Evolution of the Mexican Seismic Alert System (SASMEX)

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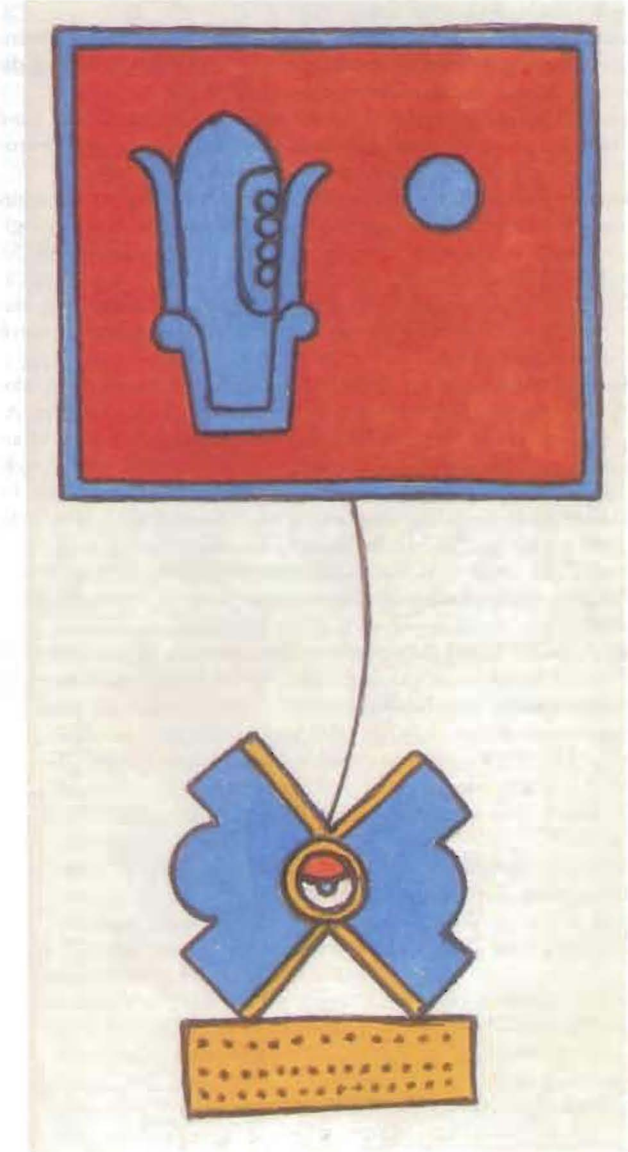
BACKGROUND

The seismic activity along the Mexican coastline, where the Cocos, Rivera, and Pacific plates collide with the North American plate, represents the source of most of the strong earthquakes experienced by the different civilizations that have developed over the centuries in the Mexican territory, as documented by the inhabitants of the Valley of Mexico prior to the arrival of the Spaniards (Figure 1), who referred to an earthquake that occurred in the year *Uno Pedernal* (One Flint), corresponding to the year 1480 (Suarez and Acosta 1996).

The Pacific Mexican coast, consisting of the states of Jalisco, Colima, Michoacan, Guerrero, Oaxaca, and Chiapas, is part of the so called fire belt and has been regarded as one of the regions with the highest seismic activity in the world. From 1875 to 2008 more than 160 large earthquakes (magnitude M > 6.5) occurred in this region (Figure 2).



▲ **Figure 1.** Time "one flint" (1480), night earthquake reference, prehispanic civilization.

INTRODUCTION

One of the major seismic catastrophes in recent Mexican history took place the morning of 19 September 1985 in Mexico City, resulting from the ground motion amplification of the **M** 8.1 earthquake that occurred off the coast of Michoacan. The effects of that earthquake caused at least 10,000 deaths and 30,000 injuries in Mexico City, which is located about 400 km away from the epicenter. The analysis of seismic records from that event allowed scientists to determine that the effect of the energy in the subsoil of Mexico City induced resonance in the structure of several buildings, which caused their collapse and the high toll in casualties; in addition, neither early warnings nor previous training for a quick emergency response in case of a major earthquake were available (Esteva 1988).

After experiencing the serious seismic effects of the 1985 earthquake, both national and international experts recommended initiatives to learn from the damages so as to prevent future seismic disasters (CONACyT and National Research Council 1986). Backing up these recommendations, the Mexico City authorities promoted the design of the Sistema de Alerta Sísmica of Mexico City (SAS), proposed among other

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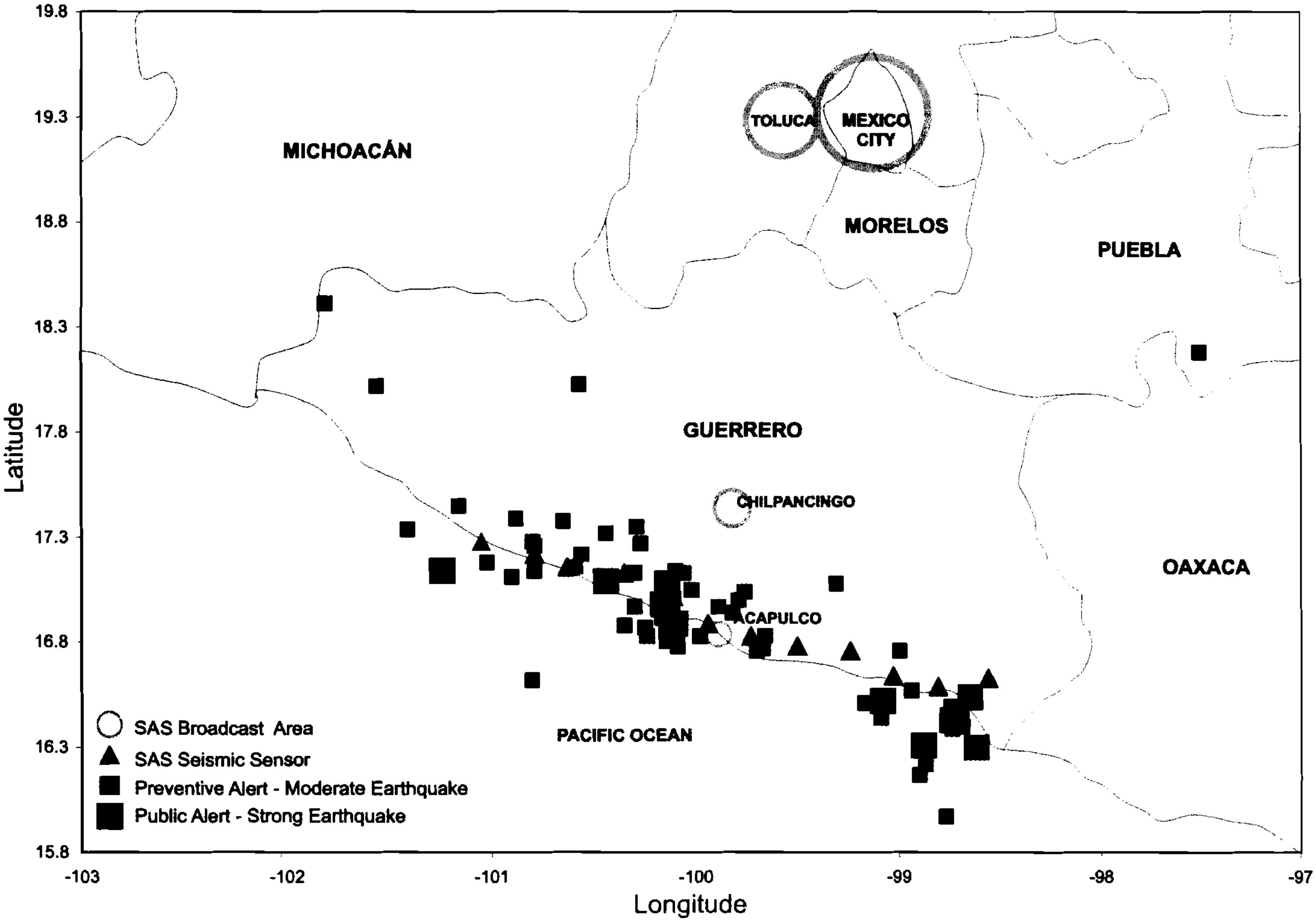


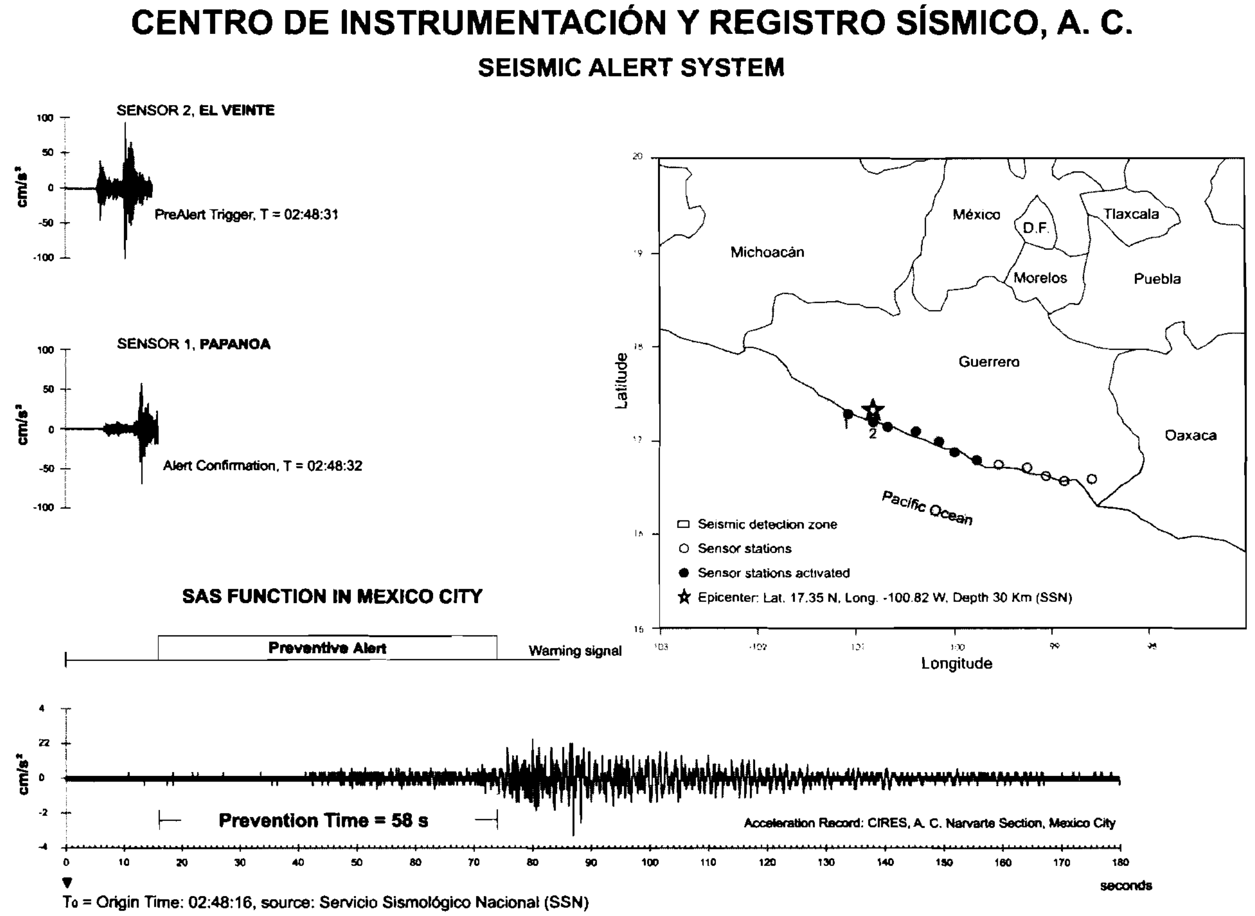
▲ **Figure 4.** SAS network and earthquakes warned between 1991 and 2009.

preventive alerts. These consist mainly of primary and secondary schools, universities, emergency and safety agencies, government buildings, and civil protection organizations, as well as the subway system operated by Sistema de Transporte Metropolitano (Metro) since 1992.

To promote awareness of seismic prevention efforts in Mexico and the potential consequences of a damaging earthquake, the CIRES Web site (http://www.cires.org.mx) shows the information contained in the alert warnings and the seismic activity detected at the FS of the SAS. The Web page of CIRES is automatically updated a few instants after the occurrence of an earthquake. SAS bulletins are issued when at least two FS detect the same earthquake, and they are relayed via e-mail to more than 1,800 users; to verify this function the regular information disclosed by the SSN and by the US Geological Survey (USGS) is also included. To enhance the efficiency of dissemination of the SAS alert warnings and to make it possible to warn the public in advance about other contingencies and natural hazards, in December of 2008, with support from the Autoridad del Centro Historico de la Ciudad de México, a digital code relay system such as that used by NOAA was installed in Mexico City. On 27 March 2009 at 02:48:32 (local time), when the SAS emitted a signal of preventive alert to warn of the risk of an **M** 5.3 earthquake occurring at the coast of Guerrero (Figure 5), the SAS took advantage for the first time of the technology derived from NOAA/SAME receivers. That event validated the effective function of this advanced resource, which, with a minor technical adjustment, has been proposed as a means of more efficiently mitigating seismic vulnerability in Mexico. At that time, eight experimental reference receivers, located in different places in Mexico City, successfully reacted and provided 58 seconds of warning.

Alternate Warning Emitters of the SAS

Although they were aware of the limited efficacy of the early warning function because of the shorter distances from their locations to seismic foci, during 2007 two of the most important cities in Guerrero, Chilpancingo and Acapulco, asked CIRES if they could receive the benefit of SAS alert warnings. A central registry and control system was installed at each city to collect the information relayed by the SAS sensors and to perform the specific adjustment on the warning ranges in terms of the parameters relayed by the FS. This alternate emitting unit of the Seismic Alert System (EASAS), although capable of adjusting the range of the local seismic alert warnings and of taking into account the particular vulnerability in each region,



▲ **Figure 5.** First SAS service with NOAA receivers activated, 27 March 2009 Guerrero M 5.3 earthquake.

failed to increase the times of opportunity between the arrival of the seismic effects and the time of delivery of their warning because it is a known fact that prevention time depends on the eventual distance between the vulnerable region and the site of the earthquake epicenter.

Seismic Alert System of Oaxaca (SASO)

As already mentioned, in 2001 CIRES developed the SASO to warn the capital city of Oaxaca against the catastrophic effects of large earthquakes in its territory, and its public service started in 2003, sponsored by the authorities of Unidad Estatal de Protección Civil de Oaxaca. The SASO constitutes a technological development that evolved from SAS. SASO has 36 FS and 11 radio relay stations to link its coastal, central, north, and isthmus regions. Since its commissioning, it has issued three public alerts and five preventive alerts based on the detection and analysis of more than 186 earthquakes (Figure 6). The SASO historical results and the evolution of the detector algorithm of earthquakes are shown in Table 2 in a similar format to Table 1. Its functioning has been intermittent due to the irregular financial support for its service.

SASO Earthquake Range Algorithms

The seismic activity in Oaxaca is high; the structure of its subduction zone makes the depth of the foci variable, increasing in terms of the distance to the Pacific coast. As a result, to the north of its territory and at the Tehuantepec isthmus region, hazardous earthquakes occur at depths larger than 100 km. On the other hand, many catastrophic intermediate-foci earthquakes have occurred under the Oaxaca central region and the Valley of Oaxaca, where the capital city is located. This circumstance made it necessary to develop better algorithms for the SASO, to reduce the time needed to determine the hierarchy of the warning to be issued and to provide longer times to mitigate the earthquake effects.

To optimize the opportunity time of the SASO alert warnings, along the coastal region where the seismic epicenters occur at depths shallower than 40 km, it was necessary to adjust the original SAS criterion developed for Guerrero so that, within a time period of $T_{SAS} = 2(t_S t_P)$ the energy reached can be defined as its growth rate, as indices of seismic risk. With such an objective in mind, two efficient new algorithms were designed for time handling whose simultaneous functions at the FS located at the central, north, and isthmus regions of Oaxaca has made it possible to determine and relay the hierarchy of the SAS warnings, public alert for strong earthquakes or preventive alert for moderate earthquakes within a maximum period of three seconds. After the beginning of the *P*-wave phase, the first method, based in a least squares regression model (Cuellar and Ramos 1999), analyzes and calculates the following fac-

It may be advisable in the future modernization plans that the SAS is currently pursuing (Espinosa-Aranda 1995; 2009, this issue) to replace the current accelerometers with modern strong-motion sensors, which offer a much wider frequency band and a larger dynamic range. The inaccuracy observed in the estimation of magnitude may be partly due to the algorithm used and partly to the limited fidelity of the instruments deployed by SAS. Apparently, some records are clipped early on during the earthquake generating process due to the instrumentation used. This assessment is difficult to make in a systematic manner, as the strong motion records generated by SAS are not openly available. The use of high-fidelity accelerometers in the future would also provide an invaluable database for scientists and engineers studying the seismicity of the Mexican subduction zone. Current instrumentation makes the records of little use outside SAS.

In terms of its geographical distribution, the current deployment of sensors covers the area of the subduction zone identified as the Guerrero seismic gap, immediately to the southeast of the rupture of the 1985 Michoacán earthquake (Figure 1). At the time when the SAS was designed, this segment of the subduction zone was considered to represent the fault zone with the highest potential to generate a large and damaging earthquake. Twenty-five years after the 1985 event, this statement is less evident, and today it may be advisable to increase the coverage of the SAS farther to the northwest, toward the rupture of the 1985 event, and to the southeast into northwestern Oaxaca (Figure 1). Historical data indicate that earthquakes producing high intensities in Mexico City occur in the segment of the subduction zone from the region where the 1985 event was located to the border between the states of Guerrero and Oaxaca, on the southern edge of where the current SAS sensors are located (García Acosta and Suárez 1997). Subduction earthquakes farther from this segment of the subduction zone have not produced intensities greater than MMI = 5 in Mexico City (*e.g.*, Figueroa 1987). Hence, subduction events outside of this area are not important from the point of view of an earthquake early warning seismic system targeted for Mexico City.

For an earthquake early warning system to be effective, the time available between the broadcasting of the warning and the arrival of the first destructive seismic waves should be as long as possible. As discussed before, Mexico City has a unique and very advantageous situation in this respect. If the SAS were to broadcast a single type of alert, it should also reconsider the algorithms used. Several researchers have recently proposed various algorithms for this purpose (Allen and Kanamori 2003; Espinosa-Aranda *et al.* 1989; Nakamura 1988; Wu *et al.* 1998; Wu and Kanamori 2005).

The broadcasting of a single alert for potentially damaging earthquakes and the avoidance of issuing alerts for small earthquakes that are hardly felt by the population may be considered as one of the future goals of the SAS. Recently, Iglesias *et al.* (2007) proposed the use of an algorithm that relates the mean-square acceleration in SAS recording stations to the expected acceleration of a reference strong-motion sensor in the outskirts of Mexico City, outside the area of soft lakebed deposits. The results presented by these authors show a high degree of reliability in identifying potentially destructive earthquakes. Furthermore, the algorithm of Iglesias *et al.* (2007) avoids the pitfalls and challenges of estimating magnitudes in the near field. The successful operation and performance of the SAS to date could be improved with better, high-fidelity instrumentation and a more effective detection algorithm that weans out small events that are of no consequence to the mission of an earthquake early warning system.

EVALUATION ON THE SOCIAL IMPACT OF SAS AND THE ASSOCIATED PUBLIC SAFETY MEASURES

The most notorious deficiency of the SAS is not in its technical operation and performance. The most evident and important shortfall is the very limited number of registered users and the lack of a public safety program that promotes the distribution and responsible use of the seismic alert system for civil protection purposes. After almost 18 years of operation, the SAS has only 230 registered users; 25 are radio and television broadcasting stations, 76 are schools of all levels, 12 are emergency and civil protection agencies, four are offices of the subway system, 79 are government offices, 33 are private institutions, and only one is a residential building. Considering the size of Mexico City these figures are disappointingly low (Figure 2).

Among the major limitations in increasing the number of users of the SAS are probably the high cost of the receivers used and the maintenance fees involved. Recently, the SAS has proposed the use of low cost radios similar to those used to receive weather information and warnings, which represent a low initial investment, are easy to install, and require essentially no maintenance.

In particular, the fact that only 76 schools out of a population of approximately 5,500 schools in Mexico City are using the SAS is totally inadequate. Schools should be the primary users of an earthquake early warning system. They are well-structured organizations with a stable population; under current law, all schools should have drills in case of emergencies. Schools represent a massive concentration of people and the 40 to 50 seconds available to evacuate them in an orderly fashion could represent a crucial element in saving lives in the case of a destructive earthquake. Recent earthquakes in China and Italy provide the best example of the value of giving schools the best tools and information to protect students in case of emergencies.

The same statement could be made about organizations responsible for dealing with emergencies and civil protection. As an example, Mexico City has 16 counties, and each one of them has a civil protection office. To this number, one may add the number of police stations and fire departments, which could benefit from a seismic alert and the design of adequate operational procedures to take in case of an emergency. The fact that only 12 offices responsible for civil protection take advantage of this early warning system is unacceptable.