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Searching for Near-Earth Asteroids with the UK Schmidt Telescope at the AAO

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Abstract. Since 1990 we have operated a program in which all plates and films exposed at the 1.2 m U.K. Schmidt Telescope (UKST) are searched for suspicious trails that may represent fast-moving (Earth-approaching) objects. When a possible near-Earth asteroid is discovered, we obtain follow-up astrometric positions using photography on either the UKST (if the object is faint) or the 0.5 m Uppsala Southern Schmidt at the same site. Further astrometric positions, once a reasonable ephemeris is available, are obtained with a large-format CCD on the 40 inch telescope of the Siding Spring Observatory (SSO).

In the near term we plan to extend our use of the UKST making use of time near bright-of-moon when the telescope is currently underused. We will conduct photographic searching by taking dedicated films in pairs of 5–10 minutes exposure, with 30–60 minutes gaps between. These will then be inspected using electronically blinked video cameras to scan the films and look for objects that have moved between the exposures. We believe that we can better than triple our current discovery rate (which is about 8–10 near-Earth asteroids per year) in this way.

In the longer term clearly the installation of a mosaic of CCDs covering some reasonable fraction of the UKST focal surface is a desideratum, and this is under consideration.

1. Introduction

Near-Earth asteroids (NEA's, apparently refractory bodies larger than ~10 m with perihelia $q<1.3$ AU) are of interest for a number of reasons. It appears that these comprise the major fraction of the cratering flux of bodies to the Earth (Shoemaker 1983; Olsson-Steel 1987; Wetherill 1989; Shoemaker et al. 1990; Weissman 1990; Bailey 1991), so that they may pose the predominant impact hazard to mankind (Chapman & Morrison 1994; Gehrels 1994), active comets representing a minor fraction of the macroscopic influx. Apart from being possible terrestrial impactors, NEA's are of interest for other scientific reasons, and as spacecraft targets of opportunity. Objects with small ΔV's are particularly

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important since these are the most accessible objects in the solar system, being easier to reach (and possibly mine) than the lunar surface (Lewis et al. 1993).

There are three broad dynamical divisions within NEA's. *Apollo* asteroids have semi-major axes $a>1$ AU and orbits which cross that of the Earth ($q<1.0167$ AU). *Atens* also cross the Earth's orbit, having aphelia $Q>0.9833$ AU, but have $a<1$ AU. *Amor* asteroids currently have $1.0167<q<1.3$ AU, but in the longer term ($\sim10^4$–10^6 yr) it is possible that some of these will evolve into Earth-crossing orbits, making impacts possible. Similarly there are various outer solar system objects that may evolve into Earth-crossing orbits (Hahn & Bailey 1990; Asher & Steel 1993), and 5335 Damocles, with $q\simeq1.65$ AU, may be representative of a class of objects which could constitute a large fraction of the Earth-cratering bodies (Steel & Asher 1992; Asher et al. 1994). As of yet no asteroids with orbits entirely within that of the Earth have been discovered (Cytherean asteroids), and even if these exist their observation would be very difficult (Hodgson 1981); even more intractable would be searches for asteroids interior to Mercury (Vulcanian asteroids: Leake et al. 1987).

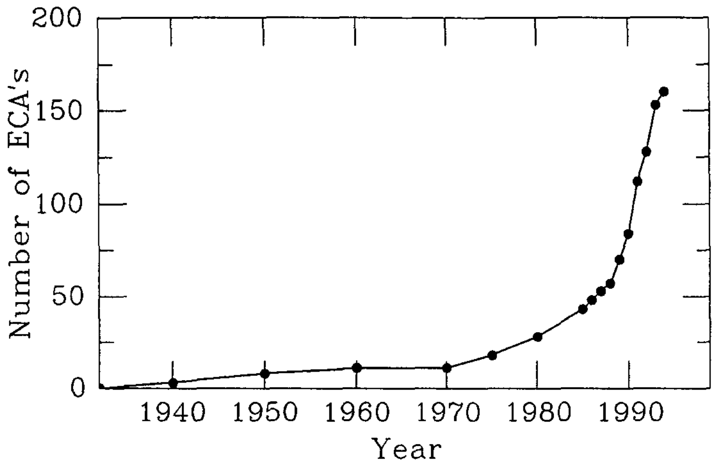

Figure 1. The history of discoveries of Earth-crossing asteroids. The cumulative number of ECA's (Apollos and Atens) with reasonably well-determined orbits is plotted against the year. The upturn in the 1970's was the result of the start of the first dedicated search program. The rapid increase in the last five years is due to: (i) greater effectiveness of the two programs using the Palomar 0.46 m Schmidt, largely due to the use of Kodak Tech Pan film; (ii) the initiation of the *Spacewatch* program; and (iii) the start of the *AANEAS* program described in this paper.

Towards the end of the nineteenth century a few Amors were discovered, but since little was known at that stage about the orbital evolution of such objects they were not perceived as being a hazard to mankind. However, after three Earth-crossing asteroids (ECA's: Apollos and Atens) were discovered in

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the 1930's it was realized that these objects must cause catastrophes on the Earth from time to time (e.g. see Watson 1941; Nininger 1942; Baldwin 1949), but nevertheless no specific search for NEA's/ECA's was carried out until the 1970's. From time-to-time an NEA would be picked up by chance on a Schmidt plate somewhere (in particular on the 48 inch Palomar Schmidt, the twin of the UKST) and then followed up so that its orbit could be determined, but through to 1970 the world-wide discovery rate was only ~1 per year.

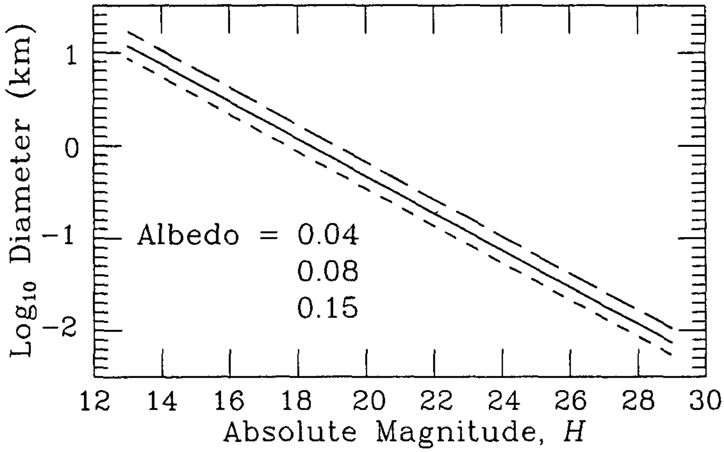

Figure 2. Diameter–absolute magnitude (H) relationship for three characteristic asteroidal albedos, using the expression of Rowe (1993). H is the apparent magnitude of an object if it were 1 AU from the Earth, and 1 AU from the Sun.

As shown in Fig. 1 there was a gradual upturn in the number of known ECA's/NEA's starting in the early 1970's when the Planet-Crossing Asteroid Survey (*PCAS*) began at Palomar using the 0.46 m Schmidt. This was initiated by E.M. Shoemaker and E.F. Helin and is continued by the latter (Helin & Shoemaker 1979; Helin & Dunbar 1990; Helin 1992). In the early 1980's E.M.Shoemaker, with C.S. Shoemaker, began the Palomar Asteroid and Comet Survey (*PACS*), still searching for NEA's with the 0.46 m Schmidt but additionally concentrating on more distant objects such as Trojans (Shoemaker & Shoemaker 1988). Both programs make use of short-exposure stereoscopic pairs of photographs to identify moving objects. The limiting magnitude of the *PCAS* and *PACS* programs is $V \simeq 17$, corresponding to a size of a few hundred metres if at a distance of ~1 AU (see Fig. 2). Area coverage for each is 40–50,000 square degrees per year. The effectiveness of these programs has been much improved from the latter half of the 1980's due to the utilization of Kodak Tech Pan film, which is superior to the emulsions used previously (Phillipps & Parker 1993; Parker et al. 1994).

Recognizing the potential of electronic detectors for near-real-time data analysis and thus the detection of moving objects, throughout the 1980's T. Geh-

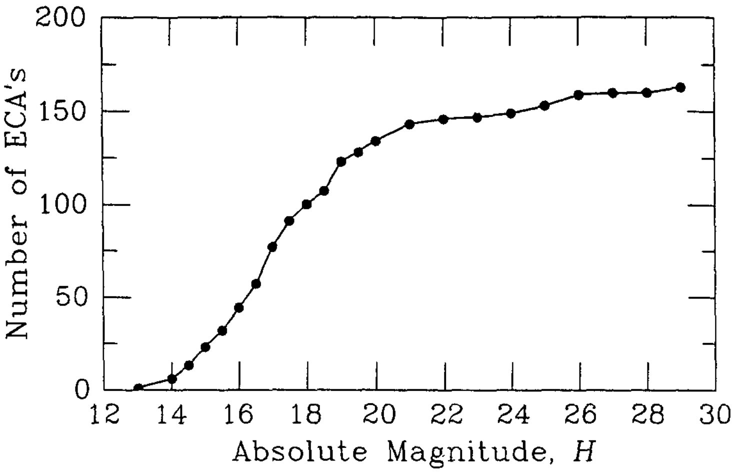

Figure 3. Cumulative number of known ECA's as a function of absolute magnitude, H.

rels developed a system at the University of Arizona based upon a CCD chip mounted on a 36 inch aperture long-focus telescope. This system is called the *Spacewatch Telescope* (Gehrels 1991; Rabinowitz 1991; Scotti et al. 1992). Its main innovative feature is the use of sky-scan mode: the right ascension drive is switched off so that the sky is swept at the sidereal rotation rate, with the CCD being read out at the same rate. In this way a swathe is scanned across the sky, with triple scans allowing any moving object to be identified. Apart from adding to the inventory of large NEA's of sizes from a few hundred metres to several kilometres, which now stands at about 280 in all, the *Spacewatch* system has also proved itself to be uniquely able to pick up very small asteroids, rendering our first detections in space of bodies much smaller than ~100 m. The *Spacewatch* data have been very important in defining the size distribution of 10–100 m bodies, about which previously very little was known (Ceplecha 1992; Rabinowitz 1993). With a limiting apparent magnitude of $V \simeq 21$ (occasionally reaching 21.5), the *Spacewatch* telescope is sensitive to much fainter objects than *PCAS* and *PACS*, but with lesser area coverage. Several objects as small as ~10 m in size have been found passing very close by the Earth, these being the intrinsically-faintest celestial objects ever detected telescopically. The record to date is held by 1993 KA_2, which missed the Earth by ~150,000 km in 1993 May (*Minor Planet Circular 22414*). This object had absolute magnitude $H=29$.

The known ECA's show a roughly linear increase in their number as a function of absolute magnitude from $H=13$–19 (Fig. 3), with a levelling off thereafter since the fainter ECA's are only presently detectable by *Spacewatch*, and the observations using that telescope began only five years ago.

The three NEA search programs described above are all based in the northern hemisphere. The first southern hemisphere program, which is the subject of this paper, started operations in 1990. Before describing that program, we first mention another asteroid survey making use of UKST data.

2. The Lowell Observatory–UKST Asteroid Survey (*LUKAS*)

Starting in the late 1980's, *LUKAS* was predominantly oriented towards the establishment of an unbiased main-belt asteroid (MBA) sample. UKST plates taken in the direction of the ecliptic near opposition, with the telescope tracked at the angular rate of MBA's at specific heliocentric distances, reveal up to ~2400 individual MBA's (under ideal conditions; 800–1600 MBA's is more usual), whereas untracked plates produce up to 400 MBA trails; there is a ~2 mag gain produced by tracking. Automatic scanning of the tracked plates makes it possible for statistical orbital parameters to be determined for each sample, and thus a model of the asteroid belt orbital and size distributions to be derived (Russell & Bowell 1990). Full orbits would be available if follow-up plates were taken spread over a few months.

Whilst the above main aim of *LUKAS* continues, a more recent development has been investigations of the use of the UKST in a search for distant (slow moving) solar system objects.

3. The Anglo-Australian Near-Earth Asteroid Survey (*AANEAS*)

From its commissioning in 1973 through to the end of 1989, five NEA's had their orbits determined as a result of detections on plates taken routinely with the UKST at SSO. NEA's may appear essentially anywhere in the sky, so this was not a question of the appropriate observations not being obtained (although any discovery shot would need to be followed up in order for an orbit determination to be made). The number of discoveries was limited by the unavailability of staff to scour the plates soon after they were exposed, coupled with the prevalent view that such searches would be of little scientific value.

Recognizing this, in 1990 we began a new program whereby all plates and films taken with the UKST are inspected under binocular microscopes in order that the tell-tale trails produced by asteroids might be identified (Steel & McNaught 1991; Steel et al. 1992b). Typical UKST exposures are 60–180 minutes long, and are conducted as part of various sky surveys. During that time a MBA will have appear to have moved by about 1 arcmin, whereas a NEA may have moved through 3 arcmin or more, allowing (in principle) a distinction to be drawn between such objects from single exposures taken for other purposes. In addition, MBA's have a motion predominantly in ecliptic longitude and very little ecliptic latitude motion, whereas NEA's may have essentially any orientation to their angular motion vectors: see Scotti et al. 1992 and Rabinowitz (1993).

The limiting asteroidal magnitude for UKST plates is typically around V=19, with about three magnitudes being lost from the stellar magnitude limit due to trailing. Since we have no control over the filter/plate/film combination used, some exposures do not reach such a limiting magnitude (e.g. near infra-red plates), but nevertheless are searched as time allows. The total sky coverage is about 40,000 square degrees per year: 800–1000 plates/films are taken each year, each covering a segment of the sky about 6.6 degrees to a side.

The aim of the *AANEAS* program, then, is to identify trails on UKST plates which may be due to NEA's. Any such object is normally identified within 24 hours of the original exposure, allowing follow-up the next night using either the 0.5 m Uppsala Southern Schmidt Telescope (which has a limiting magnitude $V \simeq 17$) or a repeat exposure using the UKST (for fainter NEA's). Once the ephemeris of a newly-discovered NEA is sufficiently well-known, observations continue with the 40 inch Cassegrain reflector at SSO, using a 2048 × 2048 pixel CCD which covers ~20 arcmin. Dependent upon various factors we can obtain astrometric positions for NEA's to $V \simeq 21.5$ with that instrument.

4. *AANEAS* discoveries to date

The number of asteroids in Mars-crossing or otherwise interesting orbits is too many to sensibly list here. Table 1 shows the NEA's discovered as a result of the *AANEAS* program. Of these, all but 1990 SA, 1990 SM, 1991 FB and 1991 RB have reasonably secure orbits. Those four were discovered in the early stages of *AANEAS*; since we have been using the SSO 40 inch telescope for follow-up we have been able to ensure that none of our discoveries are lost. Equally well, we have been responsible for securing the orbits of NEA's discovered elsewhere.

Table 1. NEA's discovered in the *AANEAS* program.

	Apollos		
4953 1990 MU	1990 SM	5645 1990 SP	5189 1990 UQ
1991 CS	1991 DG	1991 RB	5786 1991 RC
1991 VH	1991 WA	1992 HA	1993 KH
1993 UC	1993 VA	1993 VB	1994 AH_2
	Atens		
5604 1992 FE			
	Amors		
1990 SA	1991 CQ	1991 FB	1992 NA
1992 TC	1992 UB	1993 BW_3	1993 BX_3
1993 HO_1	1993 UB		
	Lost NEA's rediscovered		
4775 1927 TC	5496 1973 NA		

Apart from the above, eight comets have been discovered in the *AANEAS* program. One of these is 1990 XXII (McNaught-Russell), which has the record perihelion distance for any known long-period comet of ~7 AU. Another comet of note is 1993v (also McNaught-Russell), which is expected to be one of the brighter comets of 1994. This comet was soon realized to have a period of 1400–1500 years, meaning that it was feasible that it was observed in the sixth century.

A possible set of early observations from A.D. 574 has now been identified (*IAU Circular 5943*).

Another significant discovery is 5335 Damocles (formerly 1991 DA). This 7–15 km object is classified as an asteroid, and shows no cometary activity (Steel et al. 1992a), but nevertheless has an orbit diagnostic of being a Halley-type comet (Asher et al. 1994). It crosses the orbits of the planets Mars, Jupiter, Saturn and Uranus, and has the third highest eccentricity of any known asteroid, and the fourth highest inclination.

One lesson to be learnt from *AANEAS* is that the various wide-field telescopes which are currently in use are producing photographs which undoubtedly record unknown NEA's, and substantially these remain unrecognized (see McNaught et al. 1994). Occasionally observers at such telescopes are able to report NEA discoveries, but to a great extent the plates taken are not rigorously searched for NEA trails due to shortages of personnel. The plate libraries of such telescopes also represent a bounteous source of NEA detections; for example it is estimated that the ~14 000 plates taken with the UKST prior to 1990 may contain at least 200–250 NEA images which would be of use for orbit determination when the particular NEA's are next detected (i.e. when they are actually discovered). We are actively checking for such detections in the case of each new NEA discovery, whether made as part of the *AANEAS* program, or elsewhere. In addition, scanning of the UKST plate library is now being carried out with the COSMOS machine at the Royal Observatory, Edinburgh (ROE), so that many asteroid images may be automatically catalogued over the next few years.

Two particular cases of object recognition on old UKST plates are worthy of mention here, both discoveries resulting from searches of plates in the library at ROE by R.H. McNaught in 1993. The first is Amor-type asteroid 1977 QQ_5. McNaught was looking for an image of a recently-discovered asteroid on a plate taken in 1977, having done a backwards-integration of its orbit. By chance, nearby he found a trail which was clearly due to a NEA which had not been noticed at the time the plate was exposed. Orbit solutions based on this single trail suggested that an Amor-type orbit was most likely. Using such a sample orbit, the UKST plate log was searched and two plates taken 52 and 59 days later were flagged as possibly containing the asteroid. The asteroid was found on both plates about two degrees from the prediction and the resulting orbit allowed a fourth trail to be found giving a total observed arc of 138 days. With the knowledge of the orbit derived from those positions, we are hopeful that we will be able to recover 1977 QQ_5 in 1995.

The second, Comet 1978 XXVII (McNaught-Tritton), has an even more intriguing story behind it. In 1992 McNaught found a comet image on a UKST plate taken in 1978 (*IAU Circ. 5471*). In 1993 at ROE he managed to find an image on another plate. These two positions were linked by B.G. Marsden (Harvard-Smithsonian Center for Astrophysics) with another single-night comet detection found by S.B. Tritton (ROE) on a 1979 UKST plate. Those three positions rendered a reasonable parabolic orbit, allowing Tritton to find a fourth image on a 1980 UKST plate, following which the orbit could be determined (*IAU Circ. 5866*).

5. *AANEAS* expansion

All *AANEAS* discoveries to date have been made using UKST plates/films taken for other purposes. Whilst NEA's may appear anywhere in the sky, the optimal search region is near opposition and close to the ecliptic (Bowell & Muinonen 1994), although this is also the region where most MBA's appear. Only a small fraction of UKST plates are taken in that region.

For 6–8 days over the bright-of-moon period, when films and plates are fogged by the sky background for any exposure more than 10–20 minutes long, the UKST is not normally operated. However, long exposures are not necessary for asteroid detection: once the angle moved by a NEA within an exposure exceeds the size of the seeing disk, no emulsion density enhancement occurs. Thus it is possible to duplicate the type of observation made by the *PCAS* and *PACS* teams (i.e. separated 5–10 minute exposures to produce pairs), but with a limiting brightness two magnitudes fainter being attainable with the UKST. At the current time test exposures are being made, and a large blink comparator (using electronic rather than optical blinking) is being readied. We plan to implement this program during 1994, and we anticipate that a discovery rate of NEA's in excess of 30 per year is feasible. The use of Kodak Tech Pan 4415 film in this phase, as opposed to the glass-based emulsions still used for the completion of various UKST sky surveys which have hitherto provided most of our search material, should add to the effectiveness of our operations (*cf.* Parker et al. 1994).

The nest step to be taken in the utilization of Schmidt-type telescopes in NEA searches is the installation of CCD mosaics on the focal surface of these instruments. Because of the small size of CCD chips currently available (mostly smaller than ~8 cm in dimension) compared to the large fields of Schmidts (over 36 cm in the case of the UKST), it is not yet possible to fill those fields with CCD's; the curved focal surface also leads to coupling problems with planar CCD's. Nevertheless, this is clearly the next step in increasing the productivity of Schmidts with respect to NEA detection and follow-up. A CCD is now being implemented on the 0.9 m OCA Schmidt in France and used for asteroid observations (Maury 1994). A 0.58 m Schmidt at the Lowell Observatory is currently being equipped with a four-chip CCD camera which should attain a limiting magnitude of V=19.3, with a predicted discovery rate of ~80 ECA's per year (Bowell & Muinonen 1994). The installation of such a CCD mosaic is currently under consideration at the UKST for other astronomical purposes.

6. The *Spaceguard* plan

Despite the rapid rise in the ECA discovery rate over the past few years, the current search programs would not result in completeness of discovery down to 1 km diameter objects on a time-scale of less than some centuries. Because of this, and the recognition that asteroid/comet impacts pose a substantial hazard to mankind, in 1991–92 an international committee under NASA auspices produced a report describing how the discovery rate could be increased so as to allow at least 99% of such objects to be found and tracked within 20–25 years (Morrison 1992).

That report recommended a network of at least six dedicated telescopes to be spread over the globe in order to access the whole sky at all times. These instruments were designated to be fast ($f/1.5$ to $f/2$), and about 2.5 m in aperture although larger instruments are to be preferred. These would be driven across the sky at up to 10–12 times the sidereal rate, with CCD mosaics in their focal planes being read out at the same rate as the scanning occurs. By scanning each strip across the sky three times, moving objects can then be identified and followed up. This concept is based upon a scaling-up of the techniques developed in the *Spacewatch* telescope, discussed earlier.

Spaceguard as planned would concentrate on the region near opposition, at ecliptic latitudes of $\pm 30°$, and longitudes $\pm 60°$ from the anti-solar direction. This region would be covered at least monthly and at least to magnitude 22 (see Bowell & Muinonen 1994). Clearly if this program were to go ahead it would have implications for sky surveys concerned with other astronomical phenomena.

Any asteroid or short-period comet on a terrestrial collision course would most likely be found with several orbits warning before the impact. However, it has also been suggested that the threat from long-period comets would justify an extension to magnitude 24 or fainter (Marsden and Steel 1994), requiring two fast 4 m-class telescopes covering all higher latitudes on an annual basis so that impactors from such orbits would be found some years before the presumed collision.

Acknowledgments

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Discussion

Peterson: You imply that finding an asteroid that will hit the earth will prevent the damage, but if you found one tomorrow, nothing could be done.

Steel: This assertion is entirely in error. If an asteroid was discovered tomorrow which was identified to be on a collision course with the earth, the overwhelming probability is that the impact would not be due for some years, allowing ameliorative actions to be taken. About 40–50 % of earth-crossing asteroids will end their lives by hitting our planet, with individual lifetimes of $\sim 10^7$ yr, the impacts occurring essentially randomly with time. The threshold for global effects (killing $> 25\,\%$ of the population and likely inducing a Dark Age) is a $\sim$ 1 km asteroid. Such impacts occur about once every 10^5 yr, and it is the discovery of these which is the aim of the Spaceguard project. With suitable astrometry the orbits of such bodies may be followed forwards for 100–200 years. Taking 100 years as the interval of interest, there is a chance of about one in a thousand that an asteroid will be found which will impact the earth within that time. Even if the minimum response time is 5 years, then there is a 95 % chance that an identified risk can be dealt with (i.e. the asteroid deflected). Further, the *a priori* expectation of expenditure is $100 million (i.e. about one third of the cost of the search programme). The actual deflection process is relatively straight forward, requiring an impulse to be applied near aphelion, giving a velocity change of a few mm/s. Should the impact hazard be taken seriously? The time averaged death rate is greater than that which would result from the catastrophic loss of a full jumbo jet every week, with economic consequences being equivalent to about five jumbo jets per week being lost. That should be considered seriously and not flippantly.

Isobe: Please add several words relating to the international network to transfer information of new discoveries of near-earth objects, in order to make follow-up observations efficient.

Steel: There is already a suitable network in place, with the Minor Planet Electronic Circulars providing rapid dissemination of news of recent discoveries. There is also direct contact between groups making discoveries or performing follow up astrometry. All others wanting to become involved would be very welcome. At present there is only a handful of groups assisting in this way.