EUROPEAN COMMISSION
Research Executive Agency

SEVENTH FRAMEWORK PROGRAMME

Seventh Framework Programme
Cooperation: Space Call 3
FP7-SPACE-2010-1

Grant Agreement: 262371

GMES
Observing our planet for a safer world

PanGeo

Enabling Access to Geological Information in Support of GMES

Geohazard Description for Lyon
[Version 1]

[21 novembre 2012]

Dissemination Level:	Public	
Author:	Olivier Renault, BRGM	Date: 21/11/2012
Checked by (WP Leader):	Luke Bateson, BGS	Date: 17/1/2013
Date of Issue:	17/1/2013	

CHANGE RECORD

Version X.X of [Date] to Version X.X of [Date]

Section	Page	Detail of change

TABLE OF CONTENTS

Change Record

1 AUTHORSHIP AND CONTACT DETAILS

Olivier Renault – BRGM Rhône-Alpes – 151 boulevard de Stalingrad – 69 626 Villeurbanne Cedex - FRANCE
Tél : 0033 +4 72 82 11 52
Email : o.renault@brgm.fr

2 INTRODUCTION

The city of Lyon is situated in the Rhône department in Rhône-Alpes region. Its urban area namely "Grand Lyon", that concerns the major part of the zone of study, includes 58 municipalities. It is the third urban district of France in terms of importance and number of inhabitants (approximately 1.3 million inhabitants). The main economic resources of the city are the chemical and oil industry as well as the pharmaceutical industry. It is at the same time an industrial metropolis and an unusual city with it's « traboules" (passages from a house to the other one) or its underground cavities. In edge of the Saône river, around the cathedral Saint Jean, extends the district of Old Lyon, classified in the world heritage of the humanity by Unesco in 1998.

From a geographical point of view, the urban area has been developed around the confluence of two streams: the Rhône and the Saône river (Cf. Fig1 and 2). The "Grand Lyon" can be divided into three different topographic zones:

- On the West, the last foothills of the oriental edge of Massif Central, presenting some reliefs, in particular the Fourvière tray, the Croix Rousse hill, the Lyon tray and Millery tray ;
- In the East, the Rhone collapsed ditch establishes a big plain (plain of Lyon and the East plain) limited on the West by the Saône river and the Rhône river at the South of the confluence ;
- In the North, a small "cuesta" relief leaned in the Massif Central: it is the Mont d'Or hills which are separated of the Dombes tray by the Saône River; the dombes tray correspond to the south end of the Bressan ditch.

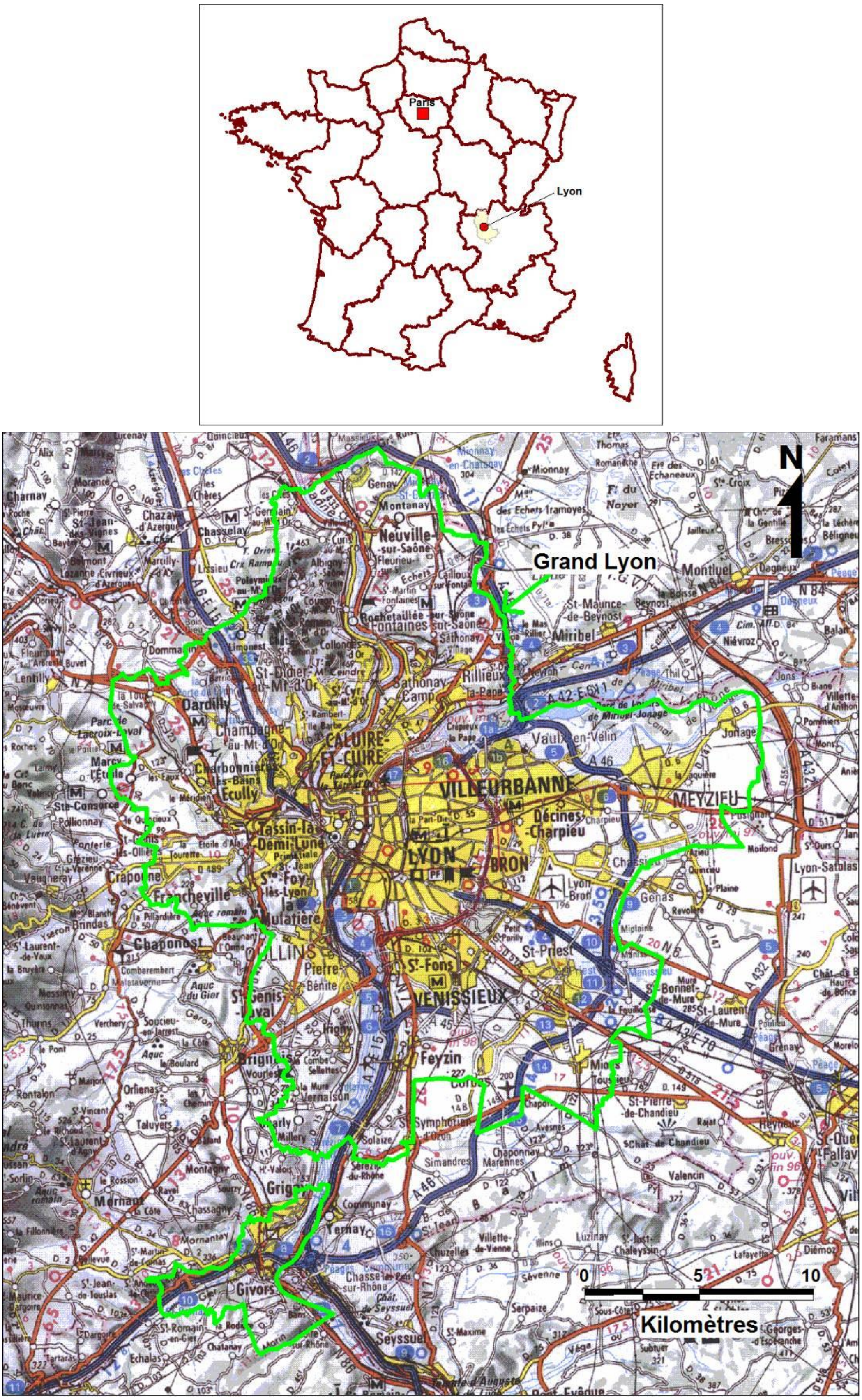

Figure 1 : Geographical frame of Lyon

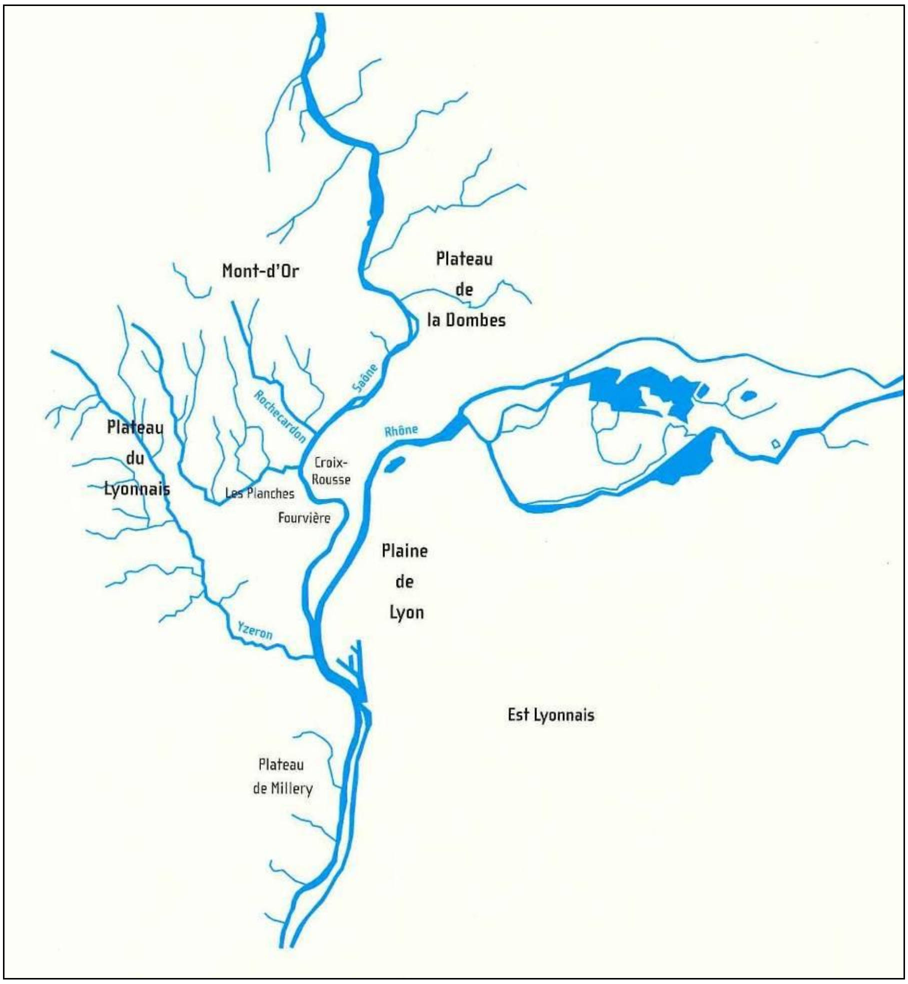

Figure 2 : Hydrographic frame and morphological entities of the Lyon urban district (Source : N. Mongereau)

From a structural point of view, the city of Lyon is situated between the oriental border of the Massif Central and the collapsed structure of the Rhône valley (Cf. figure 3). This geologic situation confers on the city a varied geology.

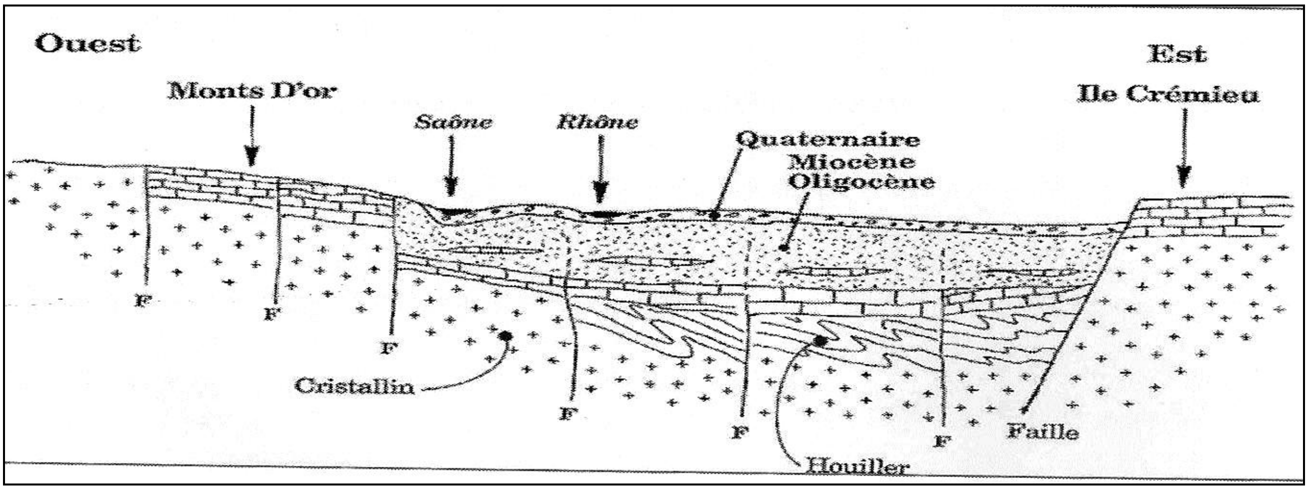

Figure 3 : Schematic cross section of the ditch of Lyon (Source : N. Mongereau)

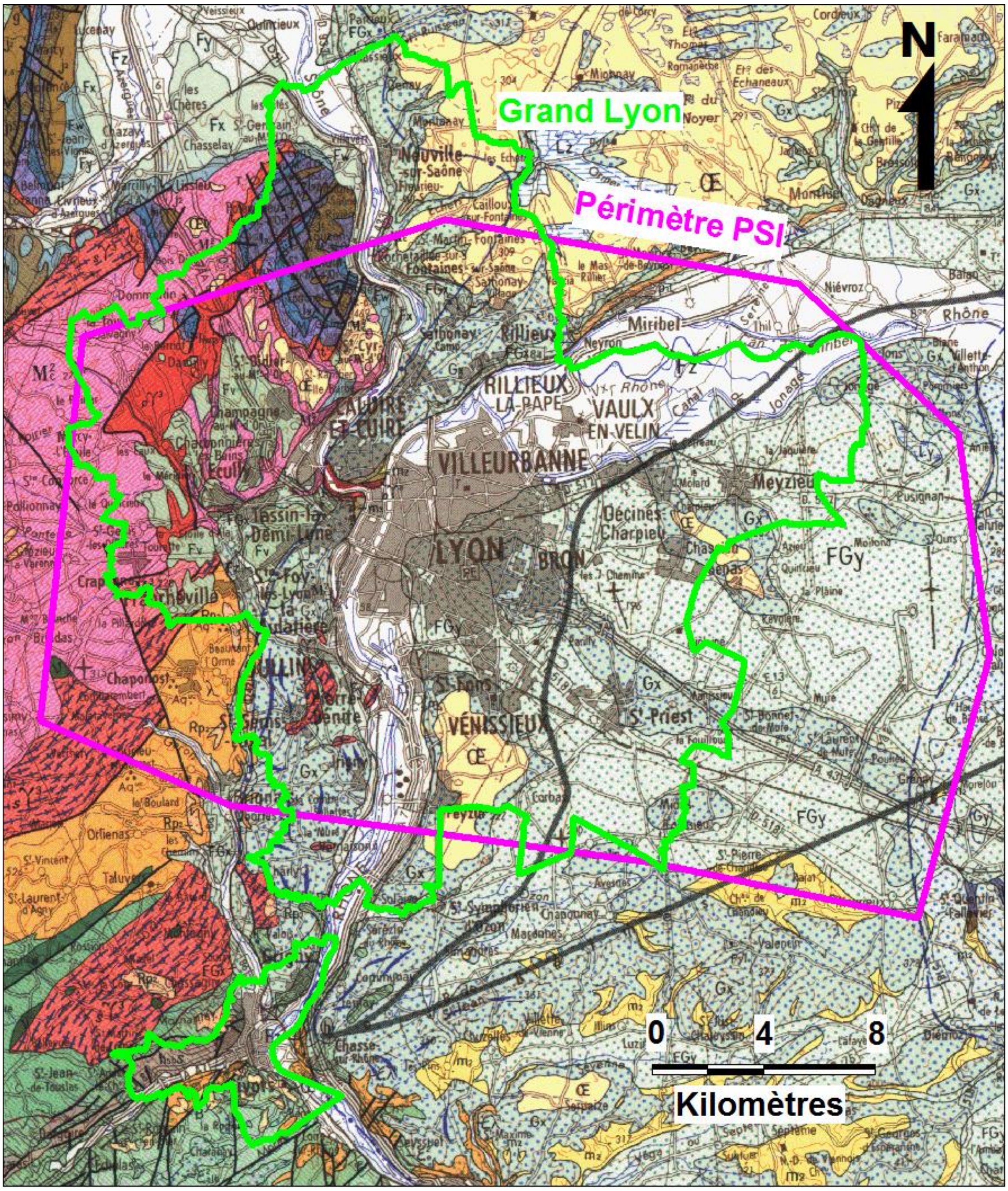

Figure 4: geological map of Lyon on the scale of 1/250 000

The rocks met within three big morpho-structural domains are the following ones (Cf. figure 4) :

- metamorphic and plutonic rocks - Granites, anatextites, leptynites - (M2c, λ, $\rho\Upsilon^3$, $s\Upsilon^3$) mainly on the west of the Rhône and the Saône rivers belonging to the border of the Massif Central. These rocks are sometimes covered by an important tertiary and quaternary thickness of gravels, sands and clays resulting from their dismantling (Rp2, Fv, Fw, Fx) and by silt (Œ). In border of Massif central, Miocene molasse (“smooth” sandstone) and pudding stones (m2, m3) appear locally on small surfaces.

- recent alluvia (Fz), mainly found in the major bed of the Rhône and the Saône river. These alluvia are mainly of sandy/rocky nature, what does not exclude clayey levels.
- Alluvia from quaternary glacial periods (FGy, FGx, Gx) who recover all the east Lyon plain. The composition of these entities is variable and always includes a sandy and rocky fraction mixed with some clay. These materials result almost exclusively from the dismantling of the alpine chain which is nearby of 150 km on average. These geological entities are covered locally by silt (Œ), in particular on the Dombes tray.

Noteworthy is the presence of a small relief in cuesta in the North of the urban area in the Monts d'Or hills. This geologic structure, leaned in Hercynian formations of the Massif Central consists of an alternation of limestones, marls and stoneware from Trias (t), Lias (Ii, Ims, I9) and Jurassic (j1, j2, j3).

The analysis of the persistent radar reflectors (PSI) vertical speeds between 1991 and 1999 on a perimeter covering partially the Grand Lyon, reveals only 5 polygons of instability which are potentially due to the ground. The extension of these zones is very reduced. There is no vast zone revealing possible ground movements.

The main movement observed (PGGH_Lyon_01) during the covered period, concerns the collapse of the ground over the tunnel of Caluire-et-Cuire built between 1994 and 1999. The observed movements are however moderated by the order 1 to 3 mm / year between 1997 and 1999.

Other very punctual instabilities due to shrink-swell clays have been identified. Three identified cases (PGGH_Lyon_02, PGGH_Lyon_03, PGGH_Lyon_05) concern isolated buildings. These disorders have been located, either in a fortuitous way from speed analysis on the PSI or in correlation with the inventory of the damages realized for the establishment of the shrink-swell clays map of Rhône department. The interest of these results is limited because they represent a low fraction of the recorded disasters.

Endly, a likely case of compressible ground (PGGH_Lyon_04) was also located from a control of ground of the data PSI.

The data used to make this work were: the geologic map at 1/50 000 scale, the ground movement inventory of Rhône department as well as the shrink-swell clays map of the Rhône department. A bibliographical and data search has been made to try to estimate the deep structural context of the Lyon urban district, susceptible to be in connection with a subsidence effect of the Bressan / Rhone ditch. Unfortunately, there are no datum (geophysics or geologic) allowing highlighting the deep structural context.

Approximately 25 sites have been visually controlled because of high speeds anomalies. Globally, it emerges from this control that the majority of these anomalies are not related to ground movements but could be related to movements of structures themselves (especially, the structures with flat roofs and the metallic structures).

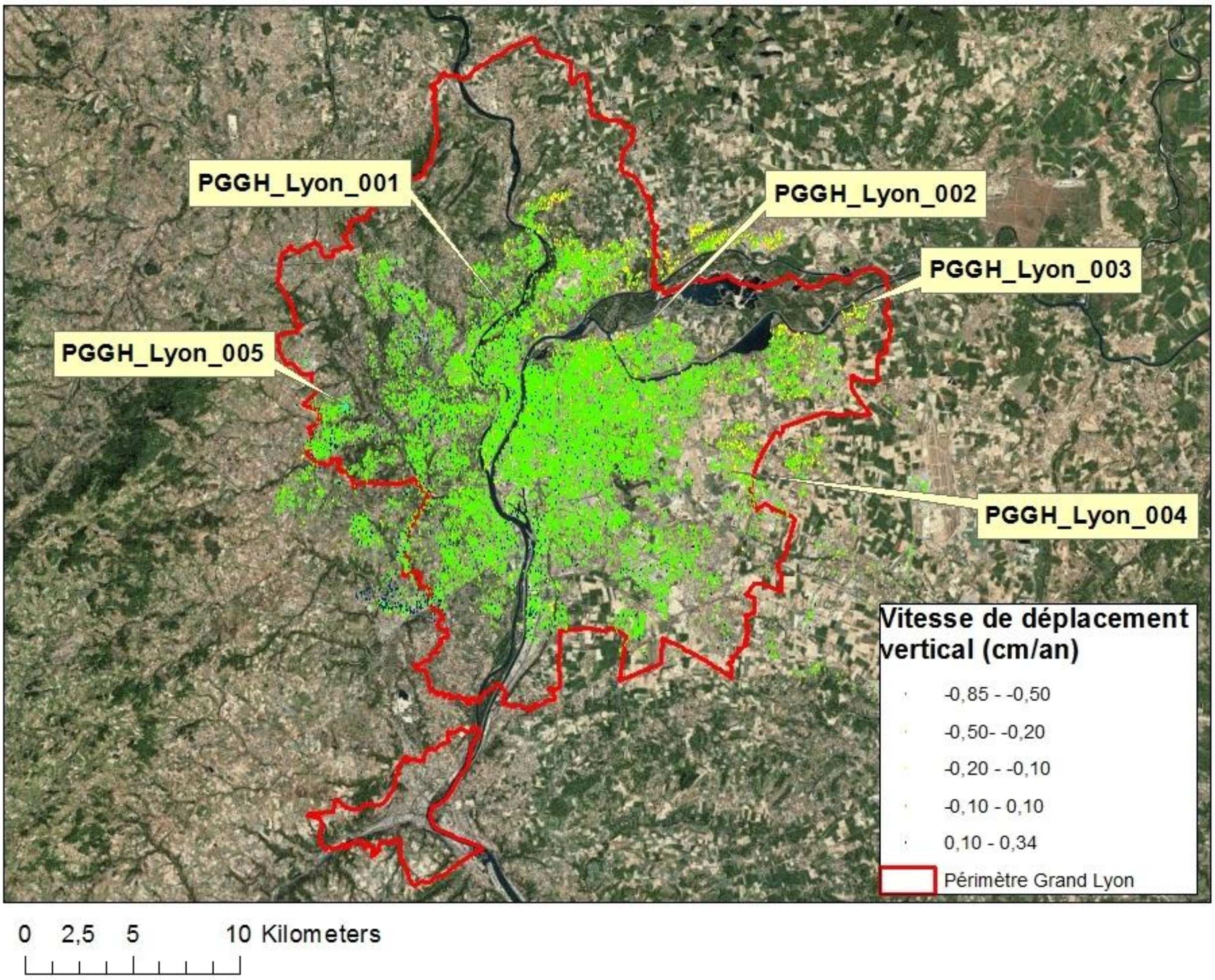

Figure 5 : Vertical speeds (cm/year)observed between 1991 and 1999 with positioning of the anomalies

Hills of Lyon can be concerned by small landslides. These landslides are often in connection with ageing or badly sized breast walls. The analysis of the PSI did not allow identify this kind of landslides described in the pre-existent database (www.bdmvt).

However, we shall notice that the speed anomalies (< -0.10 cm / year) mainly concern recent alluvia or alluvia from glacial period and also silt and loess. We cannot exclude that the increase of anomalies on these little compacted geological formations can be partially attributable on the ground; but there are no evidence – in most cases - of displacement on the structures, and if there is a soil contribution, it could be due to several different mechanisms (shrink-swell clays, compressible ground, etc.). We have also observed more anomalies of speed (<-0.1 cm/year) in the northeast of the urban area. The role of a subsidence of the Bressan / Rhone ditch has been examined but the structural data seem insufficient to connect this distortion with a natural phenomenon (structural faults affecting the deep structure). On the other hand, the location of these anomalies in border of the study zone leads to a doubt on the data reliability.

Generally speaking, we shall hold that, with the exception of 5 cases exposed below, the radar processing anomalies between 1991 and 1999 brings no certainty about the role - even limited - of the ground surface in the observed deformations.

3 PANGEO POLYGON ID 'PGGH LYON 001'

3.1 GENERAL PROPERTIES OF THE MOTION AREA

This deformation polygon corresponds to the ground collapse over the Caluire-et-Cuire tunnel that is part of the north Lyon beltway built between 1994 and 1999. The tunnel is on this section between the Rhône and the Saône River, about 2,650 km long. It has been dug largely under a residential zone situated in the municipality of Caluire-et-Cuire.

The geology met by the tunnel corresponds to gneisses and locally to the molasse (concrete sand) surmounted by a consequent thickness of glacial period alluvia and conglomerates (70 - 80 m).

The surface of the collapsed zone is about 0,16 km^2.

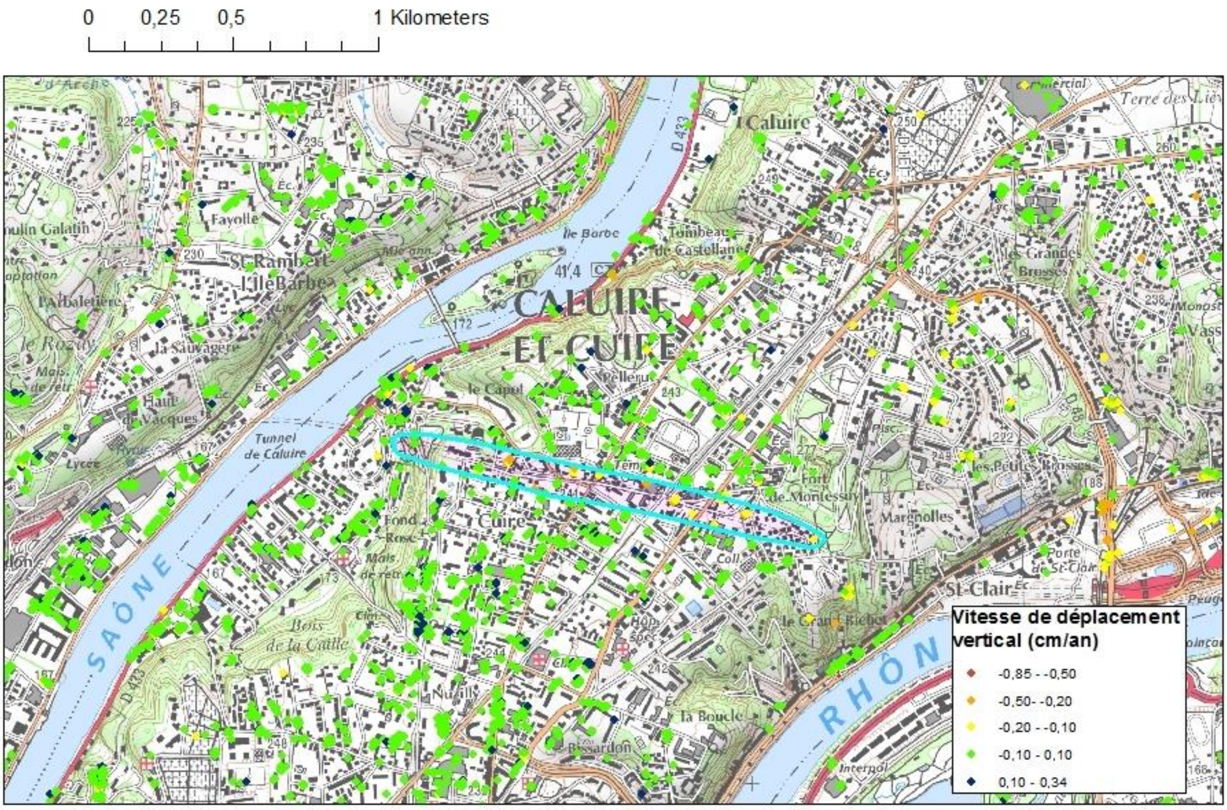

Figure 6 : Location of the anomaly PGGH_Lyon_01 on the IGN map in 1/25 000

3.2 SPECIFIC GEOHAZARD TYPE

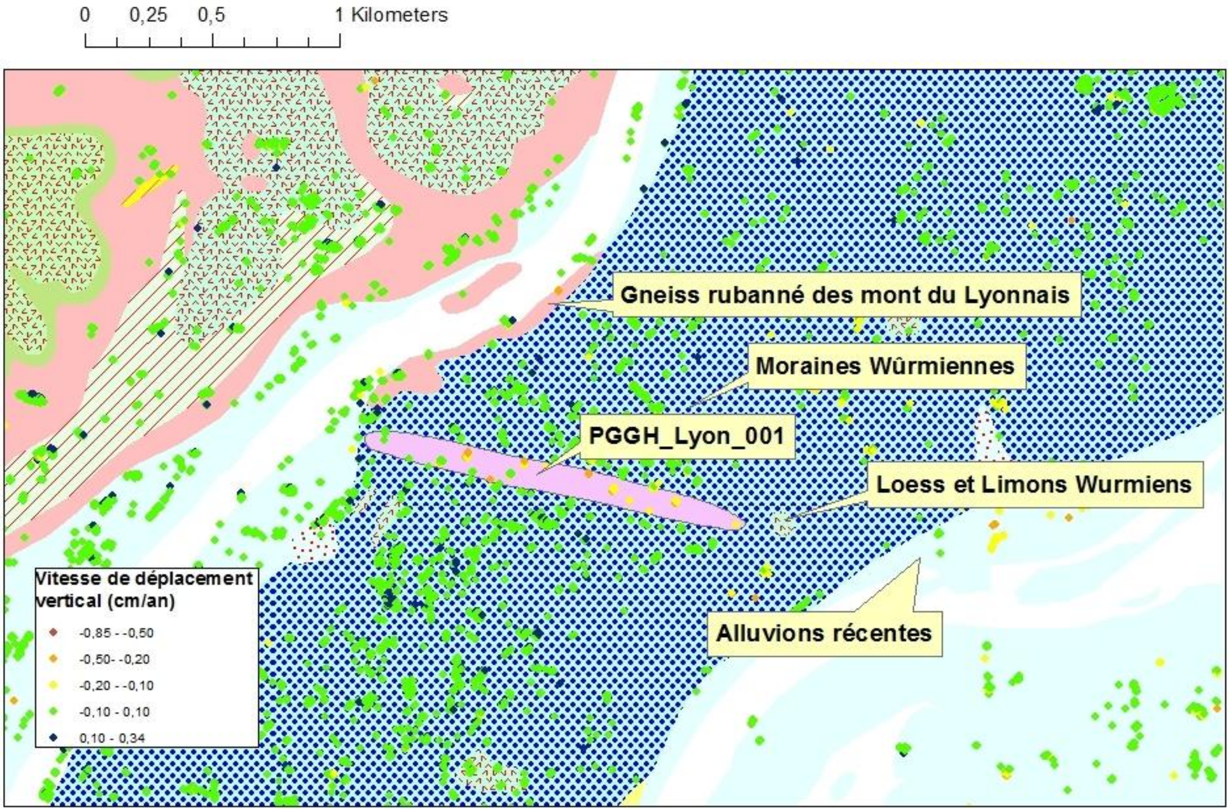

Figure 7: Location of the anomaly PGGH_Lyon_01 on the harmonized geological map

The observed ground movement is probably related to a collapse of the ground over the Caluire-et-Cuire tunnel during and after the phase of digging of the south and north tubes between 1994 and 1999. The observed speeds are generally included between 0.1 and 0.3 cm/ year.

3.3 THE DETERMINATION METHOD

The existence of a subsiding zone over the tunnel has been interpreted from the data PSI. These displacements had already been noticed within the framework of the project Terrafirma. A visual control allowed to notice light disorders on several buildings (Cf. fig. 8). However, it is not possible to connect with a good probability these disorders with the construction of the tunnel.

3.4 CONFIDENCE IN THE INTERPRETATION

We have good confidence in the interpretation because the pattern including the displacements overlaps well with the tunnel location. On the other hand, the displacements on PS are observed from 1997 and until 1999, what corresponds well to the period of realisation and completion of the tunnel.

3.5 GEOLOGICAL INTERPRETATION OF THE MOTION

The collapses over tunnels are rather frequent. In the present case, the tunnel was dug in the altered fringe of metamorphic rocks (mainly gneisses) with high pendage (70°) westward. It is possible that disorders occurred during the phase of digging, in particular during the realisation of the north tube which was dug by a tunneller from west to east between September 1994 and September 1996.

3.6 EVIDENCE FOR THE INSTABILITY

We shall find some photos of disorders observed on some buildings situated over the influence of the tunnel. We indicate that these disorders do not seem generalized. It is about light disorders (small cracks). The link of causality with the tunnel is not directly proved however.

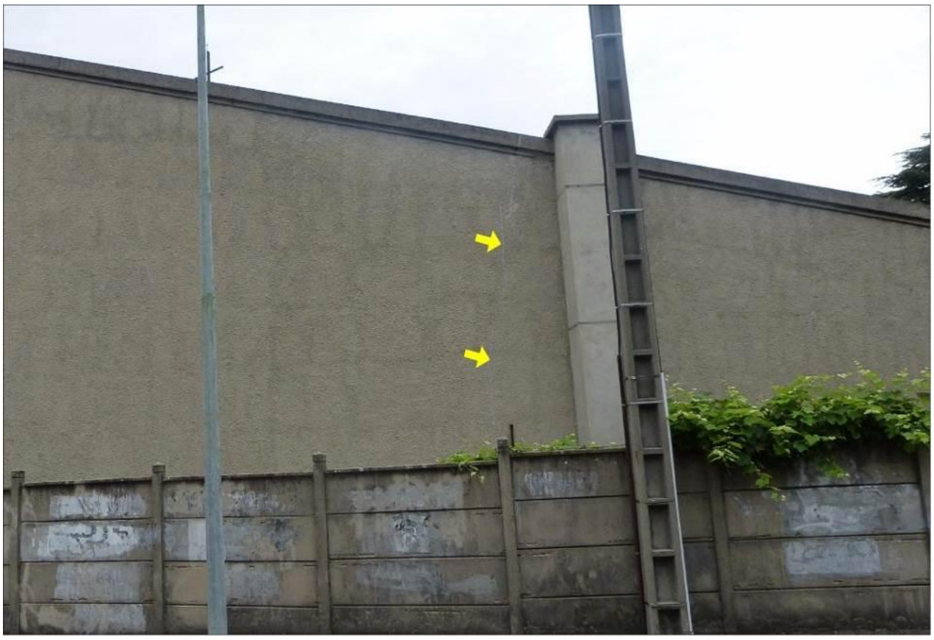

Figure 8 : photographs of the anomaly PGGH_Lyon_01

4 PANGEO POLYGON 'PGGH_LYON_002'

4.1 GENERAL PROPERTIES OF THE MOTION AREA

This zone of movement corresponds to an isolated phenomenon of shrink-swell clay on an individual house in the district of Villeurbanne Saint-Jean.

Figure 9 : Location of the anomaly PGGH_Lyon_02 on the IGN map in 1/25 000

The surface of the anomaly is about 0.08 ha. The geology observed in the sector corresponds to the recent alluvia of the Rhône River. It is probably due to a pocket of clay situated in this place. The shrink-swell clay phenomenon seems to be attested by the owners of the house who have noticed a slight periodic fissuring of their house.

4.2 SPECIFIC GEOHAZARD TYPE

The observed ground movement corresponds probably to a shrink swell clay phenomenon due to a clayey pocket in the modern alluvia of the Rhône. The observed displacements generally range between -0.2 and -0.3 cm / year.

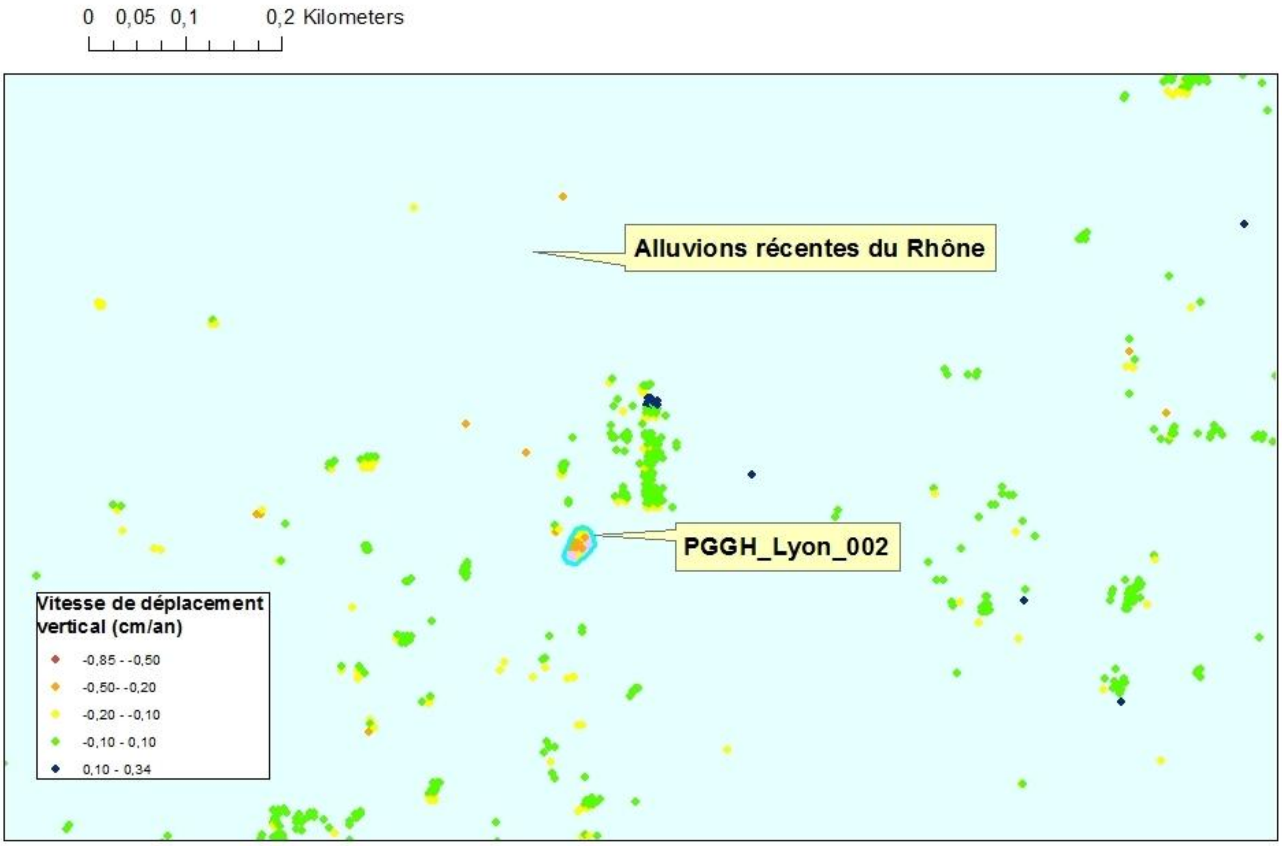

Figure 10 : Location of the anomaly PGGH_Lyon_02 on the harmonised geological map

4.3 THE DETERMINATION METHOD

The existence of the ground movement has been interpreted from the PSI data. A visual control allowed detecting some slight disorders on the building.

4.4 CONFIDENCE IN THE INTERPRETATION

The confidence in the interpretation is quite good because the movements are confirmed by the visual observations and the owner of the house.

4.5 GEOLOGICAL INTERPRETATION OF THE MOTION

The alluvia of the Rhône River present a low risk of shrink swell clays phenomenon (Cf. Report BRGM / RP-56842-FR). It is thus normal to observe locally this type of phenomenon.

4.6 EVIDENCE FOR THE INSTABILITY

Figure 11 : photograph of the anomaly PGGH_Lyon_02

The photograph above highlights a small cracking of the 1st floor with regard to the east wall.

5 PANGEO POLYGON 'PGGH_LYON_003'

5.1 GENERAL PROPERTIES OF THE MOTION AREA

This deformation polygon corresponds probably to a shrink swell clay phenomenon affecting a district of the Jonage municipality in the East of Lyon suburbs.

The area of the zone of shrink swell clay phenomenon is about 1.58 ha.
The observed geology in the sector corresponds to the recent alluvia of the Rhône River and to the fluvio-glacial deposits.

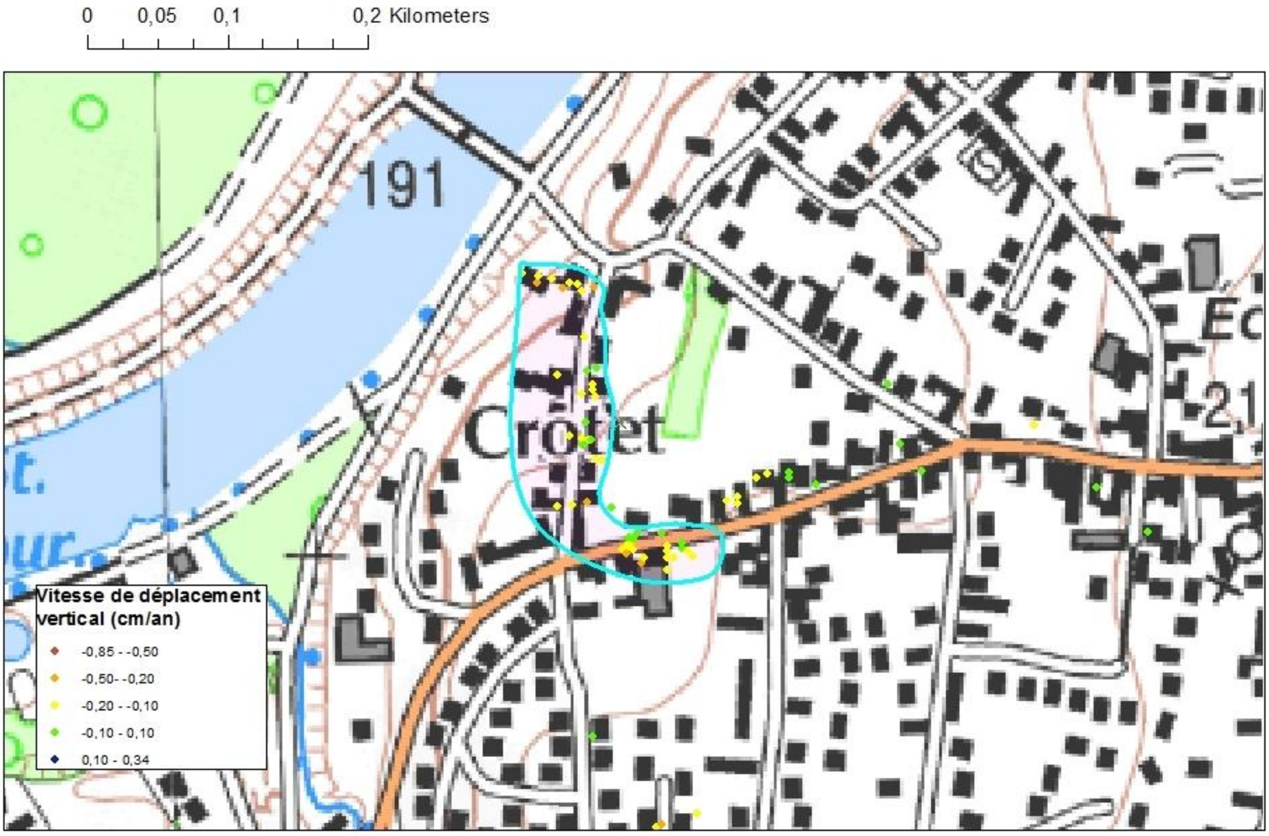

Figure 12 : Location of the anomaly PGGH_Lyon_03 on the IGN map in 1/25 000

5.2 SPECIFIC GEOHAZARD TYPE

The observed ground motion corresponds to a shrink swell clay phenomenon due to a clayey pocket in the modern alluvia of the Rhône stream. The observed displacements are generally included between -0.2 and -0.3 cm/year.

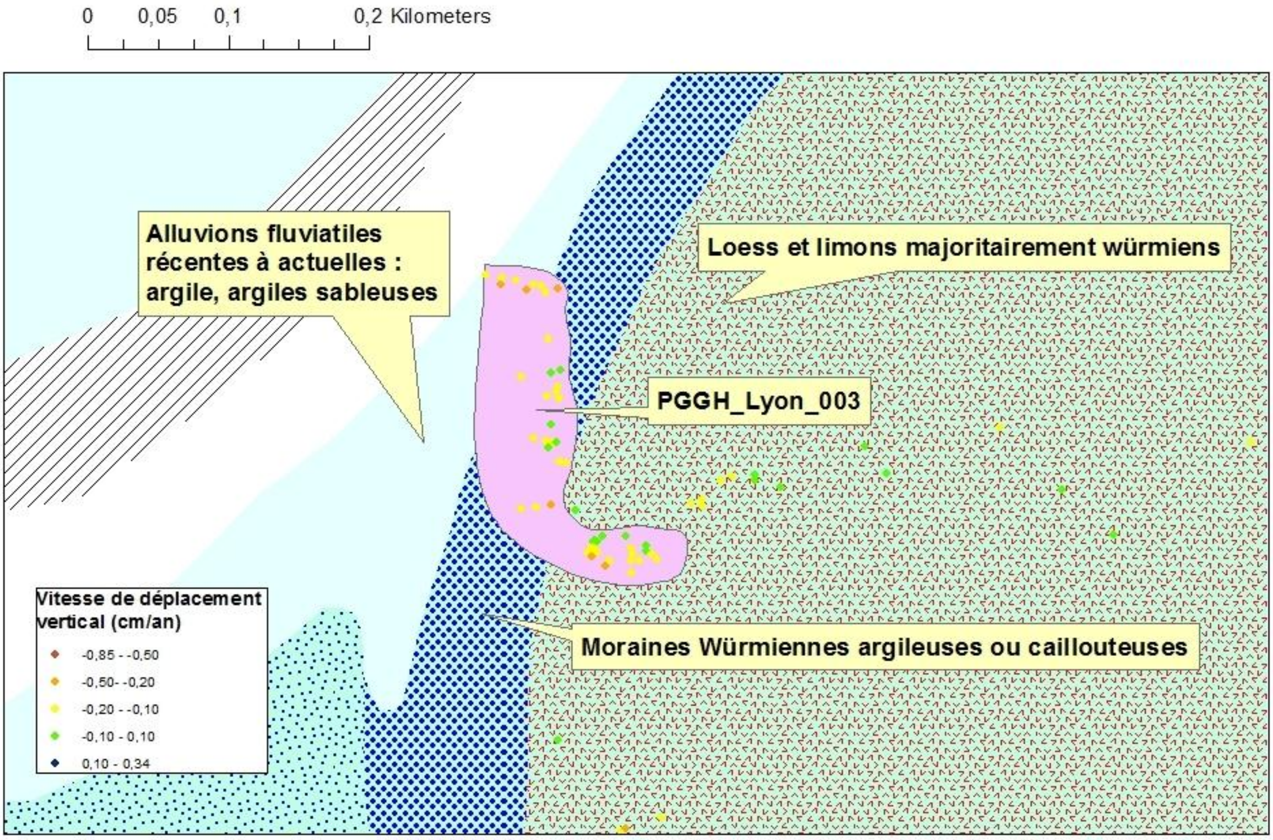

Figure 13 : Location of the anomaly PGGH_Lyon_03 on the harmonized geological map

5.3 THE DETERMINATION METHOD

The existence of a potential ground movement has been interpreted from the data PSI. A visual control allowed confirming the existence of slight disorders on some buildings. The most likely cause of the phenomenon seems to be due to the shrink swell clay phenomenon.

5.4 CONFIDENCE IN THE INTERPRETATION

The level of confidence in the interpretation is limited because we have not obtained testimony allowing giving evidence on the nature of the phenomenon.

5.5 GEOLOGICAL INTERPRETATION OF THE MOTION

The alluvia of the Rhône River present a low risk of shrink swell clays phenomenon (Cf. Report BRGM / RP-56842-FR). It is thus normal to observe locally this type of phenomenon.

5.6 EVIDENCE FOR THE INSTABILITY

Houses present signs of fissuring.

Figure 14 : photograph of the anomaly PGGH_Lyon_03

6 PANGEO POLYGON 'PGGH_LYON_004'

6.1 GENERAL PROPERTIES OF THE MOTION AREA

This movement corresponds to an isolated collapse affecting part of an industrial building situated in the east of Grand Lyon in the Mi-Plaine industrial park. The surface of the subsiding zone is very small: approximately 0.26 ha.

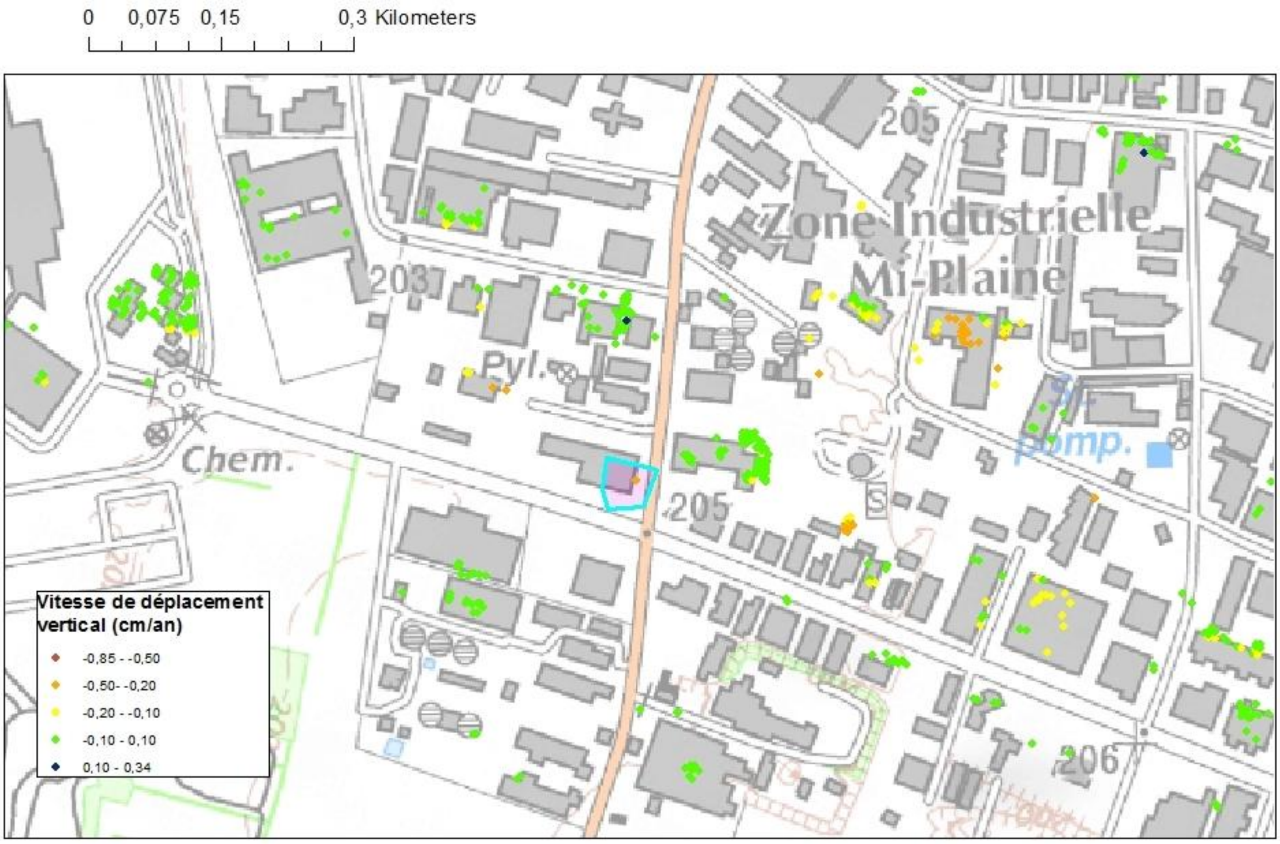

Figure 15 : Location of the anomaly PGGH_Lyon_04 on the IGN map in 1/25 000

Noteworthy is the fact that in the zone, there are many other markers of displacement, but they do not apparently correspond to ground surface movements as most of the anomalies observed in Lyon. We are here in the presence of industrial buildings with steel structure on which we cannot see any evidence of ground instability (the observed movements could be due to the structure itself).

The geology in the sector corresponds to the fluvio-glacial alluvia.

6.2 SPECIFIC GEOHAZARD TYPE

The ground displacement corresponds to subsidence of an angle of building. The speed of the movement is important: -0.49 cm / year.

6.3 THE DETERMINATION METHOD

The existence of a potential ground movement was interpreted from the data PSI. A visual control allowed noticing the existence of many cracks on the building. The likely cause of the phenomenon was not formally determined but it seems to be due to compressible ground.

6.4 CONFIDENCE IN THE INTERPRETATION

The confidence in the interpretation is limited because disorders are visible but their cause is not surely established.

6.5 GEOLOGICAL INTERPRETATION OF THE MOTION

The subsidence of the building is potentially due to a load transfer in the foundation that is too important for the ground. Indeed, the fluvio-glacial alluvia are heterogeneous and can present some problems of compressibility.

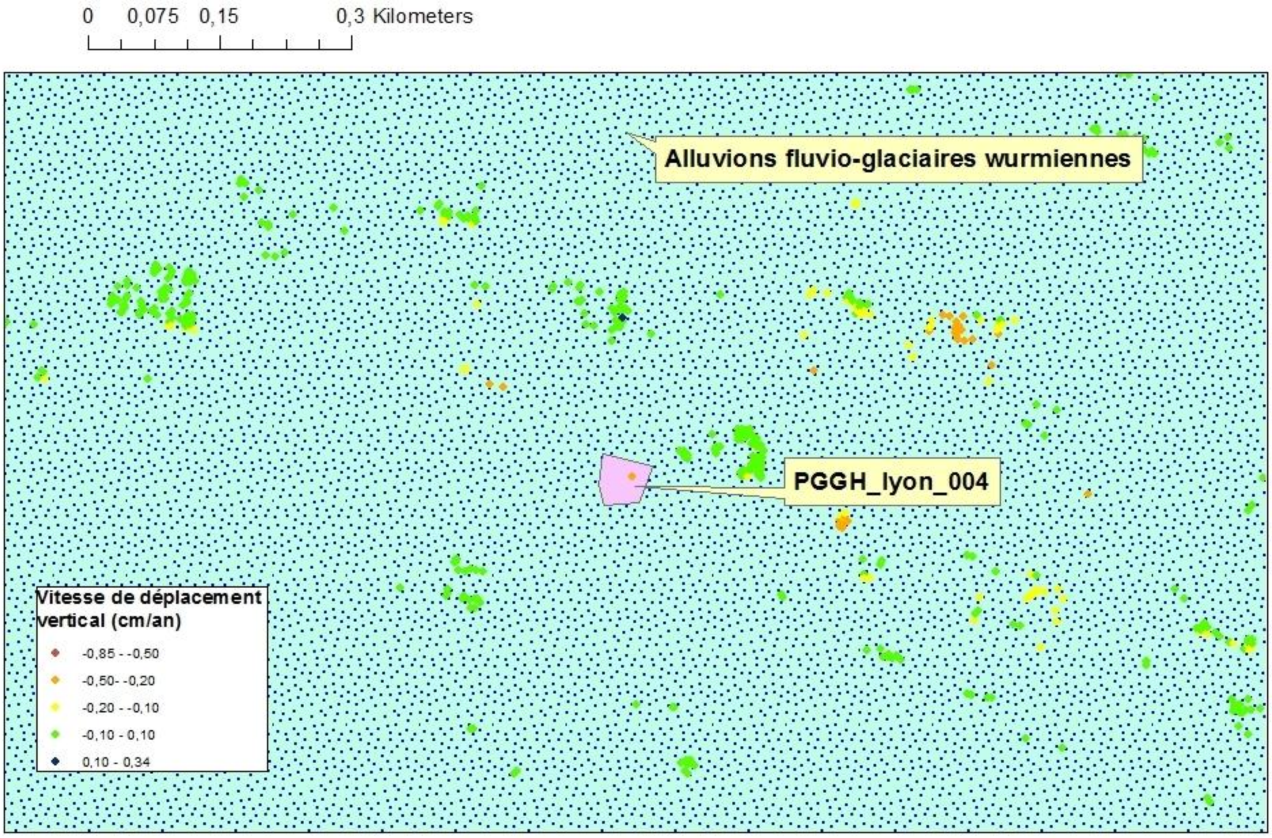

Figure 16 : Location of the anomaly PGGH_Lyon_04 on the harmonized geological map

6.6 EVIDENCE FOR THE INSTABILITY

We can see several opening cracks of 3 mm on the building.

Figure 17 : photograph of the anomaly PGGH_Lyon_04

7 PANGEO POLYGON 'PGGH_LYON_005'

7.1 GENERAL PROPERTIES OF THE MOTION AREA

This ground movement corresponds to an isolated phenomenon of clays shrinking/swelling. This zone corresponds to a disaster already inventoried during the realisation of the shrink swell clays map of the Rhone departement (Cf. ReportBRGM / RP-56842-FR).

We will point out that it is the only disaster highlighted by the PSI on 114 disasters identified in the zone of study. It is true that many of these disasters appeared during summer, 2003. The surface of the zone of subsidence is very small, estimated at 0.33 ha.

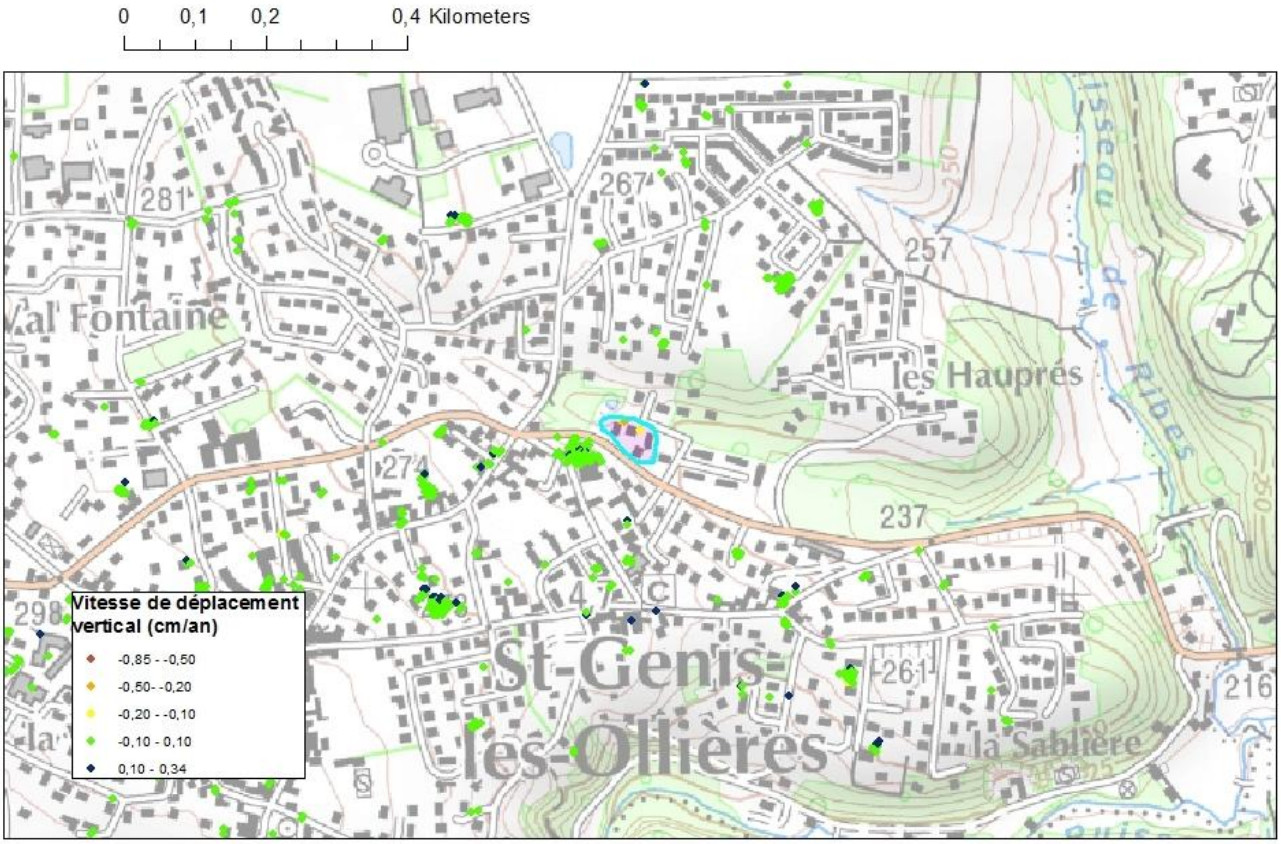

Figure 18 : Location of the anomaly PGGH_Lyon_05 on the IGN map in 1/25 000

7.2 SPECIFIC GEOHAZARD TYPE

The observed ground movement corresponds to a shrink swell clay phenomenon in alluvia from Pliocen. The observed displacement is generally included between -0.15 and -0.23 cm/year.

7.3 THE DETERMINATION METHOD

The zone of ground movement corresponds to one of the inventoried disasters for the realisation of the shrink/swell clays map of the Rhone department.

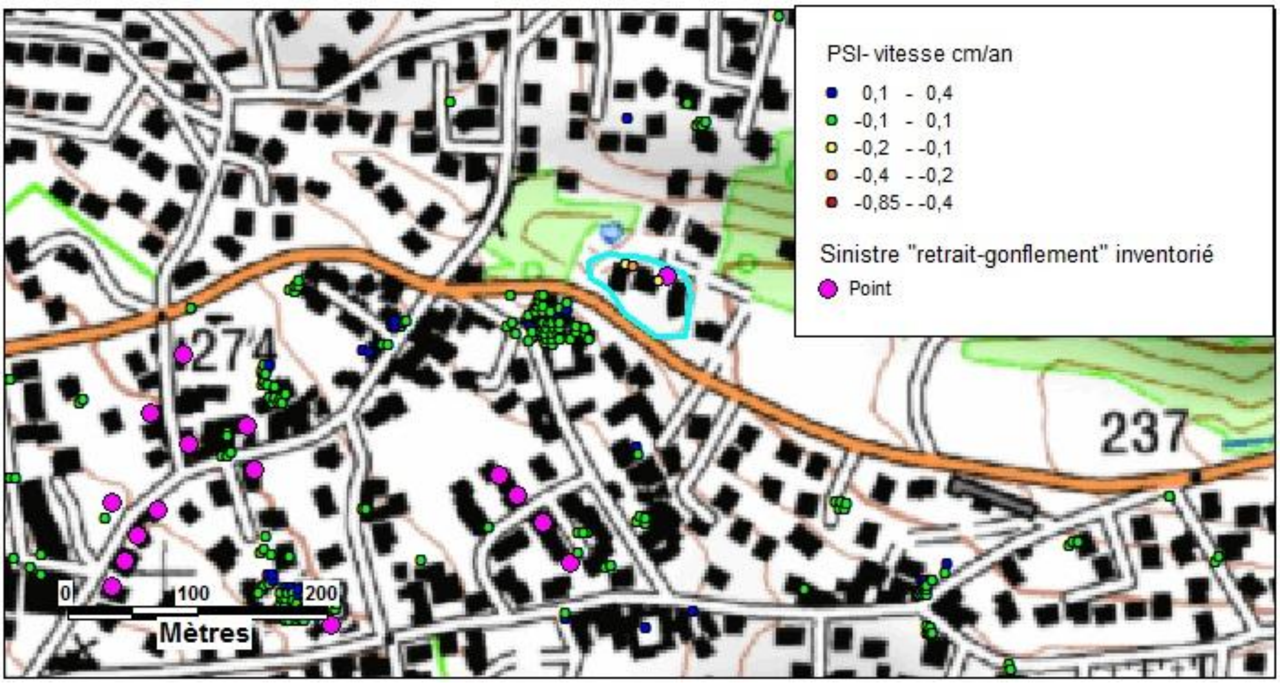

Figure 19 : Location of the anomaly PGGH_Lyon_05 compared with the damages known for shrink swell clay phenomenon

7.4 CONFIDENCE IN THE INTERPRETATION

The confidence in the interpretation is good as the causes of the disorder were established with certainty (ground study).

7.5 GEOLOGICAL INTERPRETATION OF THE MOTION

The damage is due to the presence of averagely plastic clays (index of plasticity = 18) within alluvia Villafranchiennes. This kind of geological lay is concerned by a low risk of shrink swell clay. (Cf. Report BRGM / RP-56842-FR)

FR).

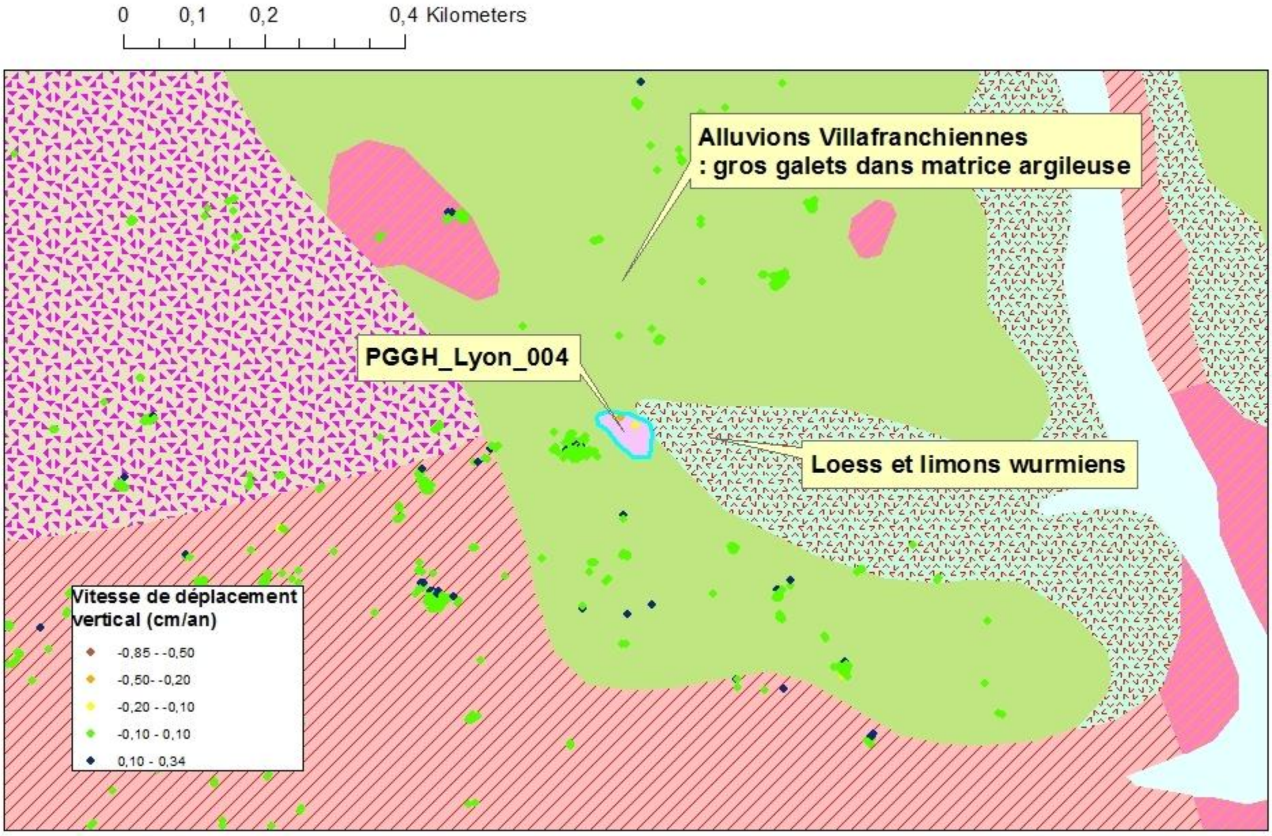

Figure 20 : Location of the anomaly PGGH_Lyon_05 on the harmonized geological map

7.6 EVIDENCE FOR THE INSTABILITY

The site has not be visited because we have already all the elements about the damage.

PANGEO GEOHAZARD GLOSSARY

Hazard

Something with the potential to cause harm.

Natural Hazard

A natural hazard is a natural process or phenomenon that may cause loss of life, injury or other impacts, property damage, lost livelihoods and services, social and economic disruption, or environmental damage. (Council of the European Union – Commission Staff Working Paper – Risk Assessment and Mapping Guidelines for Disaster Management).

Geohazard (Geological hazard)

A geological process with the potential to cause harm.

Risk

The likelihood that the harm from a particular hazard will be realised.

Types of Geohazard

1. Deep Ground Motions

Ground motion can occur at different scales and depths. This section contains the geohazards that are caused by processes in the deep subsurface.

1.1. Earthquake (seismic hazard)

Earthquakes are the observable effects of vibrations (known as seismic waves) within the Earth's crust arising from relatively rapid stress release, typically along a fault zone.

Damage to buildings and other infrastructure can be caused as the ground shakes during the passage of seismic waves. Other effects include liquefaction of water-saturated soft ground, potentially leading to a loss in ground strength and the extrusion of water-saturated sediments as 'mud volcanoes' and the like. Ground shaking can also trigger secondary events such as landslides and tsunami. Secondary effects such as these should be mapped into the other relevant PanGeo geohazard classes. Some earthquakes are associated with significant permanent vertical or lateral ground movement. Changes to drainage systems can cause flooding. There is potential for injury and loss of life during earthquakes.

Seismic hazard can be assessed by reference to the size and frequency of recorded earthquakes, although individual earthquakes are essentially unpredictable. Individual events occur on time-scales of seconds or minutes. Modern infrastructure should be designed to withstand probable local seismic events.

1.2. *Tectonic Movements*

Tectonic movements are large scale processes that affect the earth's crust. These processes can lead to areas of the crust rising or falling. Importantly it is the neotectonic movements that are still active and may therefore produce a ground motion that can be measured by PSI. Neotectonic movements are typically due to the stresses introduced through movements of the earth's plates. These types of motion are likely to be on a broad scale and so it may not be possible to measure them using the SAR scene relative measurements of PSI.

1.3. Salt Tectonics

Localised motions can be associated with the movement of evaporate deposits, these are termed salt tectonics and can produce both uplift and subsidence depending on the exact mechanisms at play.

1.4. Volcanic Inflation/Deflation

Volcanic activity can lead to the creation of lava flows, ash flows, debris and ash falls, and debris flows of various kinds. It might be accompanied by release of poisonous or suffocating gases, in some instances with explosive violence, or by significant seismic activity or ground movement. Secondary effects can include landslide and flooding. For PanGeo we are interested in hazards associated with ground instability. Ground instability associated with volcanoes tends to relate to inflation and deflation of the ground surface as magma volumes change. Secondary effects such as landslides should be mapped into the other relevant PanGeo geohazard classes.

2. Natural Ground Instability

The propensity for upward, lateral or downward movement of the ground can be caused by a number of natural geological processes. Some movements associated with particular hazards may be gradual or occur suddenly and also may vary from millimetre to metre or tens of metres scale. Note that anthropogenic deposits can be affected by natural ground instability.

Significant natural ground instability has the potential to cause damage to buildings and structures, and weaker structures are most likely to be affected. It should be noted, however, that many buildings, particularly more modern ones, are built to such a standard that they can remain unaffected in areas of even significant ground movement. The susceptibility of built structures to damage from geohazards might also depend on local factors such as the type of nearby vegetation, or the nature of the landforms in the area.

The effects of natural ground instability often occur over a local area as opposed to the effects of natural ground movements which occur over larger areas.

2.1. Land Slide

A landslide is a relatively rapid outward and downward movement of a mass of rock or soil on a slope, due to the force of gravity. The stability of a slope can be reduced by removing ground at the base of the slope, increasing the water content of the materials forming the slope or by placing material on the slope, especially at the top. Property damage by landslide can occur through the removal of supporting ground from under the property or by the movement of material onto the property. Large landslides in coastal areas can cause tsunami.

The assessment of landslide hazard refers to the stability of the present land surface, including existing anthropogenically-modified slopes as expressed in local topographic maps or digital terrain models. It does not encompass a consideration of the stability of new excavations.

Land prone to landslide will normally remain stable unless the topography is altered by erosion or excavation, the land is loaded or pore water pressure increases. Landslide might also be initiated by seismic shock, frost action, or change in atmospheric pressure.

This hazard is significant in surface deposits but may extend to more than 10 m depth. The common consequences are damage to properties, including transportation routes and other kinds of infrastructure, and underground services. Some landslides can be stabilised by engineering.

2.2. Soil Creep

Soil creep is a very slow movement of soil and rock particles down slope and is a result of expansion and contraction of the soil through cycles of freezing and thawing or wetting and drying.

2.3. Ground Dissolution

Some rocks and minerals are soluble in water and can be progressively removed by the flow of water through the ground. This process tends to create cavities, potentially leading to the collapse of overlying materials and possibly subsidence at the surface.

The common types of soluble rocks and minerals are limestones, gypsum and halite.

Cavities can become unstable following flooding, including flooding caused by broken service pipes. Changes in the nature of surface runoff, excavating or loading the ground, groundwater abstraction, and inappropriate installation of soakaways can also trigger subsidence in otherwise stable areas.

2.4. Collapsible Ground

Collapsible ground comprises materials with large spaces between solid particles. They can collapse when they become saturated by water and a building (or other structure) places too great a load on it. If the material below a building collapses it may cause the building to sink. If the collapsible ground is variable in thickness or distribution, different parts of the building may sink by different amounts, possibly causing tilting, cracking or distortion. Collapse will occur only following saturation by water and/or loading beyond criticality. This hazard can be significant in surface deposits and possibly also in buried superficial deposits.

2.5. Running Sand/ Liquefaction

Running sand occurs when loosely-packed sand, saturated with water, flows into an excavation, borehole or other type of void. The pressure of the water filling the spaces between the sand grains reduces the contact between the grains and they are carried along by the flow. This can lead to subsidence of the surrounding ground.

If sand below a building runs it may remove support and the building may sink. Different parts of the building may sink by different amounts, possibly causing tilting, cracking or distortion. The common consequences are damage to properties or underground services. This hazard tends to be self-limited by decrease in head of water.

Liquefaction of water-saturated soft ground often results as an effect of earthquake activity but can also be triggered by manmade vibrations due to construction works. It can potentially lead to a loss in ground strength and the extrusion of water-saturated sediments as ‘mud volcanoes’ and the like. Soils vulnerable to liquefaction represent areas of potential ground instability.

3. Natural Ground Movement

The effects of natural ground movement often occur over a larger area as opposed to the effects of natural ground instability, which occur over local areas.

3.1. ***Shrink-Swell Clays***

A shrinking and swelling clay changes volume significantly according to how much water it contains. All clay deposits change volume as their water content varies, typically swelling in winter and shrinking in summer, but some do so to a greater extent than others. Most foundations are designed and built to withstand seasonal changes. However, in some circumstances, buildings constructed on clay that is particularly prone to swelling and shrinking behaviour may experience problems. Contributory circumstances could include drought, leaking service pipes, tree roots drying-out of the ground, or changes to local drainage such as the creation of soakaways. Shrinkage may remove support from the foundations of a building, whereas clay expansion may lead to uplift (heave) or lateral stress on part or all of a structure; any such movements may cause cracking and distortion.

The existence of this hazard depends on a change in soil moisture and on differential ground movement. Uniform ground movement may not of itself present a hazard. This hazard is generally significant only in the top five metres of ground.

3.2. Compressible Ground

Many ground materials contain water-filled pores (the spaces between solid particles). Ground is compressible if a load can cause the water in the pore space to be squeezed out, causing the ground to decrease in thickness. If ground is extremely compressible the building may sink. If the ground is not uniformly compressible, different parts of the building may sink by different amounts, possibly causing tilting, cracking or distortion.

This hazard commonly depends on differential compaction, as uniform compaction may not of itself present a hazard. Differential compaction requires that some structure that might be susceptible to subsidence damage has been built on non-uniform ground. The common consequences are damage to existing properties that were not built to a sufficient standard, and possible damage to underground services.

4. Man Made (Anthropogenic) Ground Instability

Anthropogenic instability covers a local area which has been brought about by the activity of man. Subsidence (downward movement) of the ground can result from a number of different types of anthropogenic activity, namely mining (for a variety of commodities), or tunnelling (for transport, underground service conduits, or underground living or storage space).

Subsidence over a regional area can result from fluid extraction (for water, brine, or hydrocarbons). Uplift or heave of the ground can occur when fluid is allowed to move back into an area from where it was previously extracted and groundwater recharge occurs. This fluid recovery may include injection of water or gas.

4.1. Ground Water Management - Shallow Compaction

7.6.1.1 Ground water management may be applied for example to ensure the exploitability of existing agricultural land in lowland coastal areas. Groundwater management can lead to higher or lower water levels of phreatic groundwater and of deeper aquifers in the shallow subsurface. Groundwater occupies pore and interstitial spaces and fractures within sediments and rocks and therefore exerts a pressure. When the water is drained the pore pressure or effective stress is reduced. This leads to consolidation of especially soft sediments, such as clay and peat. This change in the sediment volume leads to subsidence. Similarly when groundwater levels are allowed to recover, uplift may be a result of increasing pore pressure.

4.2. Ground Water Management - Peat Oxidation

7.6.1.2 Ground water management may be applied for example to ensure the exploitability of existing agricultural land in lowland coastal areas. Groundwater management can lead to higher or lower water levels of phreatic groundwater and of deeper aquifers in the shallow subsurface. Peat oxidation is the chemical reaction where peat starts decomposing and will waste away with time. This loss of soil volume leads to subsidence. It occurs when layers of peat in the subsurface are exposed to oxygen. As long as peat is located in saturated ground layers this process does not take place. However peat oxidation does occur in unsaturated soils, for instance in areas where ground water management lowers ground water levels.

4.3. Groundwater Abstraction

Groundwater also occupies pore and interstitial spaces and fractures within sediments and rocks in the deeper subsurface. When this water is removed, for instance through pumping for drinking water or lowering of water levels in mines, the pore pressure or effective stress is reduced and consolidation of the sediments and rocks causes a change in the sediment and rock volume. This leads to subsidence. Similarly when aquifer levels are allowed to recover, uplift may be a result of increasing pore pressure. Deep geothermal energy systems should not lead to ground movement. They involve closed systems where water, which was extracted from a deep aquifer, will be pumped back into that same aquifer. However, geothermal heat pumps are used at shallower depths. Although these are also closed systems, ground movement might occur temporarily (e.g. seasonally) or even permanently.

4.4. Mining

Mining is the removal of material from the ground, in the context of PanGeo we consider mining to relate to the removal of solid minerals. The ground surface may experience motion due to readjustments in the overburden if underground mine workings fail.

4.5. Underground Construction

In PanGeo we are interested in underground construction that might bring about ground instability. An example of this would be underground tunnelling; the removal of subsurface material can alter the support for the overlying material therefore leading to ground motions.

4.6. Made Ground

Made ground comprises of anthropogenic deposits of all kinds such as land reclamation, site and pad preparation by sand infill, road and rail embankments, levees and landfills for waste disposal. Examples of land reclamation are artificial islands, beach restoration and artificial harbours. Reclaimed land as well as embankments and levees are generally made up of sand, which is not prone to compaction as are clay and peat. However, two ground instability processes will occur: consolidation of this artificial ground and compaction of the ground below due to the load of the artificial ground and the structure it supports, e.g. a building. Depending on its composition and mode of deposition, landfill can also be a compressible deposit.

4.7. Oil and Gas Production

Similar to abstraction of groundwater the production of oil and gas decreases the pore pressure of the reservoir rocks and therefore can cause consolidation and subsidence of the surface. Storage of material in the depleted reservoir (such as natural gas or CO^2) can lead to surface uplift.

5. Other

These are areas of instability for which the geological explanation does not fit into any of the categories above.

6. Unknown

These are areas of identified motion for which a geological interpretation cannot be found.

<u>Geohazard Groupings to be used in PanGeo</u>

1. Deep Seated Motions
    a. Earthquake (seismic hazard)
    b. Tectonic Movements
    c. Salt Tectonics
    d. Volcanic Inflation/Deflation

2. Natural Ground Instability
    a. Land Slide
    b. Soil Creep
    c. Ground Dissolution
    d. Collapsible Ground
    e. Running Sand/Liquefaction

3. Natural Ground Movement
    a. Shrink-Swell Clays
    b. Compressible Ground

4. Man Made (Anthropogenic) Ground Instability
    a. Ground Water Management - Shallow Compaction
    b. Ground Water Management - Peat Oxidation
    c. Groundwater Abstraction
    d. Mining
    e. Underground Construction
    f. Made Ground
    g. Oil and Gas Production

5. Other

6. Unknown