Institution:	Imperial College London
Unit of Assessment:	12 Engineering
Title of case study:	Shaping our Exploration of Mars
Period when the underpinning research was undertaken:	2000 - 2020

Details of staff conducting the underpinning research from the submitting unit

Name(s):	Role(s) (e.g. job title):	Period(s) employed:
Prof. W. Thomas Pike	Professor in Microengineering	2001 to present
Prof. Sanjeev Gupta	Professor of Earth Sciences	1998 to present
Prof. Mark Sephton	Professor of Organic Geochemistry	2005 to present

Period when the claimed impact occurred:	1 August 2013 to 31 July 2020
Is this case study continued from a case study submitted in 2014?	No

1. Summary of the impact

Planetary science is in the midst of revolution, and no more so than in the study of Mars, the most Earth-like of planets. The research of Professors Pike, Gupta and Sephton at Imperial College has (1) developed technologies to measure seismic activity and the interior structure of Mars based on micromachined silicon accelerometers, (2) discovered that ancient Mars was habitable through research conducted on the NASA Mars Science Laboratory *Curiosity* rover mission, and (3) developed techniques and strategies for discovering ancient life on Mars.

Since August 2013, the impact of this research has been to:

I1, I2 Provide microseismometers that were deployed on NASA's InSight mission which landed in 2018 to measure tectonic activity and the deep structure of Mars, and on NASA missions to Europa and the Moon currently in planning.

I3 Directly influence NASA *Perseverance* rover and ESA Exomars mission operations strategies and technologies.

I4 Through multiple exhibitions, communicate our new understanding of Mars and the excitement of exploration to the public inspiring learning and curiosity, and generating reflection on our place in the universe, attracting over 200,000 visitors.

I5 Provide new protocols that enable the planning and execution of a forthcoming NASA-ESA Mars Sample Return mission that attempts to detect evidence of past life on Mars.

2. Underpinning research

Over the last decade, orbital and landed missions to the Red Planet have fundamentally changed our understanding of the evolution of Mars and its potential for life. The primary questions that drive the Mars exploration programme are: What is the interior structure of Mars? Has the Martian climate ever been favourable for life development? Where should we look for evidence of past life and how? Research at Imperial College in groups led by Professors Pike, Gupta and Sephton has played a fundamental role in addressing such questions across a spectrum of inter-related activities. These range from development of novel technologies for measuring Martian geophysical processes and detecting possible Martian life, to leading exploration and research in a large international mission from NASA aimed at searching for ancient habitable environments and constraining past climate change on Mars.

Our underpinning research comprises three key strands:

U1. Development of new technologies to measure tectonic activity on extra-terrestrial planetary bodies [R1, R2]

Detecting active geological processes on Mars requires new solutions to make highly sensitive measurements (measure vibrations of the planet's surface below 1 ng (g = 9.8 m/s^2)), while able to withstand the hostile environment demanded by such a space mission. Conventional seismometer designs do not have such a dynamic range while achieving the demanded sensitivity. Pike's group has developed novel micromachined seismometers based on a silicon accelerometer that is unique in its compactness and robust packaging. The heart of the sensor is a micromachined silicon suspension and transducer of a patented design **[R1]**. The design was refined to survive the rigours of launch, landing and deployment on a planetary body **[R2]**, while delivering the highest sensitivity of any micromachined sensor to date, with a lowest-ever background noise of 0.25 ng/rtHz.

U2. Discovering an ancient habitable Mars through *in situ* robotic exploration [R3, R4]

Searching for evidence of ancient life on Mars requires robotic investigation of rocks indicative of past habitable environments on the Martian surface. Gupta is a Co-Investigator and Long Term Planner on NASA's Mars Science Laboratory *Curiosity* rover mission that has been exploring Gale crater on Mars since 2012. Based on Gupta's scientific expertise, strategic and tactical decisions were made to plan scientific observations and target the rover cameras to collect extensive image datasets along the rover traverse. Sedimentological analysis of these data by Gupta and co-workers has led to the discovery of evidence of ancient river, delta and lake deposits on the surface of Mars, together with evidence for past climate change **[R3, R4]**. These discoveries provide the first *in situ* evidence for prolonged water activity at the Martian surface and the presence of habitable environments in Mars' ancient past, and is central to guiding the search for ancient life on Mars.

U3. Development of techniques and strategies for discovering ancient life on Mars and beyond [R5, R6]

Because the search for life is a key focus for Mars exploration, there is a need for development of technologies for life detection and also protocols for searching for the best targets in search strategies. Sephton's group has developed methods, technologies and understanding that have directed the operation of life detection instruments on Mars. By recreating the geological history of Mars in the laboratory, his group has demonstrated the effects of Mars minerals on the preservation and analysis of organic matter and revealed that samples without perchlorate, sulfate and iron will be the best targets to seek evidence of past life, either when analysed *in situ* on Mars or when returned to Earth **[R5].** Sephton has developed statistical and geochemical methods that are being used to ensure that the best instruments are developed, the correct samples are chosen, and any generated data is exploited to its greatest extent **[R6]**. Such systematic methods are necessary to generate the evidence that is required to support future extraordinary claims related to alien life.

3. References to the research

R1 **Pike WT,** Standley IM, Trnkoczy A (2004), Micro-machined Accelerometer. *United States Patent 6776042*, August 17 2004.

R2 **Pike WT**, Standley IM, Calcutt SB, Mukherjee AG (2018), A broad-band silicon microseismometer with 0.25 ng/rtHz performance. *2018 IEEE Micro Electro Mechanical Systems (MEMS)*, Belfast, pp. 113-116, DOI: 10.1109/MEMSYS.2018.8346496.

R3 Williams, R.M.E., Grotzinger, J.P., Dietrich, W.E., **Gupta, S.**, Sumner, D.Y., et al. (2013) Martian fluvial conglomerates at Gale crater. *Science*. DOI: 10.1126/science.1237317.

R4 Grotzinger, J. P., **Gupta, S**., et al. (2015) Deposition, exhumation, and paleoclimate of an ancient lake deposit, Gale crater, Mars. *Science* **350**, DOI:10.1126/science.aac7575.

R5 Tan, J., Lewis, J.M. and **Sephton, M.A.,** (2018) The fate of lipid biosignatures in a Mars-analogue sulfur stream. *Scientific reports*, *8*(1),1-8. DOI: 10.1038/s41598-018-25752-7

R6 **Sephton M.A**, Carter JN, (2014) Statistics provide guidance for indigenous organic carbon detection on Mars missions. *Astrobiology*, Vol: 14, Pages: 706-713. DOI: 10.1089/ast.2014.1161.

4. Details of the impact

We now provide details of the impact generated in the period August 2013 to July 2020 and their links to underpinning research.

I1 Short period (SP) seismometer deployed on NASA InSight mission (underpinning research R1, R2)

Building on research into designing micro-machined silicon sensors, the impact of Pike's work [R1, R2] has been to provide the SP microseismometers for the NASA InSight mission that landed on Mars in 2018 and is currently still collecting data. The group designed, fabricated and packaged the microseismometers for the main seismic payload SEIS on InSight **[S1]**. This impact was achieved in a partnership with Oxford University who

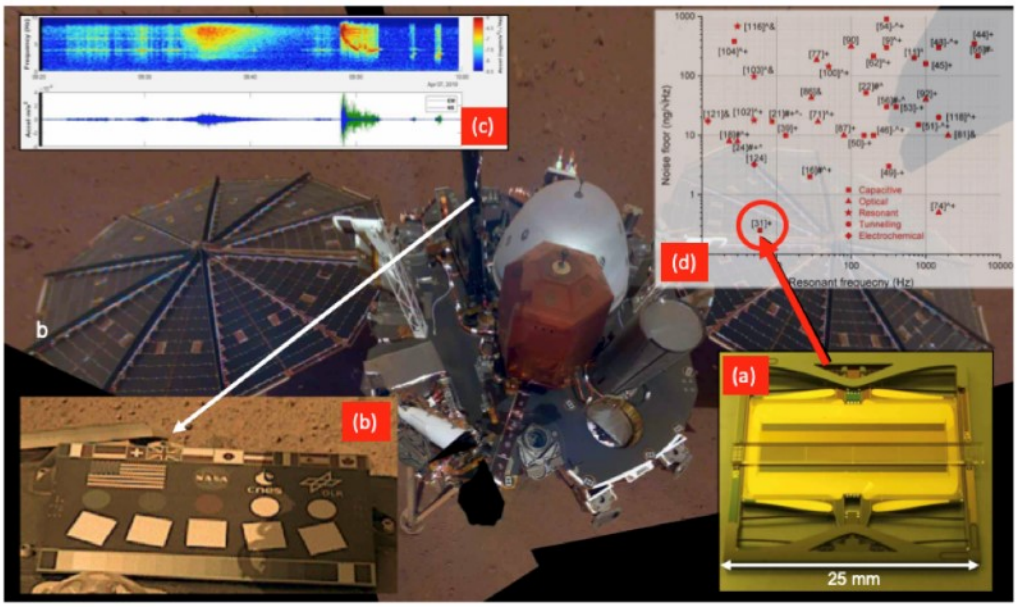

Fig. 1 The InSight lander on Mars with (a) Imperial's seismic sensor in the UK's (b) first science instrument on another planet, (c) the spectrogram and time series of the first publicly announced seismic event recorded on the microseismometer and (d) a comparison of its performance compared to all other micromachined accelerometers.

developed the sensor electronics. The microseismometers were required to operate without any levelling on the deck to characterise the lander's vibration injection into the signal of the seismic payload after deployment on the surface of Mars (Fig. 1). The Head of Space Exploration for the UK Space Agency writes **[S1]**: "*They have performed flawlessly on Mars, recording the first acoustic vibrations from another planet as well as observing its seismic signals".* They have now operated for over two years, detecting the first seismic events ('Marsquakes') on another planet and the first inversion of the interior structure of Mars **[S2].**

I2 Supply of seismic sensors to NASA for missions currently in planning to Europa, the moon of Jupiter, and the Moon (underpinning research R1, R2)

Building on their expertise in the development of microseismometers for planetary exploration, Pike's group secured a GBP400,000 contract through Jet Propulsion Laboratory (JPL) to provide seismic sensors as part of a payload on NASA's Europa Lander, a proposed mission to the moon of Jupiter, Europa. The Principal Investigator of Europa Seismic Package from JPL writes [**S3**]: "*they represent the world-leading technology available at this time in terms of the combination of their size, robustness and proven performance, with a proven heritage of successful operation on another planet.*" These sensors are also being further developed for lunar missions under this programme **[S3]**.

I3 Directly influencing NASA and future ESA Mars mission operations strategies and technologies (underpinning body of research R3, R4)

Gupta's work with NASA's *Curiosity* rover has enabled his knowledge and expertise in conducting complex geological research through robots on Mars [R3, R4] to help UK and European scientists make preparations for the ESA/ROSCOSMOS ExoMars 2022 rover mission **[S4]**, a flagship EUR1,200,000,000 project to send the first European rover to explore the surface of Mars in 2022. The UK is the second largest investor in the mission (https://www.gov.uk/government/case-studies/exomars).

Gupta's experience in conducting the research detailed in R3 and R4 aided in the design of the first UK simulated robotic field trials (MURFI Rover field trials 2016) for the UK Space Agency to provide UK scientists and engineers experience in remote rover operations **[S4].** Gupta assisted with developing the detailed workflow for the simulation, identification of operations roles, and tactical and strategic operations planning cycles. The Head of Space Exploration for the UK Space Agency writes **[S4]**:

> "*The trials provided invaluable experience for UK scientists enabling them to gain leadership roles in the ExoMars mission. Gupta has played a pivotal role in developing our young planetary science community, providing guidance and support and it is to his credit that the UK has been so successful in the recent selection of scientists on various European Space Agency Mars related working groups*".

As a consequence of his research experience, Gupta was selected by the UK Space Agency to chair their REXOC (Robotic Exploration Instrument Oversight Committee) (2018-present). "*Professor Gupta's insight has been invaluable in helping us make the UK instrument teams ready for operations and ensuring they are resourced appropriately through this critical period leading to launch* **[S4].**

Gupta's research on *Curiosity* has had important impact on preparation for NASA's latest rover, *Perseverance*, which successfully landed on Mars on 18 February 2021. The Principal Investigator of the Mastcam-Z camera on *Perseverance*) writes:

> "*Your research experience with reconstructing ancient habitable Martian landscapes together with the experience you have gained in rover mission operations has led to you becoming heavily involved in Perseverance mission surface operations preparation and scientific characterization of the landing site*." **[S5]**.

Gupta's expertise in geological analysis of Martian image datasets **[R3, R4]** has led to a collaboration with computer scientists at Joanneum Research (Graz, Austria) (https://www.joanneum.at/en/) and VRViS (Vienna, Austria) (https://www.vrvis.at) to develop a 3D visualisation program called PRo3D (Planetary Robotics 3D Viewer: http://pro3d.space) for interactively analysing 3D reconstructions of the Martian landscape. PRo3D will be utilised on the NASA Mars 2020 *Perseverance* rover mission by the Mastcam-Z camera team **[S5].**

I4 Communicate our new understanding of Mars to the public inspiring learning and curiosity, and generating reflection on our place in the universe (underpinning body of research R3, R4)

The long-term exploration of the solar system has the two major strands of searching for the possibility of past or present life outside Earth and understanding the place of Earth in the context of the evolution of other planets. These goals have great resonance with the public, at a cultural, philosophical as well as scientific level. By working closely with museums and draw from his research experience, Gupta helped them design exhibitions that communicate the latest discoveries from the *Curiosity* rover and its search for ancient habitable environments and life to large and diverse audiences **[R3, R4].** Gupta was invited to be scientific advisor to the '**Moving to Mars**' exhibition at The Design Museum in London that ran from October 2019 to February 2020 **[S6]**. He worked with the museum on developing an immersive installation in the exhibition that featured high resolution images from Mars showcasing the research in **R3** and **R4**. The Director of Audiences at the Design Museum writes **[S6]**: "*Using the Imagery and insights that Sanjeev* [Gupta] *has gained through his research we were able to turn these into a compelling seven minute narrative that conveyed to visitors the harsh conditions of Mars, the challenges of working there and unique geology it presents*". The exhibition attracted 82,231 visitors at the museum: "37%

of exhibition visitors were families. 18% of exhibition visitors were Black and Minority Ethnic (using the Arts Council England's definitions). 49% of visitors were under 34" **[S6]**.

Building on his research reporting the first *in situ* evidence of ancient rivers on Mars **[R3],** Gupta collaborated with exhibition developers at the National Maritime Museum and Royal Observatory to provide scientific materials, commentary and guidance for the '**Visions of the Universe**' exhibition which ran between June-September 2013. "*Gupta's role was crucial in getting the latest research on Mars from the mission to a public audience*" **[S7]**. The exhibition attracted 70,296 visitors over a 101 day run (Adults: 57,880 adults; Children: 12,416) **[S7]**. Also at this museum, the research in R3 and R4 was featured in an exhibition and film entitled "**Unseen: The lives of Looking**" by the artist Dryden Goodwin, which explored how Gupta analyses rover images to reconstruct ancient Martian landscapes **[S7, S8]**. The exhibition had 53,975 visitors during its run from 5th March – 26th July 2015.

I5 Provide new protocols that enable the planning and execution of a forthcoming NASA-ESA Mars Sample return mission that attempts to detect evidence of past life on Mars (underpinning research R5, R6)

Laboratory studies to investigate how life's signals on Mars would be preserved **[R5]** have provided new methods and understanding for life detection, and helped identify pathways to targeting the best samples to seek for evidence of past life on Mars. The direct impact of this research has been the selection of Sephton to help as a Returned Sample Scientist for NASA's Mars 2020 *Perseverance* rover mission **[S9]**. This is the first leg of the NASA/ESA Mars Sample Return campaign, and Sephton's research (eg., R6) is central to the selection processes of what will be undoubtably the most valuable samples in science history for return by NASA/ESA from Mars.

In the exploration of Mars and the search for life, it is imperative to avoid contamination of Mars and to protect Earth from alien biological hazards during a sample return mission. In this context, Planetary Protection Officer from European Space Agency stated: "*the combination of statistical and geochemical work*" [R6] "*is highly valuable to ensure that the best instruments are developed, the correct samples are chosen and any generated data is exploited to its greatest extent*" **[S10]**. Statistical and geochemical methods developed **[R6]** have been used for ESA space agency committee discussions [**S10**]. They have also contributed to planetary protection recommendations that stress the need for statistical approaches for the Committee on Space Research (COSPAR)/NASA/ESA Sample Safety Assessment Protocol in support of the joint NASA-ESA Mars Sample Return campaign **[S10]**, the first leg of which is the NASA Mars 2020 *Perseverance* mission.

5. Sources to corroborate the impact

[S1] Letter of corroboration from Head of Space Exploration, UK Space Agency.

[S2] Lognonné P, Banerdt WB, Pike WT. *et al.* Constraints on the shallow elastic and anelastic structure of Mars from InSight seismic data. *Nat. Geosci.* **13,** 213–220 (2020). 10.1038/s41561-020-0536-y. Link archived here.

[S3] Letter of corroboration from Principal Investigator, Europa Seismic Package, JPL, NASA.

[S4] Letter of corroboration from Head of Space Exploration, UK Space Agency.

[S5] Letter of corroboration from Principal Investigator, Mastcam-Z for *Perseverance* mission.

[S6] Letter of corroboration from Director of Audiences, Design Museum.

[S7] Letter of corroboration Senior Manager of Public Astronomy, Royal Observatory.

[S8] Movie on Unseen – the lives of looking. http://www.drydengoodwin.com/unseen_the_lives_of_looking.htm. Link archived here.

[S9] "Mars *Perseverance* Rover: How British Scientists helped with the mission", BBC News, 30 Jul 2020. https://www.bbc.co.uk/newsround/53555043. Link archived here.

[S10] Letter of corroboration from Planetary Protection Officer, European Space Agency.