are initially mentioned here. The rocks are described below with emphasis on the soluble deposits and the nature of the subsidence which results from them.

Cadeby Formation

The lowest Permian strata of the district comprise the calcareous rocks of the Cadeby Formation formerly called the Lower Magnesian Limestone. This formation rests unconformably on the Carboniferous sequence and is up to 65 metres thick. It is composed mainly of porous dolomite and dolomitic limestone, details of which are given by Smith (1974a, b). The limestone is well jointed, has very few caves, and forms an excellent hydrogeologically uniform aquifer (Aldrick 1978).

Edlington Formation

The Cadeby Formation is conformably overlain by the poorly exposed mudstones and siltstones of the Edlington Formation, formerly the Middle Marls. Away from the outcrop, which is commonly thinned by foundering and cambering, the formation generally ranges in thickness from 20 to 50 metres. Down dip, where the formation is thick, up to 40 metres of the Hayton Anhydrite is included at its base. This anhydrite passes laterally westwards towards the outcrop into a belt of secondary gypsum. The gypsum is produced by the reaction of anhydrite with the groundwater, the mechanism of which is described by Mossop & Shearman (1973). Ultimately, continued contact with the passing groundwater causes the gypsum to dissolve partially, resulting in subsidence hollows, or to dissolve fully causing the overlying strata to founder (Smith, 1972; James, Cooper &
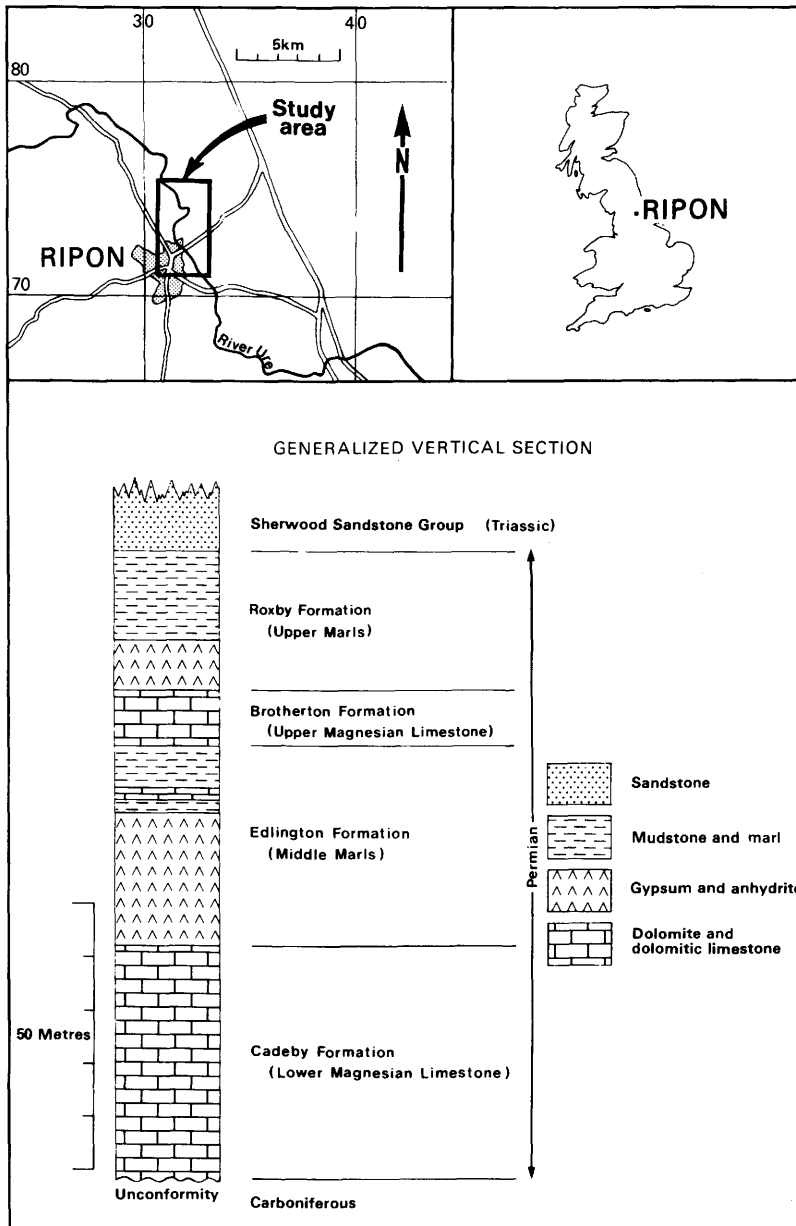
GENERALIZED VERTICAL SECTION

Sherwood Sandstone Group   (Triassic)

Roxby Formation
(Upper Marls)

Brotherton Formation
(Upper Magnesian Limestone)

Edlington Formation
(Middle Marls)

Cadeby Formation
(Lower Magnesian Limestone)

Permian

Sandstone

Mudstone and marl

Gypsum and anhydrite

Dolomite and
dolomitic limestone

50 Metres

Unconformity   Carboniferous

FIG. 1. Location map of study area and generalized vertical section.

Holliday 1981; Cooper 1986). The Edlington Forma-
tion is therefore much thinner at and near outcrop
than it is in most boreholes further to the east.

Brotherton Formation

The Brotherton Formation, formerly called the Upper
Magnesian Limestone, conformably follows the
Edlington Formation and comprises calcitic dolomites

and dolomitic limestones. These are generally uniform
and thinly bedded with the formation ranging in
thickness from 8 to 12 metres. The rock is well jointed
and bedded, ensuring high permeability. At and near
outcrop foundering of the Brotherton Formation is a
common phenomenon (Smith 1972; Cooper 1986)
caused by the dissolution of gypsum in the Edlington
Formation. Exposures of the limestone commonly
occur around subsidence hollows and have steep,

FIG. 2. Water-filled subsidence hollow which formed on 1st February 1982 at Sharow [SE 3238 7182]. The hollow was 12 m in diameter and up to 9.7 m deep.

directionally variable dips, locally up to 30 degrees. This foundering results in areas of brecciated limestone within breccia pipes that penetrate the formation. In places the overlying sequence has also descended into these subsidence pipes and small foundered areas of the Roxby Formation and the Sherwood Sandstone Group occur within the Brotherton Formation.

Roxby Formation

Above the Brotherton Formation the Roxby Formation, formerly called the Upper Marls, has many similarities with the Edlington Formation which precedes it. Near its outcrop the Roxby Formation is composed of mudstones and siltstones between 10 and 18 metres thick, but down dip eastwards it thickens to between 30 and 40 metres. Much of this increase in thickness is due to the presence of the Billingham Anhydrite Formation near its base and possibly the Sherburn Anhydrite Formation (formerly the Upper Anhydrite) in the middle of the sequence. Like the anhydrite in the Edlington Formation these anhydrite units pass westwards up dip into zones of secondary gypsum. They then pass into a zone of dissolution and have largely been removed by the action of groundwater. As a result of the dissolution of the gypsum in both the Edlington and Roxby Formations the overlying beds are commonly foundered. This subsidence affects strata well up into the overlying Triassic Sherwood Sandstone Group, which is in places dropped down to the level of the Brotherton Formation.

Sherwood Sandstone Group

The Sherwood Sandstone Group follows the Roxby Formation with a rapid interbedded transition over a few metres. The sandstones, considered to be in part of Triassic age, are red, porous, massive and about 300 metres thick with a wide outcrop extending eastwards. They are moderately jointed and form one of the main aquifers in the district.

Quaternary deposits

The bedrock is cut through by a deep buried valley along the line of the present River Ure. This valley is partially filled with pre-Devensian gravels overlain by Devensian till which also blankets the adjacent bedrock. The low-lying areas of till are in turn partially overlain by fluvio-glacial gravel terraces which are dissected by the present drainage system with its associated flat alluvial flood plains.

Gypsum dissolution and subsidence

Gypsum dissolves rapidly in flowing water at a rate approximately 100 times faster than limestone. At Ripon Parks, 5 km north of Ripon, a 3 metre cube of gypsum which fell into the River Ure dissolved almost completely in only 14 months (James et al. 1981).

In the Ripon area there is considerable groundwater flow from the high ground, both to the west and east of the town, down to the Ure Valley. Here the water emerges into the gravels of the buried valley system. Water moves readily down dip towards the valley through the two limestone formations and their overlying gypsum beds. Water also percolates through the Sherwood Sandstone and escapes into the Ure valley through the Permian sequence. Evidence for this water movement comes from numerous springs and from the calcareous tufa cemented gravels in the buried valley system near Ripon (Abraham 1981; Morigi & James 1984). Sulphate-saturated groundwater found in boreholes near Ripon Race Course (Cooper 1986) also indicates the passage of water through the gypsum beds.

The phreatic flow of groundwater through the rock dissolves the gypsum mainly along the joints. This has produced a cave system in the gypsum with caverns at the intersections of the joints (Cooper 1986). As the dissolution of the gypsum continues at a rapid rate the caverns enlarge, amalgamate, become unstable and ultimately collapse. The dates and locations of historically recorded subsidences are shown in Fig. 10. When failure of the cavity roof occurs a breccia pipe may work its way up to the surface causing subsidence features to develop (Cooper 1988). These range from slight sagging, to small crown holes with large voids beneath, through to complete catastrophic collapse (Fig. 2). The larger subsidences may be up to
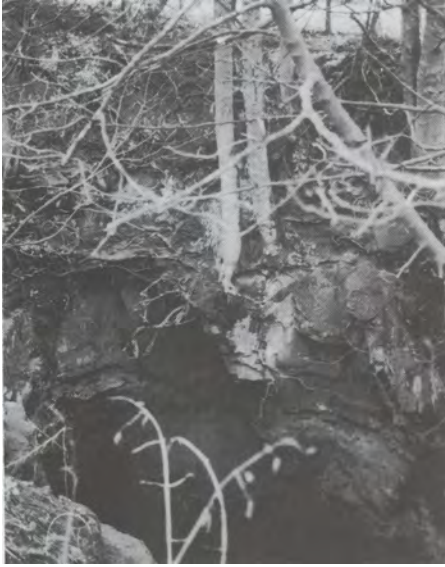
FIG. 3. Subsidence hollow formed in July 1834 near Ripon Railway Station [SE 3186 7260]. The cylindrical hollow is 14 m in diameter and 15 m deep with red Sherwood Sandstone exposed in its sides.

20 metres deep and 30 metres across. Some of the large failures have been felt as very local earthquakes caused by the roof plug of rock dropping into the cavity.

The physical nature of the major subsidence hollows depends on the surface geology. Cylindrical shafts generally form where rock is present at the surface (Fig. 3), but failure of the sides in superficial deposits causes conical depressions to develop (Fig. 4). These subsidence features occur in a linear or

FIG. 4. Subsidence hollows at Corkscrew Pits [SE 320 732] Hutton Conyers. These pits are shown on Figs 6B, 7B & 8 near the caravan site.

grid-like pattern directly related to the joint-controlled cave system beneath (Cooper 1986).

Once initiated the cave systems appear to maintain some water flow even after a collapse has occurred. Consequently areas adjacent to or in line with known subsidence hollows are more at risk from future subsidence.

Anomalies associated with the subsidence

The initial 1980–81 survey and the study by Cooper (1986) showed that in addition to the obvious subsidence features outlined above, subtle variations in soil colour and vegetation occurred related to incipient subsidence. A geophysical survey (resistivity and EM31 conductivity) was carried out during 1981 near Hutton Conyers (in the field behind the far subsidence hollow of Fig. 4). This survey failed to identify any definite underground cavities, but did show considerable variation in soil moisture content which could possibly manifest itself in vegetation variations. Excessively wet areas were found associated with incipient subsidence hollows and a very dry area, possibly related to better drainage over a cavity, was also noted.

The fact that the subsidence relates to jointing and commonly forms a strong rectilinear pattern is also useful. It implies geophysical, soil and vegetation anomalies in line with known subsidences are more likely to be related to the subsidence pattern than to be caused by other means. These lines of evidence suggested that airborne multispectral scanning (MSS), which might pick out slight soil or vegetation changes, could be a useful survey instrument to locate incipient subsidence features.

Airborne multispectral scanner survey

Field conditions

The Ripon area was surveyed in the spring and autumn of 1986. The NERC Piper Chieftain aircraft carried the Daedulus scanner and a conventional stereo air photography camera. Details of the aircraft, scanner and NERC remote sensing programme are given by White (1986) and Williams (1984). The potential of the multispectral scanner and other remote sensing methods to detect subsidence are briefly reviewed by Edmonds, Kennie & Rosenbaum (1987).

The Ripon multispectral survey was multitemporal, flown in the spring and autumn, to look at the vegetation during periods of maximum stress. The survey flights were all made in a north–south direction. While the surveys were being flown ground data was also gathered and noted on 1:10 000 scale

maps. This involved recording the types and heights of crops, areas of puddles or dampness, areas of poor crop growth and any other abnormalities such as manure heaps which could give misleading results.

The spring survey was initiated on 13 May 1986 when two runs of data were gathered. Because of heavy cloud cover the area was re-flown on 16 May and three more runs were collected. During this period the weather conditions had been very wet; consequently, numerous wet areas and puddles of standing water were present. Approximately 60% of the survey area had fields of winter barley up to 40 cm high, 20% of the area was grazing land, 10% ploughed and the remaining 10% potatoes, rape in flower and other crops.

The five runs of autumn data were gathered on 11 September 1986. Soil conditions were dry, visibility was good and there was patchy cloud. The 60% of the area down to winter barley had mainly been harvested leaving stubble and burnt stubble, with some 10% of the total area already ploughed and re-sown. The 20% of the area down to grass was well cropped and parched with yellowed areas. Most of the potato and beet fields were being harvested and the rape fields were stubble.

Scanner details and data resolution

The Daedulus AADS 1268 ATM scanner collects an image of the ground in electronic form recording eleven channels of data on high-density digital tape. These channels cover the visible, near infra-red and thermal part of the electromagnetic spectrum (Table 1) (White 1986; Williams 1984). The scan angle (+43°) and instantaneous field of view (2.5 mrad) are constant so that swath-width and resolution of the instrument is largely dependent on the height at which it is flown. The Ripon area was surveyed from a height of around 800 m giving a resolution of 1.5–2.0 m on the ground (Fig. 5); this was the
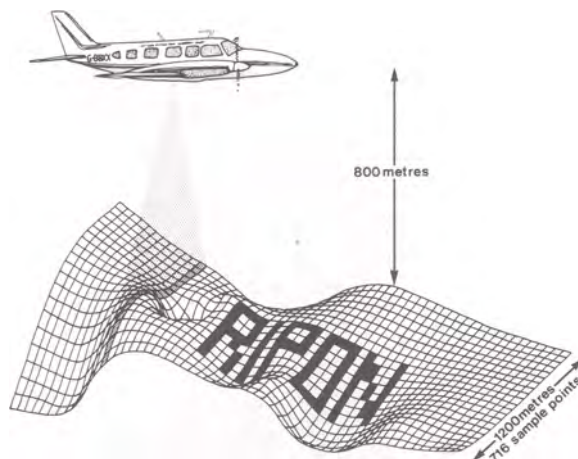

FIG. 5. Data collection using an airborne multispectral scanner. Aircraft height about 800 m, swath width about 1.2 km, sample point size 1.5–2.0 m, 11 channels of data (Table 1). The scanner sweeps in lines 716 sample points wide across the ground as the aircraft moves forward.

maximum resolution for the 1986 scanner campaign. Thus for each sample point of approximately 1.5–2 metre square, eleven channels of data were collected, each channel recording the average intensity of reflected or emitted radiation over a narrow spectral band for the sample point. Each swath was 716 pixels or sample points wide giving a ground width of about 1.2 km. The high resolution was essential to pick out the smaller subsidence features which the initial field survey showed to be upwards of 1.5 m in diameter. The collection of scanner information at this high resolution produces a very large data-set. Consequently only a small area of about 6 km^2 was collected by the Ripon survey. After collection the electronic data was processed into a standard digital form on computer compatible tape by Hunting Surveys Ltd. These digital recording were then re-constituted by computer as television pictures with each pixel representing an approximate two metre square sample point on the ground.

Data processing

The digital data was processed and studied at BGS Keyworth using the VAX 8600 computer coupled with an International Imaging Systems (I^{2}S) Model 75 image processor. A photographic record of the computer enhanced results was made using either a Dunn 633 microcolour camera attached to the I^{2}S Model 75 or a conventional camera photographing the monitor screen. An Optronics colour film writer remotely situated at Swindon was also used.

Each of the ten data runs was visually assessed in unenhanced form using single wavebands and various

TABLE 1. *Daedulus 1268 11 channel multispectral scanner*

Band	Band widths (μm)		
1	0.42–0.45	Blue	
2	0.45–0.52		
3	0.52–0.60	Green	Visible
4	0.605–0.625		
5	0.63–0.69	Red	
6	0.695–0.750		
7	0.76–0.90		
8	0.91–1.05		Infra-red
9	1.55–1.75		
10	2.08–2.35		
11	8.5–13.0		Thermal IR

FIG. 6. (A) Multispectral scanner image of subsidence hollows in the area south of Low Common Farm and north of Ripon Clock Tower (see Fig. 10 for location and Fig. 7A for explanation). This image was gathered under complete cloud cover. It uses bands 11, 9, 10 and is scaled giving a false colour image that shows water filled hollows as red on a purple-green background. This band combination also shows vegetation changes in subdued subsidence areas. This image has slight oblique distortion (Fig. 10). (B) Multispectral scanner image of subsidence hollows near Hutton Conyers (see Fig. 10 for location and Fig. 7B for explanation). This image uses bands 7, 11, 5. It was gathered in full sunlight and has been scaled. The false colour image shows variations in soil and vegetation. Compare with Fig. 8 of the same area.

waveband combinations. The most promising com-binations of wavebands were then used, simply scaled (a digital stretching enhancement using the standard I²S techniques) and visually re-assessed to see what subsidence features could be found. Areas of

interest were then outlined and selectively scaled to bring out the maximum amount of detail from the images. Details in sub-areas of the images were sharpened using the I²S cubic convolution zoom facility. Some of the images with patchy cloud shadow
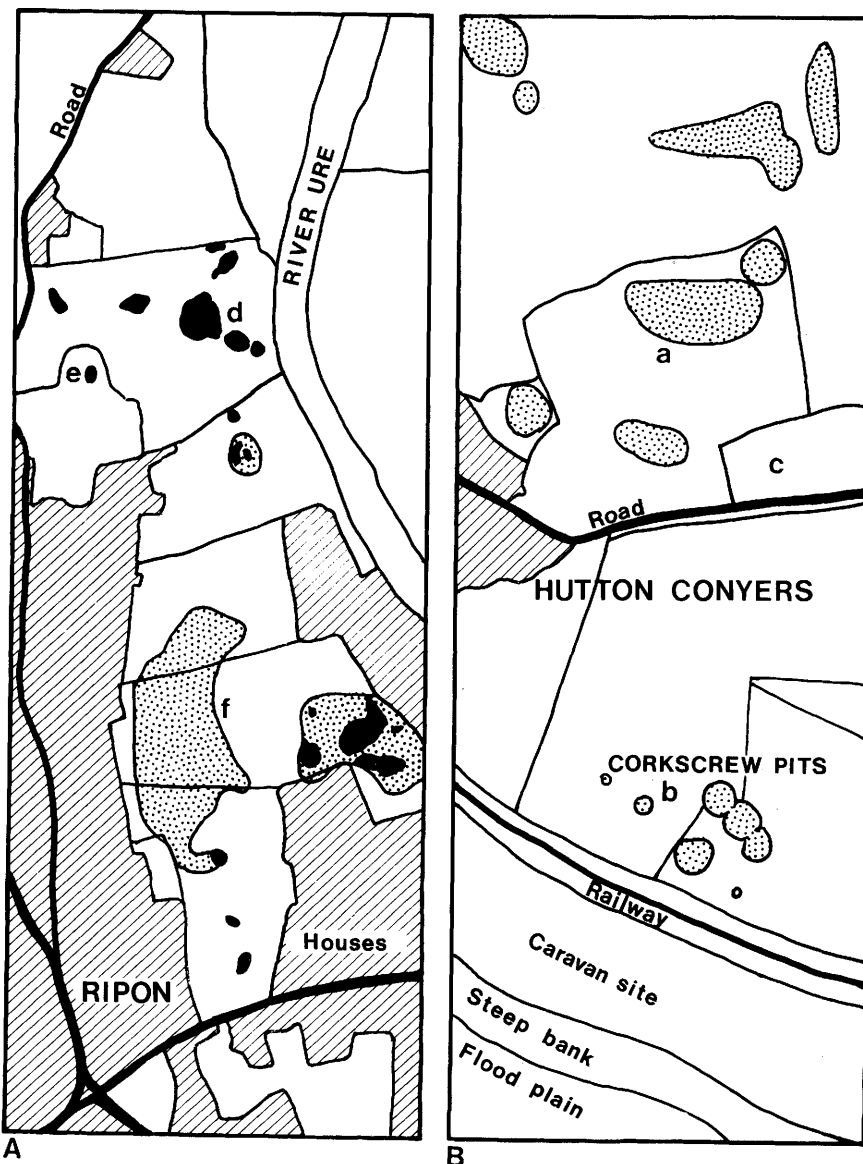
FIG. 7. Explanation to Figs 6A and 6B; black areas, water filled subsidence hollows; stippled areas, subsidence hollows shown by vegetation changes; diagonal line ornament, mainly houses, roads and industrial sites. a, healthy vegetation (grass-coloured red) with rough grass and tipped material in adjacent subsidence hollow; b, slight vegetation variation (winter barley) showing incipient subsidence hollow in line with marked subsidence hollows; c, uniform vegetation masking subsidence hollow; compare with Fig. 8; d, line of water-filled subsidence hollows; e, water filled subsidence hollow surrounded by trees; f, vegetation variation (grass and rough pasture).

were difficult to process and generally the dark areas were best avoided.

For one run of data, secondary images consisting of hybrid colour ratio composites were made by Dr. F. M. W. Hopper, but in fact did not show much greater detail in the subsidence areas.

Results from various waveband combinations

For all ten runs 'near natural' colour combinations (bands 5, 3 and 2 in red, green and blue respectively) were assessed, scaled and selectively scaled. These

images showed soil colour changes due to lithology and moisture variation on both the spring and autumn surveys in addition to areas of poor germination in the spring crops; areas of water in subsidence hollows showed as shades of grey. Numerous subsidence features were delineated from these images including some not already known from the field survey (Fig. 9B).

The false colour combination using the near infra-red, thermal and red wavebands (bands 7, 11, 5) showed considerable scope for identifying vegetation variations (Fig. 6B). With this band combination healthy vegetation shows red on the images (Fig. 6B and Fig. 7B, a) and cold areas of water show black; water-filled subsidence hollows being particularly clear. The spring-flown images were generally better than the autumn ones for crop detail, the winter barley showing some variation (Fig. 6B and Fig. 7B, b) but the autumn stubble none. In retrospect surveys during spring and summer may have provided more detail for areas heavily cropped with winter barley. The images of short and parched grassland taken in the autumn showed considerable variation and numerous details of the subsidence features.

Some of the runs of data collected in the spring had considerable cloud cover, resulting in fairly dull images in the visible and near infra-red wavebands. These images, however, provided more detail in the thermal and far infra-red wavebands. A combination of bands 11, 9, and 10 showed water filled subsidence hollows with a red colour on a general background of green or purple-green for vegetation (Fig. 6A and Fig. 7A, d). This waveband combination also detected water in deep subsidence hollows surrounded by trees and enveloped in shadow (Fig. 6A and Fig. 7A, e). Vegetation variations in subsidence areas also showed up well (Fig. 6A and Fig. 7A, f).

When satisfactory enhanced results were produced they were photographed to make hard copies. These were then studied and the subsidence features transferred to a 1:10 000 scale map. Figure 9B shows all the subsidence features delineated using only the MSS survey technique.

Subsidence and geological features identified by the MSS survey

When compared with the known distribution of subsidence hollows (Cooper 1986) it was found the majority were detected by the MSS survey. In addition new definite or probable sites of subsidence were identified. These include linear belts of soil and vegetation anomalies along Skittergate Gutter [SE 320 714], near High Common Farm [SE 310 726] and east of Ure Bank [SE 326 725]. South of Low Common Farm [SE 313 721] the MSS survey also showed details of individual subsidence areas within a large subsidence hollow (Fig. 6A and Fig. 7A, f); this detail

was not apparent on the air photographs. Approximately 30% of known subsidence hollows were not detected by the MSS survey. These included numerous hollows in the vicinity of Ripon Golf Course [SE 311 732] where the vegetation pattern was confused by greens and bunkers. Of the other hollows not detected many were surrounded by trees or in shadows at the edges of woods. However, some water-filled hollows in these situations were identified by the thermal and far infra-red wavebands (Fig. 6A and Fig. 7A, e). Hollows in built-up areas were impossible to detect using the MSS technique. Some pronounced hollows in uniform green fields also proved to be blind to MSS surveying due to the lack of shadow effects and uniformity of the grazed vegetation (compare Figs 6B and 7B, c with Fig. 8). Some bare fields of soil also showed an apparent uniformity even when they contained subsidence hollows.

As a tool for general geological mapping in this lowland Permo-Trias and Quaternary terrain MSS proved disappointing. The area of river alluvium could vaguely be distinguished, especially where recent floods had left braided gravel deposits. One area known to be very well drained glacial sand and gravel also showed as a soil anomaly. In general no definite geological boundaries could be discerned. The two-dimensional images of fairly uniform farm land were inferior to the stereoscopic photographic images of the same areas.

Stereo air photograph survey

Conventional stereoscopic aerial photographs were taken during the multispectral scanner survey. These photographs in monochrome were very detailed with a print scale of between 1:4000 and 1:5000. Due to the low level at which the survey was flown the resolution of these photographs was exceptional (0.2–0.3 m) (Fig. 8) with details as small as individual molehills in fields visible. This compares with the 1.5–2.0 m resolving power of the MSS survey. The stereo air photographs were assessed using a Wild stereoscope; the results of this analysis being shown in Fig. 9A. The stereo photographs picked out most of the marked subsidence hollows even in built up areas, in some areas with tree cover, and on Ripon Golf course. They also showed subtle hollows in uniform areas of grass and barley and most of the water-filled hollows were readily indentified because of different reflections of light on adjacent photographs. Unlike the MSS survey the air photographs were usable even with areas of patchy cloud shadow.

The stereo air photography also identified much of the glacial and recent geology of the Ripon area. The most marked feature, the flood plain of the River Ure and its tributaries, was obvious because of its flatness and marginal features (bottom of Fig. 8; see Fig. 7B

◄—Z———————   100m

FIG. 8. Stereo pair of photographs of subsidence hollows near Hutton Conyers (see Fig. 10 for location). Note also the bluff and alluvial flat just below the caravan park at the bottom of the photographs. To view this use a pocket stereoscope or hold a 15 cm high piece of grey card vertically between the two photographs in line with your nose, stare at the photographs, but let your eyes relax. You should see three images with the central one in 3D.

for explanation). The river terraces and fluvio-glacial terraces were also discernible even where affected by subsidence or covered with housing. Areas of till with their undulating topography were recognizable, but this morphology becomes intermingled with the subsidence features. No geological map is presented here because the results are already published as BGS 1:10 000 scale map SE 37 SW.

Conclusions

The pattern of subsidence determined by this study is clearly better than that recorded from the field survey alone (Cooper 1986). The MSS survey picked out the general pattern of subsidence hollows and revealed details within the subsidence areas, defined by variations in vegetation, that were not visible on the
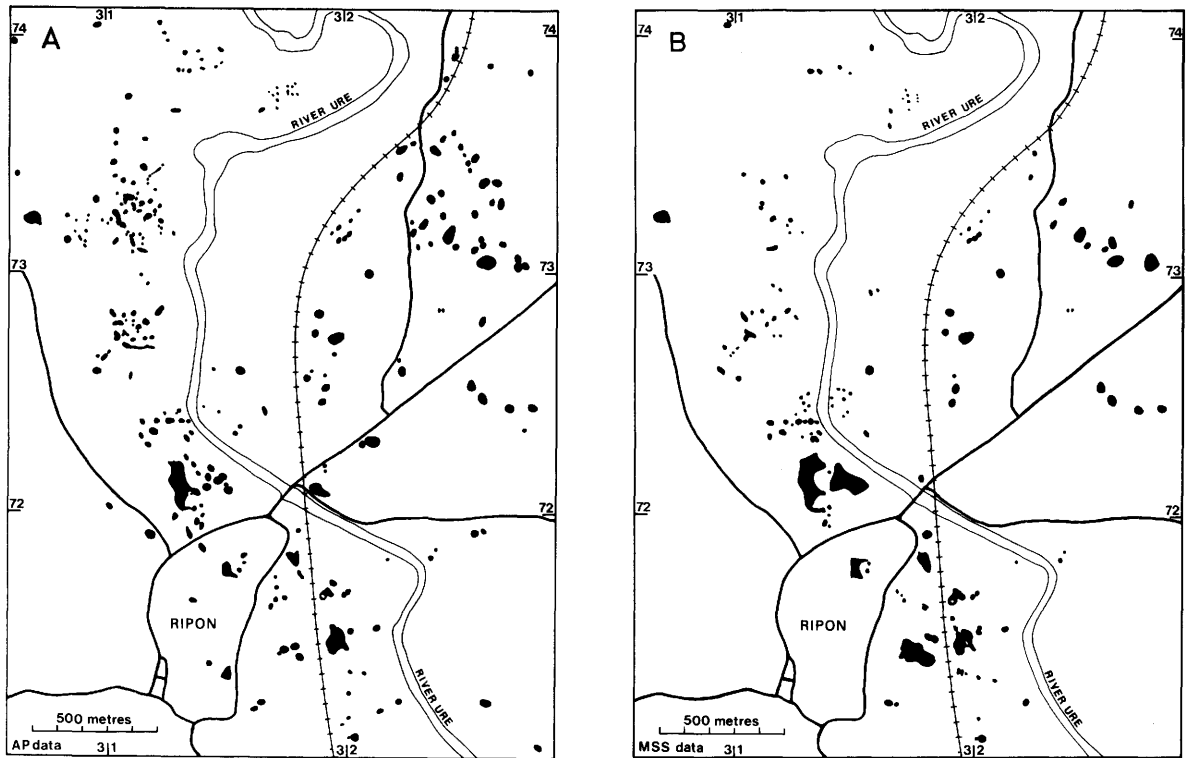
FIG. 9. (A) The subsidence pattern derived from stereo air photograph data. (B) The subsidence pattern derived from MSS data.

air photographs (Fig. 6A and Fig. 7A, f). Generally the images obtained in full sunlight yielded the best results (Fig. 6B), although one image gathered under complete cloud cover showed considerable detail in the far infra-red and thermal parts of the spectrum (bands 11, 9, 10). This image was particularly useful for delineating water-filled subsidence hollows (Fig. 6A and Fig. 7A, d, e). In a few places there were discrepancies between the MSS, air photograph and field surveys; these were checked on the ground. The problems mainly arose with the coarser resolution of the MSS data; for example, this was inadequate to identify an area of coarse vegetation around a telegraph pole [SE 3204 7318].

For most of the area (Fig. 9A) the stereographic air photograph survey yielded quicker and better overall results than the MSS survey (Fig. 9B). The recent air photographs were of a larger scale, exceptionally high quality and would not have been available if the MSS survey had not been undertaken.

Combining the information obtained by the MSS, air photograph and field surveys with the historical data gives the most accurate map of the subsidence pattern (Fig. 10). For completeness Fig. 10 includes some subsidence areas in the built up part of Ripon determined by Griffin (1986) from a building

subsidence damage survey. A new record of a recent subsidence hollow [SE 3133 7182] 5 m long, 3 m wide and 3 m deep which formed on 31 March 1987 is also included. Now the groundwork has been done it would be possible to map accurately many of the subsidence features remotely in the rest of the 100 km long subsidence belt.

The techniques described here could also be applied to other natural and man-made subsidence features. In limestone the dissolution is largely bedding and joint-controlled, commonly resulting in rectilinear cave systems; in the chalk the rock is more permeable and dissolution is less controlled by jointing (Culshaw & Waltham 1987). Over both lithologies subsidence can occur and these techniques could be used to define the subsidence pattern. The methods are also potentially applicable to the assessment of subsidence patterns over shallow mineral workings.
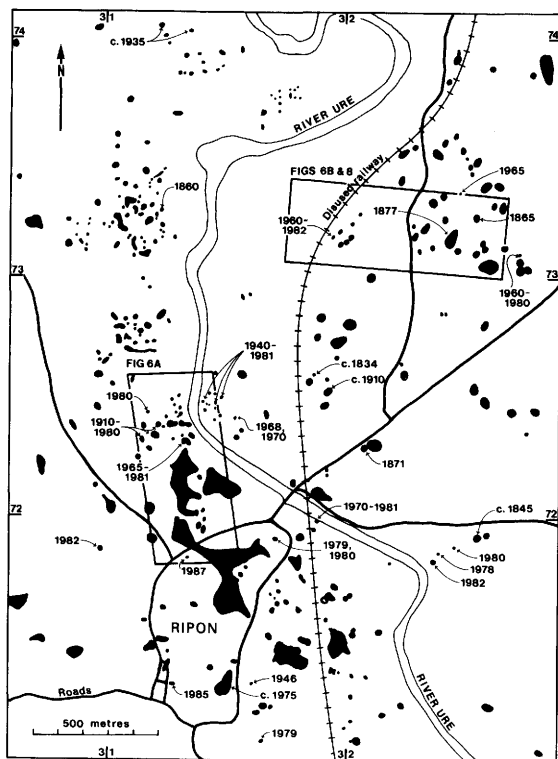
FIG. 10. The distribution of subsidence hollows in the Ripon area with dates of subsidences where known (updated from Cooper 1986). The areas of Figs 6, 7 & 8 are shown as inset boxes).

References

ABRAHAM, D. A. 1981. The sand and gravel resources of the country west of Boroughbridge, North Yorkshire. Description of the 1:25 000 resource sheet SE36. *Mineral Assessment Report, Institute of Geological Sciences*, **78**.

ALDRICK, R. J. 1978. The hydrogeology of the Magnesian Limestones in Yorkshire between the River Wharfe and the River Aire. *Quarterly Journal of Engineering Geology* **11**, 193–201.

COOPER, A. H. 1986. Subsidence and foundering of strata caused by the dissolution of Permian Gypsum in the Ripon and Bedale areas, North Yorkshire. *In*:

HARWOOD, G. M. & SMITH, D. B. (eds.). *The English Zechstein and Related Topics*, Geological Society, London, Special Publication **22**, 127–138.

—— 1988. Subsidence resulting from the dissolution of Permian gypsum in the Ripon area; its relevance to mining and water abstraction. *In*: BELL, F. G., CULSHAW, M. G., CRIPPS, J. C. & LOVELL, M. A. (eds) *Engineering Geology of Underground Movements*, Geological Society, London, Engineering Geology Special Publication **5**, 387–390.

CULSHAW, M. G. & WALTHAM, A. C. 1987. Natural and artificial cavities as ground engineering hazards. *Quarterly Journal of Engineering Geology* **20**, 139–150.

EDMONDS, C. N., KENNIE, T. J. M. & ROSENBAUM, M. S. 1987. The application of airborne remote sensing to the detection of solution features in limestone. *In*: CULSHAW, M. G., BELL, F. G., CRIPPS, J. C. & O'HARA, M. (eds) *Planning and Engineering Geology*, Geological Society, London, Engineering Geology Special Publication **4**, 125–132.

GRIFFIN, D. A. 1986. *Geotechnical assessment of subsidence in and around Ripon, North Yorkshire due to natural solution*, MSc Dissertation, University of Newcastle upon Tyne.

JAMES, A. N., COOPER, A. H. & HOLLIDAY, D. W. 1981. Solution of the gypsum cliff (Permian, Middle Marl) by the River Ure at Ripon Parks, North Yorkshire. *Proceedings of the Yorkshire Geological Society*, **43**, 443–450.

MORIGI, A. N. & JAMES, J. W. C. 1984. The sand and gravel resources of the country north-east of Ripon, North Yorkshire. Description of 1:25 000 sheet SE37 and part of 47. *Mineral Assessment Report, Institute of Geological Sciences*, **143**.

MOSSOP, G. D. & SHEARMAN, D. J. 1973. Origins of secondary gypsum. *Transactions of the Institute of Mining and Metallurgy*. **82,**B147–154.

SMITH, D. B. 1972. Foundered strata, collapse breccias and subsidence features of the English Zechstein. *In*: RICHTER-BERNBURG, G. (ed.) *Geology of Saline Deposits*. Proceedings of the Hannover Symposium (Earth Sciences 7), Unesco, Paris, 255–269.

—— 1974a. Permian. *In*: RAYNER, D. H. & HEMINGWAY, J. E. (eds.). *The Geology and Mineral Resources of Yorkshire*, 115–144. Yorkshire Geological Society.

—— 1974b. The stratigraphy and sedimentology of the Permian rocks at outcrop in North Yorkshire. *Journal of Earth Sciences, Leeds Geological Association*, **8**, 365–386.

——, HARWOOD, G. M., PATTISON, J. & PETTIGREW, T. H. 1986. A revised nomenclature for Upper Permian strata in eastern England. *In*: HARWOOD, G. M. & SMITH, D. B. (eds.). *The English Zechstein and Related Topics*, Geological Society Special Publication **22**, 9–17.

WHITE, S. J. 1986. NERC airborne remote sensing programme for 1986. *NERC News Journal*, **3**(10), 14–17.

WILLIAMS, D. F. 1984. Overview of the NERC airborne thematic mapper campaign for September 1982. *International Journal of Remote Sensing* **5**, 631–634.